Tony Schwarber
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ANC–23
Feb. 1951

Sandwich Construction For Aircraft

Part I

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

MUNITIONS BOARD
AIRCRAFT COMMITTEE

ANC–23 BULLETIN

Sandwich Construction For Aircraft

Part I

Fabrication, Inspection Durability and Repair

DEPARTMENT OF THE AIR FORCE
AIR MATÉRIEL COMMAND

DEPARTMENT OF THE NAVY
BUREAU OF AERONAUTICS

DEPARTMENT OF COMMERCE
CIVIL AERONAUTICS ADMINISTRATION

(Edition February 1951)

ISSUED BY THE SUBCOMMITTEE ON AIR FORCE-NAVY-CIVIL AIRCRAFT DESIGN CRITERIA
OF THE MUNITIONS BOARD AIRCRAFT COMMITTEE

THIS BULLETIN

Prepared By

FOREST PRODUCTS LABORATORY
FOREST SERVICE
UNITED STATES DEPARTMENT OF AGRICULTURE

and by

ANC-23 PANEL ON SANDWICH CONSTRUCTION FOR AIRCRAFT
SUBCOMMITTEE ON AIR FORCE-NAVY-CIVIL
AIRCRAFT DESIGN CRITERIA

AIRCRAFT COMMITTEE
MUNITIONS BOARD

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NOTICE

The reader is hereby notified that this bulletin is subject to revisions and amendments when and where such revision or amendment is necessary to effect agreement with the latest approved information on fabrication, inspection, durability, and repair of sandwich construction for Aircraft. When using this document, the reader should therefore make certain that it is the latest revision and that all issued amendments, if any, are included therein. When ordering this document from the Superintendent of Documents, U. S. Government Printing Office, a request for all revisions and amendments thereto should be made to insure receipt of a complete bulletin.

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Navy Model F7U jet-propelled fighter plane featuring sandwich skin.

CONTENTS

CHAPTER 1

INTRODUCTION

1.0. Purpose and Scope of Bulletin

This Part I of ANC–23 Bulletin has been prepared for information in connection with the fabrication, inspection, durability, and repair of sandwich assemblies for both military and commercial aircraft. Part II consists of design criteria for sandwich construction.

The technical material in this bulletin is based principally on data obtained in tests conducted at the U. S. Forest Products Laboratory, supplemented by that obtained in a survey of current sandwich design and fabrication methods in United States aircraft plants.

1.1. Acknowledgment

The ANC–23 Panel on Sandwich Construction of the Air Force-Navy-Civil Subcommittee on Aircraft Design Criteria and the Forest Products Laboratory express their appreciation to aircraft manufacturers and others for the valuable assistance given in connection with various parts of this bulletin. Special acknowledgment is made to the following aircraft manufacturers and material suppliers who contributed information and illustrations: Aircraft Specialties Co., Hicksville, N. Y.; Bell Aircraft Corp., Niagara Falls, N. Y.; Bloomingdale Rubber Co., Chester, Pa.; Boeing Airplane Co., Seattle, Wash.; B. B. Chemical Co., Cambridge, Mass.; California Reinforced Plastics Co., Berkeley, Calif.; Consolidated Vultee Aircraft Corp., San Diego, Calif.; Cornell Aeronautical Laboratory, Inc., Buffalo, N. Y.; Chance Vought Aircraft Division, United Aircraft Corp., Dallas, Tex.; Chrysler Cycleweld Division, Detroit, Mich.; CIBA Co., Inc., New York, N. Y.; Douglas Aircraft Co., Inc., El Segundo, Calif.; Durez Plastics and Chemicals, Inc., North Tonawanda, N. Y.; East Coast Aeronautics, Inc., Mount Vernon, N. Y.; Fairchild Guided Missiles Division, Fairchild Engine and Airplane Corp., Farmingdale, N. Y.; Glenn L. Martin Co., Baltimore, Md.; B. F. Goodrich Co., Akron, Ohio; Goodyear Aircraft Corp., Akron, Ohio; Hamilton Standard Propellers Division, United Aircraft Corp., East Hartford, Conn.; Industrial Plastics Co., Gardena, Calif.; Lockheed Aircraft Corp., Burbank, Calif.; Monsanto Chemical Co., Springfield, Mass.; Narmco, Inc., San Diego, Calif.; North American Aviation, Inc., Inglewood, Calif.; Owens-Corning Fiberglas Corp., Newark, Ohio; Pacific Laminates, Costa Mesa, Calif.; Piasecki Helicopter Corp., Morton, Pa.; Republic Aviation Corp., Farmingdale, N. Y.; Rohm & Haas Recinous Products Division, Philadelphia, Pa.; Skydyne, Inc., Port Jervis, N. Y.; Sponge Rubber Products, Shelton, Conn.; United Shoe Machinery Co., Beverly, Mass.; U. S. Plywood Corp., New York, N. Y.; Western Products, Inc., Newark, Ohio; and Zenith Plastics Co., Gardena, Calif.

1.2. Sandwich Construction

1.20. Definition. The American Society for Testing Materials defines structural sandwich construction thus:

> "A laminar construction comprising a combination of alternating dissimilar simple or composite materials assembled and intimately fixed in relation to each other so as to use the properties of each to attain specific structural advantages for the whole assembly."

This definition is necessarily general. For aircraft application sandwich constructions are usually employed in structures as flat or curved panels. They are made of three or more laminations of widely dissimilar materials that can be considered to be homogeneous when bonded together. The function of the central layer, or core, is to separate the other layers or facings to obtain a panel that is sufficiently stiff to avoid elastic instability, and to support these facings, so that they will not become elastically unstable when highly stressed. Thus a sandwich panel is itself a structure that should be designed for the use to which it is to be put. Such panels are particularly useful in aircraft because of the possibility of utilizing light-weight core materials and thus obtaining strong, rigid panels of minimum weight.

The following is a list of a few typical production and experimental applications of sandwich construction in aircraft:

- Bulkheads.
- Control surfaces.
- Doors.
- Empennage skins.
- Floors.
- Fuselage skins.
- Hydraulic control panels.
- Partitions.
- Radio antenna housings.
- Radomes.
- Shear webs.
- Wing skins.

1.3. Illustrations and Trade Names

The use of detail drawings and other illustrations in this manual to show current construction practices does not constitute an endorsement by any Government agency of the methods and practices shown. Likewise, the mention of any trade name or proprietary product does not imply such endorsement.

1.4. Patents

Various aircraft manufacturers have employed sandwich constructions of different types, a few of which are covered by United States patents. This bulletin is issued with the warning that if the subject matter should be protected by United States patents or patent applications, this publication cannot be held to give any protection against action for infringement.

CHAPTER 2

MATERIALS

2.0. Core Materials

2.00. Descriptions, Densities, and Usual Forms. To permit an aircraft structural sandwich to perform satisfactorily, the core must transmit stresses and still conform to definite weight limitations. The stresses imposed on the core vary with the strength requirements of the sandwich over a wide range, depending upon the application (ref. 2–8 to 2–24); consequently, the allowable weight of the core must be adjusted to the use. Densities within the range of 0.05 to 0.25 specific gravity (3 to 16 pounds per cubic foot) have found use in aircraft, but the usual specific gravity is 0.13±0.03 (6 to 10 pounds per cubic foot).

Requirements other than strength frequently dictate the choice of the core material. For example, in radar or radio-antenna housing applications (ref. 2–9, 2–33, 2–41) properties such as the dielectric constant and rate of moisture absorption are of greatest importance, with strength, although important, being secondary.

For reference a partial list of manufacturers making commercial or experimental core materials follows. This list does not mean that any or all of the core materials made by these manufacturers are approved for use in aircraft. Inquiries concerning approval should be addressed to the applicable agency.

Aircraft Specialties Co.,
Hicksville. Long Island, N. Y.

California Reinforced Plastics Co., Inc.,
Berkeley, Calif.

Goodyear Aircraft Corp.,
Akron, Ohio.

Industrial Plastics Co.,
Gardena, Calif.

Glenn L. Martin Co.,
Baltimore, Md.

Lockheed Aircraft Co.,
Burbank, Calif.

Monsanto Chemical Co.,
Springfield, Mass.

Narmco, Inc.,
San Diego, Calif.

Rubatex Division,
Great American Industries, Inc.,
Bedford, Va.

Sponge Rubber Products Co.,
Shelton, Conn.

United States Plywood Corp.,
55 West Forty-fourth Street,
New York 18, N. Y.

Western Products, Inc.,
Newark, Ohio.

2.000. *Natural Core Materials.* The selection of natural core materials is confined to wood, principally balsa, with mahogany, spruce, and poplar being used for inserts and edge banding. Quipo, a low-density wood similar to balsa, has been considered, but because of inferior properties, as well as supply problems and availability, it has not been used commercially for cores.

2.0000. *Balsa.* Balsa, when properly selected, has excellent properties for core applications. It has been used both in the flat- and end-grain orientation. The first major application of sandwich construction in aircraft, the British Mosquito, used flat-grain balsa for the core, but for current uses in structural sandwiches the end-grain application is used almost exclusively. Navy Department Specification 39B9 (Aer) Balsa (for Sandwich Construction Core), covers Navy Bureau of Aeronautics requirements for this type material.

The primary reasons for the use of balsa as a core material are its characteristics of light weight, uniformly high compressive and tensile strength and moduli, retention of strength through wide ranges of temperature, ease of machining, and good bonding characteristics. Like any product of nature, these characteristics vary with growth conditions over a wide range. This means that proper selection, inspection, and grading of balsa are of utmost importance for aircraft use. Some of the defects that must be eliminated from the core are decay, compression failures, seasoning defects, wane, pith, large knots, and excessive slope in grain. Other natural blemishes that have no appreciable effect on strength, such as stain, bird's-eyes, small burls, and insect holes, are acceptable.

Another type of cellular structure peculiar to balsa, sometimes called "corcho," yields very low tensile-strength values parallel to the grain, and therefore material of this type is unacceptable for structural applications. Extensive investigations of the fiber characteristics of balsa have shown that corcho is actually natural balsa that has a specific gravity, on an air-dried basis, of less than 0.08 (5 pounds per cubic foot). This low-density balsa has very few long fibers and a large number of short, large-diameter fibers with very thin walls. It is therefore evident that corcho cannot be considered a defective type of balsa, but that it is rather balsa of low density. The "scratch test" is commonly employed to determine the presence of so-called corcho within a balsa stick. This test consists of drawing a thin, flat, blunt instrument, such as a dull knife or key, radially across the transverse end surfaces of a balsa plank. Corcho will rupture easily under slight pressure, which results in the removal of a portion of the wood that appears to be like pith, as shown in figure 2–1. This test, when applied to higher-density balsa, merely bends the fibers slightly at the end and never ruptures them. The test is rather crude, and as its success is dependent to a large extent on the manner in which an individual operator applies the test, the testing is normally done by one or two highly trained operators.

The specific gravity of balsa as a species, as well as within individual trees, varies over a wide range. Tests on a limited number of balsa sticks

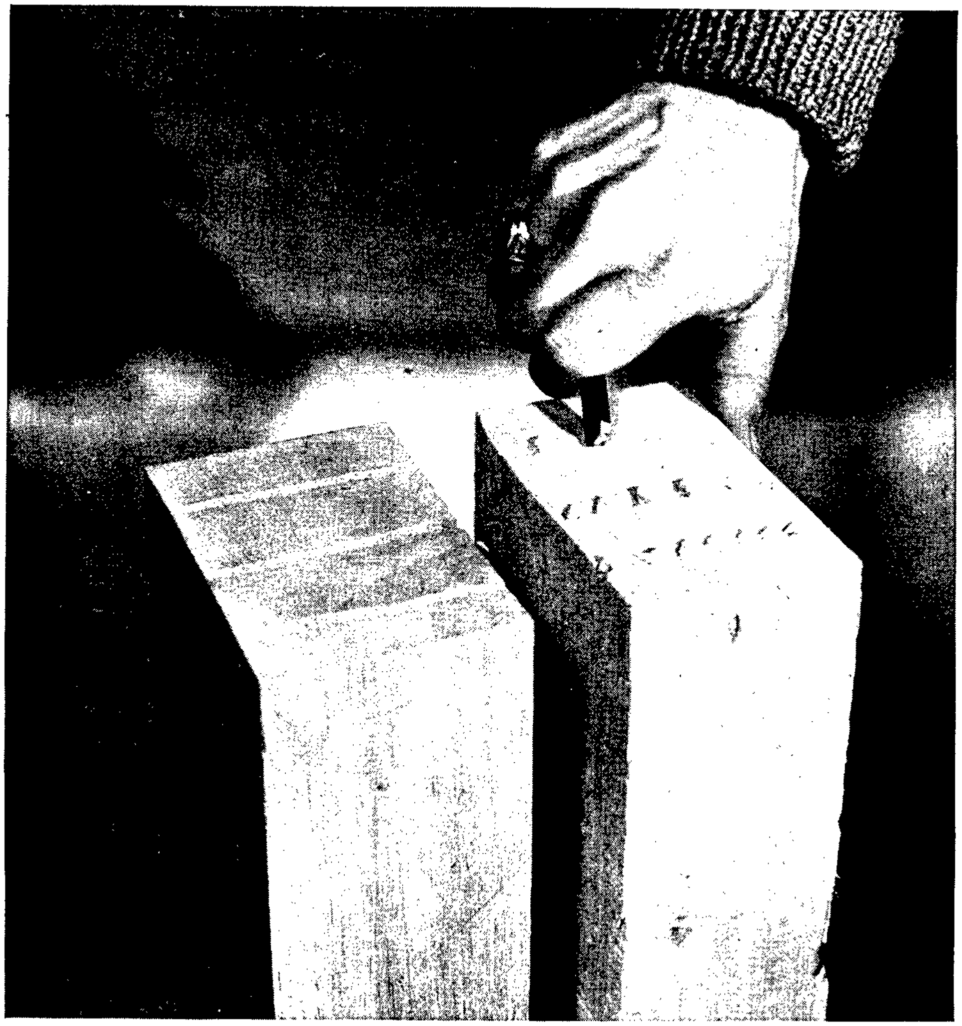

Figure 2–1. Low-density balsa ("corcho") ruptures easily when scratched with a blunt edge (right), while high-density balsa fibers merely bend (left).

selected at random have shown a range in specific gravity among individual sticks of 0.054 to 0.334 (3 to 21 pounds per cubic foot). Specific-gravity determinations of specimens cut from individual sticks have shown a variation of several hundred percent between adjacent growth rings. Also, within what appears to be a single growth ring, the density may vary considerably in a distance of a few inches in the tangential direction. Only slight variations in density have been found within one growth ring in the grain direction (longitudinal).

The density of balsa planks may be determined in several ways, the most common of which is based on weight and volume measurements of surfaced planks at a moisture content of 8 to 12 percent. Another method, which is considerably faster and appears to be sufficiently accurate, is by flotation. By this method a balsa plank of uniform cross section is carefully floated in a vertical position in a tank of water. The water in the tank sometimes contains a small amount of water-soluble dye to make the flotation mark easily visible. Density of the plank may be determined by the ratio of the wetted length to the over-all length, or can more quickly be found by laying the plank on a suitably graduated board such as is shown in figure 2–2. If the plank is allowed to remain in the tank only a few seconds, the moisture absorbed is negligible and the plank will dry quickly.

Balsa planks, after being inspected and graded for density, should be very accurately piled with stickers between the layers and with an air space between the individual planks in the layer. The storage space should be maintained at a relative humidity of 40 to 65 percent in order to maintain the moisture content in the balsa at about 8 to 12 percent.

2.0001. *Mahogany.* Certain portions of sandwich panels, such as points of attachment and exposed edges, sometimes require a high-strength insert. End-grain mahogany is often used at these points. The specific gravity of this mahogany, determined by weight and measurement of planed boards at 8 to 12 percent moisture content, is normally between 0.40 and 0.56 (25 and 35 pounds per cubic foot). The following defects are considered as having an adverse effect on the strength properties of mahogany as a core material and therefore are not permitted: decay, seasoning defects, unsound or loose knots, compression failures, and wane. Blemishes, such as mineral streaks, small knots, pinworm holes, and interlocked grain, are acceptable.

2.0002. *Spruce.* As a substitute for mahogany for high-density core inserts, end-grain spruce has sometimes been used. Its relatively poor machining properties across the grain and the difficulty in bonding to the end-grain surfaces have

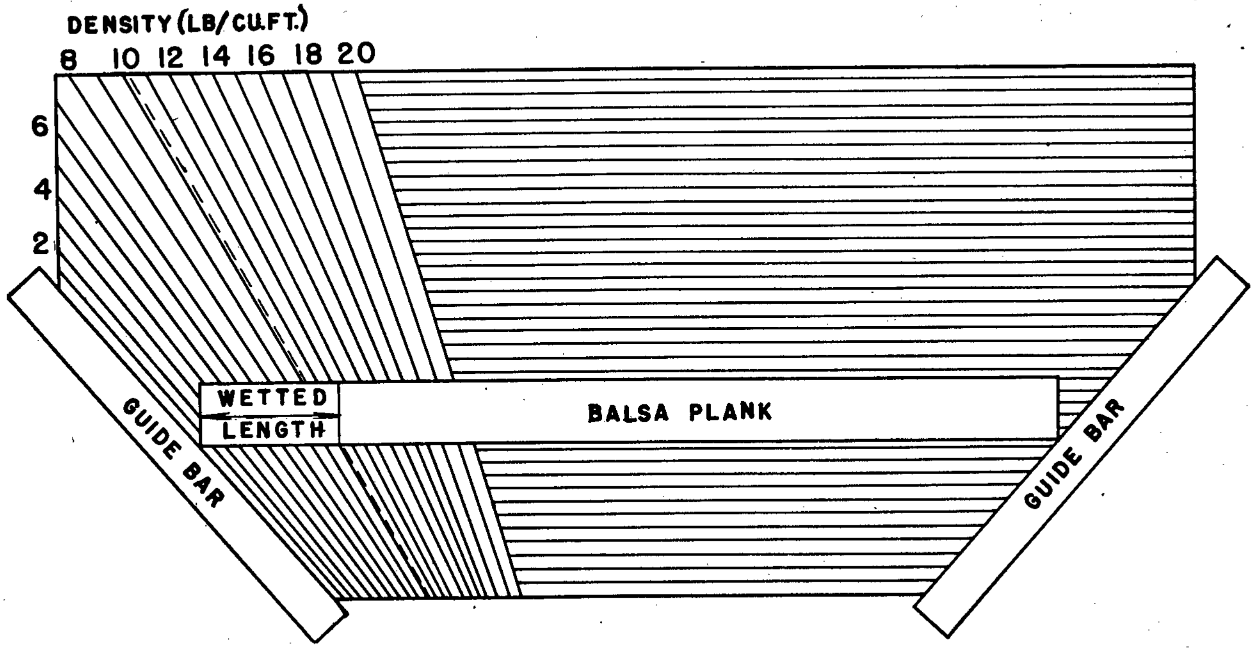

Figure 2–2. Graduated board for determining density of balsa by flotation method. The balsa plank shown in the example has a density of 10¼ pounds per cubic foot.

definitely limited its use to an occasional experimental or emergency application.

2.0003. *Poplar.* End grain poplar is reported to have found limited use for core inserts. Its selection for density and quality should be similar to that for mahogany.

2.0004. *Plywood.* Edgings of sandwich panels sometimes include a band of plywood cut so that alternate bands of the surface to be glued to the facing are end grain. Ease of obtaining long strips of partially end grain material and its dimensional stability are reasons for the choice of plywood edgings.

2.001. *Foamed or cellular materials.* To overcome the principal disadvantages of all natural core materials, particularly undesirable variation in density and high moisture absorption, attempts have been made to develop synthetic core materials having satisfactory strength properties. All otherwise suitable base materials have too high a specific gravity when used as a solid mass; therefore they are foamed, expanded, or processed by other means to reduce the apparent density to the practical range. These expanding processes are subject to control; consequently, the properties of the resulting core material can be predicted and confined within relatively narrow limits. A description of some of the more promising low-density materials currently used follows.

2.0010. *Cellular cellulose acetate.* Cellulose acetate, which is prepared by acetylation of wood or cotton cellulose after being expanded to form a lightweight closed-bubble structure, has found many applications in lightly stressed aircraft sandwich structures. Early materials of this type were expanded between heated platens to form thereby elongated cells and a material having nonisotropic properties. More recently, an extrusion process has been adopted that produces a more nearly isotropic material that has essentially spherical cells. The inclusion of a small amount of very fine chopped-glass fiber improves the strength properties to a considerable degree, and the material commercially used should contain these glass fibers.

Cellular cellulose acetate is available in board form approximately ¾ by 5½ inches in cross-section, and in four specific-gravity classes ranging from 0.06 to 0.15 (4 to 9 pounds per cubic foot) before the skins formed in the extrusion process were removed. The density of each class was controlled within limits of ±0.016 specific gravity (± 1 pound per cubic foot). In addition to the sizes indicated, the material is also available in extrusions of any shape not exceeding 13 square inches in cross sectional area.

2.0011. *Expanded rubber.* Rubber, both natural and synthetic types, can be expanded and cured to form a hard closed-cell structure suitable for cores in certain types of aircraft sandwich application. The density after expansion can be controlled to reasonable limits within the approximate specific gravity range of 0.1 to 0.3 (6 to 19 pounds per cubic foot). The manufacture of expanded-rubber cores, usually referred to as "cellular hard rubber," falls into two classes: (1) fully cured in the form of slabs or loaves, and (2) expanded and cured in place between the facings of the sandwich.

The fully cured form of expanded butadiene-acrylonitrile hard synthetic rubber has been extensively used as core material for sandwich construction radomes, in densities ranging from 8 to 12 pounds per cubic foot. U. S. Air Force Specification R26603 covers U. S. Air Force requirements for this type of material. This construction produces a material that absorbs very little moisture.

Rubber cores expanded in place are sometimes used when the shape of the sandwich structure is such that it is impossible to form the facings around the core in the usual manner. Sandwich propeller blades are an example. The rubber material is inserted in the form of a partially cured dough and is completely expanded and cured to the proper density between the sandwich facings by use of suitable heating restraining dies.

2.0012. *Polystyrene.* Foamed polystyrene has been considered for core material, but tests on samples to date have shown it to be unacceptable. Owing to its extremely low density (1 to 2 pounds per cubic foot), the mechanical properties of foamed polystyrene are very low.

2.0013. *Foamed-in-place core materials.* In order to obtain the radiation-transmission characteristics desired, certain types of sandwich radomes require a sandwich construction with very homogeneous facings and core, together with tapering thickness of the sandwich, and very close control of facing, core, and sandwich construction thickness throughout. To obtain all of these characteristics, emphasis has been placed on the development of a core material that can be foamed-in-place between, and will adhere to accurately premolded laminated glass fabric base plastic facings. This type of core material, while not as strong as glass fabric honeycomb, offers advantages of uniform cell structure, elimination of core joints, thinner and more uniform bonding layer between facings and core, use of accurately premolded void-free inner and outer skins which can be readily inspected for defects before assembly, and greater flexibility in manufacture. Formulations based on combinations of alkyd resins and metatolylene diisocyanate (TDI) have proved to be most satisfactory for this purpose. Using these materials it has been possible to produce uniform density foams having density of 3 to 30 pounds per cubic foot, materials of a density of 10 to 12 pounds per cubic foot are most commonly used. In addition to their use in radomes, alkyd-diisocyanate foams have also been used to a limited extent for stabilizing hollow steel propeller blades and aluminum alloy control surfaces.

2.0014. *Other cellular plastics.* Many of the numerous synthetic resins, such as the phenolic, urea, or polyester types, can be mechanically or chemically foamed and cured to produce an expanded lightweight core material. While several of these foams have been made on a laboratory basis, none has shown sufficient promise to be offered on a commercial scale. Certain cellular thermoplastics, such as polymethyl methacrylate, polyvinyl chloride, and polyvinyl formal, have also been made experimentally, but have not shown sufficient promise to be used and produced.

2.002. *Honeycomb cores.* In the past few years increasing emphasis has been placed on cores made of sheet material fabricated in such a manner that when it is cut in cross section it presents a structure that resembles a bee's honeycomb. By varying the sheet material, thickness, and cell size, a wide range of properties and densities can be produced. Presently available honeycomb core materials for aeronautical applications cover a specific gravity range of 0.05 to 0.16 (3 to 10 pounds per cubic foot).

Three types of honeycomb cores, resin-impregnated glass cloth, resin-impregnated cotton cloth, and aluminum foil, have already found considerable application in aircraft sandwich, while resin-impregnated paper shows definite promise. Experimental work is currently being done on honeycomb core structures of other sheet materials, such as asbestos, glass-fiber mat, and magnesium foil. Some show promise, whereas others, like glass-fiber mats, do not lend themselves well to the corrugating process. End Extract

All honeycomb cores, regardless of material, possess rather low thermal-insulating properties, because of the high transmission by radiation. The *K* factor for all is about 0.30, except for aluminum honeycomb which is considerably higher.

Because of the variations and combinations possible according to type of sheet, fiber direction, type of resin, and cell size used, with the close control feasible for each, honeycomb should prove to be a versatile and practical core material with an exceedingly broad specific-gravity range.

2.0020. *Glass-cloth honeycomb.* Glass cloth impregnated with a polyester or phenolic resin and fabricated into a honeycomb structure is available in three hexagonal cell sizes, 3/16, 1/4, and 3/8 inch. The normal specific gravities are approximately 0.15, 0.13, and 0.08 (9, 8, and 5 pounds per cubic foot), respectively, however the density of each cell size can be varied over a considerable range.

The material is normally fabricated in blocks or slices. Some of these core materials, because of excellent dielectric properties and low rate of moisture absorption, are used in sandwich radar-antenna housings (ref. 2–45).

U. S. Air Force Specification 12050 and Qualified Products List 12050–1 cover glass-cloth honeycomb for aircraft use.

2.0021. *Cotton-cloth honeycomb.* Blocks of cotton-cloth honeycomb core material approximately 8 by 12 inches in cross-section and several feet long, with the cells parallel to the 12-inch dimension, are available commercially. The cells are roughly hexagonal in shape, and about 7/16 inch in diameter. Two densities are available: 0.06 specific gravity (4 pounds per cubic foot) formed from a 4-ounce cotton duck, and 0.12 specific gravity (8 pounds per cubic foot), from an 8-ounce duck. In each case the cloth is impregnated with a phenolic-type resin to provide acceptable compressive strength and moderate resistance to moisture. Cotton-cloth honeycomb is utilized mainly in sandwich partitions, bulkheads, and baggage-rack floor panels, as its dielectric and moisture-absorption properties are unsuitable for radar application. Moreover, because of the relatively large cell size currently available, the facings must be comparatively thick to obviate local buckling over each cell.

2.0022. *Aluminum honeycomb.* Sheets of aluminum foil, after being corrugated, can be cemented together to form a honeycomb structure. By varying foil thickness and cell size the density of the resulting structure may be closely controlled over a rather wide range. Core material having hexagonal cells ¼, ⅜, or ½ inch across is currently available in block form. Perforations in the cell walls have been used in some cases for the purpose of permitting volatiles to escape and to permit the passage of air through the core. By varying the combinations of cell size and foil thickness, a density range of 0.03 to 0.13 (2 to 8 pounds per cubic foot) can be covered. The lighter foil gages lend themselves to limited double curvature forming.

2.0023. *Paper honeycomb.* Paper, after being impregnated with a phenolic resin, can be corrugated by a variety of means, including the standard corrugating rolls used in the paper-box-board industry, and assembled to yield a honeycomb core material. It can also be strip-bonded in the flat and then expanded, similar to the familiar paper Christmas bell, and cured in the expanded state to form a honeycomblike construction.

Use of any paper base honeycomb materials for radomes is subject to approval of the Air Force, Navy, or Civil Aeronautics Authority as applicable.

2.003. *Waffle-type core material.* A core material composed of resin-impregnated glass-fiber mat fabricated into a configuration resembling a waffle is at present being made on an experimental basis (fig. 2–3). The ¼-inch-square tapered indentations are spaced approximately on 7/16-inch centers. The material is available in thicknesses of 0.234, 0.280, and 0.300 inch, with each having approximately the same specific gravity, 0.175 (11 pounds per cubic foot).

This core is being developed principally for use in radomes, where uniform and exact thickness is of prime importance. It does not lend itself well to sandwich-construction radomes requiring tapered thicknesses.

2.004. *Multiwave corrugated core.* Recently a core material employing a new configuration, variously referred to as "multiwave" or "double-corrugated," has been fabricated on an experimental scale and has undergone preliminary evaluation tests. Material fabricated to date has employed aluminum foil (fig. 2–4), but the theory of multicorrugation to improve compressive strength of cores made from exceedingly thin

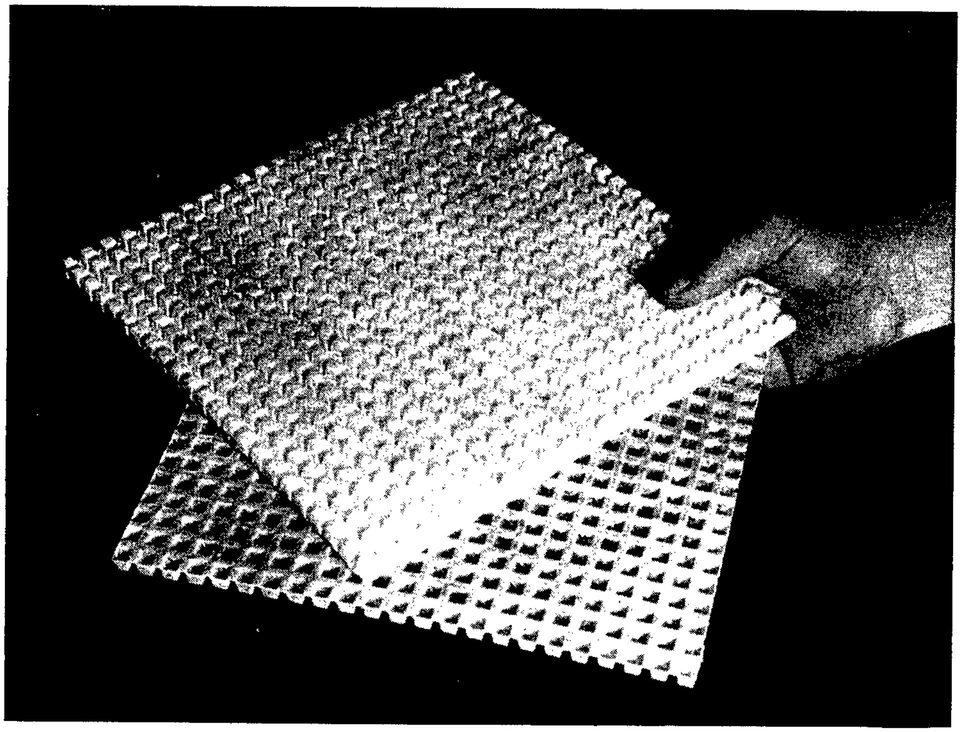

Figure 2–3. Waffle-type core material of resin-impregnated glass-fiber mat.

sheets should apply equally well to other materials, such as resin-impregnated glass cloth or paper.

One type of this core material offers two possible advantages over honeycomb: (1) It can be readily formed to severe compound curvature, and (2) hot air may be passed through it in one direction for possible use in de-icing certain portions of a sandwich construction.

2.005. *Embossed metal core.* Thin gages of aluminum sheet, embossed or dimpled into a configuration presenting a series of rows of square or triangular lands on either side, have been tested as a core material. Tests have also been made on this material as a skin stiffener (being spot welded to one facing) and a limited number of tests as the core of an all-metal spot-welded sandwich (ref. 2–10).

Although strength-weight ratios of sandwiches incorporating this core have been lower than for similar sandwiches having end grain balsa or honeycomb cores a spot welded all-metal sandwich construction of this type may have application where high temperature resistance must be considered.

2.006. *Corrugated metal core.* Corrugated aluminum, similar in configuration (but not in size) to the corrugated paper used in corrugated paper boxes, has been used as a core material (ref. 2–36). In most applications, it was attached to the facings by means of rivets.

2.007. *Mechanical properties.* Information on the mechanical properties of core materials is given in ANC Document 23, Part II.

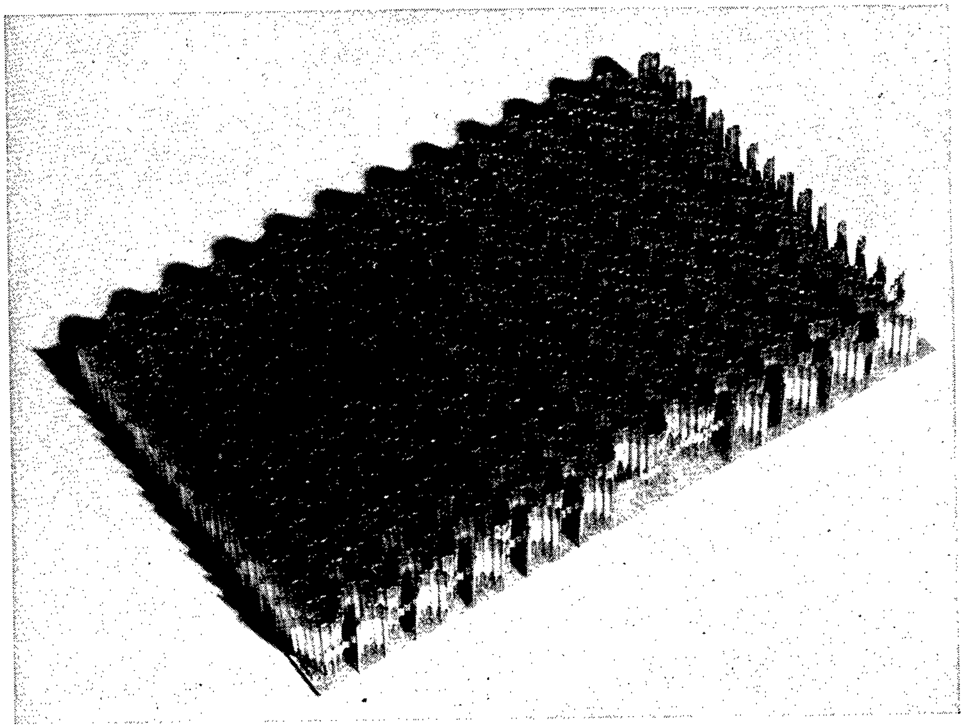

Figure 2–4. Multiwave core material of aluminum foil.

2.1. Facing Materials

2.10. FUNCTIONS, DESCRIPTIONS, USUAL FORMS. The facings of an aircraft sandwich part serve many purposes, which depend largely upon the application, but in all cases they carry the major applied loads. The stiffness, stability, configuration, and, to a large extent, the strength of the part are determined by the characteristics of the facings. To perform these functions the facings must be adequately bonded to a core of acceptable quality. Facings sometimes also have additional functions, such as providing a profile of proper aerodynamics smoothness, a rough nonskid surface, or a tough wear-resistant floor covering. To fulfill these special functions better, one facing of a sandwich is sometimes made thicker or of slightly different construction than the other.

Two types of facings, classified as to fabrication, are in common use: (1) Rigid, strong materials, such as metal, fiber-reinforced plastic, or plywood sheets that are bonded to the core, or (2) fabric, or mat materials that are "wet-laminated" in place, with the laminating resin serving to give the facing acceptable rigidity and also to form the bond to the core. Since each facing material has its advantages and limitations, the specific composition must be chosen with care to suit (*a*) the use requirements of the sandwich, and (*b*) fabrication, assembly, and maintenance details. A brief description of some of the common facing materials in current use follows.

2.100. *Metals.*

2.1000. *Aluminum.* The stronger alloys of aluminum, such as 75S–T6, 24S–T3, or 14S–T6, in sheet thicknesses usually ranging from 0.012 to 0.064 inch are commonly used as facings for structural as well as for nonstructural sandwich applications. For maximum corrosion resistance, both during processing and ultimate exposure in use, sheets coated with corrosion-resistant aluminum alloy (clad) are preferred.

Efficient use of sandwich construction often demands that the panels be highly stressed in compression parallel to the plane of the facings; therefore extreme care in handling aluminum sheets to avoid wrinkles, dents, and "half moons" is imperative. These defects in the sheets seldom can be pressed out completely in processing and, therefore, could lead to premature failure of the panel.

2.1001. *Steel.* Steel sheets have found limited use as a facing material in aircraft sandwich construction. The outstanding example is in sandwich propeller blades. As power output of engines increases and consequently propellers become larger, sandwich-type blades may find more extensive use. For most conventional sandwich applications, steel has several disadvantages, such as poor corrosion resistance and high weight.

The chief advantage of stainless steel sheet is its high resistance to abrasion. Typical is the use of this metal as a leading edge cover for helicopter rotor blades. In a bonded structure, employing stainless steel sheet, the inherent high temperature resistance of the material is of minor importance since the bond itself will fail at a relatively low temperature.

2.1002. *Magnesium.* Magnesium alloy sheets have been used only experimentally as facing materials, but will probably find increasing application because of their low density and high stiffness.

2.101. *Resin-impregnated materials.*

2.1010. *Glass cloth.* Resin-impregnated glass-cloth facings possess acceptable properties for structural sandwiches when properly fabricated. Because of its excellent dielectric characteristics when fabricated with the proper resin, this type of facing is used almost universally for sandwich construction radomes. A variety of weaves are available commercially, which make it practicable, by orienting the fiber directions in the facing, to achieve a wide range of directional strength properties.

Glass-cloth facings are commonly "wet-laminated" in place by laying them up, one layer of cloth at a time, after the cloth is impregnated with a tacky, low-pressure, laminating resin. Thus the process has the distinct advantage of being well suited to shapes of compound curvature. There is also some use made of dry lay-up procedures in which the resin is in the intermediate cure stage.

Less frequently, the cloth is first processed into thin, flat or curved laminates and later bonded to the core in fabricating the sandwich panel (ref. 2–43), or used as facings for foamed-in-place cores.

2.1011. *Glass-fiber mats.* Glass fibers are also commercially available in the form of mats, but owing to the relative nonuniformity in thickness and resin content, and also because of the low strength when compared to glass cloth, mats have found little use in aircraft sandwich construction.

2.1012. *Paper.* Resin-impregnated-paper facings have found occasional use in sandwich floor panels, partitions, and flat nonstructural parts.

2.102. *Plywood.* Although plywood facings were used successfully in the British Mosquito, which was the first major structural application of sandwich in aircraft, they are seldom used currently in the United States. Such lightly stressed applications as bulkheads, partitions, and baggage racks represent the extent of this use.

The quality of veneer and adhesive bonds in plywood facing material should conform to the current issue of Specification MIL–P–6069, although the construction details may be varied to suit the application. Details of plywood construction variables are presented in ANC Bulletin 18.

2.11. STRENGTH PROPERTIES. The strength properties of common facing materials are presented in various publications of the Air Force-Navy-Civil Subcommittee on Aircraft Design Criteria (ref. 2–4, 2–5, 2–6).

2.2. Adhesives and Resins

2.20. ADHESIVES.

2.200. *Types.* In the fabrication of plywood-faced sandwich parts conventional synthetic-resin adhesives of the resorcinol, phenol, or melamine types developed for wood-to-wood bonding are generally used. The selection of the particular type of adhesive depends upon the durability requirements, the effect of adhesive solvents on the core material, and the limits of bonding conditions as defined by the bonding process, such as assembly time, pressure, and curing conditions. The properties and general recommendations for the use of these adhesives, formulated for wood bonding, are described in ANC–19 Bulletin, "Wood Aircraft Inspection and Fabrication" (ref. 2–7); Specification MIL–A–5433, "Adhesive, Application of Room-temperature and Intermediate-temperature-setting Resin (Phenol, Resorcinol, and Melamine Base)" (ref. 2–28); Specification MIL–A–5534, "Adhesive; High-temperature-setting Resin (Phenol, Melamine and Resorcinol Base)" (ref. 2–42), Specification MIL–A–5535, "Adhesive; Application of High-temperature-setting Resin (Phenol, Melamine, and Resorcinol Base)" (ref. 2–43); and in JAN–A–397, "Adhesive, Thermosetting-Resin, Room-Temperature and Intermediate-Temperature Setting, Waterproof (Phenolic, Resorcinol, and Melamine Base) (For Wood)."

The fabrication of sandwich parts with metal facings requires the use of other resin adhesives recently developed for bonding metal to metal and metal to wood. These adhesives are often very complex, and their chemical composition is not generally so well known as those of the woodworking adhesives. It is therefore necessary to classify these adhesives according to the curing temperature and techniques by which they are used, rather than by chemical type. The three general types of adhesives for bonding to metals are here classified as (1) single direct-bonding adhesives, high-temperature-setting; (2) combination on two-step adhesive; and (3) single direct-bonding adhesive, room-temperature-setting.

2.2000. *Direct-bonding adhesive, high-temperature-setting.* A large group of adhesives developed for structurally bonding metal to other materials requires the curing of the joint under pressure at temperatures of 250° to 350° F. Chemically, these adhesives are usually composed of two resins, one being a thermoplastic resin or other elastomer such as polyvinyl formal, polyvinyl butyral, or polyvinyl acetate, or synthetic rubber, and the other being a thermosetting resin, such as phenol-formaldehyde, combined with solvents in such proportions that the necessary characteristics of adhesion to metal, flow during cure, heat resistance, and durability of the joints are obtained. In addition to liquid adhesives for direct bonding to metals, a number of film adhesives are available for this purpose.

Some of the high-temperature-setting adhesives are supplied in dual parts, a liquid and a powder, a liquid and a film or tape, or as two liquids. These dual adhesive systems are used to obtain better adhesive flow characteristics during curing. A resin having high viscosity during cure is applied directly to the metal and a second resin having low viscosity during cure is applied over the other adhesive. This combination of adhesives will then result in an adequate film thickness being supplied by the high-viscosity resin and good surface contact between adhesive films being supplied by the low-viscosity resin. This dual-adhesive system is also required in some bonding processes because the resins used were not found to be compatible in a single solvent.

Since practically all of these adhesives are comparatively new, the following partial list gives the trade names and manufacturers of the direct-bonding, high-temperature-setting adhesives that show promise for use in bonding metal to metal or metal-faced sandwich parts in aircraft construction.

Adhesive	*Manufacturer*
Araldite I	CIBA Co., Inc. Greenwich and Morton Sts. New York 14, N. Y.
Bloomingdale FM–45	Bloomingdale Rubber Co. Chester, Pa.
Bostik 7026	B. B. Chemical Co. 784 Memorial Dr. Cambridge, Mass.
Cycleweld C–3, C–5, C–6, and 55–9	Chrysler Corp. Cycleweld Division Detroit 31, Mich.
Metlbond M3C, MN3C, and MN3C Tape	Narmco, Inc. 2934 Pacific Hwy. San Diego, Calif.
Permacel Film J1 and J2	Industrial Tape Corp. Highway 25 New Brunswick, N. J.

Plastilock	B. F. Goodrich Co. Akron 18, Ohio.
Plycozite 117C	U. S. Plywood Corp. 55 West 44th St. New York, N. Y.
Reanite 3615	The U. S. Stoneware Co. Akron 9, Ohio.
Redux and Redux Film	Rohm & Haas Co. Resinous Products Division Washington Sq. Philadelphia 5, Pa.
Sila-bond A-B	Pacific Laminates 1550 Newport Ave. Costa Mesa, Calif.

Adhesives of the direct-bonding, high-temperature-setting type should meet the requirements of Military Specifications MIL–A–5090 (Aer) "Adhesive; Synthetic Resin (For Clad Aluminum Alloy)" (ref. 2–31); MIL–A–928 (Aer) "Adhesive; Synthetic Resin (For Clad Aluminum Alloy to Wood)" (ref. 2–30); or Air Force Specification No. 14164, "Adhesive, Metal to Metal, Structural" (ref. 2–47) in order to be suitable for use in aircraft construction. Qualified Products Lists of the adhesives meeting the specification requirements are available from the Service issuing the specification.

2.2001. *Combination or two-step-process adhesives.* Adhesive processes for bonding core material to metal have also been developed whereby pressure can be applied at room or slightly elevated temperatures. In these processes, commonly called two-step processes, adhesives of the same type as used for direct bonding to metals and known as "primers" or "primary adhesives," are applied on the metal surface only. The primary adhesive is cured without pressure on the metal in an oven or on the platens of a hot press at temperatures of 300° to 335° F., and the final bonding of the primed metal to the core material is then done under pressure at room or slightly elevated temperatures by use of a secondary adhesive, such as the resorcinol, melamine, or phenol resins of the type formulated for wood bonding.

To be suitable for use in aircraft construction, adhesives of this type should meet the requirements of Military Specifications MIL–A–5090, "Adhesive; Synthetic Resin (For Clad Aluminum Alloy)" (ref. 2–31); MIL–A–928 (Aer), "Adhesive; Synthetic Resin (For Clad Aluminum Alloy to Wood)" (ref. 2–30), or Air Force Specification No. 14164, "Adhesive: Metal to Metal, Structural" (ref. 2–47). Qualified Products Lists of the adhesives meeting the specification requirements are available from the Service issuing the specification.

A modification of the two-step process has been to bond metal to cotton duck or to wood veneer with heat and pressure by use of direct-bonding, high-temperature-setting adhesives. The cotton or wood surface is then bonded to the other faying surface with a room-temperature-setting resin adhesive of the types formulated for wood bonding. This modified method has not yet found much application in the bonding of sandwich constructions for aircraft.

2.2002. *Room-temperature-setting adhesives.* Adhesives for direct bonding of metals to other materials at room temperatures are available, but at present most of these adhesives do not result in bonds that are comparable in either strength or durability to those obtained by direct high-temperature-setting or two-step methods and, therefore, they have not been approved by the Air Matériel Command or by the Navy Bureau of Aeronautics for use in bonding structural sandwich constructions. A number of adhesives of the room-temperature-setting type are modified-polyvinyl-resin or rubber-base adhesives that have either low initial strength, excessive creep characteristics for structural joints, or poor resistance to moisture, so that they cannot be considered as structural adhesives for aircraft. Some of these adhesives are recommended as direct-bonding adhesives for cure at higher temperatures or as primers cured at room or high temperatures in the two-step adhesive process, and they generally give better results when used under these conditions. They, however, do not perform so well as the adhesives of the direct-bonding, high-temperature-setting or the two-step types previously described.

A recent development has been the formulation of room-temperature-setting adhesives using epichlorohydrin resins. While these adhesives appear to have promise for bonding metal to metal, the adhesives have not been developed sufficiently to be accepted by the Military Services for structural bonding of aircraft parts.

2.201. *Storage and mixing of adhesives.* While some of the adhesives for bonding to metals can be stored for long periods at room temperatures, the manufacturers of a number of these adhesives recommend that the adhesives be stored at temperatures of 35° to 70° F. in cans fitted with tight covers to prevent the loss of solvents and contamination of the adhesive with dirt and moisture. At these temperatures the storage life will vary from 4 months to several years, depending upon the type of adhesive. The relative stability of adhesives during storage can be determined by making periodic tests, such as given in section 5.02.

As many of these adhesives are sensitive to the presence of moisture, additional precautions should be taken with them to prevent contamination of the adhesive with condensed atmospheric moisture. When adhesive shipments are received, the contents should be thoroughly agitated and then be removed to smaller containers and placed in storage at 35° to 70° F. The containers should be filled completely so that there will not be any moisture-laden air entrapped. Each such container should be of a size that will hold no more than can be used during the normal storage life of the adhesive at room temperature. For use, the container should be removed from cold-storage condition and allowed to warm to room temperature, with care being taken to see that cans are tightly sealed to avoid condensation of moisture during this warming-up period. Containers partially filled with adhesives that are especially sensitive to moisture, should not be returned to the cold-storage chamber, but the contents should first be removed to smaller containers.

With some of these adhesives for bonding metals the component parts tend to settle out in storage. In these instances, it is the manufacturer's recommendation that such adhesives be agitated in the container at least once every two weeks during storage and be thoroughly mixed prior to using. Adhesives that are gelled or heterogenous after mixing should not be used, unless methods of breaking the gel are given by the manufacturer.

Most of the adhesives for bonding metals are supplied as one-part adhesives, that is, they require only thorough stirring before being ready to use. A few of these adhesives are supplied as two resin ingredients to be applied successively to the faying surfaces, and the manufacturer's instructions should be closely followed in this regard.

Frequently, the viscosity of the adhesive as received will be too great for proper use by the method of application being used. The manufacturer's recommendation as to the proper method of thinning should be closely followed. The solvents for use with these adhesives are usually carefully formulated by the manufacturer to insure long-term compatibility of the solids, proper flow, assembly, and curing requirements.

The secondary adhesives used in the two-step bonding processes are usually normal woodworking adhesives conforming to the requirements of Specification MIL–A–397, class 1, and the manufacturer's recommendation for storage and mixing should be closely followed. Some of these recommendations are given in the ANC–19a Bulletin, "Wood Aircraft Inspection and Fabrication" (ref. 2–7).

2.202. *Method of application.* The adhesives can be applied to the faying surfaces of sandwich constructions by any convenient means that will result in a uniform spread of the adhesive, such as brush, hand roller, conventional roll glue spreader, gear-type applicator, and spray gun, and in a few instances by dipping. General recommendations are given in U. S. Air Force Specification 20044 "Adhesive Bonding of Metal Aircraft Parts; General Specification For," (ref. 2–51).

2.2020. *Application by spraying.* For the production of large assemblies, spraying of the adhesives for bonding metals has generally been adopted as the most practical method of attaining a uniform spread on thin facings and complicated curved shapes. The spraying techniques with the various adhesives will vary slightly. However, following the thinning of the adhesives to a spraying consistency as described in section 2.201, the following general procedure can be followed when using conventional spray guns to apply the adhesive:

(1) The pressure of the air-supply line should be adjusted to 15 to 25 pounds. With some adhesives the manufacturer recommends the use of line pressures as high as 40 pounds to secure proper spraying. There should also be a suitable trap in this air line to remove oil and moisture from the air.

(2) The spray head and spreader adjustment of the gun should be adjusted to give a fan-type spray.

(3) The fluid adjustment of the gun should be adjusted to give the required film thickness per pass when the gun is passed over the surface at a uniform rate of 300 to 400 inches per minute at a distance of 8 to 10 inches from the work

(4) Adhesives should be applied to the surfaces by use of the above recommended gun adjustments and distances of the gun from the work. It is the usual procedure to apply each adhesive coat by a double pass consisting of a pass across the surface and then back again. Between application of each adhesive coat, an air-drying period of 5 minutes to 1 hour, depending upon the amount of adhesive applied, type of adhesive, type of solvent, and humidity and temperature conditions of the spray room, should be allowed. Adhesive films should be applied in a minimum of two coats, and the manufacturers of some adhesives specify the use of as many as six coats. When possible, surfaces should be turned between coats so that successive coats can be applied at right angles to each other so as to minimize irregular adhesive films.

The adhesive, as sprayed on the surface, should generally result in a uniform film having a surface without any pinholes, cobweb, blushes, orange-peel effect, blisters, runs, or other surface blemishes. With certain of the direct-bonding, high-temperature-setting adhesives, which have good flow characteristics while curing under pressure, some surface defects can be tolerated. With adhesives that are being used as metal primers in the two-step process, there is practically no flow when they are cured without pressure, and it is therefore necessary to obtain a smooth surface in spraying or to remove the defects by sanding after the film has been cured. Some of the possible defects in spraying these adhesives are shown in figure 2–5. The defects encountered in spraying are sometimes characteristic of the adhesive formulation being sprayed, but some defects may have additional causes, as follows:

1. Excessive cobwebbing of the adhesive spray may be due to too high an air-to-adhesive ratio for the gun, to the use of low-boiling-point solvents, or to holding the spray gun too far from the work, which results in excessive solvent volatilization before the spray strikes the surface.

2. Orange-peel effect and wrinkling of the surface film may be due to high air pressures, to excessive adhesive application, to holding the gun too close to the work, to the incomplete atomizing of the adhesive, or to the use of adhesive solutions that do not contain enough high-boiling solvents to allow sufficient flow for the surface to smooth out before drying.

3. Pinholes and bubbles in the adhesive film may be due to the use of too heavy an application of adhesive, to use of adhesive formulations that have been thinned too much with low-boiling solvents, or to the application of successive adhesive coats over adhesive coats that have not dried sufficiently.

4. Blushing (a dull, cloudy effect on the sprayed surface) of the adhesive film may be due to the condensation of moisture on the surface during spraying or to the inclusion of moisture in the adhesive. Condensed moisture is due to the cooling of the atmosphere above the work by the rapid evaporation of the adhesive solvents. Factors that contribute to condensation are high temperatures and relative humidities in the spray room, low temperatures of the materials being coated, adhesive solvents with excessively low-boiling points, and high rate of air flow across the drying film. The regularly formulated adhesives for spraying can be used in atmospheric conditions of 55° to 75° F., provided the relative humidity is 55 percent or less. Spraying can be done at temperatures as high as 100° F., but then the relative humidity should not exceed 30 percent. Adhesives especially formulated can be sprayed at higher humidities. Blushing can also be caused by moisture from the air supply being incorporated into the adhesive being sprayed.

5. Running of the adhesive film may be caused by overthinning the adhesive, using high-boiling solvents that do not volatilize rapidly enough, or applying too much adhesive. Adhesives having a high degree of running may be sprayed more efficiently on surfaces placed in a horizontal position.

6. Lifting or blistering of the adhesive film is said to be caused with some adhesives if a heavy coat of adhesive is applied over an adhesive that has been allowed to air-dry too long.

7. Irregular particles in the adhesive film may be caused by improper mixing and thinning of the adhesive, overaged adhesives (see sec. 2.201), blocked air passages in the gun, moisture and impurities entering the gun from the air supply, dried adhesive particles being deposited by using the gun too far from the work, too high an air-to-adhesive ratio for the gun, or by the use of a low-boiling solvent.

2.2021. *Application by other methods.* Ordinary brushing of the adhesive will suffice if the surfaces are small or if spraying equipment is not

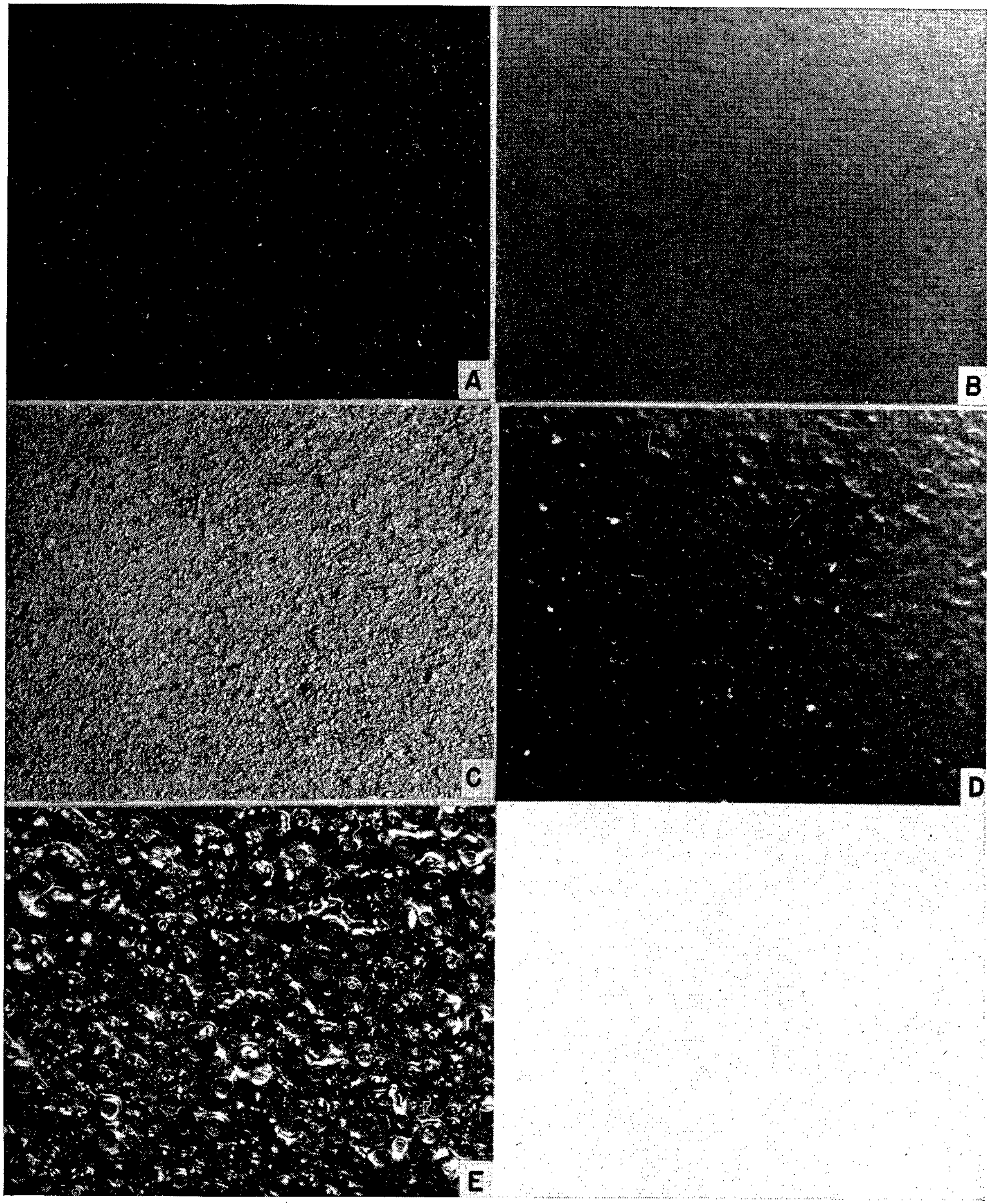

Figure 2–5. Appearance of the same adhesive when properly and improperly sprayed on metal facings. Surfaces magnified several times. A, normal surface (good practice); B, blushed surface; C, cobwebbed surface; D, wrinkled surface; E, surface with bubbles.

available. Hand rollers and conventional roll glue spreaders are also convenient methods used in applying these adhesives in the bonding of sandwich constructions. Generally, the adhesives formulated for such applications are of higher viscosity than for spray coating and will not evaporate so readily. This difference is particularly important in roller-coating large sheets by machine. Dipping of the core into the adhesive or into a film of the adhesive spread on a glass plate is also used in some manufacturing processes as a means of applying adhesives to certain types of cores.

Secondary adhesives of the woodworking type used in the two-step process of bonding are usually applied to the surfaces with brush, hand rollers, or roll glue spreaders rather than by spraying.

2.203. *Amounts of adhesive applied.* The amount of adhesive that should be applied is dependent upon a number of factors, such as the type of adhesive used, the type of surface being bonded, and the strength of the materials being bonded. The amount of adhesive required is also dependent upon the degree of adhesive flow during the formation of the joints. The degree of this flow depends on the bonding conditions, such as assembly time, temperature, and pressure, in addition to the type of adhesive being used.

2. 2030. *Direct-bonding adhesives.* The adhesive manufacturers recommend that dry-film thicknesses of 0.002 to 0.005 inch be applied to each metal surface when bonding metal to metal or to other surfaces for optimum joint quality with the direct-bonding, high-temperature-setting adhesives. An equivalent amount of adhesive applied to the cores has been found satisfactory in bonding sandwich constructions, although in many instances the adhesives will be partially absorbed by the core. While the adhesive spread on both core and facing is about equal in many processes, frequently with balsa and expanded foamed cores most of the adhesive is applied on the metal facing, and with honeycomb-type cores, most of the adhesive is applied to the core. There is some evidence that a heavy fillet of resin applied to the honeycomb cores results in the best bonding. Most manufacturers of sandwich constructions try to control the amount of direct-bonding adhesives applied to the sandwich joint to a dry weight of not more than 50 pounds per 1,000 square feet of single adhesive line.

2.2031. *Combination two-step-process adhesives.* Adhesive manufacturers generally recommend that when bonding metal to wood with two-step processes, the metal-priming adhesive be applied to the metal so as to result in a total dry-film thickness of 0.002 to 0.005 inch. These same film thicknesses of priming adhesives have been successfully adopted for use in bonding metal to the core materials by the two-step processes.

Secondary adhesives of the type used in the two-step method of bonding are usually applied to both faying surfaces for a total wet spread as high as 50 pounds per 1,000 square feet of single bond line (25 pounds per 1,000 square feet of single surface), or are spread on one surface only for a wet spread of about 30 pounds per 1,000 square feet of single bond line. Double spreading is usually used when unfavorable bonding conditions, such as irregular surfaces, long assembly periods, or low pressures, are used. In the bonding of sandwich construction, the secondary adhesives are sometimes applied only to the primed metal surfaces either to reduce the total adhesive weight in the sandwich or because the solvents of these adhesives affect the core materials. When such single spreading is used, the core may be sized with a dilute solution of a compatible resin to avoid excessive penetration of the secondary adhesive into the core.

2.204. *Assembly periods in bonding.*

2.2040. *Direct-bonding adhesives.* In the bonding of metal-faced sandwich parts with direct-bonding, high-temperature-setting adhesives of the type formulated for metal bonding, assembly periods of 8 to 24 hours are usually allowed between the application of the adhesives to the surfaces and the application of pressure to the joint. With some adhesives, assembly periods as long as several months have been successfully used.

When it is more convenient to use short assembly periods (1 to 8 hours), it is frequently necessary to precure the adhesive film at an elevated temperature without pressure to remove excess solvents that might otherwise cause excess flow of the adhesive or blistering of the sandwich parts. The amount of precuring should be carefully controlled, as excessive precuring often results in weak joints due to inadequate flow of the adhesive during application of heat and pressure to the joint. The adhesive manufacturers usually recommend the precuring conditions to be used, as these conditions are dependent upon the composition of the adhesive as well as upon the bonding conditions under which the adhesive is used. With some adhesives, precuring is required even following open-assembly periods of 8 to 24 hours because of the slow rate of evaporation of the solvents from the adhesive film. Precuring is also used with some adhesives to cause some preliminary chemical reaction of the adhesive components in order to improve the heat resistance of the joint. Precuring conditions vary from drying in an oven for 30 minutes to 1 hour at temperatures of 180° to 230° F. to precuring on the platens of a press without pressure for 5 to 15 minutes at the normal curing temperature (300° to 335° F.). If the adhesive film blisters when precured, the application of the adhesive coats has probably been too heavy, the air-drying period prior to precuring has been too short, or the precuring temperature being used is too high.

In some applications, it has been found possible to use adhesives in the form of tapes or films so as to eliminate the use of long assembly periods.

2.2041. *Two-step-process adhesives.* The metal-priming adhesives used in the two-step processes are usually allowed to air-dry for 12 hours to 1 week between the applying and the curing of the primer. When air-drying periods of less than 12 hours are necessary in the bonding process, a precure of 30 minutes to 1 hour at temperatures of 180° to 230° F. may be required after such short air-drying so that blistering will not occur in the primer film during curing.

The assembly periods that can be used with the secondary adhesives in the two-step bonding processes are dependent on the type of adhesive and bonding conditions being used. With the room-temperature-setting resin adhesives of the woodworking type, the total assembly time between spreading of the adhesive and the application of pressure to the joint usually cannot exceed 15 minutes, and immediate assembly can be used. With the intermediate-temperature-setting phenol-resin adhesives, open-assembly periods of 1 to 8 hours are frequently allowed between spreading and application of pressure to the joint.

2.205. *Curing time and temperature considerations.* In the curing of adhesives when bonding sandwich constructions, the adhesive manufacturer's recommendations should be closely followed. Metal-faced sandwich panels bonded with direct-bonding, high-temperature-setting adhesives are usually cured by maintaining bond-line temperatures of 300° to 350° F. for 10 to 25 minutes. Some of these high-temperature-setting adhesives show practically no evidence of cure at temperatures lower than 300° F.; others are said to cure patrially at temperatures as low as 250° F. if the curing period is greatly increased, and to cure at temperatures as high as 300° F. with greatly reduced curing periods.

Metal-priming adhesives for use in the two-step bonding processes may be precured to reduce the formation of bubbles, and then they are usually cured in an oven or on the platens of a hot press at temperatures of 300° to 350° F. for 10 to 25 minutes. Secondary adhesives of the room-temperature-setting type are cured sufficiently to remove the joints from pressure after 4 hours at 75° F. or higher. Secondary adhesives of the intermediate-temperature-setting type should be cured for 30 minutes to 1 hour at bond-line temperatures of 95° to 180° F.

2.206. *Bonding pressure.* In the bonding of facings to core materials, bonding pressures should usually be the maximum pressures that the core materials will withstand at the bonding temperatures. These maximum pressures for the various core materials and the methods of applying bonding pressures on sandwich parts are discussed in section 4.2.

2.207. *Strength of adhesive bonds.* The various organizations that have done research work on the fabrication of sandwich constructions or the development of adhesives for this purpose have usually devised their own individual types of test specimens and test methods for determining the quality of adhesive bonds. In general, these methods consist of tests of the adhesive bonds of the sandwich panel by (1) tension normal to the facings, (2) shear of the facings from the core, and (3) stripping of the facing from the core. Specimens used by the Forest Products Laboratory in its tests of adhesives and adhesive bonds for sandwich constructions and which are illustrative of the types of specimens so used are discussed in Forest Products Laboratory Report No. 1556 and in section 5.3. The results obtained on these specimens are intended as a means of comparing the quality of adhesive bonds and are not intended for use in sandwich design. The results obtained with the strip specimen do not always correlate with results obtained with the tensile and the shear-type specimens, as the more flexible the adhesive bonds the higher the strip-test value

Table 2–1. Results of joint tests on sandwich test specimens fabricated with several adhesives and processes

Specimen construction	Type of specimen [1]	Adhesives									
		Bostik 7008		Cycleweld 55-9		Plycozite 117c		Redux		Cycleweld C-3 with Durez 12041 secondary adhesive	
		Average [2] joint strength	Average [2] material failure	Average [2] joint strength	Average [2] material failure	Average [2] joint strength	Average [2] material failure	Average [2] joint strength	Average [2] material failure	Average [2] joint strength	Average [2] material failure
		Load [3]	*Percent*	*Load* [3]	*Percent*	*Load* [3]	*Percent*	*Load* [3]	*Percent*	*Load* [3]	*Percent*
Aluminum to end-grain balsa (sp. gr. 0.112 to 0.144).	Tension (type 1)	1,300 to 1,589	55 to 94	1,435 to 1,510	19 to 74	1,315 to 1,919	78 to 83	1,360 to 2,079	67 to 94	1,147 to 1,268	47 to 90
	Shear (type 2)	329 to 361	3 to 69	237 to 306	23 to 40	405	100	333 to 467	17 to 97	343 to 386	22 to 73
	Strip (type 3)	20.4	0 to 32	18.2	23	24.9	27	23.5 to 25.7	0 to 10	33.8 to 36.3	0 to 5
Aluminum to end-grain balsa (sp. gr. 0.177 to 0.208).	Tension (type 1)	----------	----------	[4] 1,710	3	2,221	31	2,981	19	[4] 1,687	18
	Shear (type 2)	----------	----------	487	15	476	100	383	37	366	42
	Strip (type 3)	----------	----------	33.5	20	28.1	13	35.2	10	30.1	0
Aluminum to end-grain mahogany (sp. gr. 0.400 to 0.561).	Tension (type 1)	[4] 1,579	0	4,960	1	3,071	5	4,029	0	[4] 1,807	5
	Shear (type 2)	834	2	925 to 941	0	851	5	892	87	623	0
	Strip (type 3)	36.4	0	47.0	10	41.0	5	38.5 to 59.3	0	58.8	0
Aluminum to cellular cellulose acetate (sp. gr. 0.096 to 0.112) (DuPont).	Tension (type 1)	179	93	----------	----------	----------	----------	----------	----------	----------	----------
	Shear (type 2)	78	91	----------	----------	----------	----------	----------	----------	168	88
	Strip (type 3)	3.9	94	----------	----------	----------	----------	----------	----------	9.8	22
Aluminum to paper honeycomb (3/16-inch cell size, sp. gr. 0.088 to 0.112) (FPL).	Tension (type 1)	285 to 402	71 to 99	334 to 436	97 to 100	491 to 500	25 to 90	438 to 679	96 to 100	319 to 486	10 to 88
	Shear (type 2)	118	70	----------	----------	139 to 152	9 to 77	170 to 315	14 to 38	223	6
	Strip (type 3)	6.7	40	----------	----------	3.6 to 5.9	13 to 47	8.1 to 12.1	10 to 12	8.7	3
Aluminum to glass-fabric honeycomb (3/16-inch cell size, sp. gr. 0.128 to 0.160) (Western Products)[5].	Tension (type 1)	640	25	621	6	[4] 267	0	561 to 711	0 to 16	512	0
	Shear (type 2)	181	24	258	56	156	0	276	21	149	0
	Strip (type 3)	12.0	0	17.8	0	6.4	13	14.2	0	11.7	0
Aluminum to cotton-fabric honeycomb (7/16-inch cell size, sp. gr. 0.064) (U. S. Plywood).	Tension (type 1)	171 to 283	79 to 100	----------	----------	206 to 211	95 to 97	208	98	----------	----------

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[1] The types of specimens are: tension, type 1—1-inch aluminum cubes bonded to a 0.2- to 0.5-inch thick section of core or a section of sandwich construction of 0.020-inch aluminum facings bonded to a 0.2-inch core; shear, type 2—a plywood-type shear specimen fabricated from a sandwich panel of 0.020-inch aluminum facings on 0.2-inch thick core; and a strip specimen, type 3—a 1-inch wide section of facing for stripping from a sandwich panel of 0.020-inch aluminum on 0.2-inch core. For further information on these bond-joint specimens see sec. 5.3 and Forest Products Laboratory Report No. 1556.

[2] Each average result is for tests on 8 or more joint specimens (3 or more with strip specimens, type 3) believed to be representative of acceptable joints with the combination used. When a range of values is given, they represent the averages obtained on two or more groups of test specimens.

[3] Load is the strength in pounds per square inch for the tension and shear specimens. Load for the strip specimens is given in inch-pounds.

[4] These results represent best joint strengths obtained for the adhesive and joint combinations, but other information on the adhesive indicates that higher-strength joints might be obtained under better bonding conditions.

[5] Used as received. Not dipped in thinned resin.

will be. Some companies that use strip specimens as a means of evaluating quality of bonded joints also include tests at elevated temperatures to eliminate adhesives that are too thermoplastic.

Table 2–1 presents results obtained in tests of several adhesives for fabricating these sandwich test specimens. These results represent, in most instances, acceptable bond quality when using the respective combinations of specimen constructions and adhesives to which they pertain.

In tests of adhesives for sandwich bonding, it is frequently desirable to determine the quality of the adhesive at stresses higher than can be developed in sandwich constructions. For this purpose, lap-joint shear, block-shear, block-tension, or plywood-type specimens of aluminum to aluminum or of aluminum to birch of the types described in chapter 5 have been used. The lap-joint shear specimen of aluminum to aluminum and the tension-normal specimen of aluminum block to aluminum block have been more widely used than these other types of aluminum-to-aluminum and aluminum-to-wood joint specimens. The lap-joint shear and the tension-normal tests have been written in ASTM Standard D1002–49T (ref. 2–3), and in ASTM Standard D897–46T (ref. 2–1).

Joint tests for use in evaluating adhesives for bonding metal to metal are also described in Federal Specification MMM–A–175 Adhesives, General Specification, Test Methods (ref. 2–48).

Table 2–2 presents results obtained in tests of several adhesives in fabricating joint specimen of metal to metal and metal to wood. These results represent, in most instances, acceptable bond quality when using the respective combinations of specimen constructions and adhesives to which they pertain.

2.208. *Properties of adhesive bonds.* Adhesives used for the bonding of sandwich constructions must result in bonds that are durable when exposed to high temperatures, low temperatures, high humidities, conditions of alternating high and low temperatures and humidity, and to immersion in water and aircraft fluids and resistance to salt solutions and salt spray. These bonds should also have good strength and should show low creep properties when stressed at low and at elevated temperatures, and should have good resistance to fatigue stresses.

2.2080. *Durability of adhesive bonds when immersed in fluids and after exposure to temperature and humidity conditions.* Numerous laboratory exposure tests have been made on bonds fabricated with adhesives of the type used for bonding metal-faced sandwich constructions. There has been very little standardization of these tests; and since most investigators have usually evaluated only a single adhesive process, there is little comparative data that can be presented. The Air Matériel Command and the Navy Bureau of Aeronautics in their specifications (refs. 2–47 and 2–31) for metal-to-metal adhesives have established certain requirements that approved adhesives should meet. For the Air Matériel Command, $\frac{1}{2}$-inch lap-joint specimens of 0.064-inch 24ST clad aluminum alloy should show a strength of 1,000 pounds (2,000 p. s. i.) after exposure to such conditions as 30-day salt-spray exposure, 30-day immersion in water, 7-day immersion in ethylene glycol, 7-day immersion in anti-icing fluid, 7-day immersion in hydraulic oil, and 7-day immersion in hydrocarbon fluid. For the Navy Bureau of Aeronautics, 1-inch lap joints of 0.064-inch 24ST clad aluminum alloy should show a strength of 1,500 pounds per square inch after a 250-hour salt-spray exposure, 1,500 pounds after a 7-day immersion in aromatic fuel, and 2,000 pounds after a 7-day immersion in ethylene glycol.

Durability-test data are given in reference 2–15 of a number of these adhesive processes with lap-joint test specimens of cold-rolled steel and of clad aluminum alloy bonded to three-ply, $\frac{3}{16}$-inch yellow birch plywood. With the adhesives evaluated, bonds between clad aluminum and birch plywood maintained 60 to 75 percent of their original strength when tested wet after soaking in water for periods up to 24 weeks. Bonds made with these adhesives between steel and birch plywood were not so durable as those between the aluminum and birch plywood, since the steel corroded rapidly. The adhesive bonds of birch plywood to steel and to aluminum showed little or no effect of immersion up to 1 year in aircraft fluids (isopropyl alcohol, ethylene glycol antifreeze, lubricating oil, high-octane and regular gasoline), as the bond strengths were then 70 percent or more of the original dry strength.

Another investigation (ref. 2–16) made by the Forest Products Laboratory is reported where three two-step adhesive processes were tested for their durability in tension joints of 17ST aluminum alloy to end-grain balsa. Exposure conditions that were used included immersion in water,

Table 2-2. Results [1] of tests on lap-joint shear and on tension-normal specimens of aluminum to aluminum and aluminum to birch fabricated with various adhesives

Adhesive	Shear strength				Tensile strength
	½-inch lap-joint [2] of 0.064-inch 24ST clad aluminum	1-inch lap-joint [2] of 0.064-inch 24ST clad aluminum	½-inch lap-joint [2] of 0.032-inch 24ST clad aluminum alloy to 3 ply, 3/16-inch birch plywood	Plywood type specimen [2] of 2 faces of 0.032-inch 24ST clad aluminum to 1/16-inch birch veneer core	Tension normal specimen of aluminum block to block
	Pounds per square inch	*Pounds per square inch*	*Pounds per square inch*	*Pounds per square inch*	*Pounds per square inch*
Araldite I	3, 960 to 4, 600	3, 220 to 3, 475	-------------------	-------------------	7,000 to 7,500 (¼ by ¼ inch square).
Bloomingdale FM-45	3, 892	2, 925	1, 354 to 1, 474	610	4,500 (¼ by ¼ inch square).
Bostik 7008	2, 800 to 4, 400	2, 660 to 3, 590	1, 758 to 2, 298	790 to 936	
Cycleweld 55-9	3, 200 to 3, 560	2, 330 to 3, 400	1, 810 to 2, 102	689 to 713	3,150 to 4,910 (1 by 1 inch square).
Cycleweld C-3	2, 500 to 3, 410	2, 568 to 2, 888	1, 526 to 1, 950	1, 035 to 1, 061	
Cycleweld C-3 [3]	2, 600 to 3, 400	2, 506 to 2, 850	1, 122 to 1, 674	944 to 963	
Metlbond M3C	3, 000 to 3, 500	2, 341	1, 320	865	
Metlbond MN3C	3, 230 to 3, 270	2, 950	1, 670 to 2, 106	951 to 1, 140	1,856 (cylinder with 2-square inch cross-section).
Plycozite 117c	3, 900 to 4, 520	2, 600 to 3, 100	1, 240 to 1, 610	664 to 784	7,900 (1.75-inch diameter cylinder).
Redux	4, 160 to 4, 500	3, 000 to 3, 500	1, 404 to 1, 592	677 to 689	4,540 to 6,560 (1 by 1 inch square).
					3,400 to 4,180 (1-inch diameter cylinder).
					2,400 to 2,600 (cylinder with 2-square inch cross-section).
Sila-bond A-B	-------------------	2, 166	1, 904	1, 063	

[1] These test results were obtained from several different laboratories and represent averages for varying numbers of test specimens. The ranges represent normal variations as indicated by available data. Since joint strength values for any adhesive will depend to a considerable extent on the conditions under which the adhesive is used and since it cannot be assumed that different adhesives were each used under equally favorable conditions, these data are primarily of value to illustrate the approximate range of values obtained in practice with different test specimens. The reader is cautioned against making direct comparisons of different adhesives.

[2] Further information on the dimensions and testing of these specimens is included in sec. 5.3 and Forest Products Laboratory Report No. 1556.

[3] Metal primer with Durez 12041 secondary adhesive.

isopropyl alcohol, lubricating oil, ethylene glycol, high-octane and regular gasoline, exposure at 80° F. and 97 percent relative humidity, exposure at 158° F. and 20 percent relative humidity, alternating exposure at 158° F. and −67° F., and alternating exposure of 97 and 30 percent relative humidity at 80° F. Exposure periods up to 1 year were included to evaluate the durability of these bonded joints. With one of the bonding processes practically no effect of these several exposure conditions (gasoline, alcohol, glycol, and oil immersions were not included for this particular process evaluation) was noted except for a slight decrease in joint strength and in the amount of failure in the balsa when soaked for periods up to 1 year in tap water. With a second bonding process, immersion for periods up to 1 year in isopropyl alcohol was the only exposure to reduce materially the quality of the joints by decreasing the amount of original failure in the balsa from 50 to 20 percent and decreasing the strength of the joint to about one-third of its original dry strength. The third adhesive process showed a decrease in the quality of the bonds when exposed to high-humidity conditions and to immersion in regular and high-octane gasoline. Adhesive bond strengths after 1 year were only one-third to one-half of the original dry strength, and the failures in the balsa had decreased from 65 to 20 percent.

The Air Matériel Command has reported some investigations (refs. 2–37, 2–38, and 2–40) where lap-joint panels (½-inch overlap) of stainless steel and 10 aluminum alloys bonded to themselves using 5 of the structural-type metal-bonding adhesive processes were exposed to salt-water spray corrosion resistance tests. Bonds made to the clad aluminum alloys and to stainless steel were generally found to maintain most of their original strength after 30 days' exposure to salt-water spray, while bonds made to the bare aluminum alloys had practically no strength. It was found, however, that bonds made with certain of the adhesives did not prove to be durable even when bonding to the clad aluminum alloys and stainless steel.

Other information on the durability of adhesive bonds in sandwich constructions is included in chapter 6, where the durability of the various components of sandwich constructions is discussed.

2.2081. *Strength of adhesive bonds at low and at elevated temperatures.* The strength of adhesives in sandwich joints at low and at elevated temperatures is dependent upon the chemical types and degree of cure of the adhesive. The Air Matériel Command in its proposed specification for structural metal-to-metal adhesives (ref. 2–47) has specified that the adhesives maintain a strength of at least 625 pounds (1,250 p. s. i.) when tested at 178° to 182° F. in ½-inch lap joint of 0.064-inch 24ST clad aluminum alloy and of 1,250 pounds (2,500 p. s. i.) when tested at −65° to −70° F. The Navy Bureau of Aeronautics in its specification for adhesives for metals (ref. 2–31) specifies that 1-inch lap joint of 0.064-inch 24ST clad aluminum alloy maintain a strength of at least 1,000 pounds per square inch when tested at 180° F.

Information obtained from adhesive manufacturers and fabricators that use adhesives of the types formulated for bonding metal-faced sandwich parts indicates that lap-joint specimens of aluminum-to-aluminum bonded with the more heat-resistant of these adhesives lose from 50 to 70 percent of their room-temperature strength when tested in shear at 200° F. Lap-joint shear specimens of this type usually have maximum strength at some temperature between room temperature (80° F.) and −20° F., depending upon the physical properties of the adhesive used. With some adhesives the strength of lap-joint shear specimens at −70° to −80° F., is only 10 to 40 percent of the room-temperature strength.

Data are reported (ref. 2–23) in which ½-inch lap joints of 0.064-inch 24ST clad aluminum alloy were bonded with six different processes and tested at temperatures from 80° to 600° F. At 80° F. these adhesive bonds had strengths of 1,500 to 2,000 pounds (3,000 to 4,000 p. s. i.), but as the testing temperature was increased to 250° F. only one of the adhesive processes produced bonds that had a strength of more than 800 pounds. At a testing temperature of 450° F. bonds made with this one adhesive had a strength of about 500 pounds (1,000 p. s. i.).

There is some evidence that the more heat-resistant adhesives will have strength in tension normal to the bonded joint of 600 to 1,000 pounds per square inch when tested at 200° F., and that as the testing temperature is lowered to normal room temperatures, the strength of these adhesive bonds tested in tension increases. At temperatures lower than room temperatures, down to −80° F., the tensile strength of most adhesive bonds is equal to or higher than obtained at room temperatures.

This evidence, while showing that adhesives do lose strength at elevated temperatures and that adhesive bonds having concentration of stresses will fail at lower loads when tested at low temperatures, does not indicate that the present adhesives are unsuitable for bonding structural sandwich constructions that will be subjected to loads at low and elevated temperatures. Since the strength of the adhesive bond at room temperature is usually several times greater than that actually required to stabilize the facings of the sandwich construction, the strengths when tested at these low and elevated temperatures are still satisfactory for most sandwich applications.

2.2082. *Creep properties of adhesive bonds.* In order to be used as a structural adhesive for bonding sandwich constructions, adhesives should have low creep properties when the adhesive bond is loaded at room and elevated temperatures. Although only limited information has been obtained on the creep properties of adhesive bonds, available data indicate that adhesives of the type now used for bonding metal-faced sandwich construction will show creep of 0.001 to 0.005 inch in lap-joint specimens of aluminum to aluminum when stressed at one-third to one-half of their maximum joint strength for periods of 100 to 1,000 hours at room temperatures. When the exposure temperature is increased to 160° F., creep as much as 0.010 inch has been observed. Very little creep is usually noted in creep tests in the interval between 100 and 1,000 hours, as most of the creep occurs during the first 100 hours of loading. In a specification for a structural metal-to-metal adhesive (ref. 2–47), the Air Matériel Command proposes that an approved adhesive should be capable of making a ½-inch lap joint of 0.064-inch 24ST clad aluminum alloy that will withstand 800 pounds at room temperatures, or 400 pounds at 178° to 182° F., for 200 hours without failing or showing a creep of more than twice the thickness of the adhesive film.

2.2083. *Fatigue resistance of adhesive bonds.* Because various investigators of the fatigue resistance of adhesive bonds have adopted different testing procedures, it is difficult to compare the results obtained. In a majority of these tests, lap-joint specimens stressed either in cantilever bending or in axial loading have been used. The Forest Products Laboratory used (ref. 2–14) a lap-joint specimen of aluminum to wood stressed in cantilever bending in a constant-deflection fatigue-test machine to compare the fatigue resistance of wood-to-metal adhesives. Better fatigue resistances in this test were usually obtained with the direct-bonding, high-temperature setting adhesive processes than with two-step adhesive processes.

The Air Matériel Command, in its specification No. 14164 for structural metal-to-metal adhesives (ref. 2–47), specifies axial loading of a ⅜-inch lap-joint specimen of 0.064-inch 24ST clad aluminum alloy as a means of comparing fatigue resistance of various adhesives. In order to meet the terms of this specification, the ⅜-inch bonded joint must be capable of withstanding without failure in tension axial loading 10 million zero to 245-pound-load cycles at both room temperature and at a low temperature (−65° to −70° F.). The Air Matériel Command has made some fatigue tests (ref. 2–39) in which two structural adhesives for bonding metals were tested in a manner similar to that required by their specification. The fatigue characteristics of these two adhesives were quite different. The adhesive showing a much higher original bond strength had the better fatigue strength up to 50,000 cycles, but between 50,000 and 10,000,000 cycles the second adhesive had the better fatigue strength. The fatigue strength in this type of test is closely related to the elasticity of the adhesive film.

2.2084. *Impact resistance of adhesive bonds.* Investigations have been made of the impact resistance of adhesives of the type used for bonding metal-to-metal and metal-faced sandwich constructions. These tests usually involve loading a lap-joint, block-shear, or a block-tension specimen in compression or tension by the use of a pendulum-type impact-testing machine or "stripping" the facing from a sandwich part with a similar-type machine.

The procedures and test specimen for determining the impact resistance of bonded metal-to-metal joints have not been generally standardized. Lap-joint tests have been used considerably in obtaining comparative impact-test data because of the ease of fabrication of the test specimen and the lower-capacity test machine required. A standard impact block-shear type of specimen has recently been included in Federal Specification MMM–A–175 Adhesives, General Specifications, Test Methods (ref. 2–48); Air Force Specifications No. 14164, Adhesive, Metal to Metal, Structural (ref. 2–47); and ASTM Tentative Standards D950–47T (ref. 2–2). For this specimen a

1-square-inch bar of metal, ⅜ inch thick, is bonded to a 1- by 1¾-inch block of metal, ¾ inch thick, to result in a bonded area of 1 by 1 inch. The two blocks are then sheared apart by applying an impact load at a head velocity of 11 feet per second on the edge of the upper and smaller block while the lower block remains clamped in position. Results are expressed in foot pounds per square inch. The Air Matériel Command, in its Specification No. 14164 for structural metal-to-metal adhesives (ref. 2–47), has selected this specimen for use and requires approved adhesives to have an impact strength of 10 foot-pounds at room temperatures and 5 foot-pounds at −65° to −70° F.

2.21. IMPREGNATING RESINS.

2.210. *Types.* Resins employed in laminating facings of aircraft sandwich constructions are almost universally of the so-called contact-pressure type (requiring little or no pressure during cure), sometimes referred to merely as contact resins. They are usually either special types of phenol resins or thermosetting polyester resins and are relatively new in the plastic industry. The term "polyester," used for convenience, includes both resins that are polymeric esters of an acid and an alcohol and those which are copolymers of such polyesters and monomers, such as monomeric styrene. Normally supplied as liquids, and varying in viscosity from a waterlike consistency to that of a thick sirup, these resins are available commercially from several manufacturers. Cure or polymerization is effected by the use of a peroxide, such as benzoyl peroxide or tertiary butyl hydroperoxide, and in most cases at temperatures ranging from 150° to 300° F.

Some phenolics have been used mixed with various proportions of polyamide, vinyl, and silicone resins to obtain resins having specific properties desired.

A partial list of typical contact and low pressure resins and suppliers follows. This list does not mean that any or all of the resins made by these manufacturers or suppliers are approved for use in aircraft. Inquiry concerning approval should be addressed to the applicable agency.

Resin	*Manufacturer*
Plaskon 900 Series Resins	Plaskon Division Libby-Owens-Ford Glass Co. 2112–24 Sylvan Ave. Toledo 6, Ohio.
Selectron 5000 Series Resins.	Pittsburgh Plate Glass Co. Grant Bldg. Pittsburgh 19, Pa.
Paraplex Resins	Rohm & Haas Co. Resinous Products Division Washington Sq. Philadelphia 5, Pa.
Bakelite Resins	Bakelite Corp. Plastics Division 30 East 42d St. New York 17, N. Y.
Laminac Resins	American Cyanamid Co. 38 Rockefeller Plaza New York 20, N. Y.
Thalid Resins	Monsanto Chemical Co. Plastics Division Springfield 2, Mass.
Vibrin Resins	Naugatuck Chemical Division of United States Rubber Co. Rockefeller Center New York 20, N. Y.
Conolon Resin	Narmco, Inc. San Diego, Calif.
Diallyl Phthallate Resin	Shell Chemical Corp. 500 5th Ave. New York, N. Y.

A list of low-pressure or contact-pressure resins approved under U. S. Air Force Specification 12049, for aircraft use, types I, II, and III, is available in Air Force Qualified Products List 12049–1.

A wide range in characteristics in available in laminates produced from these resins. Resin formulations are available that may be cured to yield products varying from hard and rigid to almost rubberlike compositions. For sandwich facings, however, where rigidity and strength are important, only the rigid types have found use.

The specific gravity of these various commonly used resins after curing falls within the range of 1.05 to 1.45.

2.211. *Tank life.* When used in connection with the polyester laminating resins, the term "tank life" refers to the length of time during which the resin remains usable in a tank or container after the catalyst has been added. Resins are available in modifications ranging in tank life from a few hours to several days. Tank life is related to the gel time and also to the curing time required. The kind and quantity of catalyst employed, operating temperatures, and the presence of light all have an effect on the tank life. The requirements of the specific application determine the optimum tank life, but normally it is adjusted to a period of about 6 to 24 hours.

In general the modified phenolics have a tank life in excess of 6 months.

2.212. *Assembly life.* The term "assembly life" designates the permissible maximum time that may be allowed to elapse between the application of the resin to the glass cloth, or other reinforcing sheet, and the time at which the assembly is cured. Like tank life, assembly life can be varied by adjusting the resin components and the amount and type of catalyst. The fabrication of small parts that can be laid up quickly can be accomplished with a resin having a very short assembly life and advantage taken of the short curing time. Large parts, such as a radar housing or a complete outer-wing panel, require many hours, and sometimes days, to lay up, and therefore often require a resin having an assembly life of several days.

Temperature in the workroom has an effect on assembly life. The higher the temperature, the shorter the permissible time. Some resins having relatively volatile resin-forming constituents change in composition when exposed to the air. While this change may not materially affect the final cure of the resin, it does have a marked effect on the viscosity or tackiness of the impregnated glass cloth, and therefore often makes fabrication difficult due to loss of tackiness.

2.213. *Solids content.* Most of the copolymer resins are furnished as liquids composed of 100 percent resin-forming constituents and, therefore, on this basis are 100 percent solids. In use, however, there is often a loss in weight due to evaporation of some of the more volatile components. With certain resins this loss may be considerable, depending upon the room temperature, lay-up time, and character of the volatile component. Fabrication processes should be controlled to minimize loss of volatile components. As resin content of a finished part is specified on the proportion of the weight of cured resin to its total weight, it is important to know this loss and to allow for it when impregnating the filler. In a test at the Forest Products Laboratory on a specimen of glass cloth impregnated with a typical low-viscosity polyester resin, this loss amounted to about 20 percent of the liquid weight of the applied resin as a result of an hour's lay-up time at 80° F. Other resins of the higher-viscosity type lost only about 2 percent in weight in a similar liquid test. The phenolics have from about 20 to 50 percent solids.

2.214. *Curing conditions.* As the name implies, the contact-pressure resins may be cured at exceedingly low pressures. The term "contact pressure" has been used to define the pressure range from 0 (contact) to the pressure obtained in a vacuum bag (maximum about 14 pounds per square inch). Higher pressures may be used when necessary, provided resin content is not reduced below acceptable bonds, to assure contact on certain complicated parts or in the use of certain polyester and phenol resins; but, in most cases, it does not improve the properties of the laminate when glass-cloth fillers are used, and it may damage the glass fibers if pressure is excessive (sec. 4.2004).

A rather wide selection of temperatures may be employed for proper cure, depending largely on the type and amount of catalyst employed and on the heating equipment available. The curing cycle with polyester resins involves first a change from a liquid to a gel, which is followed immediately by further polymerization into the final thermoset form. Normally, this is accomplished at temperatures of 200° to 250° F., with the time being varied to suit the specific resin. Recently, specially compounded catalysts have been formulated that promote cure of some of these resins at temperatures as low as 80° F.

Considerable heat is generated during the cure of some resins; therefore, the actual temperature in the laminate may be above that of the heating medium. To avoid excessive temperature, therefore, in thick solid sections, as at fittings, low initial curing temperatures and long curing cycles are recommended. Means for removing heat, such as water cooling ducts, can be incorporated in molds.

The cure of most contact-pressure resins is not inhibited by exposure to air. Those that are thus affected may be compounded with special ingredients to overcome the inhibiting effect. Proper cure is inhibited, however, by most rubber compositions. Therefore, when expanded-rubber cores are specified, they must be specially treated, usually with a surface coating of extra catalyst. Rubber molding bags may also prevent proper cure; therefore the laminate must be covered with a protective sheet, such as regenerated cellulose fiber. To insure an adequate cure, laminates can be subjected to a secondary curing period or so-called heat-treatment period.

2.215. *Tests for cure.* There is no simple test for adequate cure that can be applied to all the contact-pressure resins. Pronounced undercure is evidenced by tackiness, softness of the laminate, and low strength. Hardness, however, cannot be used as a general criterion of degree of cure, as individual resins exhibit considerable variation in hardness. For any specified combination of resin and filler, some means of measuring hardness may be employed as an inspection device after its readings have been adequately correlated with the pertinent strength characteristics of the laminate.

2.216. *Strength properties.* Physical properties, such as the tensile, compression, shear, and flexural strengths and moduli, of the pure resins are available from the resin manufacturers, but they are of little practical value in predicting the strength properties of a sandwich facing. The physical properties of the laminates made from these resins are important, but they depend largely on the filler.

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CHAPTER 3

DESIGN

3.0. Design

Information on basic strength and elastic properties of sandwich construction, together with formulas, is given in ANC Document 23, Part II.

CHAPTER 4

FABRICATION

4.0. Cores

4.00. Preparation for Use. From the position of the sandwich fabricator the core as received is a raw material, and therefore the manufacture of the core stock will not be considered in this manual. All core materials described in chapter 2 must be prepared for use by the sandwich fabricator. This preparation consists of machining in some manner or, in isolated cases, of mixing, pouring, or expanding the raw materials. Some of the more common means of preparing typical cores for assembly into sandwich structures are presented here.

4.000. *Balsa.* Two methods of core preparation are in use for balsa—(1) band sawing end-grain slabs from large bonded billets and sanding to finished thickness, or (2) sawing end-grain slabs to finished thickness from planks, followed by edge bonding to the proper core size. Both methods require that the selected balsa planks be accurately jointed and planed to a rectangular or square cross section. Conventional woodworking machinery, such as a jointer, rip saw, and cabinet planer, may be used.

For method (1) the planks are edge bonded and laminated into billets approximately 26 by 26 inches in cross section and 4 to 10 feet in length. A room-temperature-setting resorcinol resin conforming to the requirements of Specification MIL–A–397 is recommended for this bonding operation. Typical billets are shown in figure 4–1. After being conditioned for at least 48 hours the billets are sized on a jointer to remove clamp marks and adhesive squeeze-out. In this jointing operation it is important that the billets be machined to an accurate rectangular shape so that they may be laid up later into the mosaic pattern of the core without hand fitting. Next the billets are rough-cut into end-grain slabs on a band saw and these slabs are edge bonded into cores of the desired shape and size. This bonding operation may be done using nail pressure as shown in figure 4–2, or in a specially designed high-frequency edge-bonding machine. If mahogany inserts or edgings are required, they are prepared in a similar manner and bonded in place at this time. The finished core thickness is produced by several passes through a drum sander. A traveling-bed type of machine having two or three drums has been found to be most suitable for this operation. For maximum accuracy, a slow feed (about 15 feet per minute) and a light cut (0.005 inch per pass) are recommended. An accurate caul board should be used if the traveling bed of the sander is inaccurate.

By method (2) the balsa planks are cut to about 3 feet in length and accurately surfaced on four sides to remove all crook and evidence of head-saw marks. This operation can readily be done on a jointer and a planer. It is necessary to adjust the feed-roll and chip-breaker pressure on the planer to eliminate crushing of the balsa. Planks of any available cross section are acceptable, but it is important that all corners be exactly 90° for subsequent fit in the edge-bonding operation. End-grain slabs of the desired thickness are cut on a circular cross-cut saw running at about 3,600 revolutions per minute and having about 5½ teeth per inch. By keeping the saw in good condition and removing all end play from the arbor, tolerances of ±0.003 inch can be maintained. In spite of the carefully controlled technique used in sawing the balsa, the end-grain surfaces of the slabs are occasionally slightly wavy. The growth rings of higher density produce ridges, and the rings of lower density form shallow valleys. Tests made on typical slabs revealed that it was possible to have a density variation of as much as 2 to 1 in adjacent rings one-half inch apart. Figure 4–3 shows an end-grain slab that had very noticeable ridges, and figure 4–4 is a photomicrograph of the sawn surface of a similar slab showing the two types of surfaces.

Cores of the desired size can be made by method (2) by bonding these individual slabs together. Nail pressure or the use of a high-frequency edge-bonding machine may be used with phenolic or resorcinol adhesives. After assembling, the cores are lightly sanded with fine sandpaper on a wood block to remove adhesive squeeze-out and other minor surface imperfections and are then trimmed

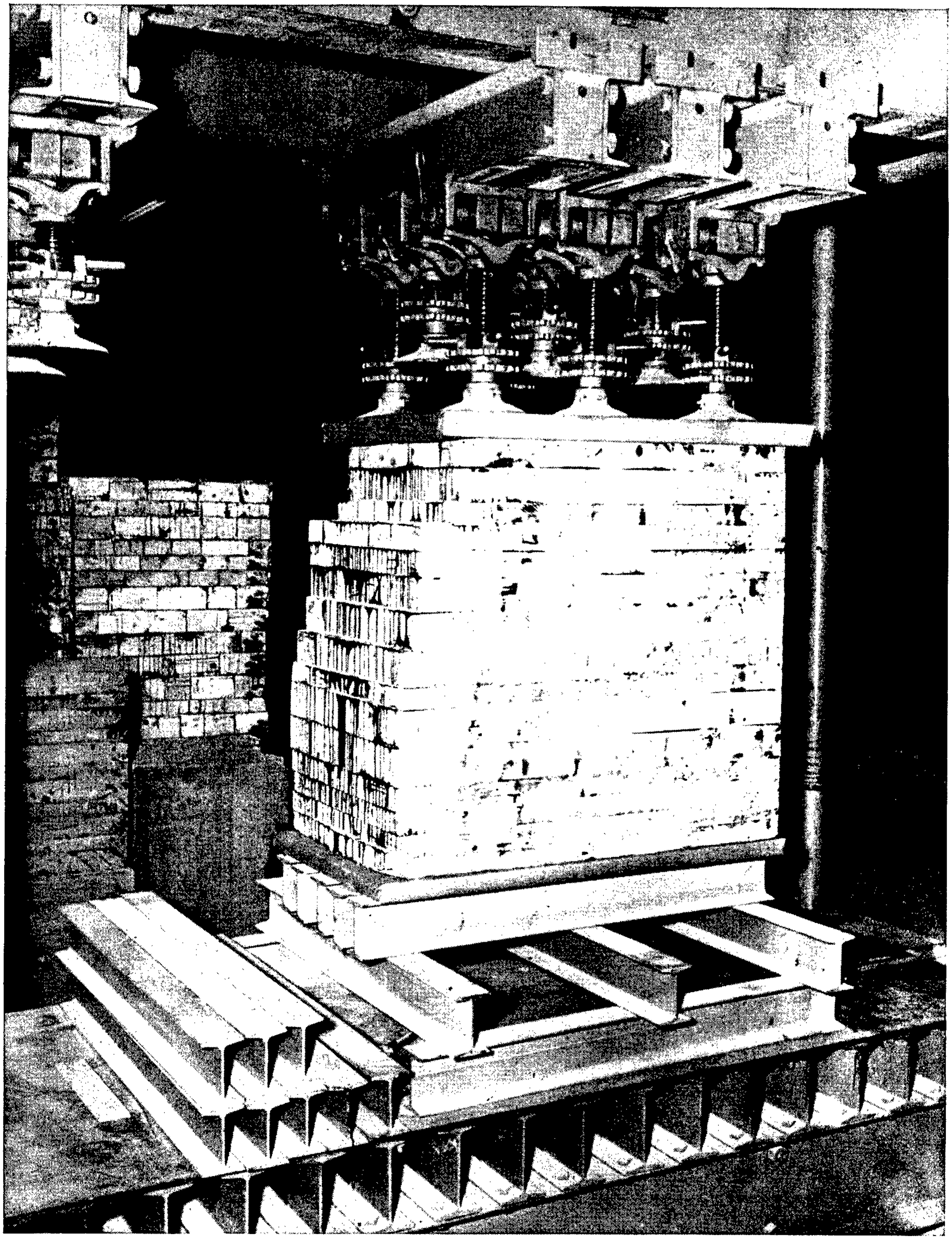


Figure 4–1. Typical billets made by edge bonding and laminating balsa planks.

Figure 4–2. Using nail pressure to edge bond end-grain slabs of balsa into larger panels.

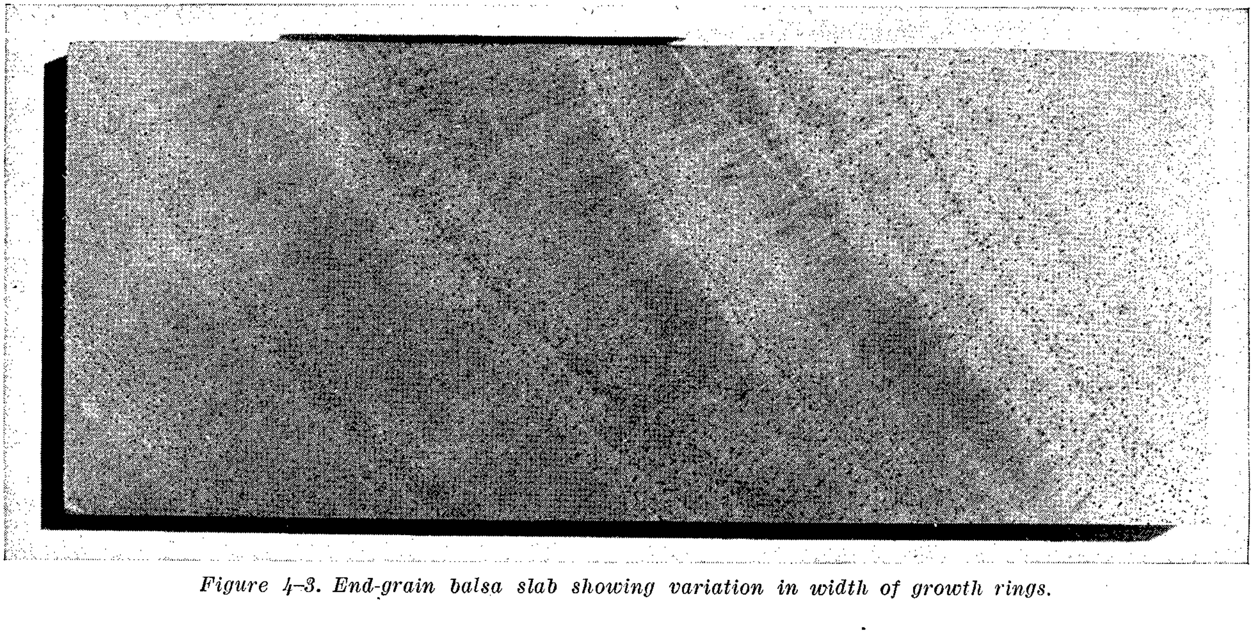


Figure 4–3. End-grain balsa slab showing variation in width of growth rings.

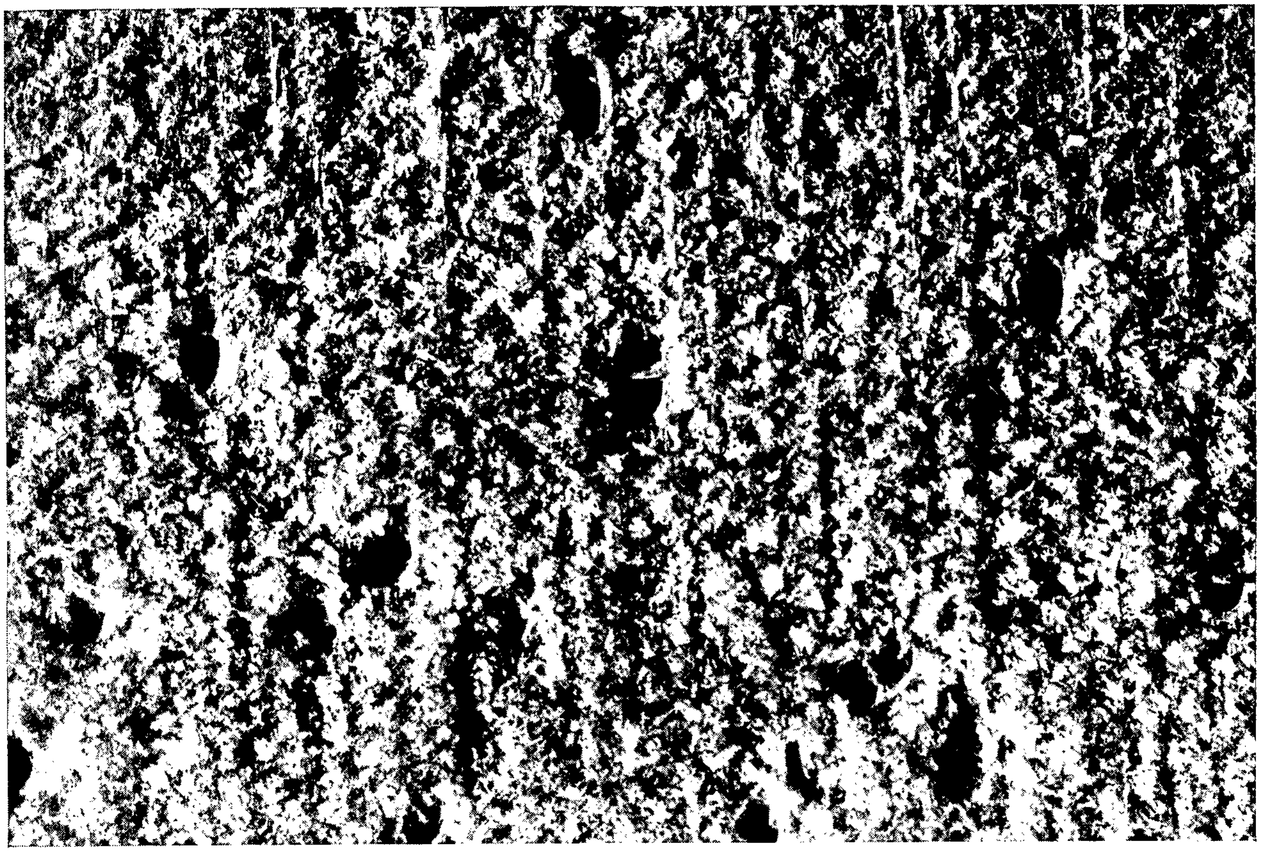


Figure 4–4. Photomicrograph of sawed end-grain balsa slab. Lower half is low-density material on the surface of which the sawing produced a valley, while the upper half is higher-density material on which the sawing produced a slightly raised surface.

to size. A typical end-grain balsa core is shown in figure 4–5.

For special applications, such as at the trailing edge of a helicopter blade, where top and bottom skin join, it is necessary to provide a beveled edge on the core. One simple method of accomplishing this on balsa cores is by using a sanding drum.

4.001. *Cellular cellulose acetate.* The extruded bars of cellular cellulose acetate are easily machined by ordinary woodworking methods. They may be dimensioned by jointing one side and edge before they are cut to proper thickness and width. The cabinet planer may be adapted to the thickness-planing operation, but because of the relatively low crushing strength of the material it is necessary that the feed-roll and chip-breaker pressure be reduced considerably. With thin cores it is sometimes necessary to resaw the cellular cellulose acetate bars on a wood-cutting band saw running at 4,000 feet per minute and having five teeth per inch. If the sawing operation is carefully done and the saw is in good shape, the surface produced is satisfactory for use, so that the slabs need not be planed to final thickness. Thickness tolerances of ±0.005 inch should be maintained.

There is a possibility of adapting a conventional woodworking molder or sticker of the four-head type to the sizing operation on bar-type synthetic cores such as extruded cellular cellulose acetate. Width and thickness sizing would thus be combined in one operation similar to the processing of conventional lumber surfaced on four sides. If this operation is done at the core-extrusion site, the material removed (representing a minimum waste of about 30 percent) could possibly be salvaged and reprocessed.

Strips of cellular cellulose acetate may be edge bonded to form sheets either with a durable adhesive or with a slow-acting solvent, such as dioxane. A special adhesive spreader incorporating a

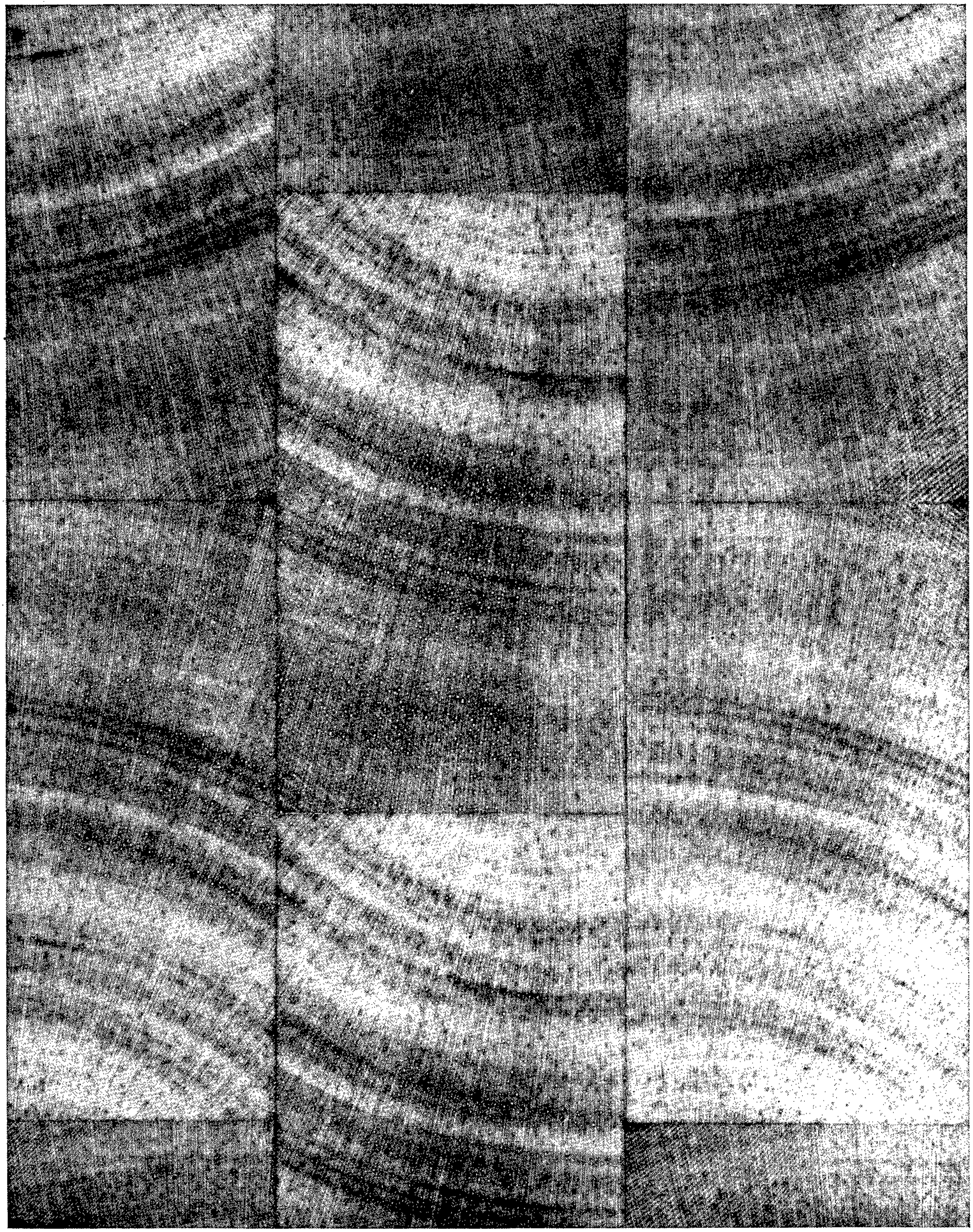


Figure 4–5. End-grain balsa core of uniform density in the range of 6 to 9 pounds per cubic foot.

narrow spreading roll for applying adhesive or solvent to the edges of the strips is shown in figure 4–6. It will be noted that the applicator roll is somewhat narrower than the thickness of the strip and thus minimizes adhesive squeeze-out. An adhesive spreader of this type is equally suitable for use with balsa or expanded rubber cores.

Figure 4–6. Special narrow-roll adhesive spreader for applying adhesive to core strips.

For applications requiring maximum strength, cellular cellulose acetate bars, approximately 1¼ inches wide, are sometimes wrapped with strips of impregnated glass cloth immediately before fabricating, as shown in figure 4–7. These wrapped bars are then forced tightly together before applying the facings. A small section of a typical sandwich part having a core of wrapped bars is shown in figure 4–8.

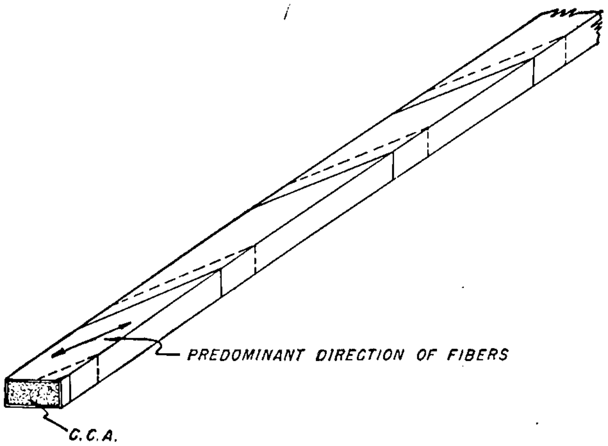


Figure 4–7. Typical bar of cellular cellulose acetate wrapped with impregnated glass cloth immediately before fabricating.

4.002. *Cellular hard rubber.* Blocks of cellular hard rubber as received are prepared for use as core materials by removing the outer one-eighth inch on a jointer and by planing to proper thickness after resawing on a band saw if necessary. The band-sawing operation is similar to that used on cellular cellulose acetate. An allowance of

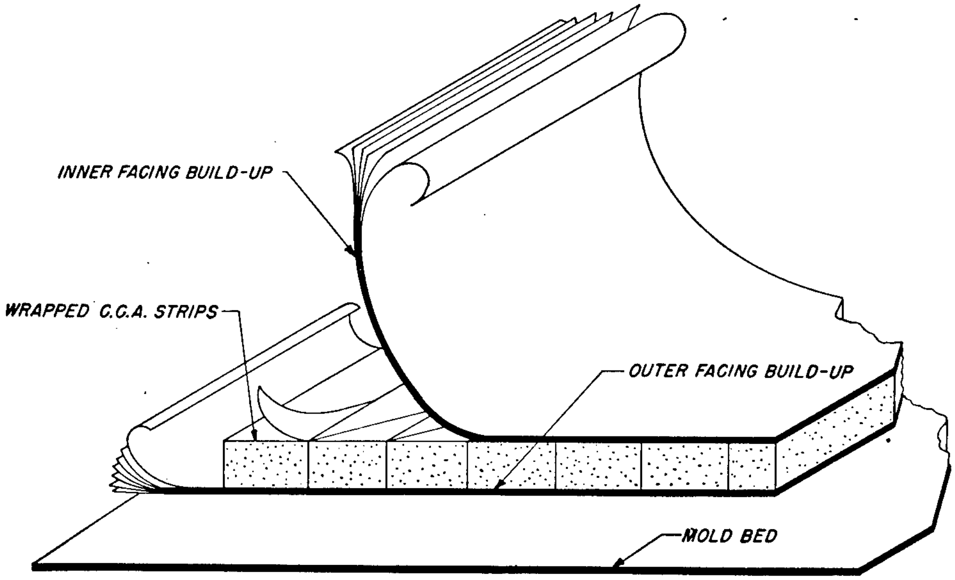


Figure 4–8. Typical section of sandwich part having core of wrapped cellular cellulose acetate bars.

about one-sixteenth inch on each side should be made for the planing operation for removal of the feed-roll marks. It has been found that cellular hard rubber can be planed to a minimum thickness of about one-fourth inch by feeding it through the planer on a back-up board. It is necessary, however, to reduce the feed-roll and chip-breaker pressure to a minimum to avoid crushing.

If large flat panels are required, the slabs of cellular hard rubber may be edge bonded with a room-temperature-setting resorcinol adhesive conforming to the requirements of Specification MIL–A–397 for convenience in handling. However, most sandwich structures made from cellular-hard-rubber cores are for radar applications and therefore are usually of compound curvature. For cores of this type the material is cut or tailored to fit the mold and is preformed, if necessary, as described later.

Since the presence of rubber inhibits the cure of most laminating resins when the two are in intimate contact during the curing cycle, the rubber cores must be sized with additional catalyst. A suspension (about 15 percent concentration) of the catalyst in water spread or brushed on the rubber core and allowed to dry is often employed. Some catalysts (such as benzoyl peroxide) are not soluble in water and must be applied as a suspension prepared by adding a small amount of ethyl alcohol (5 percent) to the water before adding the catalyst. The material must be stirred or agitated during application to keep it in suspension. A solution of catalyst in acetone should not be used, as acetone appears to affect the strength properties of the rubber core.

4.003. *Glass-cloth honeycomb.* Blocks of glass-cloth honeycomb core material may be cut to finished thickness on a band saw. It has been found that a 14- to 32-tooth metal-cutting band saw running at 1,500 to 3,600 feet per minute produces a satisfactory cut. If the material shows a tendency to delaminate on cutting it may be advisable to mount the saw on the wheels so that the teeth travel backwards or to use a disk abrasive saw. Either technique results in less jarring and tearing and therefore minimizes the delamination. Thickness tolerances of ±0.005 inch should be maintained. The fuzzy character of the sawn surface is shown in figure 4–9.

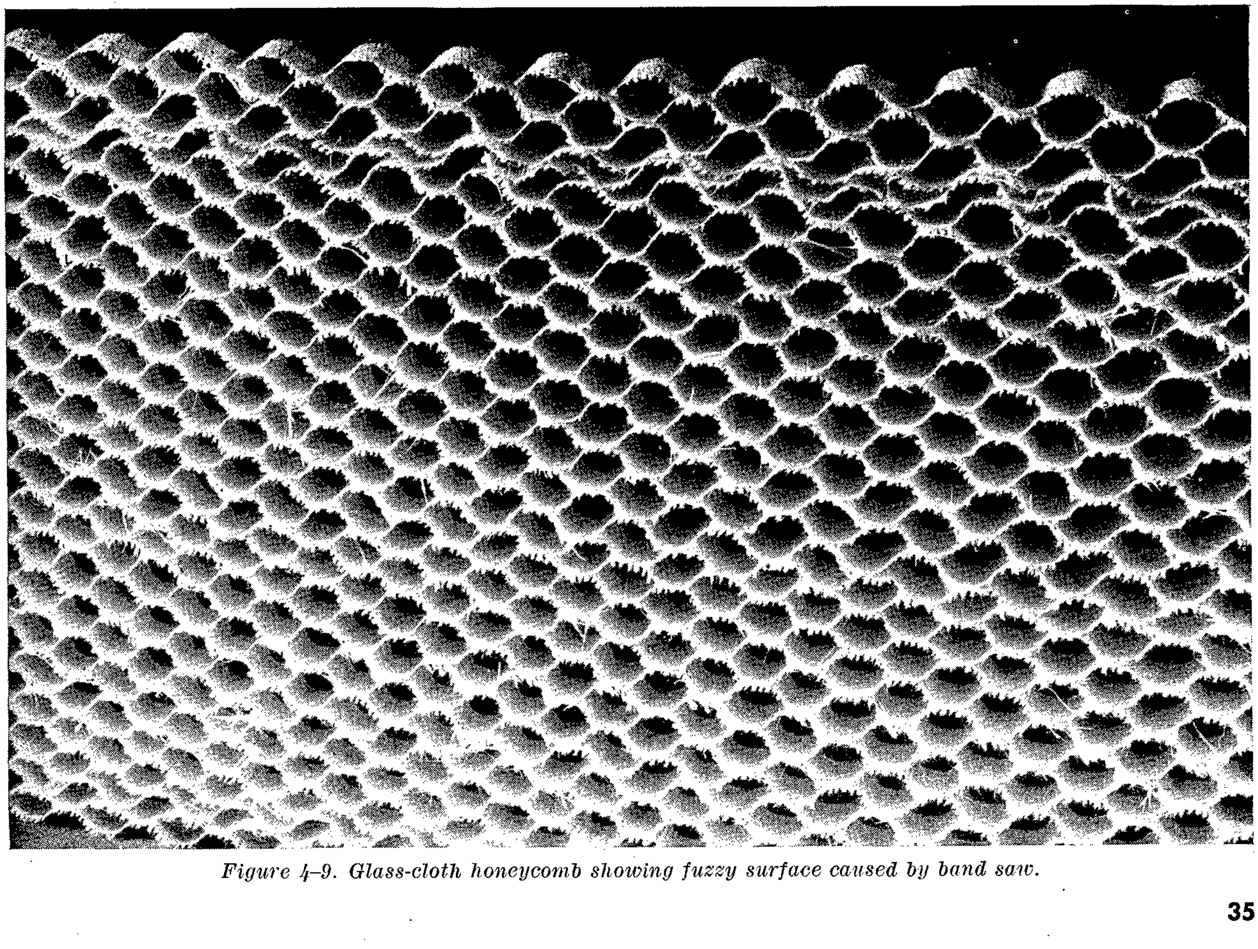


Figure 4–9. Glass-cloth honeycomb showing fuzzy surface caused by band saw.

Precautions must be taken to remove the fine resin and glass dust that results from the sawing operation. This may be done by drilling holes in the wood fence near the saw and applying suction to the far side to draw up the dust, as shown in figure 4–10. In addition, an adequate respirator or dust filter should be worn by the operator when large quantities are cut.

Figure 4–10. Band-saw set-up featuring perforated fence and suction hose for dust removal.

For convenience in handling when fabricating large flat parts, the slices of glass-cloth honeycomb core may be edge bonded in the usual manner by hand pressure or on a high-frequency machine. Glass-cloth honeycomb is used for radome applications and therefore must be tailored very carefully to fit the curvature of the mold. This requires smaller pieces, which are cut from the sawn slices.

Immediately before use the pieces of glass-cloth honeycomb cores should be treated with the same resin that is to be used in the facings. Two methods of treatment are in common use. The pieces may be dipped in a thin solution (normally about 20 percent) of the resin in acetone and used as soon as the acetone has evaporated, or unthinned resin may be roller-coated on the surfaces. Either method supplies additional resin at the interface between the core and the facings, and thus provides increased bond strength and, in addition, a tacky surface that aids in laying up complicated shapes.

4.004. *Cotton honeycomb.* Cotton fabric honeycomb as received from the manufacturer is in the form of long blocks, as described in chapter 2. These blocks are cut to proper thickness on a band saw. The saw may be an ordinary wood-cutting band saw having four teeth per inch and running at about 3,600 feet per minute, or may be of the new widely spaced fine-tooth type. The nature of the surface formed by the band saw is shown in figure 4–11. If a smoother surface is desired, the sawn slabs may be planed in a cabinet planer by using an accurate back-up board. Thickness tolerances of ±0.005 inch should be maintained. Figure 4–12 shows a convenient means of checking the thickness of cotton honeycomb cores. This device may also be used on cores of any type.

Strips of cotton honeycomb core material may be edge bonded together to form sheets of the desired size by conventional means, usually by employing an adhesive of the resorcinol type.

4.005. *Aluminum honeycomb.* Aluminum honeycomb is normally received in the form of blocks very similar in size and shape to the blocks of cotton-fabric honeycomb (fig. 4–13). These core blocks can be cut into slices on a metal-cutting band saw. High cutting speeds and fine-tooth blades are desirable for best results. Dimensional tolerances can be held to ± 0.005 inch.

For applications where slightly lower core strengths can be tolerated, the core may be cut slightly oversize (about $\frac{1}{32}$ inch) and rolled to required thickness (± 0.003 inch) by running the core through metal rollers. As the core passes between the rolls, the edges of the cells are bent slightly without excessively wrinkling or deforming the cell walls. The ability of the aluminum honeycomb core to roll over at the edges instead of buckling at the cell wall assists in molding contoured sections of varying thicknesses. The core can be cut to slightly over size and pressed to the exact contour between dies.

Another characteristic of aluminum honeycomb core is its ability to withstand molding at higher temperatures without ill effects. Higher molding temperatures often increase the strength of the adhesive bond between facings and core and also sometimes improve the creep characteristics of the adhesive by raising its softening point.

Aluminum honeycomb has another characteristic, that of retaining a desired shape after preforming. In molding a cylindrical section, for example, the core segments can be rolled to contour prior to coating with adhesive. Double-curvature core sections, pressed to shape over a preformed die, retain this shape reasonably well.

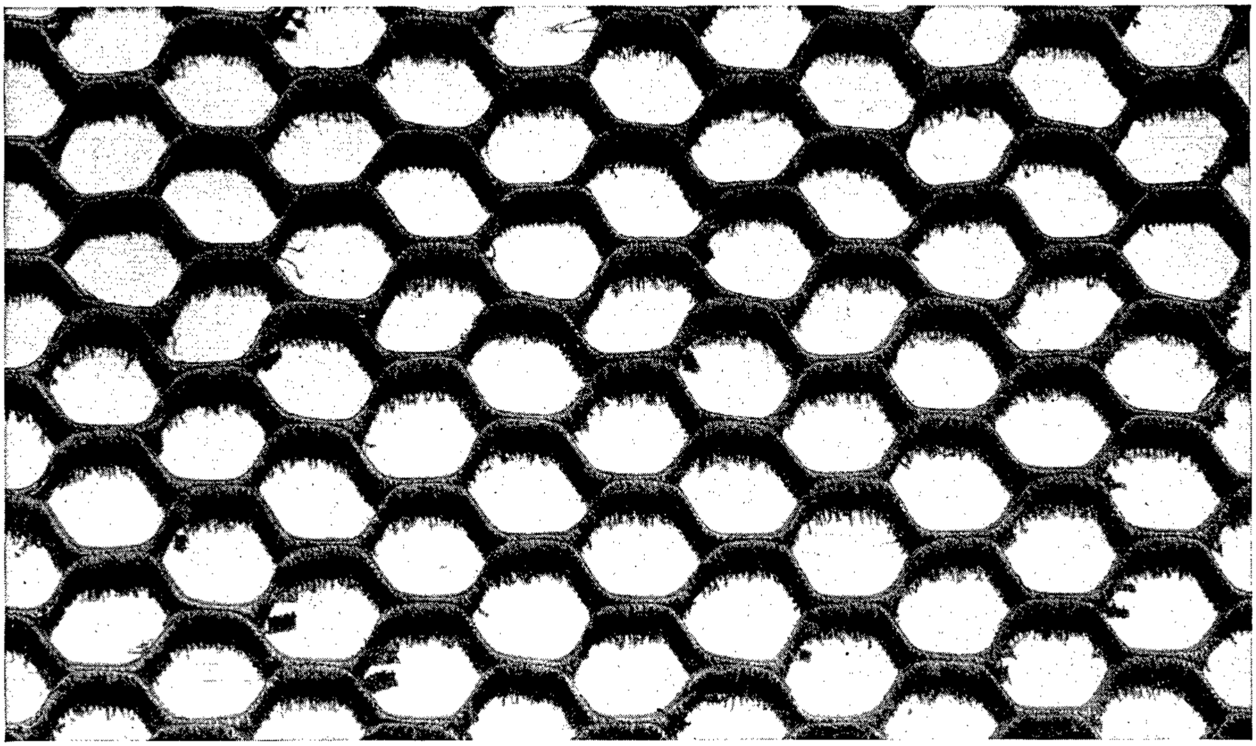


Figure 4–11. Cotton-cloth honeycomb showing character of surface produced by a 14-tooth metal cutting band saw.

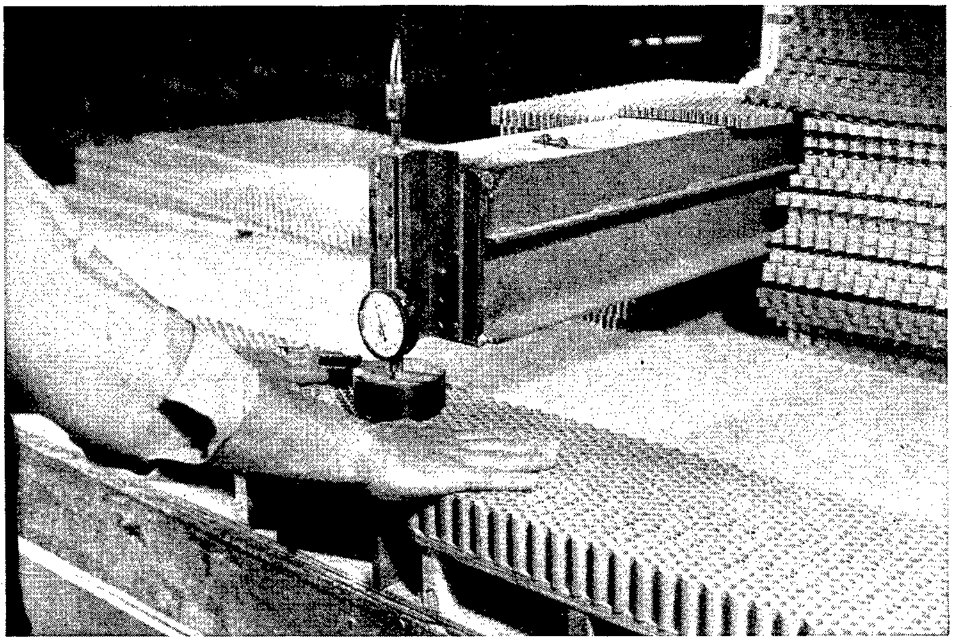


Figure 4–12. Dial indicator with special base affords a convenient means of checking the thickness of honeycomb cores.

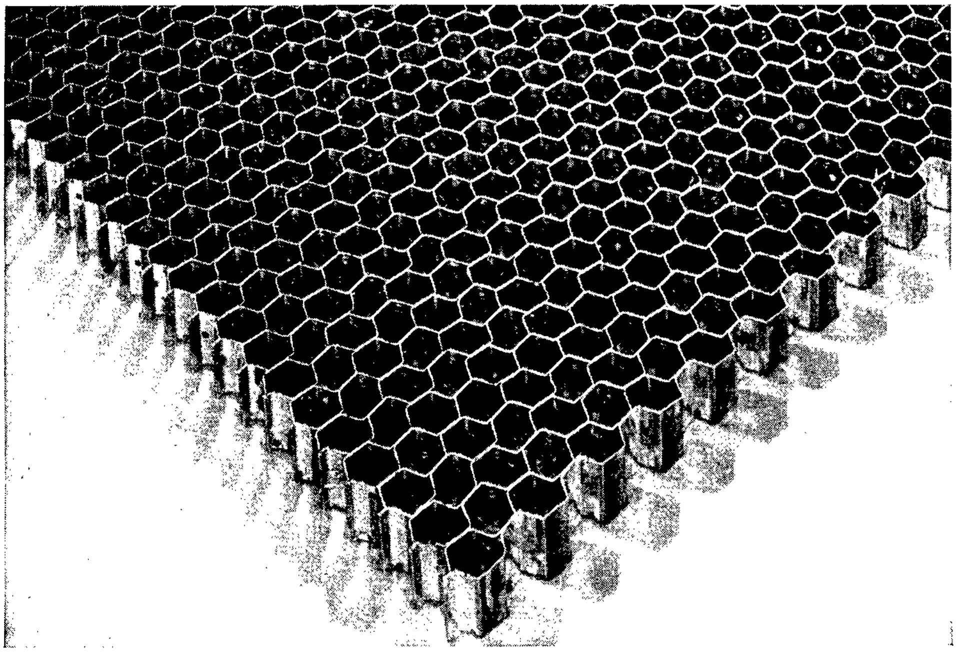


Figure 4–13. Typical core section of aluminum honeycomb fabricated from perforated aluminum foil.

4.006. *Paper honeycomb.* To date paper honeycomb core material has been used only experimentally in aircraft structures, and, consequently, types have not been standardized. The small-cell type with high resin content can be sawed on a circular saw into smoothly cut slabs having thickness tolerances of ±0.003 inch if the block is less than 3 inches thick. It may also be cut on a band saw into slices having slightly roughened surfaces and somewhat larger tolerances. The large-cell type with low resin content is usually cut on a band saw.

Paper honeycomb of the so-called "Christmas-bell" expansion type is sawed to exact thickness before expanding. If desired, these solidly packed unexpanded slabs may be jointed or planed in a special jig to provide smooth surfaces when the material is expanded.

4.007. *Foamed-in-place cores.* Foamed-in-place core materials consist of two components, an alkyd resin and a diisocyanate, the latter generating the gas that produces the foam. When the two components are mixed, the temperature must be controlled within a certain range, usually just at or below room temperature. If the temperature falls below the critical range, the components will become too viscous, with a danger of moisture condensation; and if the temperature exceeds the mixing range, the foaming action will start. The resin and diisocyanate are not readily miscible and therefore require about one-half hour to mix thoroughly. Because of the nature of the compounds used, the mixing equipment should be placed under a hood, and workers should be protected by gloves and fresh-air hoods. When thoroughly mixed, the liquid is poured into the mold and heated to the desired temperature until expansion ceases. Temperatures from room to 200° F. have been used for this step. After expansion ceases, the core material is given a final cure for about 2 hours at a slightly higher temperature.

4.008. *Dough-type cores.* Cores expanded in place from a dough-like insert of synthetic rubber must be prepared in strict accordance with the manufacturers' instructions; and, as they are usually formulated for a specific use, such as core of hollow propellers, no general methods of preparation can be set forth.

4.009. *Waffle-type cores.* Waffle-type cores are fabricated to an exact thickness by the manufacturer; therefore no machining or sizing operations are required other than a light sanding to prepare the surfaces for use.

The material is then tailored to fit the mold, is dipped in a thin solution of the laminating resin, and is wet-laminated between the glass-cloth facings exactly as when wet-laminating with glass-cloth honeycomb core.

4.1. Facing Materials

4.10. Preparation for Use. Facing materials as received are not ready for use until they have been suitably prepared. Metals must be cleaned, glass cloth must be impregnated with the proper amount of resin, and plywood must often be sanded. In addition, all facings must be carefully inspected immediately before use to insure proper results. Too much emphasis cannot be placed on the importance of properly preparing facing materials, particularly metals; and therefore it is imperative that all process specifications be specific on the method of cleaning and on the conditions of storing before use.

4.100. *Cleaning metals in preparation for bonding.* It is essential in good bonding practice that greases, waxes, oils, loose oxides, and other contaminants be removed from metal surfaces before adhesives are applied. Many different methods are recommended by adhesive manufacturers for preparing metal surfaces for bonding and should be followed closely. In general, these methods can be classified as (1) abrasion, (2) solvent cleaning, (3) alkaline-detergent cleaning, (4) chemical etching, and (5) combinations of these methods. A discusion of some of the more common of these cleaning methods follows.

4.1000. *Abrasion.* Surfaces may be abraded by sandblasting, wire brushing, or rubbing with steel or aluminum wool, emery cloth, or sandpaper. Abraded particles are then removed by blasting with air, wiping with a clean cloth, or washing with water and quickly drying. The type and fineness of the abrasive and the amount of abrading necessary will depend upon the type of metal being cleaned and the amount of contamination to be removed. With clad aluminum-alloy sheets, care should be taken that the abrasive does not include other metals likely to set up electrolytic forces causing corrosion and that the abrading does not entirely remove the clad surface and thus lower the corrosion resistance of the sheet. Aluminum wool and iron-free emery cloth should be used. Abrasion cleaning is especially applicable when loose or protective oxides are to be removed from areas of metals that would be difficult to immerse in etching solutions. In removing oxide surface coatings from metals by abrading, the greases, waxes, and oils are also removed if the amount of these contaminants is not excessive. It is not, however, generally recommended that metals be prepared for bonding solely by the use of abrasive methods.

4.1001. *Solvent cleaning.* Greases, waxes, and oils can be removed from metal surfaces being prepared for bonding by using such solvents as stabilized trichlorethylene, methyl ethyl ketone, acetone, benzene, naphtha, ethyl acetate, or methyl alcohol. Carbon tetrachloride and unstabilized trichlorethylene are not suitable solvents because of possible breakdown of the solvents prior to use resulting in formation of substances found corrosive to some metals such as aluminum. There are several methods by which these solvents can be used in removing surface contaminants. One of the simplest methods is to apply the solvents to the metals by wiping with a clean solvent-soaked cloth. Surfaces may often be cleaned more effectively by abrading with a solvent-soaked brush or steel wool than by wiping with solvent-soaked cloth. Solvent cleaning is frequently used to remove identification lettering or excess greases from metal surfaces before cleaning by other methods, or it may be used to complete the removal of greases, waxes, and oils following incomplete cleaning by other methods. Metal pieces can also be degreased by immersing them in the solvents at room temperature. Degreasing by immersion in hot solvents is usually not practical because of the high volatility of most suitable solvents and of the resultant fire and health hazards. When degreasing by immersion in solvents, the solvent is usually agitated or the pieces brushed in the solvent to obtain efficient cleaning. Following removal from the original solvent bath, the metal pieces are frequently dip-rinsed in a second bath of clean solvent or wiped with a solvent-soaked cloth to remove any thin film of contaminant that may remain. Spray cleaning with solvents in closed chambers or degreasing in solvent vapors is also employed for cleaning metals with solvents. All of these solvent-cleaning methods have been used for cleaning metals in preparation for bonding with a number of adhesives, provided that no loose oxides are present. One of the disadvantages of solvent cleaning is that it is difficult to control at all times the cleanliness of the solvents being used. Care should also be taken when using this solvent method of cleaning to insure that the hands and other parts of the body do not come in prolonged contact with the solvents, that there is adequate ventilation, and that there is no source of fire near inflammable solvents.

4.1002. *Alkaline detergents.* Greases can be removed from metal surfaces by immersion for 5 to 10 minutes at 200° to 210° F. in alkaline solutions having 4 to 8 ounces of suitable detergent cleaner per gallon. Detergent solutions are also used for degreasing by scrubbing the warm solutions over the metal surfaces. These cleaners, many of which can be obtained as proprietary compounds, are usually composed of two or more of the following ingredients; trisodium phosphate, sodium metasilicate, sodium orthosilicate, sodium tetraborate, sodium carbonate, sodium hydroxide, rosin soaps, and wetting agents. Some of the formulations of these ingredients that have been used are (4–8 ounces of mixture per gallon of water):

(1) 85 percent sodium orthosilicate.
    10 percent sodium carbonate.
    5 percent sodium resinate.
(2) 38 percent sodium metasilicate.
    25 percent sodium hydroxide.
    25 percent sodium carbonate.
    6 percent rosin soap.
    6 percent alkyl aryl sodium sulphonate (wetting agent).
(3) 32 percent trisodium phosphate.
    16 percent sodium hydroxide.
    46 percent sodium carbonate.
    6 percent rosin.
(4) 90 percent sodium metasilicate.
    10 percent alkyl aryl sodium sulphonate (wetting agent).

It is recommended that low-alkalinity solutions, such as the last formulation containing only sodium metasilicate and wetting agent, be used when degreasing such metals as aluminum that might be rapidly attacked by highly alkaline solutions. Upon removal from such detergent solutions, the metal should be rinsed thoroughly in hot water (140° to 170° F.), and then be quickly air-dried. In cleaning aluminum for bonding it has been found desirable in some instances to follow the water rinse in this method with a rinse in a dilute acid solution (5 percent chromic acid), and then by another water rinse in order to complete the removal of the metasilicate residue before drying. Care should be taken throughout this cleaning process to insure that cleaning solutions are not allowed to dry on the metal, as they will then often be very difficult to remove.

4.1003. *Chemical etching.* There has been some evidence that merely removing the greases, waxes, and oils from metal surfaces with solvents or alkaline detergents is not sufficient preparation of the metal surfaces for bonding with certain adhesives. The adhesion with these adhesives to metals has been improved when the metals were further treated with etching solutions. Etching solutions have also been used, in preference to abrading methods, to remove oxide coatings from metals. Etching solutions can be used for both degreasing and etching of the metal in preparation for bonding. Since an irregular distribution of grease or wax on a metal surface will protect the metal to varying degrees from the etching process, it is generally recommended that grease be removed by one of the previously mentioned methods before placing the metal in the etching bath. Many proprietary compounds, both of the acid and alkaline type, are available for removing oxides and etching metal surfaces. An acid-etching method that has given very good results in preparing aluminum for bonding, consists of immersing the aluminum for 5 to 10 minutes at 140° to 150° F. in a solution of 10 parts by weight of concentrated sulfuric acid, 1 part sodium dichromate, and 30 parts water, rinsing in cold and hot water, and then quickly air drying. Clad aluminum sheets that have been subjected to this bath usually have a satin sheen rather than a bright mirror finish. In production cleaning of aluminum for bonding with certain adhesives, immersion periods as short as 3 minutes, in the sulfuric acid-sodium dichromate solution and a rinse with only cold water followed by a forced dry was also found to be a satisfactory cleaning method.

A method that has been used for cleaning aluminum by etching at room temperatures consists of immersing the aluminum in a solution of 40 percent by volume of butyl alcohol, 30 percent isopropyl alcohol, 10 percent phosphoric acid (85 percent), and 20 percent water, and then following with adequate rinsing and drying.

A process for cementing metal to metal and metal to wood requires that steel be prepared for bonding by pickling for 2 to 4 minutes at 60° to 70° F. in a solution of 10 percent by volume concentrated sulfuric acid, 10 percent concentrated nitric acid, and 80 percent water, then rinsing in cold water, and then immersing for ½ to 1 minute at 60° to 90° F. in a bright-dipping bath of 50 to 60 percent by volume of concentrated hydrochloric acid, 2 percent hydrogen peroxide (30 percent concentration), and 38 to 48 percent water. This procedure is then followed by rinsing in cold and hot water and quickly air-drying.

4.1004. *Combinations of cleaning methods.* To obtain thorough cleaning of metals for bonding, many fabricators are using several of the cleaning methods in combination. Some of the greases, waxes, and oils may first be removed by wiping, abrading, or scrubbing with solvents or detergents. Removal of these contaminants may then be completed by immersion of the metal in a detergent solution, and finally the metal may be etched. When cleaning metals by abrasion methods, solvents are also quite frequently first used to insure the removal of greases, waxes, and oils.

4.1005. *Inspection of cleaned metal surfaces.* To determine if a metal surface has been cleaned free of greases, waxes, and oils sufficiently to be bonded, many fabricators use the water-film test. This test consists of running cold tap water over the surface, allowing the excess water to run off, and then inspecting the surface for areas where the film breaks due to the presence of greases, oils, and waxes (fig. 4–14). Surfaces that show areas with such breaks in the water film should be recleaned before bonding. It cannot, however, be assumed that metal surfaces will be satisfactory for bonding if there are no areas that show water breaks in the water-film test. There has been some evidence that poor adhesion has been obtained to "no-break" surfaces because of thin films or stains from the cleaning solutions, loose oxides, or loose particles on the surface, or that the adhesive may require an etching of the surface in addition to being free of impurities.

4.1006. *Storage of clean metal surfaces.* After metal surfaces have been prepared for bonding, it is essential that the adhesives be applied to the surface before it becomes contaminated. Clean metal surfaces may be stored for periods as long as 8 hours in a dry, grease-free atmosphere. When storage of longer than 8 hours is necessary, clean metal sheets should be wrapped in a grease-free protective covering. When so protected, clean aluminum surfaces have been stored for periods as long as 1 week, and longer periods may be allowable. When handling clean sheets of metals, clean

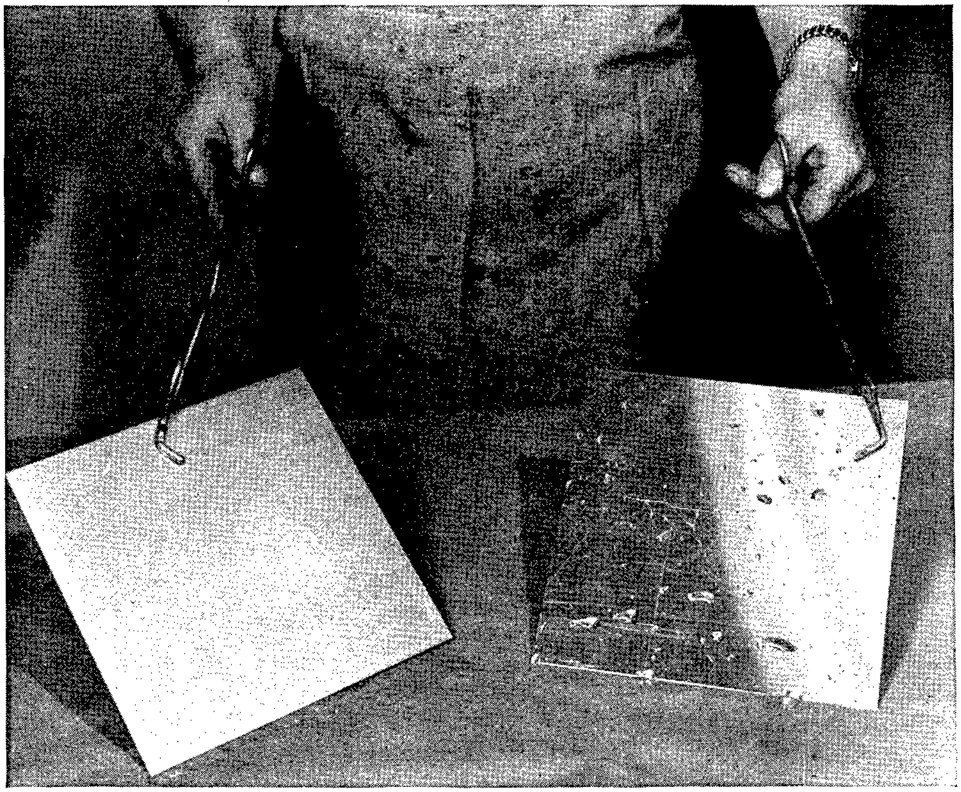


Figure 4–14. Appearance of water-film on a metal surface that is free from grease (left) and on a metal surface that has not been degreased (right). Note the continuous water film on the cleaned surface (left) and the nearly complete absence of a water film on the greasy surface (right).

gloves should always be used so as to prevent any contamination of the surfaces with fingerprints.

4.101. *Plywood.* No special preparation is required for plywood if the surface to be bonded is clean and free from contamination. If, however, there is any question of its bondability, the surface should be lightly sanded with fine sandpaper immediately prior to application of the adhesive.

4.102. *Glass cloth.* Glass cloth to be used for reinforcement of facings should be stored and handled to maintain the original cleanliness of the material. The adhesion of resin to glass fibers is adversely affected by oil, dirt, or moisture; and, therefore, clean, dry storage is imperative. Careful handling to avoid "snags" and sharp folds in the cloth is advisable, as these imperfections may result in a local reduction in strength of the finished facing. Requirements for laminated glass-cloth-fabric-base materials that are to be molded at low pressures, are given in U. S. Air Force Specification No. 12051.

4.1020. *Resin impregnation.* The preparation of glass cloth for use consists of impregnating it with the proper amount of resin and cutting it to the desired shape. The sequence of these operations depends on whether the resin is applied by hand or by machine. For exploratory, experimental, or small-scale production, resin is often applied by hand after the cloth has been cut to size. One method of hand impregnation particularly suited to high-viscosity resins is shown in figure 4–15. Low-viscosity resins may be easily spread or poured directly on the cloth. With either type of hand impregnation it is advisable to roll the coated sheets on a metal tube and allow a few hours for diffusion of the resin.

Larger-quantity production requires machine impregnation, with the type of machine depending largely on the viscosity of the impregnating resin. A knife coater such as is shown in figure 4–16 has been used successfully with high-viscosity resins. The amount of resin applied by this type of coater depends upon the tension in the cloth, and, therefore, adequate provisions must be made for adjusting and maintaining uniform tension across the machine. Another type of machine coater for high-viscosity resins, which employs a resin-coated roller as an adapter on a conventional adhesive spreader, is shown in figure 4–17. The amount of resin applied is directly related to the clearance between the knife and the applicator roll, as well as to the pressure between the rolls. Low-viscosity resins are more adaptable to conventional coating machines. Figure 4–18 illustrates diagrammatically several types of coaters that might be used.

With any type of machine coater it is often impractical to maintain continuously the exact desired resin content throughout the roll, or from roll to roll, as resin content is normally checked by increase in roll weight. Adjustments in resin content can be made at the time the rolls are used if the average resin content of each roll is known. Alternate sheets of high and low resin content can be laid up, or, in extreme cases, dry sheets may be interleaved as required to produce the proper resin content in the cured facing. If the resin content of all rolls is too low, some or all must be recoated.

It is often advantageous to impregnate glass cloth with the liquid resin well in advance of laying up the facings. This can be done with all resins that are fairly viscous and that permit storage of the impregnated material under refrigeration for a reasonable period of time before final use.

4.1021. *Resin content.* The resin content of glass-cloth facings is expressed as the ratio of the weight of cured resin to the total weight of the cured facing. The resin content of a cured facing (sec. 2.213) may be somewhat different from the resin content of the coated uncured cloth. Optimum specific-strength properties normally result when resin contents are within the range of 35 to 45 percent, depending upon the specific gravity of the resin. Resin contents substantially below this range result in insufficient stabilization of glass fibers in compression and in low-strength interlaminate bonds, while high resin contents may result in crazing and increase weight without a comparable increase in strength. Excess surface resin on laminate will often crack or craze.

4.1022. *Void-free laminates.* Specially prepared glass cloth reinforced facings, essentially free of the minute voids normally present in these facings, are sometimes required. Void-free laminates are characterized by the following advantages over conventional laminates:

(1) Better rain erosion resistance.
(2) Better base for rain erosion coating.
(3) Greater uniformity.
(4) Smoother surface.
(5) Lower moisture vapor transmission rate.
(6) More nearly transparent (facilitating inspection).

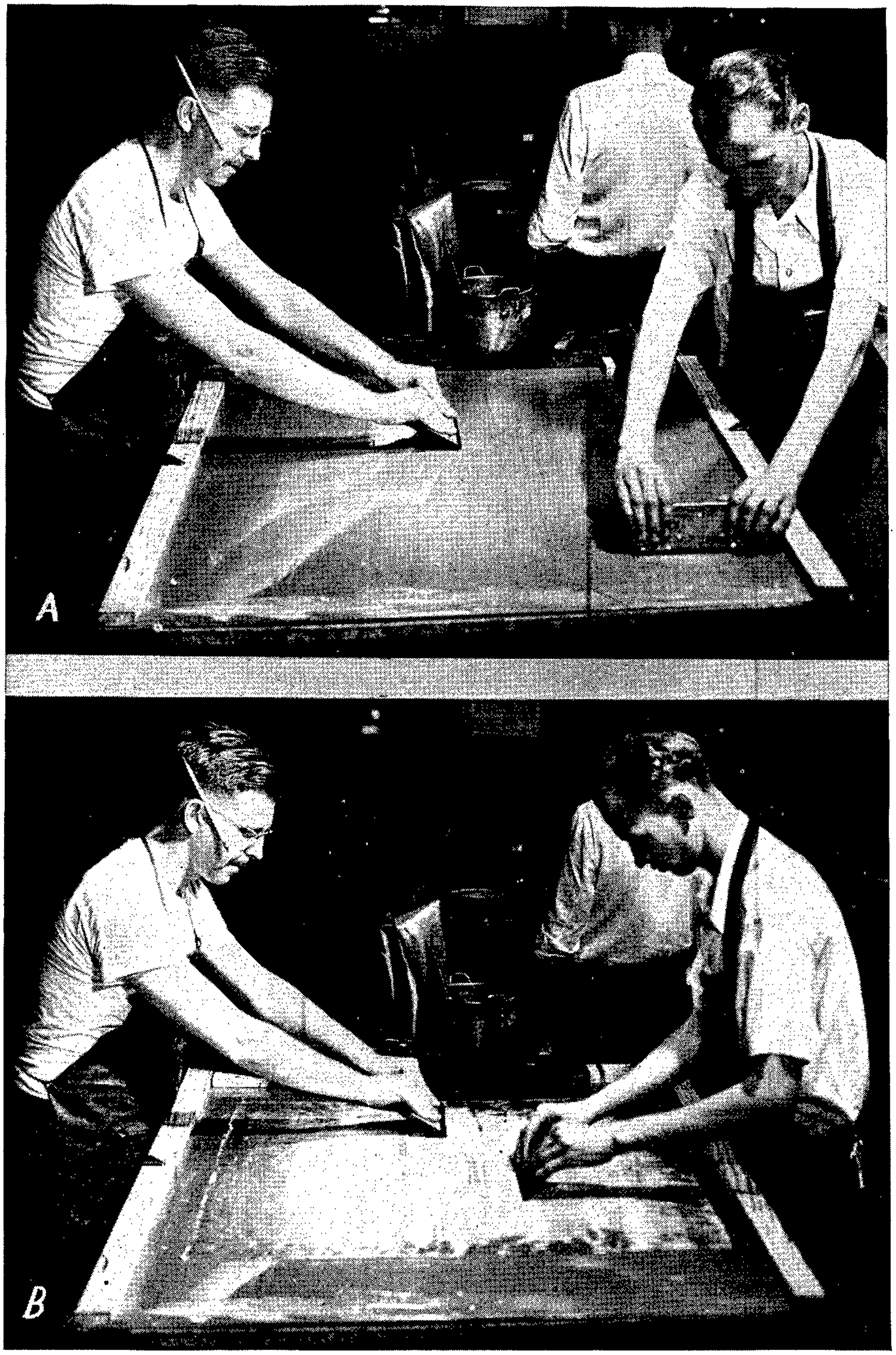


Figure 4–15. Hand spreading high-viscosity laminating resins on glass cloth. A, applying film of resin to stainless-steel sheet; B, working glass cloth into resin film to impregnate the cloth.

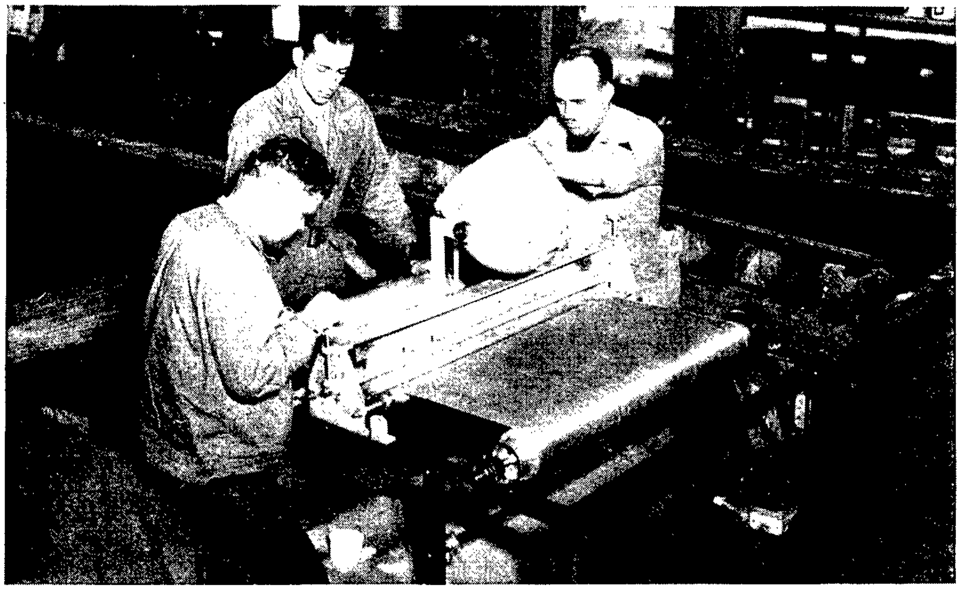


Figure 4–16. Knife coater used for applying resin to glass cloth.

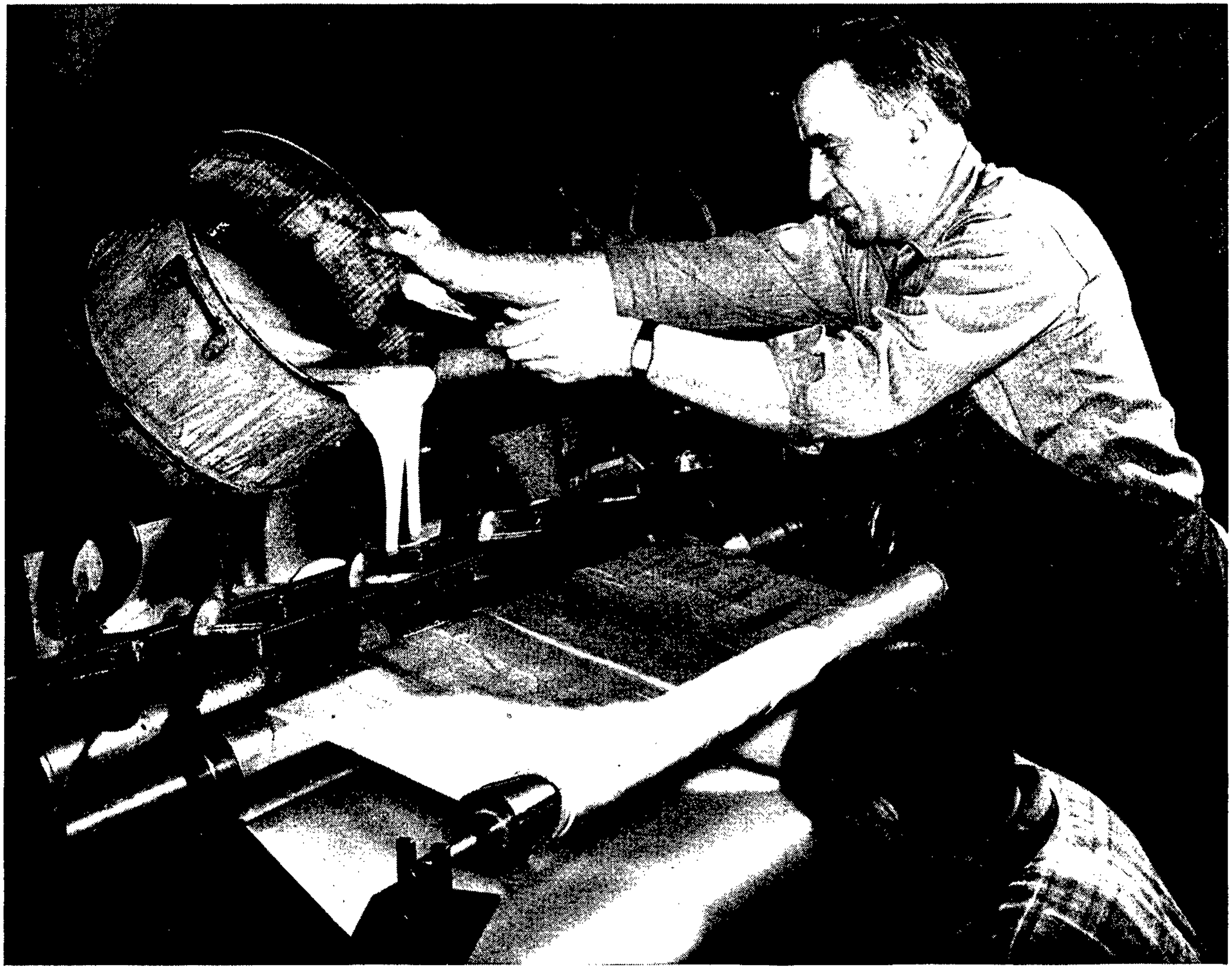
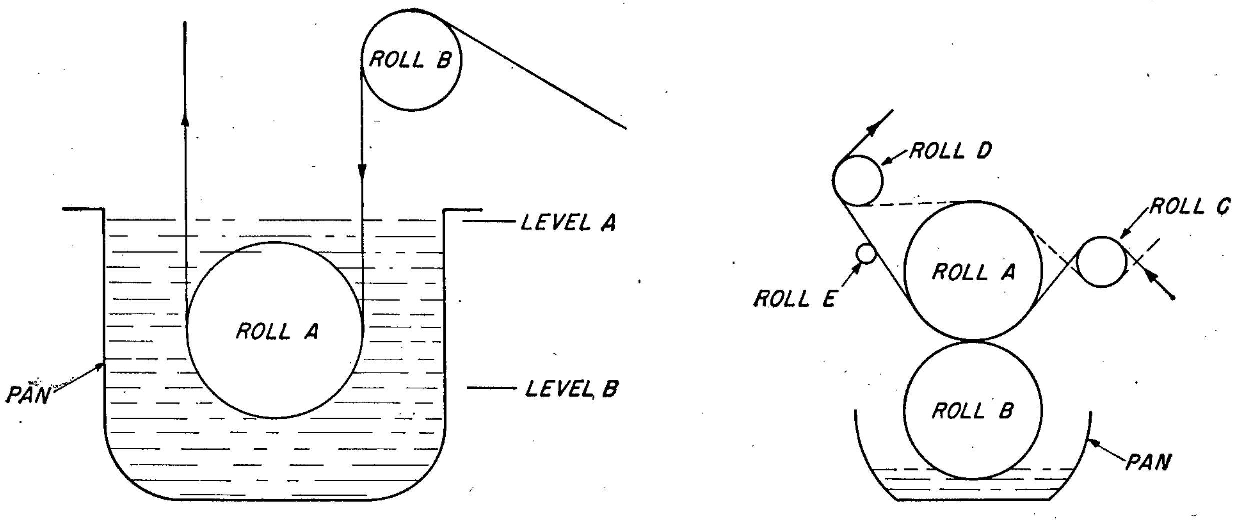
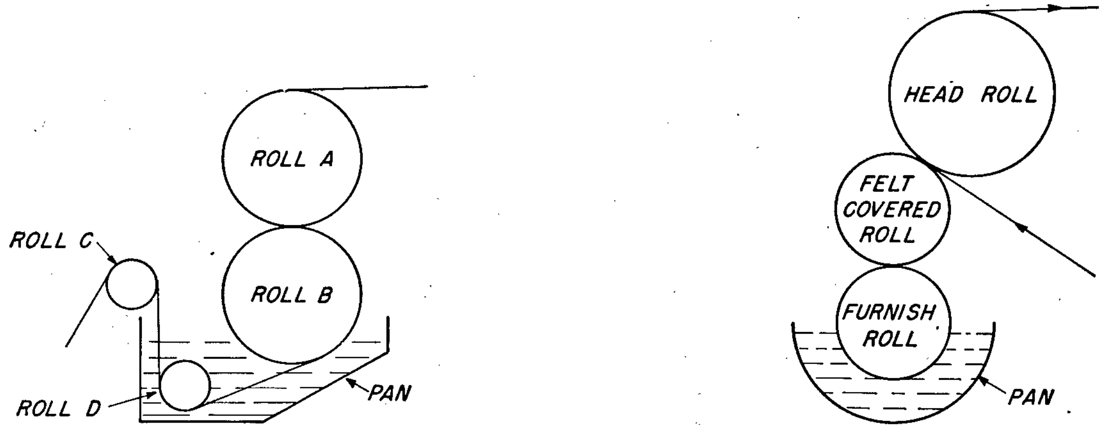


Figure 4–17. High-viscosity, laminating resin being spread on glass cloth with a machine spreader employing a resin-coated roller as an adapter to a conventional adhesive spreader.



A. DIP COATER

B. ROLL COATER



C. ROLL COATER

D. BRUSH COATER

Figure 4–18. Diagrammatic sketch of several types of coaters that might be used with low-viscosity resins.

The production of void-free laminates normally is accomplished in the following manner, with some variations depending on viscosity of resin or shape of part.

The required plies of glass cloth are laid on a smooth metal mold, using a suitable separator, and coated (by pouring) with an excess of low viscosity resin. It may also be advisable to apply some of the resin to the mold before laying on the glass cloth. A short period is allowed for the resin to diffuse through the layers of cloth. The assembly is then covered with a polyvinyl alcohol sheet, sealed at the edges, and evacuated. While a constant partial vacuum is maintained all air entrapped in the glass cloth weave is worked out through the edges. This working is accomplished by means of a wiping action of a wood or rubber straight-edge having a rounded edge. Without reducing or releasing the vacuum the assembly is then heated to about 160° F. until the resin has jelled (about 1 hour for ⅛-inch laminates). The cure is completed at about 240° F.

4.2. Sandwich Fabrication Techniques

Sandwich constructions currently in use in aircraft, or in the experimental stages of fabrication, are of many combinations of cores and facings.

Some of the combinations currently finding use in the United States are listed below:

Core	*Facings*
Balsa	Aluminum
Balsa	Glass-cloth laminate
Cotton honeycomb	Aluminum
Cotton honeycomb	Metal
Cellular cellulose acetate (wrapped bars).	Glass-cloth laminate
Foamed in place	Steel
Glass-cloth honeycomb	Glass-cloth laminate
Waffle type	Glass-cloth laminate
Expanded rubber	Steel
Cellular cellulose acetate	Glass-cloth laminate
Cellular cellulose acetate	Aluminum
Metal honeycomb	Metal
Cotton honeycomb	Plywood
Paper honeycomb	Plywood
Paper honeycomb	Aluminum
Cellular hard rubber	Glass-cloth laminate
Corrugated metal	Aluminum

Sandwich parts in aircraft are of any configuration from flat to severe compound curvature; and, consequently, a fabrication technique must be chosen that can be adapted most readily to the specific core-facing combination and configuration.

Fabrication techniques may be divided into classes according to curvature of product, type of facing or core, equipment required, method of applying pressure, or according to some other characteristic. For the purposes of this discussion techniques are classed principally according to the method used to apply pressure.

4.20. MEANS OF APPLYING PRESSURE.

4.200. *Fluid pressure.* The molding of sandwich parts by means of fluid pressure applied through flexible bags or blankets of impermeable material has found application in making sandwich parts of various degrees of curvature. Typical parts include all combinations of single and compound curvature, cylinders, paraboloids, portions of a sphere—in short, any piece for which a mold can be made and later separated from the finished product.

The fundamental procedure of molding with fluid pressure is the same for all processes in common use. In principle, the technique consists of attaching temporary superimposed layers of facings and core in a mold of the desired shape, and molding these into a unit structure by the application of heat and fluid pressure through a bag or blanket. The fluid may be air, steam, steam-air mixture, or an inert gas. Processes are relatively simple and provide a means by which sandwiches of single or compound curvature, and of constant or varying thickness in any arrangement of facings and core, can be produced. Flat sandwich parts can also be made by fluid pressure molding, but can normally be produced more economically by other means. The fluid-pressure technique is largely limited in use to the production of parts that can be manufactured by no other practical means. In general, parts that fall in this category will have one or more of the following characteristics: Appreciable compound curvature, variable thickness, single-curvature bends approximating 180°, parts too large to be made practicably by mating dies, or quantity too small to justify mating dies.

The processes permit the use of thermosetting resins and metal-to-metal adhesives with long assembly periods. Pressures within the range of 5 to 75 pounds per square inch are common. Figure 4–19 illustrates diagrammatically the processes in use at present: A, the vacuum bag process; and B and C, techniques employing higher pressures.

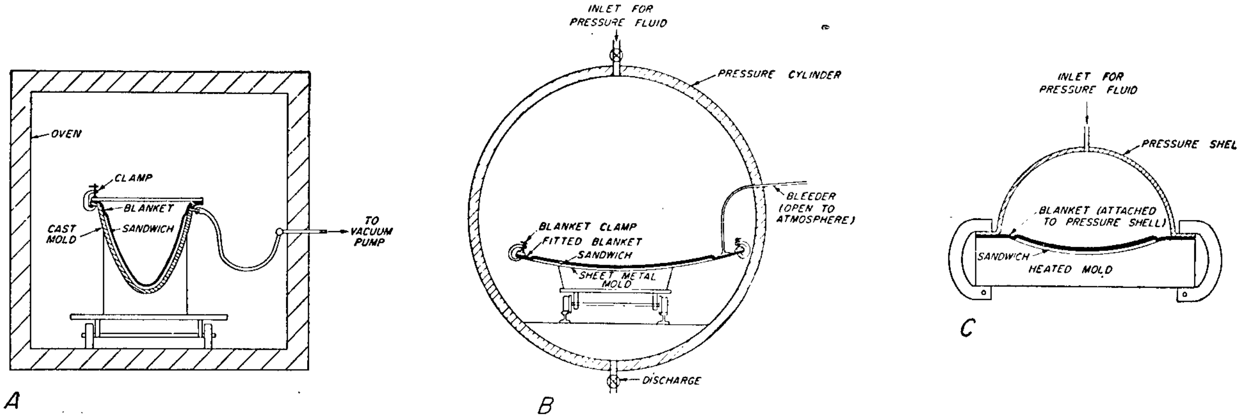


Figure 4–19. Three typical methods of applying fluid pressure.

4.2000. *Molds.* The forming of any piece by means of fluid pressure requires a mold of some type. These molds, sometimes called forms or dies, are broadly classified as male or female. Male molds have the desired shape on the convex surface while female molds (*A*, *B*, and *C*, fig. 4–19) have the desired shape on the concave surface. Female molds are used almost exclusively for all curved aircraft sandwich panels, as smoothness of the convex surface on the finished part is important. The surface of the sandwich next to the mold is always smoother than the surface exposed to the bag or blanket.

Metal molds are usually made of sheet steel, aluminum, or cast iron. Alloys having low melting points are also reported to be in limited use. Molds of single or slight compound curvature are made of sheet material one-sixteenth to one-fourth inch thick. A typical mold of thin sheet steel adequately supported by a steel framework is shown in figure 4–20. Two well-designed bleeder inlets are shown on the surface attached to a common bleeder connection extending from the end. Molds of severe compound curvature, such as for a radome, are often cast. Thin sheet-metal molds have the advantage of very rapid heat transfer, while heavy cast-metal molds heat more slowly. For any kind of externally heated mold the rate of heating is affected by the heating medium, of which steam is faster than air. Metal molds that are in continuous use may require cooling before they can be used for the next lay-up. This is particularly true of small molds of considerable thickness. Large molded pieces require a longer time for removal; and, consequently, the mold may be sufficiently cooled before it is again ready for use.

Molds of the type shown in figure C, 4–19 are heated internally. They may be of cast iron and be cored for steam heating, or may be of a low-melting alloy poured around a network of copper heating tubes. Cooling, if necessary, may be done with cold-water circulation. One application of this type of mold for producing sandwich skins for helicopter blades is shown in figure 4–21.

Female metal molds have recently been successfully made by means of an electrodepositing process on reusable cast phenolic male forms. Molds of this type are normally about one-quarter inch thick, being deposited from nickel, a nickel alloy, iron, or copper, sometimes with nickel or chrome faces. The process is particularly adaptable to molds of compound curvature. Molds several feet in width and length have been made by this process.

Female metal molds are sometimes heated by means of flexible steam coils that are metal-sprayed in position on the outside surface. The proper spacing and configuration of the coils must be determined with care to avoid excessive temperature variation. If the sandwich part being molded is unusually thick (more than one-half inch) it may be necessary to provide for supplemental heating on the inside (blanket side). This may be done with electric heaters and fans under a portable canopy.

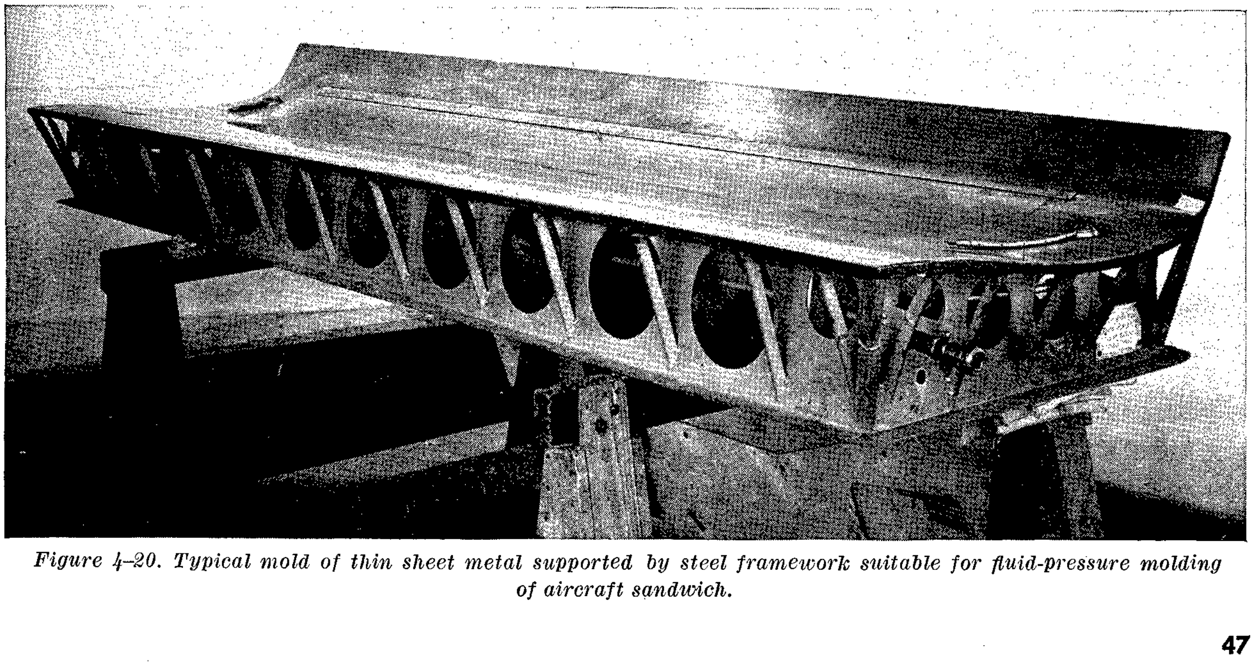


Figure 4–20. Typical mold of thin sheet metal supported by steel framework suitable for fluid-pressure molding of aircraft sandwich.

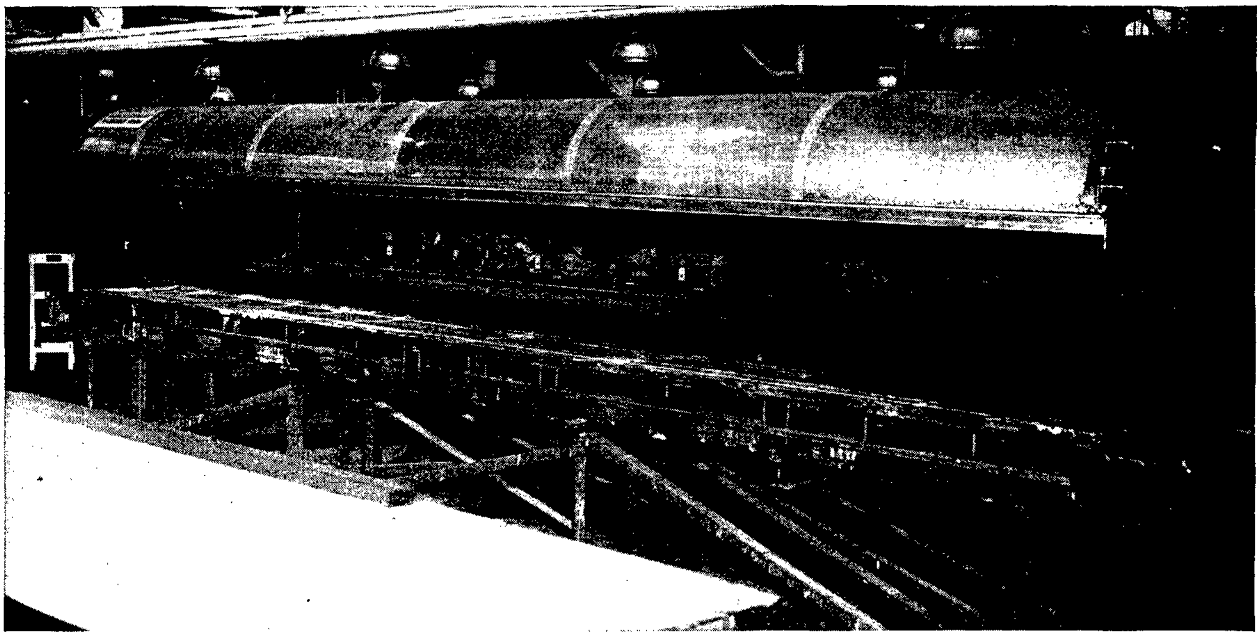


Figure 4–21. Internally heated mold for producing sandwich skins for helicopter blades.

Wood or plaster molds are sometimes used for exploratory work where only a few pieces fabricated at room temperature are required.

Molds of compreg or impreg type materials when properly designed have found limited use.

4.2001. *Bags or blankets.* The purpose of the bag or blanket is to provide a flexible impermeable barrier between the fluid under pressure and the mold. The piece being molded is pressed between this flexible bag and the rigid surface of the mold; and, therefore, the full fluid pressure is applied at right angles to the surface of the part regardless of the shape. The pressure at certain points within curved parts may, however, be slightly less than the full fluid pressure by the amount necessary to shape or force the facings or core into place.

Bags are classified as full bags or blankets. A full bag is a complete envelope of impervious flexible material, completely closed and having only a tube or bleeder connection for inflation or evacuation. A blanket is a sheet that normally fits the mold without wrinkling and that is sealed by some temporary means to its edges *A*, *B*, and *C*, fig. 4–19). The bleeder may be attached either to the mold or to the blanket.

The useful life of a bag depends on the type of material, the heating medium used, the temperature of the cycle, and the care used in handling. The type of bag material depends largely on the molding process, the temperature, and the heating medium. The use of steam requires bags made of specially compounded natural or synthetic rubber. When hot air is used, polyvinyl-alcohol film or cellophane may be used and discarded after one operation. Soft aluminum foil has been successfully used as bag material in some high-temperature molding operations.

Whenever a steam-air mixture is used and the air is introduced under pressure from a compressor, an adequate after-cooler and air filter should be installed between the compressor and the cylinder. The life of a rubber bag is considerably increased when all traces of oil in the form of vapor or small drops are removed from the air.

When a rubber bleeder hose is employed, it must not collapse and close when external pressure is exerted upon it during the molding cycle. Collapse of the bleeder hose within the cylinder is difficult to observe. Emission of a slight amount of air or steam from the bleeder does not guarantee that it is functioning properly. Flexible metal hose, a copper tube, or a suitably reinforced rubber hose is recommended for the bleeder.

In using the method shown in *B*, figure 4–19, careful attention should be given to the inside surface of the bleeder fitting in the bag. If this fitting is very smooth and flat it may make an airtight fit and stop the bleeder from functioning. Grooves in this fitting, as shown in figure 4–22, or a piece of coarse burlap or screen bonded to it, will usually suffice.

4.2002. *Pressure and temperature equipment.* All pressure equipment for use with fluid-pressure molding should be hydraulically tested to a pressure of at least double that of the maximum working pressure to be used. An adequate safety valve should always be installed if the steam or air is drawn from a supply line that is in excess of the pressure at which the cylinder was tested.

The devices placed within the pressure cylinder for controlling and recording conditions should be carefully installed. Heavily jacketed controls will lag and therefore will not record the actual cylinder temperature during the rapid heating period. A jacketed thermometer was found in experiments at the Forest Products Laboratory to be as much as 20° to 30° F. below the reading on a bare thermocouple in heating a cylinder 2 feet in diameter and 6 feet long to 250° F. in 5 minutes with a steam-air mixture.

If temperature stratification exists in the cylinder, a temperature-recording bulb at the top of the cylinder may be 30° F. or more above the actual temperature at the bottom of the cylinder, and provision for circulation should therefore always be made if possible. A good check on uniformity of temperature may be obtained by inserting bare thermocouples in the top and bottom of the cylinder.

4.2003. *Amount of pressure.* The pressures used in fluid-pressure molding of sandwiches vary from a partial vacuum drawn on the bag (less than atmospheric pressure) to a maximum of about 75 pounds per sequare inch. Vacuum alone normally produces sufficient pressure for sandwich constructions involving contact-pressure laminating resins, but is insufficient for operations such as bonding aluminum or plywood facings on end-grain balsa cores. In determining the proper pres-

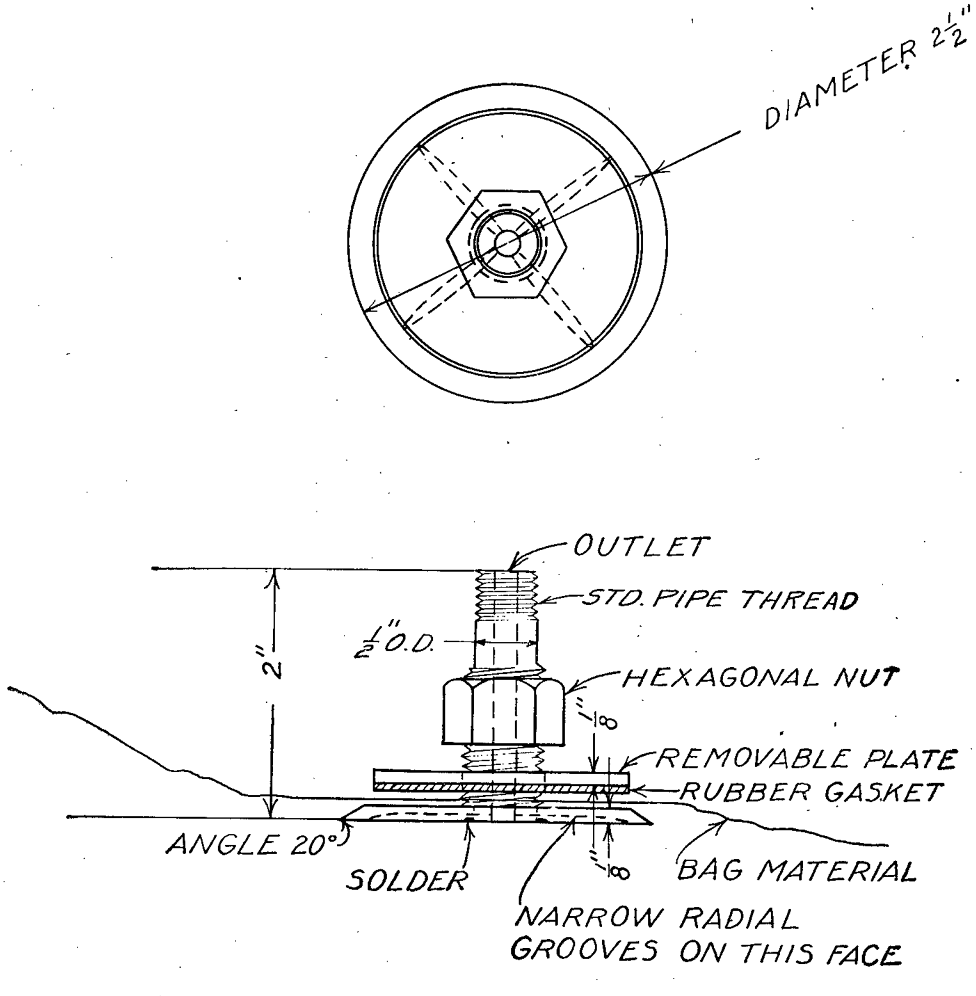


Figure 4–22. Metal bleeder connection designed for rapid attachment to bags.

sure, consideration should be given to the pressure limitations of the core as given in table 4–1. These values were obtained between rigid surfaces and, therefore, are integrated or average values; whereas with the uniform distribution, characteristic of fluid pressure, the weaker spots in the core fail first. Considering the unavoidable nonuniformity of all core materials, fluid molding pressures should not exceed approximately 50 percent of the proportional-limit pressures of table 4–1.

Table 4–1. Compressive strength of six core materials as determined in a heated press on specimens ½ inch thick

Core material	Temperature	Density	Approximate proportional limit	Load at 0.050-inch compression
	°F.	*Pounds per cubic feet*	*Pounds per square inch*	*Pounds per square inch*
Balsa	300	6.19	More than 400	[1] 400
Cellular cellulose acetate (Du Pont).	Room	6.65	130	[2] 220
	225	6.29	90	140
	250	6.20	90	130
	275	6.36	70	120
	300	------	70	120
Cellular hard synthetic rubber (Sponge Rubber Products).	Room	6.86	140	[2] 160
	225	7.47	10	30
	250	8.13	10	20
	275	7.39	Less than 10	20
Phenolic and polyester-paper honeycomb (FPL).	Room	5.79	550	[3] 550
	225	5.76	120	170
	250	------	110	160
	275	5.80	90	160
	300	5.71	90	140
Polyester-glass-cloth honeycomb (Western Products).[4]	Room	8.18	390	420
	225	8.73	120	160
	250	8.50	90	150
	275	8.42	80	120
	300	8.88	70	110
Phenolic-cotton-cloth honeycomb (U. S. Plywood).	Room	3.50	230	280
	225	3.86	120	[2] 170
	250	3.61	100	140
	275	3.70	90	120
	300	3.77	80	120

[1] Load at 0.010-inch compression.
[2] Value estimated from curve.
[3] Load at 0.027-inch compression.
[4] Tested as received. Not dipped in thinned resin.

Considerations other than the characteristics of the core often dictate pressure requirements. Wet laminating with glass-cloth reinforced facing is an example. There is an optimum molding pressure for each type of weave and for each viscosity of laminating resin. In addition, the pressure and type of core have a pronounced effect on the final resin content; and, consequently, for optimum strength properties, the molding pressure for each specific combination of cloth weave, resin viscosity, and core must be carefully considered. In general, strength properties continue to increase with pressure within reasonable limits. A pressure of 30 to 50 pounds per square inch appears to be a practical range with most cloth weaves and low-pressure resins. The use of certain modified phenolic-type resins requires pressures as high as 80 pounds per square inch; while with other low-viscosity, contact-pressure resins, 10 pounds per square inch is sufficient.

When fluid pressure is used, all variations in thickness of core, facings, or adhesive spread result in nonuniformities or waviness in the facing next to the blanket. Under some forms of loading the stresses on the core-to-facing bond are proportional to the magnitude of these irregularities, and, therefore, it is imperative to keep these irregularities to a minimum.

4.201. *Rigid dies.* Molding or bonding pressure is often applied to sandwich panels by pressing them between surfaces made of metal or some other rigid material. The force is normally applied by a hydraulic piston or screw threads, and stops may be used in some cases to obviate excessive crushing of the core.

The simplest form of rigid-die application is the conventional hydraulic press. A multiple-opening hydraulic hot press is shown in figure 4–23 being loaded with flat sandwich parts. Stops between the platens are sometimes necessary to avoid or control compression of some of the weaker cores, but many of these flat panels have an edge banding of denser material that serves the same purpose as stops.

A set of mating rigid dies for a curved sandwich part normally represents a considerable investment because of the accuracy of fit required. Consequently, they are used only for large quantities of parts for which exact specifications as to size, thickness, and shape have been established. To expedite production, heated dies are common and, if production schedules dictate, cooling of the dies may be required in some cases. The method of heating will depend upon the size of the dies, rate of heating required, or availability of equipment, and may be supplied externally by conduction in a hot press, or internally by steam, hot water, or electricity. Cast aluminum dies having external copper heating tubes, metal-sprayed in place, have also been used.

The actual magnitude of the pressure applied on any point in a sandwich part between a set of curved dies is subject to so many variables that it is seldom known. Curvature of the part, thickness uniformity, modulus of elasticity of the core material, and accuracy of the dies all affect the pressure applied at any specific point. Optimum conditions may be determined by careful inspection and destructive testing of several exploratory parts made at calculated pressures ranging from inadequate contact to definite crushing of the core. If stops are used between the dies, the thickness of the stops or sandwich should be varied over a range sufficient to give similar results.

4.202. *Semirigid dies.* Platens or dies having one or both mating surfaces somewhat resilient are sometimes used to simulate fluid-pressure molding. The resilient surfaces provide a more uniform distribution of pressure than do rigid surfaces without resorting to the use of a fluid under pressure. The hardness of the resilient liner or caul is determined by the characteristics of the sandwich part being pressed. If it is too hard or too soft, it will not produce the desired results. The most suitable material can usually be determined only by trial. For example, a soft-textured wool blanket was found satisfactory for pressing glass-cloth facings on end-grain balsa cores at 15 pounds per square inch, while ⅛-inch cotton-duck pads were necessary for bonding aluminum facings to end-grain balsa core at 300 pounds per square inch. Rubber, chipboard, paper, and felt have also found use.

A resilient pad used on only one side of a sandwich results in one smooth surface (next to the die), and in one irregular surface that conforms roughly to the thickness variations of the core. Resilient pads used on both surfaces result in slight irregularities in both surfaces of the part. For sandwich parts exposed to the air stream, smooth surfaces are essential, and, therefore, only one resilient pad can be used; whereas, for internal sandwich structures, such as floors, partitions, or shear webs, one or two pads may be used.

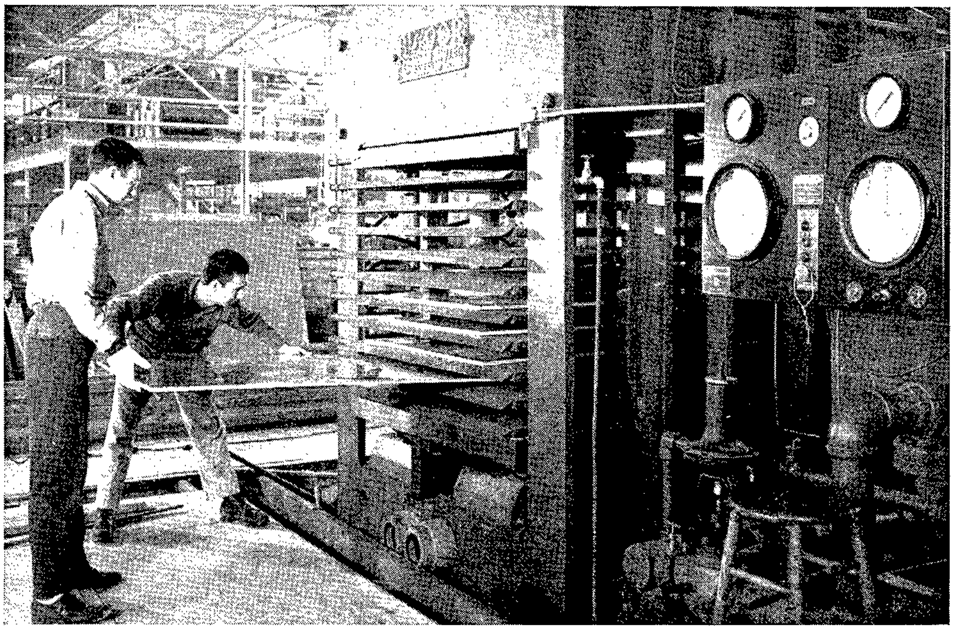


Figure 4–23. Multiple-opening hydraulic press being loaded with flat sandwich parts.

A process similar to "hydropressing" of metal might be used for slightly curved sandwich parts by forcing a soft rubber plug of the proper shape into a heated die.

4.203. *Expanding cores.* Pressure is applied by the core itself when foamed-in-place or dough-type cores are used. These sandwiches require no externally applied pressure, but instead a restraining mold that supplies the required heat to expand and cure the core.

With laminated facings of glass cloth and foamed-in-place cores, the facings are molded first, usually on a set of male and female heated dies employing fluid pressure applied through a bag or blanket. With the facings in place, the uncured liquid core mixture is poured into the female mold and the male mold is quickly lowered and clamped in place. The core material then expands and is finally cured by application of heat to form the bond between the core and facings. A cross-sectional sketch of a set of dies of this type is shown in figure 4–24.

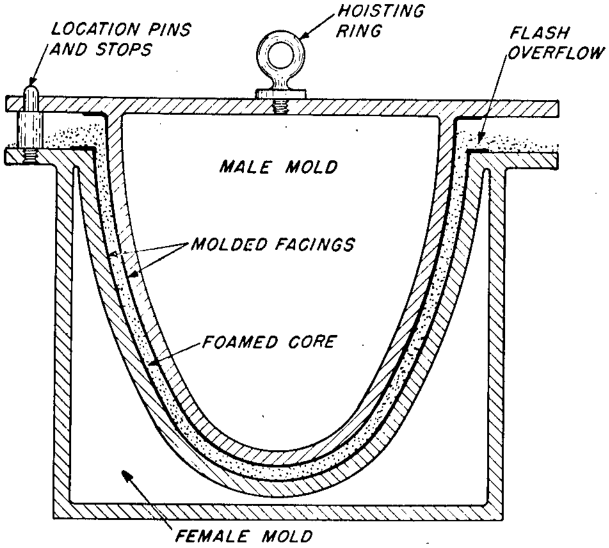


Figure 4–24. Diagrammatic sketch of a heated mold for use with poured cores.

Sandwiches employing dough-type cores are fabricated in a similar manner, except that the core, in the form of an uncured or partially cured rubber dough, must be carefully placed to produce uniform density, after expansion. If steel facings are used, as in a propeller blade, they are previously formed, welded, and primed before being placed in the restraining mold. A rather substantial mold is necessary, as pressures of about 75 pounds per square inch may result from the expansion of the core. Figure 4–25 shows diagrammatically a typical mold for this operation.

4.21. Techniques for Curved Parts. Parts of single or compound curvature are sometimes made by the same methods as are used on flat parts, but for certain combinations and degrees of curvature special techniques are required.

4.210. *Single curvature.* A few tests were made at the Forest Products Laboratory to determine the limits of curvature of various core materials and of a few sandwich constructions. These bending tests and fabrication trials were limited primarily to single curvature.

Parts with only slight single curvature can readily be molded by merely draping the core and facings in a concave mold and later applying pressure by means of a blanket or a mating die. An assembly of this kind utilizing a thin steel mold and fluid pressure exerted through a bag is shown in *B*, figure 4–19.

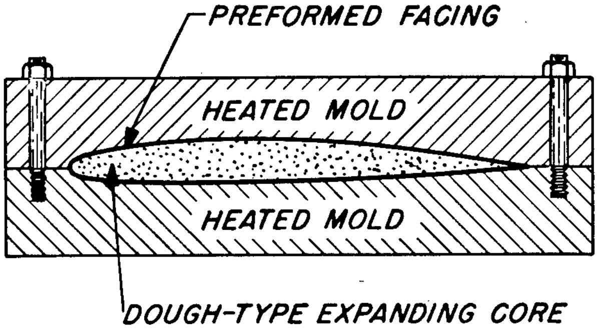


Figure 4–25. Typical restraining mold for use with expanding dough-type cores.

As the curvature becomes more severe, it becomes more difficult to bend the core to shape and to draw it down firmly to the mold surface. The anticlastic (saddle-shaped) curvature, which most core materials tend to assume upon bending, causes some difficulty even at moderate curvature. This characteristic is particularly noticeable with honeycomb cores. The limitations imposed on curvatures of core materials by their tendency to assume an anticlastic curvature vary with the thickness and type of core and have not been fully investigated, but parts having one piece ¼-inch thick fully cured paper honeycomb cores approximately 30 inches square have been molded to a 30-inch radius with no special preparation or treatment.

Often the severity of curvature to which a panel can be molded by the "draping method," or one-step molding process, is limited by breakage of the core material in bending. An attempt to evaluate this limitation was made at the Forest Products Laboratory by determining the approximate breaking radius of 1-inch wide strips of four typical core materials in a variety of thicknesses from one-eighth to one-half inch. If a factor of safety against breakage of about 2 would be applied to these radii, it was believed that reasonably safe working radii would result. These working radii have been investigated in an exploratory manner by bending larger sheets of core material between thin sheets of aluminum, and table 4–2 presents the results. This table may be used in estimating an approximately safe working radius for typical core materials in fabricating curved parts by the draping method.

Table 4–2. Approximately safe bending radius for typical core materials

Thickness of core in inches	Radius in inches
⅛	6
3/16	11
¼	18
5/16	24
⅜	32
7/16	40
½	50

If it is desired to make curved sandwich panels having radii smaller than the safe working radii of table 4–2, special means of forming the core must be employed. Some core materials, such as cellular cellulose acetate, cellular hard rubber, and paper honeycomb lend themselves somewhat to post-forming while hot. Another method, which perhaps is less cumbersome, is to bond or laminate one facing to the core in the first operation, to bend the assembly to approximately the proper shape (with the faced side being the convex side), and to bond the inner facing to the core in a second molding operation. Figure 4–26 shows the bending operation being performed in a conventional hand-operated sheet-metal rolling machine. The part being bent is end-grain balsa bonded to one aluminum facing. An alternate procedure, which is somewhat similar, is illustrated in figure 4–27. Fundamentally, this process is the same as is used in steam bending wood by employment of a metal tension band. The core material to be bent is positioned between two stops on the tension sheet and bent over a form of the proper shape

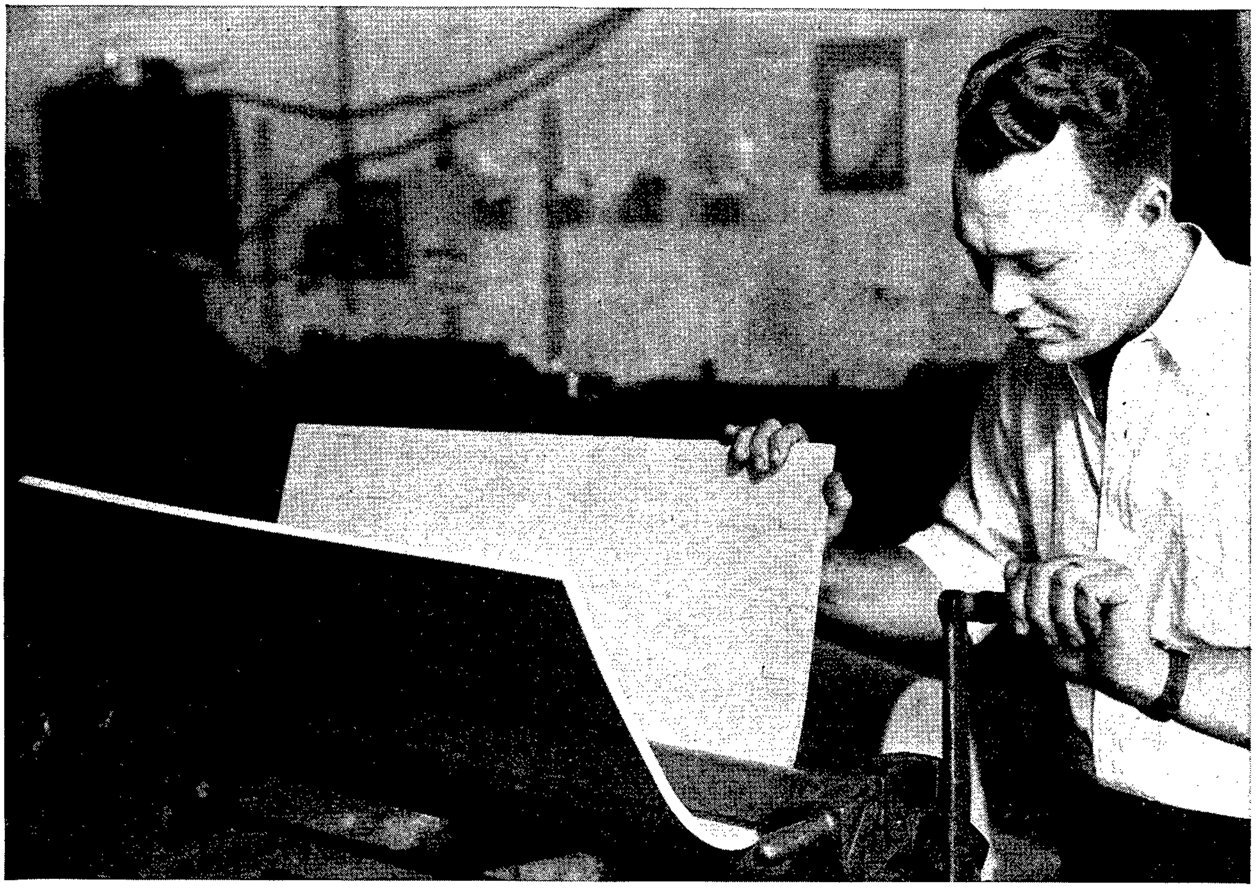


Figure 4–26. End-grain balsa core, bonded to one aluminum face, being bent on a conventional hand-operated sheet-metal rolling machine.

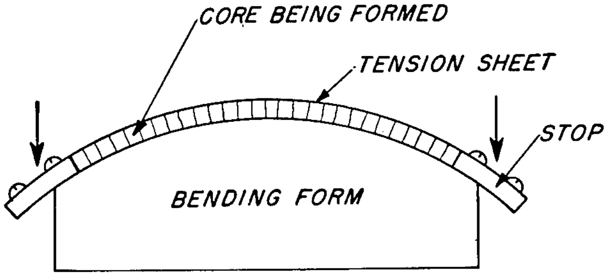


Figure 4–27. Core being formed by means of a tension sheet

so that the metal sheet takes all of the tension stresses and the core is deformed by compression.

4.211. *Compound curvature.* The amount of compound curvature that can be formed in a sandwich part without resorting to special techniques is limited by the facings, the core, or both. In addition, the relation of the respective curvatures in intersecting planes may have an effect on the details and relative ease of fabrication, but in general panels having appreciable compound curvature present difficult fabricating problems. Certain combinations of materials, such as glass-cloth facings wet-laminated to a glass-cloth honeycomb core, accommodate compound curvature more readily than do others, such as aluminum facings bonded to a balsa core.

Parts having only a very moderate amount of compound curvature may be made by the one-step process in the same manner as flat parts or parts having moderate single curvature. If possible, the core should be prepared as a single sheet and laid in place between the facings; but if the stiffness of the core is the limiting factor, it may be tailored in place from small pieces. No tests, other than by trial, are available for guidance as to the maximum curvature feasible.

For severe compound curvature, one-, two-, or three-step fabricating processes may be indicated. Glass-cloth facings on glass-cloth honeycomb cores can normally be laid and molded in a single operation, unless for some specific reason, such as minimum inclusion of air bubbles in the facings, it is necessary to mold the facings separately. When foamed-in-place cores are used the fabrication is done in two steps: (1) Facings, usually of glass cloth reinforced plastic, are formed on male or female molds or between mating dies, and (2) core is poured and cured between the facings (held in proper position by dies as shown in figure 4–24) thus forming the sandwich part. Likewise, when expanded rubber is employed as a core material, the fabrication is done in two steps: (1) Preforming the core sections and (2) molding the facings on the preformed core. Other combinations, such as aluminum facings on a balsa core, require a three-step process: (1) Forming the facings, (2) preforming the core, and (3) bonding the facings to the core. Aluminum facings may be formed by a carefully controlled hammering or stretching technique. Balsa cores of compound curvature are produced by building up the desired shape or by dampening one surface and then drying the core in the proper curved position.

Honeycomb cores of compound curvature are sometimes produced from sections cured to a cylindrical shape. If suitable allowance is made for anticlastic curvature these sections may be made to fit a mold of severe compound curvature. The relation among the radii involved is presented in the following formula:

$$\frac{1}{R_{o\alpha}}=\frac{1}{R_\alpha}+\frac{1}{R_\beta\mu_{\alpha\beta}} \quad \text{or} \quad \frac{1}{R_{o\beta}}=\frac{1}{R_\beta}+\frac{1}{R_\alpha\mu_{\beta\alpha}}$$

$R_{o\alpha}$ = radius of cylinder to which honeycomb is formed, the α natural axis running around the bend.

$R_{o\beta}$ = radius of cylinder to which honeycomb is formed, the β natural axis running around the bend.

4.22. Mold-Release Agents. Some means of insuring easy removal of the part from the mold must be provided to avoid damage to the part being formed and to the mold.

Metal facings next to mold or caul surfaces of metal present no problem if both surfaces are clean and free from adhesive squeeze-out. However, if the metal facings include joints, adhesive may squeeze through and form a bond unless adequate mold treatment is provided. In this case, a very thin film of wax applied directly by wiping or in a solution is adequate protection against sticking.

To minimize warping and distortion of large aluminum-faced sandwich panels formed on steel molds a mold release agent or lubricant is beneficial and is sometimes a necessity.

The use of glass-cloth facings wet-laminated in place, or the molding of preformed glass-cloth facings, presents a more critical mold-release problem, as in either case the resin comes in direct contact with the mold surface. For flat parts, or parts of single curvature, a sheet material, such as cellophane or polyvinyl alcohol, serves very well. Cellophane of the plain, colored type (PC) approximately 0.002 inch thick (600) has been most suitable. Thinner sheets of cellophane have a greater tendency to wrinkle, and thus to leave imperfections in the surface of the sandwich. There appears to be a tendency for cellophane to wrinkle if left in contact with most laminating resins for several hours; and, therefore, it is advisable to complete the cure as soon as possible after exposing the cellophane to the resin-impregnated glass cloth.

Glass-cloth facings of compound curvature require the use of mold-release coatings, rather than sheets, in order to avoid the imprints of unavoidable wrinkles. Parts are sometimes released from polished metal molds without the use of a coating, but for insurance against sticking a coating is recommended. Mold-release coatings of various types are being used, and no general recommendation can be made for all resin and mold combinations. The final choice can best be made after a few exploratory tests. Following is a list of commonly used mold-release coatings:

Liquid or paste wax.
Silicone grease.
Vegetable lecithin.
Methyl cellulose.
Polyvinyl alcohol lacquer.
Cellulose acetate butyrate dope.
Aluminum or zinc stearate.

Since most of these coatings are applied as very thin films to avoid possible contamination of the resin, the molds must be highly polished to obviate mechanical adhesion. In some cases a combination of two coatings has been found necessary. Where the surface is subsequently to be painted, mold release agents containing silicone should not be used.

4.23. ATTACHMENT DETAILS. All sandwich parts must be attached to the framework of the aircraft and often to other similar parts; and, therefore, means for transferring the concentrated stresses imposed at these attachments must be provided. Occasionally, on very lightly stressed parts, unreinforced bolt holes or subsequently inserted reinforcements will suffice, but in most structural applications local reinforcements must be incorporated during fabrication.

4.230. *Edge reinforcements and doublers.* Sandwich parts are normally joined over a framing member, and it is common practice to incorporate a continuous-edge reinforcement to facilitate the transfer of stresses. There are many ways of accomplishing satisfactory edge reinforcing, so that such details as loads to be transferred, type of facings and of core, attachment fittings, and importance of smoothness of surface, should be considered before selection is made. Typical edge reinforcements for aluminum-faced and glass-cloth-faced parts are shown in figure 4–28. Many of these would also be suitable for parts having plywood facings.

Some edge treatments, such as those shown by *A*, *C*, *D*, *E*, and *G* in figure 4–28, serve as an effective moisture seal in addition to providing rein-

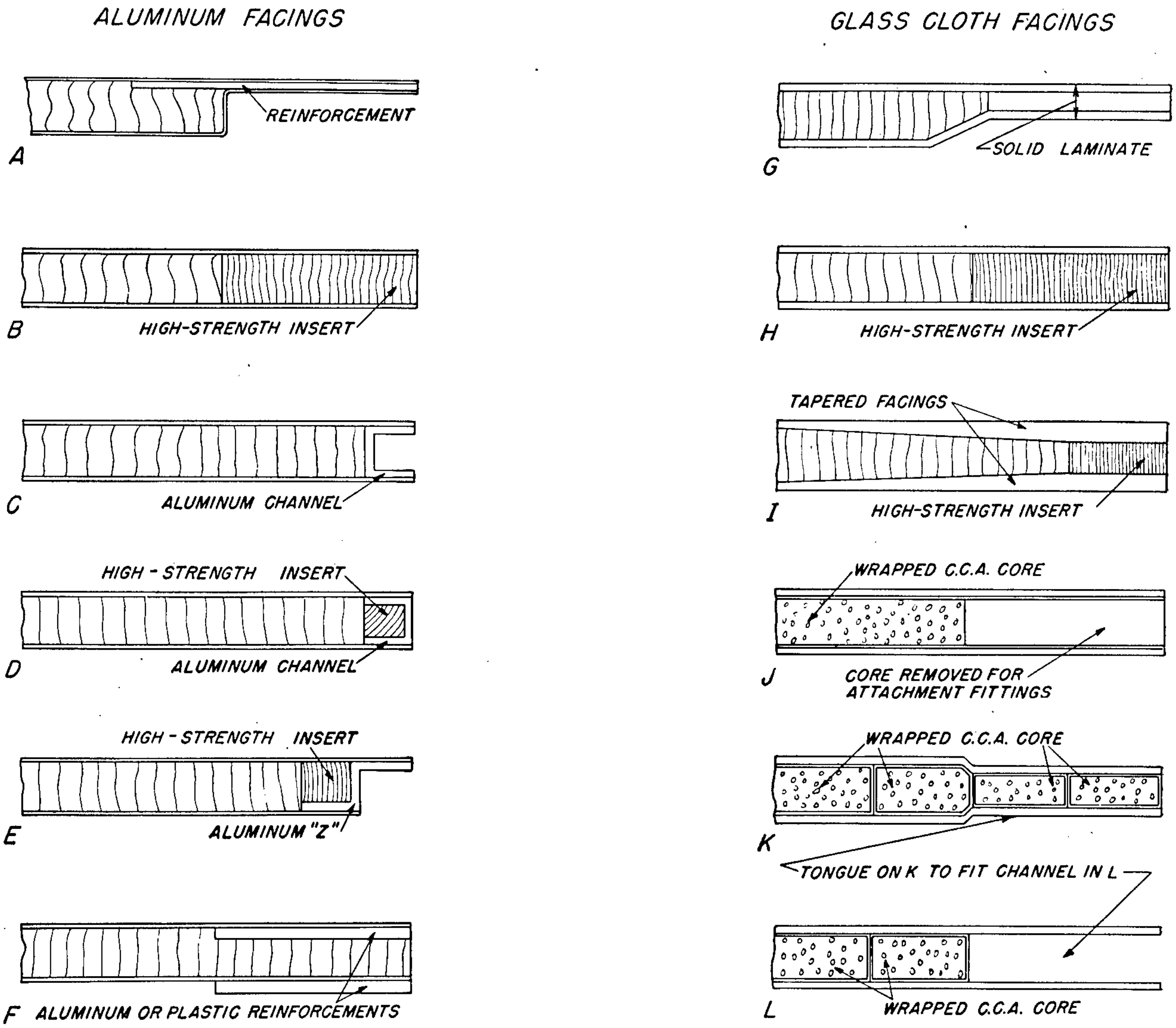


Figure 4–28. Typical edge treatments.

forcement. Others depend upon edge coating to seal out moisture and miscellaneous aircraft fluids. High-strength inserts may be of a variety of materials, including end-grain mahogany or spruce, plywood (flat or on edge), or reinforced plastics. Additional bolt-bearing area may be provided by reinforcements or by increasing face thickness.

4.231. *Doublers and inserts.* The design of a sandwich structure may be such that loads must be transferred to or from individual parts at points other than at their edges. Inserts in the part are required at these attachment points if the loads are of appreciable magnitude, such as over wing ribs or fuselage bulkheads. Typical inserts are presented in figure 4–29. These may be in the form of strips, inserted continuously across the panel, or as local reinforcements under individual bolt fittings. Shear loads on attachment bolts may require additional reinforcement, as shown in *B*, figure 4–29, to provide adequate bolt-bearing area. *D*, figure 4–29, shows one method of densification of metal honeycomb by means of inserts. Densification by compressing the core of metal honeycomb is another method sometimes employed.

4.232. *Cut-outs.* Openings in sandwich parts for inspection, drainage, or adjustment of fittings

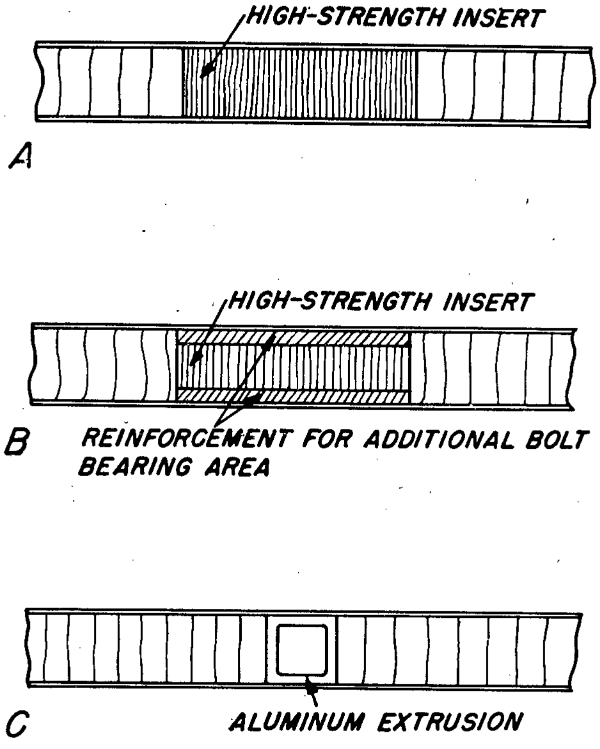


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Figure 4–29. Typical high-strength inserts installed during fabrication.

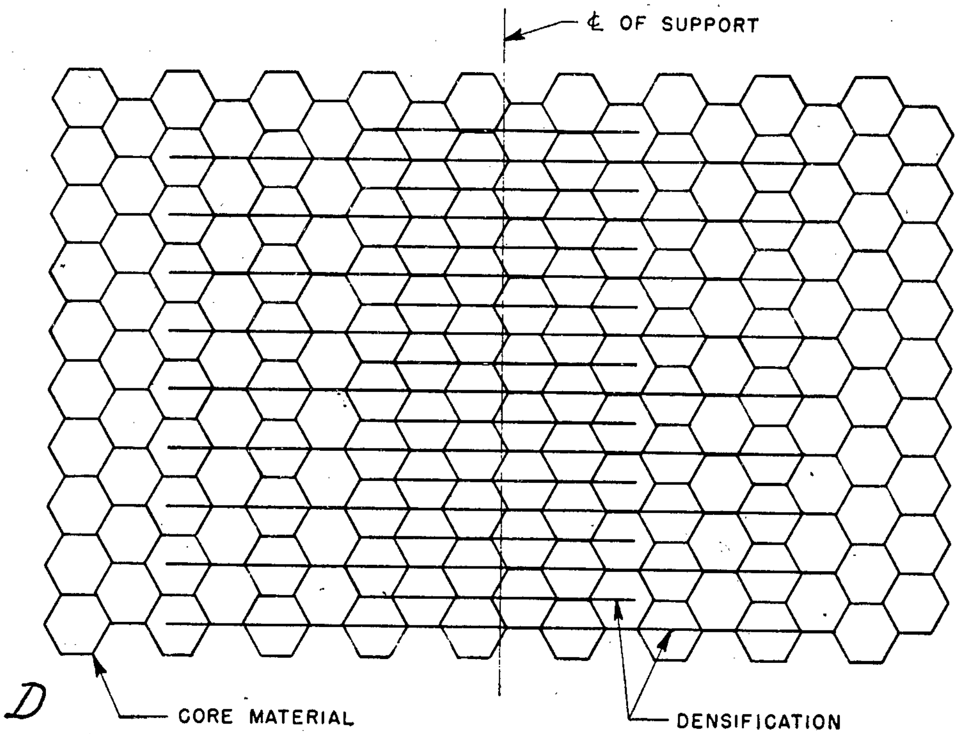

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Figure 4–29.

must often be provided. Tests have demonstrated that with certain ratios of opening-to-panel size there is a concentration of stress around the cut-outs that may require consideration in design. Experience has shown that these increased stresses can often be carried by high-strength core inserts or edge treatments around the opening, as shown in figure 4–28. If the cut-out requires a cover, the means of attachment must be considered in choosing the proper edge reinforcement around the cut-out. Drain holes must often be provided with special edge treatment to protect the core from moisture.

4.233. *Joints in facings.* Part sizes in excess of available facing widths make joints in the facings a necessity. This presents no particular difficulty with glass cloth, as the individual sheets may be overlapped slightly during lay-up. Overlaps should be staggered so that no more than one is present in any cross-section.

Facing materials of the sheet type, such as aluminum and plywood, must be joined when large sizes are required. Since the type and quality of joint is dictated by the application, some must of necessity be flush while others will permit a projection from the surface. Typical joints are illustrated in figure 4–30. *A* and *B* may be used either for aluminum or plywood and differ only in the location of the butt plate. Internal butt plates are required for all exterior facings exposed to the air stream, while exterior butt plates are preferred, because of simplicity, for all unexposed surfaces. The overlap joint shown in *C*, figure 4–30, is used only with lightly stressed thin aluminum facings where its inherent eccentricity is not objectionable. Plywood facings may be joined as in *D* and *E*, figure 4–30. Scarf joints are normally bonded prior to fabricating the panel, whereas butt joints over high-strength inserts are fabricated as an integral part.

4.234. *Attachment fittings.* Sandwich parts are attached to the air frame by means of bolts, rivets, or screws. Accessories, such as shelves, fittings, and mounting brackets, are often fastened to the parts by the same means. Inspection-door covers are sometimes fastened by means of special quick-opening fittings. Most of these attachment fittings require holes through the panel, usually specially prepared to fit the attachment or adaptor.

A few miscellaneous types of attachment fittings for metal-faced sandwich parts are shown in figure 4–31. All of these are of the type that can be inserted or attached to completely fabricated parts. Whenever inserts, sleeves, or bushings are employed, tolerances on the part thickness must be carefully maintained to insure proper fit. Figure 4–32 shows two methods of countersinking metal-faced sandwiches—by drilling; and by pressing.

It is generally considered good practice to use attachment fittings that distribute the load to both facings rather than those that attach to one

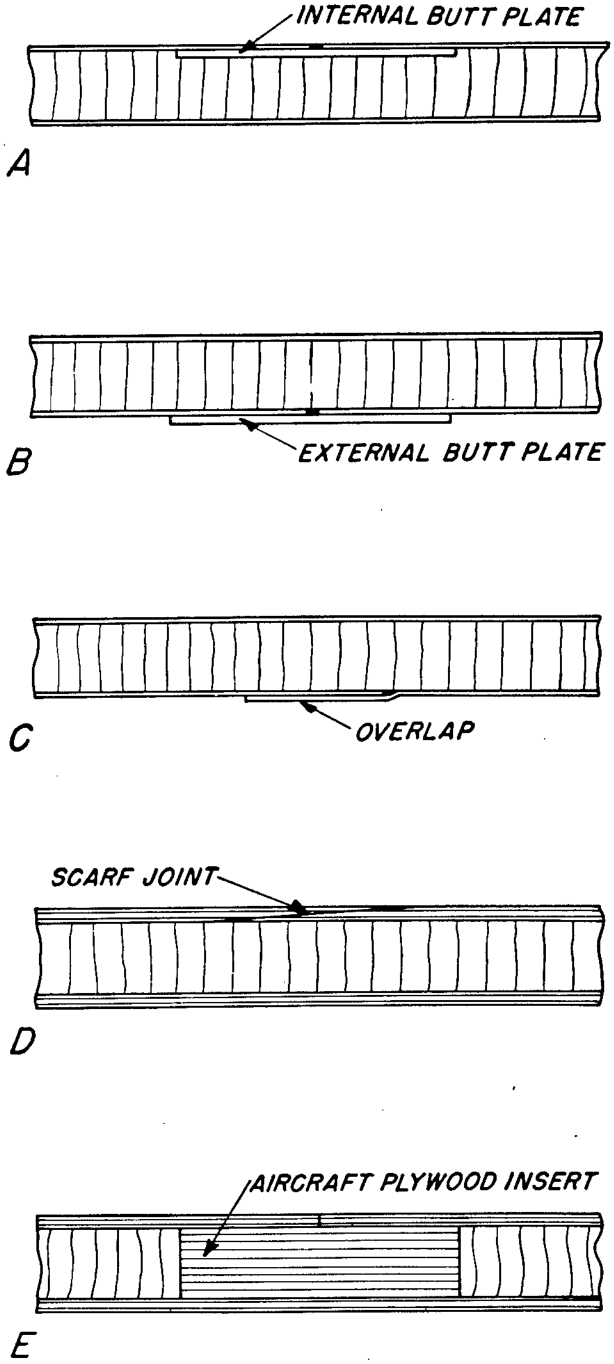

Figure 4–30. Typical joints in sandwich facings.

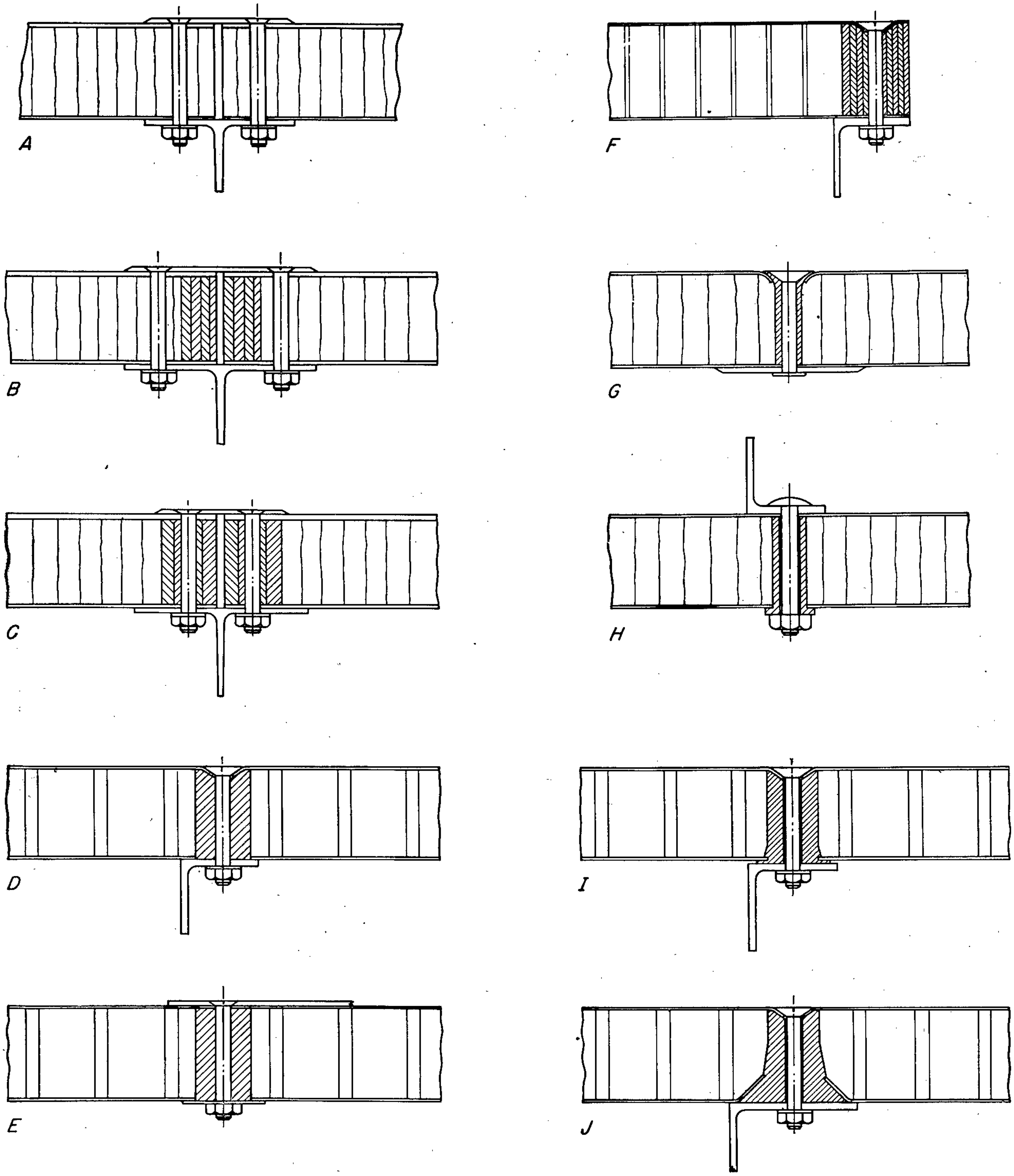

Figure 4–31. Typical attachment fittings for aluminum-faced parts.

facing only. Lighly stressed attachments on nonstructural parts are exceptions, as are attachments so designed that they apply no cleavage stresses to the facing. Occasionally, attachment fittings of the latter type are bonded to one facing by a metal-to-metal adhesive. Figure 4–33 shows a fitting of this type. Small rivets or screws are inserted at points likely to be subjected to cleavage. These

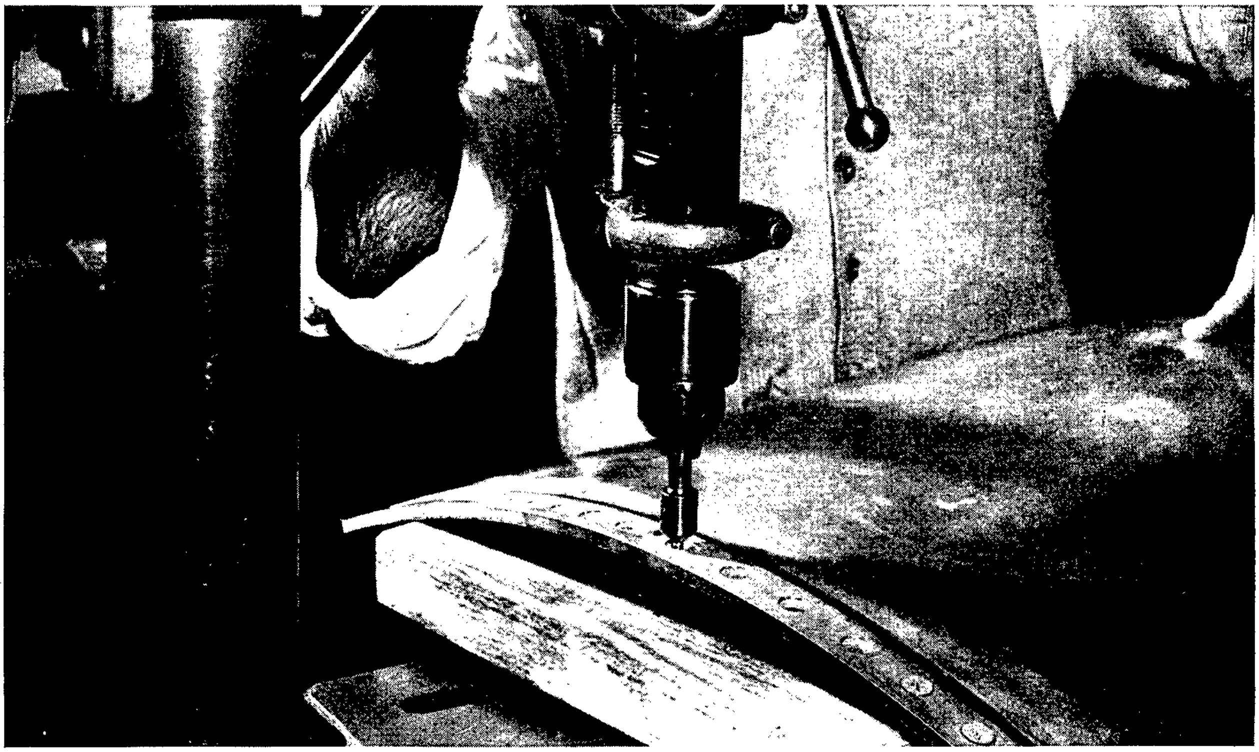

Figure 4–32. Two methods of treating bolt holes in a sandwich part—drill countersinking.

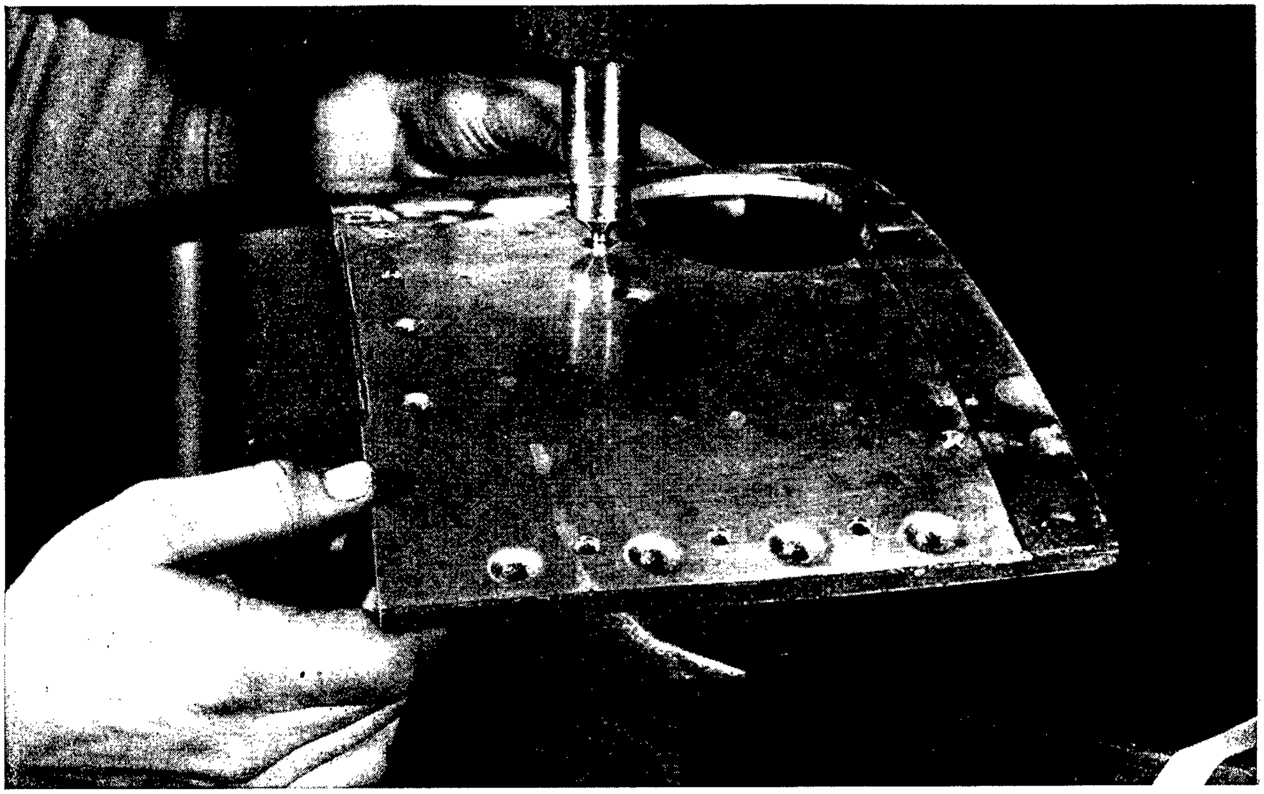

Figure 4–32.—Continued—Press countersinking.

rivets also provide the metal-to-metal contact necessary for proper electrical grounding of all metal parts of the aircraft.

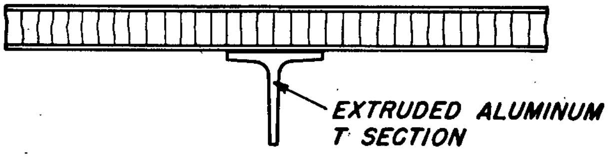

Figure 4–33. T-section bonded to one facing of an aluminum-faced sandwich.

Some of the attachment methods shown in figure 4–31 may also be employed on sandwich panels having glass-cloth or plywood facings; but, however, because of the characteristics of these facings, special types of attachments that employ bonded joints are often preferred. A few typical attachments for parts having glass-cloth facings are illustrated in figure 4–34.

4.24. Trimming. Parts, after fabrication, often require trimming and subsequent cleaning to achieve final dimensions and to remove rough edges, adhesive squeeze-out, or resin flash. The trimmed parts require careful handling to protect sharp corners and edges from damage. Figure 4–35 illustrates one method of protecting corners of trimmed parts before final assembly on the aircraft.

Countersunk rivets, used for attaching the parts to the aircraft framework or for securing internal

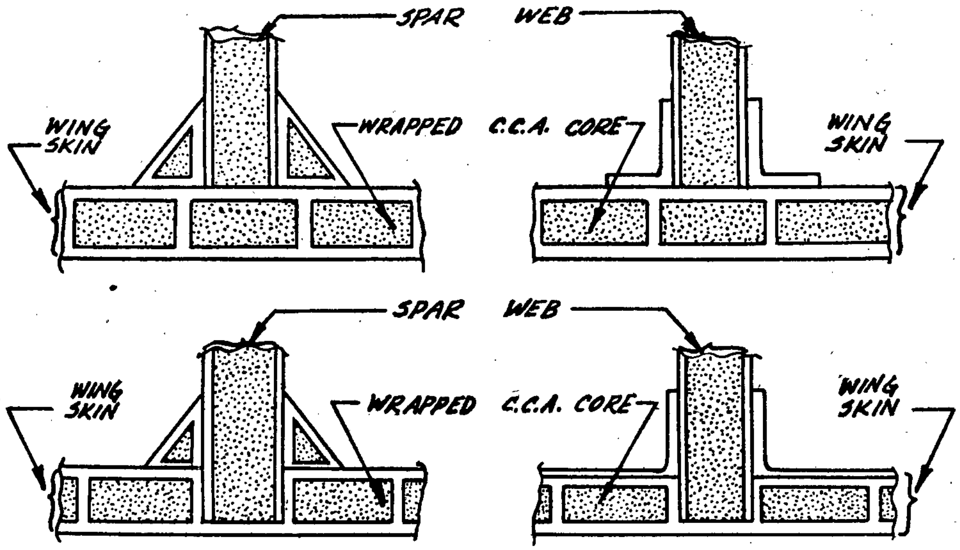

Figure 4–34. Typical attachments for sandwich parts having glass-cloth facings.

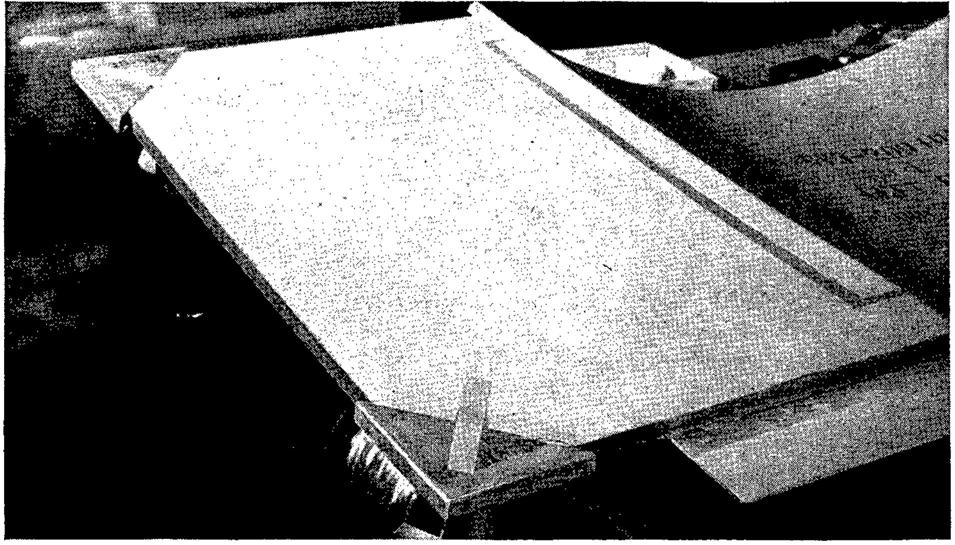

Figure 4–35. Temporary metal corner guards used to protect sandwich part during handling.

fittings, are often not sufficiently smooth for high-speed performance. Rivets of this type are machined after fabrication by shaving with a special tool.

4.25. Finishing. The proper finishing system for a sandwich part is normally determined by the facings. Finishes for facings should be in accordance with the requirements of the Air Force, Navy, and Civil Aeronautics Administration, as applicable. Rain-erosion protection of plastic parts and electrical or dielectric properties often influence the choice of a finish.

The edges of all parts not protected by a banding of aluminum or glass-cloth laminate should be sealed to reduce the rate of moisture absorption. Wood-banded edges of plywood, mahogany, spruce, or balsa are often given two coats of aluminized spar varnish. Cellular cellulose acetate or expanded-rubber core edges have been satisfactorily sealed by one heavy coat of lead primer (1,000 parts white lead paste, 97 parts raw oil, and 9.4 parts drier), followed by two coats of aluminized varnish.

4.26. Safety Precautions. The fabrication of sandwich constructions requires many operations which, if not properly supervised, could be hazardous. In general, the safety precautions specified and employed by the paint and varnish industry should be followed, but where local codes exist they should be observed whenever applicable. Each operation must be analyzed, and protection provided, if necessary, against fumes, vapors, dust, skin infections, fire, and explosion.

Solvents, such as benzene, toluene, methyl alcohol, carbon tetrachloride, and trichloroethylene, used in cleaning metals, thinning adhesives, and washing equipment are toxic, and adequate ventilation must be provided to reduce the concentration of solvent vapors to less than 200 parts per million parts of air. Fumes or mists from chemical cleaning solutions should be drawn into hoods so that these chemicals cannot be inhaled or come in contact with the skin.

Commonly used resins of the phenolic and polyester types are not considered generally toxic, but

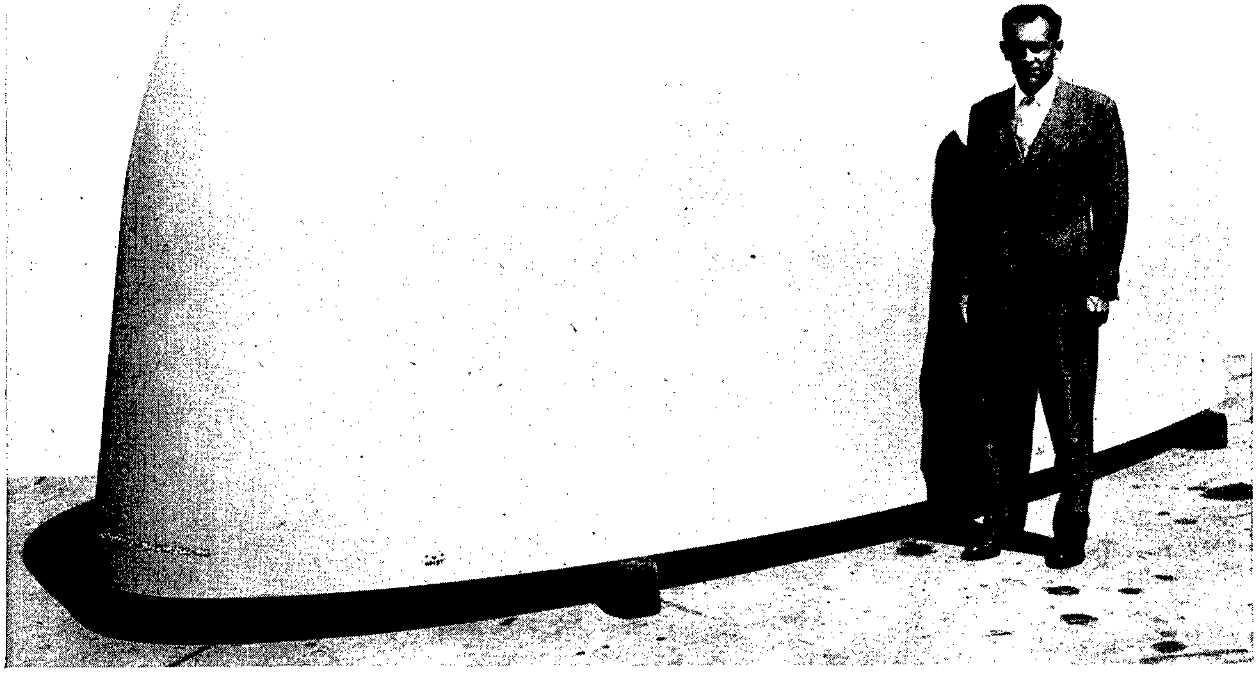

Figure 4-36. Large experimental radome of sandwich construction.

certain individuals seem to be allergic to these materials, as evidenced by skin eruptions, sinus infections, or running eyes, and must be relieved of any contact with the aggravating material.

Dusts formed as a result of machining plastic parts should be removed by an effective exhaust system, and in addition respirators should be worn when dust particles capable of causing lung infection are present. Some of the dusts from glass cloth and phenolic laminates are irritating to the skin and require the use of protective skin creams to prevent irritation. Dermatitis may also be caused from contact with some of the solvents and adhesives, therefore rubber gloves should be worn when experience has demonstrated the need for protection.

Emphasis should be placed on personal cleanliness as a general precaution against discomfort from skin infection. Clothes should be changed after each shift and hands washed frequently to remove dangerous accumulations of irritating materials.

Many of the solvents employed are highly inflammable, therefore standard precautions for storage and use of inflammable materials must be enforced. Benzoyl peroxide, a catalyst used with many of the polyester type resins, is also highly inflammable in the dry powder form and care should be taken that this chemical is stored in a cool place and that it is not subjected to any heat, such as the friction of grinding.

4.27. Specifications. The fabrication of completed sandwich parts can best be controlled by means of clear, concise process and material specifications. Since the size (fig. 4–36) and use to which sandwich constructions are put vary widely, it is essential that the specifications should control all stages of manufacturing, define plus or minus limits where they are required, and specify acceptable materials to be used directly or indirectly in the fabrication process.

CHAPTER 5

INSPECTION AND TEST METHODS

5.0. Inspection of Raw Materials

Once fabricated, the quality of sandwich construction parts cannot be determined readily by any known nondestructive methods of inspection. Therefore carefully controlled systematic inspection of raw materials, in accordance with rigid materials specifications, must be made, and the fabrication must be rigidly controlled by strict adherence to rigid process specifications.

Applicable quality control specifications are U. S. Air Force Specifications 20044, 12043, 12049, 12050, 12051, 12053, R12046, and R26603.

Although a detailed inspection procedure for all materials is beyond the scope of this manual, a brief discussion of the inspection methods employed on some of the key materials is presented for guidance.

5.00. Cores. Specifications normally designate acceptable density ranges and minimum strength properties for core materials (ref. 5–10). The acceptance of material for use therefore depends on careful inspection for weight and strength consistency. Natural core materials, such as balsa and mahogany, vary over a wider weight range than synthetic cores, making inspection for density conformance of prime consideration. Tensile, compression, or other tests, as presented in section 5.2, are sometimes made as part of the inspection, either to insure proper strength requirements or as a check on other properties such as the proper cure of the resin in a cotton or paper honeycomb core. Some of the common characteristics of typical core materials that require investigation by inspection are presented in table 5–1.

Table 5–1. Principal characteristics of core materials requiring inspection

Core material	Characteristics (in order of importance)
Balsa and mahogany	Density, defects,[1] slope of grain, moisture content.
Cotton and paper honeycomb.	Cure, configuration, bonding, density.
Cellular cellulose acetate.	Defects,[2] density.
Aluminum honeycomb	Bonding, configuration, density.
Glass-cloth honeycomb.	Configuration, bonding, resin content, density.
Expanded rubber	Cure, dielectric properties, uniformity of structure, density.
Foamed-in-place	Foaming characteristics, uniformity of foam, density.

[1] Common defects in balsa are knots, rot, wormholes, wane, checks, and splits.

[2] Common defects in cellular cellulose acetate are blowholes and unexpanded spots.

5.01. Facings. Materials employed for facings, such as aluminum, glass-fabric-reinforced plastic, and plywood, present no unusual inspection problems. Aluminum must normally conform to applicable Army-Navy specifications and must be free from contamination, corrosion, and wrinkles. Glass cloth before impregnation must be clean, properly treated, and of a definite and uniform weave pattern. For U. S. Air Force applications glass-fabric-reinforced-plastic facings must conform to U. S. Air Force Specifications No. 12049 and No. 12051 (ref. 5–9, 5–11). Plywood can usually be inspected in accordance with Military Specification MIL–P–6069 (ref. 5–6). Information on the inspection of plastic facings is given in ANC-Bulletin 17 (ref. 5–4), and of metal in ANC-Bulletin 5a (ref. 5–3).

5.02. Adhesives and Resins. Adhesives and laminating resins must first be evaluated for their suitability and performance in the type of application for which their use is intended. Once a particular adhesive or laminating resin has been selected, inspection must be made to determine that the various batches as received are of the same quality as the original samples, and that the adhesives and laminating resins are not used when the quality of their performance has been reduced by overaging or improper storage. Tests of bond strength have been widely used as a means of originally selecting the adhesive, determining the conditions under which the adhesive can be used, and as a means of inspecting the uniformity of the adhesive. Other tests, such as physical appearance, pH, viscosity, specific gravity, and solids content, have also been used to aid in inspecting the uniformity of an adhesive (ref. 5–9, 5–10, 5–11).

5.020. *Adhesive bond strength tests.* In general, most of the joint tests described in this section are particularly applicable to adhesives for bonding metal faces to cores in sandwich materials. Tests for evaluation of laminating resins, such as are used for impregnation of glass cloth, are not so well standardized. These resins may, however, be evaluated by making typical sandwich parts and testing specimens from these parts by one or more of the strength test methods described. It should be noted that the quality of an adhesive as determined by any strength test will depend both on the adhesive sample used and on the conditions under which the adhesive was used. For this reason it is important that the proper bonding conditions be used in the fabrication of test specimens.

Sandwich fabricators, in evaluating and controlling the quality of adhesives, have used many types of test specimens. Among the types used are those tested in tension normal to the plane of the sandwich, plywood-shear-type specimens from sandwich constructions, strip or peel specimens of sandwich construction, beam-bending-flatwise (flexural) specimens of sandwich construction, lap-joint shear specimens of metal to metal and metal to wood, and block-shear specimens of metal to metal. The dimensions and testing procedure for specimens representative of these types of joint specimens are covered in Forest Products Laboratory Report No. 1556 (ref. 5–8) (tension normal to the plane of the sandwich, bending flatwise tests of sandwich construction, and strip specimens of sandwich construction) and in section 5.3 (plywood-shear, lap-shear, and block-shear).

In originally evaluating adhesives for their processes, fabricators may use several types of these specimens to obtain preliminary information. Such information may concern the strength of the adhesive in joints of material of the type to be bonded; the allowable bonding conditions under which the adhesive can be used; the performance of the adhesive in joints when subjected to conditions simulating actual service, such as exposure at high and low temperatures and humidities, and soaking in various fluids, and when subjected to fatigue, impact, and creep stressing.

Adhesive bond strength tests to check the quality of the various batches of adhesive or the quality of the adhesive after storage are usually made with only one type of specimen that has been found in earlier tests to be easy to prepare and test and that yet serves as a good criterion of the performance of the adhesive. Two types of specimens that have been used to a considerable extent in this type of quality-control testing of adhesives are the lap-joint shear specimen of 0.064-inch 24ST clad aluminum alloy (sec. 5.31) and the block-shear specimen of ¼-inch-thick aluminum plates (sec. 5.33).

Secondary adhesives of the types used for bonding primed metal to cores can be tested by using primed metal in the lap shear or block shear specimens, or they can be tested, as are adhesives for bonding plywood facings to cores, by the use of plywood and block-shear specimens as described for woodworking adhesives in Specification MIL–A–397; Bulletin ANC 19, "Wood Aircraft Inspection and Fabrication" (ref. 5–5); in Federal Specification MMM–A–175, Adhesives, General Specifications, Test Methods (ref. 5–13); or in ASTM Standards as D905–47T (ref. 5–1) and D906–47T (ref. 5–2). Adhesive quality-control tests are usually made on dry specimens at room temperatures, but some fabricators include high temperature and soaking conditions for further evaluation of the adhesive.

5.021. *Other adhesive inspection tests.* In inspecting adhesives to control the quality of the materials being used in the fabrication of sandwich constructions, the adhesives should first be examined to see that the color and uniformity of mix are the same as observed in previously acceptable batches of the adhesive. Most fabricators then use some additional tests, such as viscosity, pH, specific gravity, or solids content, to establish further that the batch of adhesive under test is of the same formulation as batches of the adhesive previously used and accepted. As these quality-control tests are merely a comparison of the properties of the sample under test with those properties previously obtained on acceptable samples of the adhesive, any method of determining viscosity, pH, specific gravity, or solids content that gives reproducible results will prove satisfactory. When any of the foregoing tests indicate that the properties of the adhesive are not the same as those obtained with other samples of this adhesive, rejection is usually dependent on whether or not the sample gives satisfactory results in joint strength tests.

5.1. Inspection of Completed Parts

Sandwich parts are inspected for conformance to dimension, weight, configuration, uniformity, and strength requirements of the applicable specification. The relative importance and tolerances allowable for each characteristic depend upon the application. Radar-antenna housings demand panels of uniform and exact thickness, while structural panels demand, primarily, certification of adequate bond strength. Secondary structural parts are less critical, but must be of proper size and shape.

Radomes, after visual inspection for conformance to dimensional requirements, are often inspected for dielectric properties and possible distortion of image by a scanning apparatus that simulates conditions in actual use.

Structural parts must be critically inspected for areas of questionable bond between facings and core. Areas having no bond are usually readily detectable by several of the common inspection methods, but areas having merely subnormal bond strength are exceedingly difficult to locate by inspection or nondestructive test methods.

5.10. INSPECTION METHODS.

5.100. *Visual inspection.* Visual examination made immediately after a sandwich panel has been removed from the press or bag when cured with heat, often reveals unbonded areas as blisters. These blisters remain extended for a short period only or until the drop in panel temperature reduces the internal pressure of the panel. During this short interval in which the blisters are visible, they may be outlined with a wax crayon for future location and possible repair. Such blisters are visible on aluminum-faced and glass-cloth-faced panels but are not so readily seen when plywood facings are used.

Visual inspection methods appear to have only limited possibilities. If a part has blisters upon removal from the press or bag, the presence of defective areas is demonstrated and the part can be rejected or marked for salvage immediately. If no blisters are visible, however, the absence of defective areas is not proved and the part must be subjected to further tests by a more dependable method. Glass-cloth facings, particularly void-free laminates, permit inspection of the core and sometimes aid in detecting poor bonds.

5.101. *Special lighting.* The use of lights has been tried for determining faulty areas or blisters in various types of sandwich construction, but mainly in panels with glass-cloth facings. By varying the arrangement and angle of lighting some blistered areas can be detected, but not with any degree of reliability. Poorly bonded areas cannot be detected by means of lights.

5.102. *Tapping.* Tapping is one of the simplest methods in use for testing for voids in the adhesive bond between the facings and the core of a sandwich part. The only equipment necessary for this test is a small piece of metal, such as a coin or a small, light hammer. During inspection by tapping parts should be freely supported, as on three padded points to eliminate sound interference from the support. A well-bonded area will produce a clear tone, while an unbonded area usually produces a lower tone or a dull thud.

This method has been found to be reasonably satisfactory for detecting areas where the facings of the sandwich are not firmly attached to the core. It has been found, however, that if there is intimate contact between the facing and the core no difference in tone quality can be detected between these areas and those that are well bonded. Poorly bonded areas, therefore, cannot be differentiated from well-bonded areas by means of tapping. Tests have shown that very light tapping is more selective than are heavy blows. Considerable experience is required to locate defective areas consistently, because parts of different construction give off different tones and the tones on a single part vary with the position on the part. Variation in tone is especially noticeable within a few inches of the edge.

5.103. *Ultrasonic inspection.* Metal products, such as steel castings, forgings, and tinplate, are sometimes inspected by the use of ultrasonic vibrations. Hidden flaws, voids, and other defects are located by their attenuating effect upon high-frequency vibrations. Tests have been made to determine the possibility of using ultrasonic vibrations for the inspection of sandwich parts. In these tests the transmitter and the receiver units were entirely submerged in water and mounted so that they could be made to contact the part at directly opposite points on the facings. Each unit covered an area of about 1 square inch. The part was passed between these two units while under water. Observations during these tests revealed considerable variation in attenuation when aluminum-faced parts having balsa cores were passed between the heads. The variation was attributed to the variations in the density of the core. It was found from repeated trials that poorly bonded areas could not be located, but that areas having actual voids between the facings and the core could be consistently detected.

Although no tests were made, this method would appear to be quite ineffective when used on sandwich parts having honeycomb core. The voids in the honeycomb are continuous from face to face, so that the presence of an additional void in the bonded joint between the facing and the core undoubtedly could not be detected.

5.11. NONDESTRUCTIVE TESTS.

5.110. *Exposure to vacuum.* The force exerted by vacuum-induced air pressure in the core may be used to apply a moderate load on the bond between facings and core in sandwich parts, provided the facing and the core materials are relatively impervious to air. The magnitude of this force is dependent entirely upon the rate of air flow through the facings and core of the part, but under ideal conditions cannot exceed atmospheric pressure, or about 14 pounds per square inch.

Tests made by this method on aluminum-faced parts indicated that areas having a poor bond could not be detected, and areas having no bond whatever were difficult to locate unless they were large or the facings were very thin. Defects of this type can be located more easily and with a greater degree of accuracy by tapping; and, therefore, testing by vacuum appears to have little value.

5.111. *Vacuum-cup test.* The vacuum-cup method of inspection is similar in principle to the exposure of the entire part to vacuum. A portion of the facing is covered by an inverted container on which a vacuum is drawn. Vacuum-induced air pressure within the portion of the part under the container exerts a force tending to push the facing off, provided the facing is impervious to air.

An instrument operating on this principle and incorporating a dial indicator for actual measurement of the movement of the facing is shown in figure 5–1. It is reported that instruments of this type have been used with some degree of success on flat parts having aluminum facings, but are not suitable for curved parts or parts having facings slightly pervious to air. A modification of this instrument, finding limited use on slightly curved sandwich parts, is shown in figure 5–2.

5.112. *Internal-pressure test.* After exposure to air pressure for several hours, a sandwich part having airtight facings and a core that is slightly pervious to air, tends to develop an air pressure within the core (and in any voids between the facing and the core) equal to the external pressure. If this external pressure is suddenly released, the

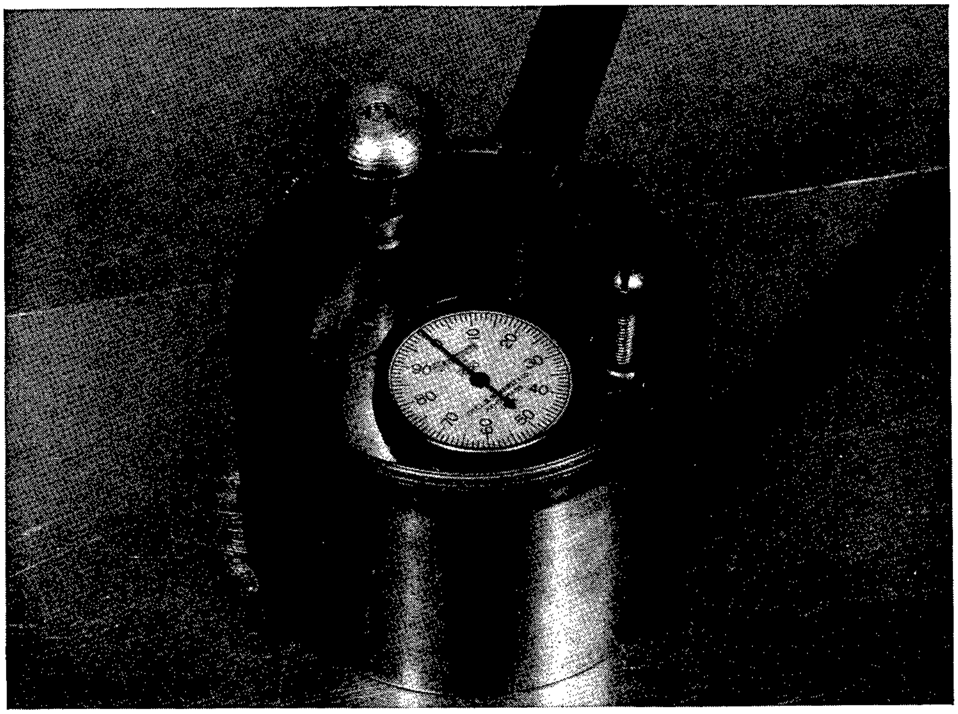

Figure 5–1. Vacuum-cup device for testing bond in flat sandwich parts.

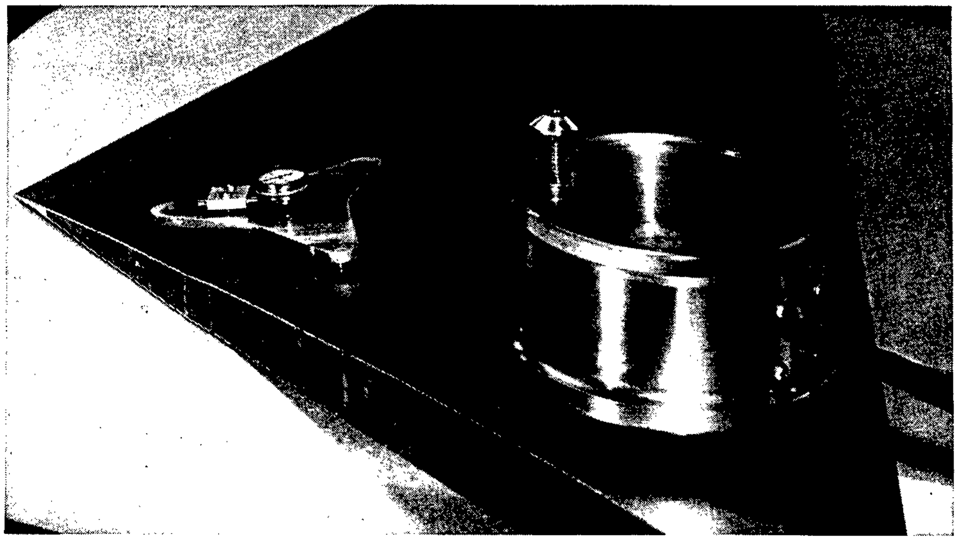

Figure 5–2. Vacuum bond-testing device for use on slightly curved sandwich parts.

air entrapped within the voids exerts a temporary force on the facing that may cause a blister. Any void or unbonded area can then be easily located by visual inspection. This test has been found to give satisfactory results with certain combinations of facings and core. Tests have shown that only voids can be located consistently. Poorly bonded areas, however, cannot be located by this method.

The range of the internal pressure test can be further increased by conducting the test at an elevated temperature so that the adhesive bonds will be stressed while hot. Tests have indicated that poorly bonded areas can also withstand this test, but that unbonded areas develop blisters by which they can be easily detected.

The results of this test are largely dependent upon the sandwich construction. For example, it has been found to yield fairly satisfactory results on parts having aluminum facings and balsa or paper honeycomb cores, but to be unsatisfactory on parts having cotton honeycomb cores, regardless of the facing, due to the fact that cotton honeycomb allows air to move freely in and out of the cells.

5.113. *Button-tension test.* A mechanical pulling test for inspecting sandwich parts has been used with some degree of success. Two similar types of test equipment have been developed for this test and are shown in figure 5–3. With either apparatus a small aluminum button is temporarily bonded to the facing; and later, by means of a tension force on the botton, the bond between the facing and the core under the button is exposed to a known stress. After suitable calibration on a specific sandwich construction, minimum acceptance values for the instrument can be established and used in nondestructive testing.

By means of these button tension tests areas of poor bond can be located. Since the test is time-consuming and rather involved, it is considered impractical, however, for use over a complete part, but it appears to have application for "spot" tests and tests on areas known to be highly stressed.

5.12. Specifications. None of the inspection or nondestructive test methods in use at present appears to be an entirely dependable means of inspecting sandwich parts for quality of joints. Therefore, it is considered that adherence to adequate material and process specifications, supplemented by sufficient destructive tests, must be relied upon to insure uniform high-quality joints in sandwich panels.

5.13. Test Methods. Experience in the testing of sandwich constructions has been sufficiently extensive to establish procedures. They are described in Forest Products Laboratory Report No. 1556 (ref. 5–8).

5.2. Test Methods for Core Materials

Core materials are sometimes difficult to test because they may not have sufficient rigidity or hardness to support strain gages or because they may be available only in thin sheets. A number of methods of test have been devised. They are described in detail in Forest Products Laboratory Report No. 1555 (ref. 5–7).

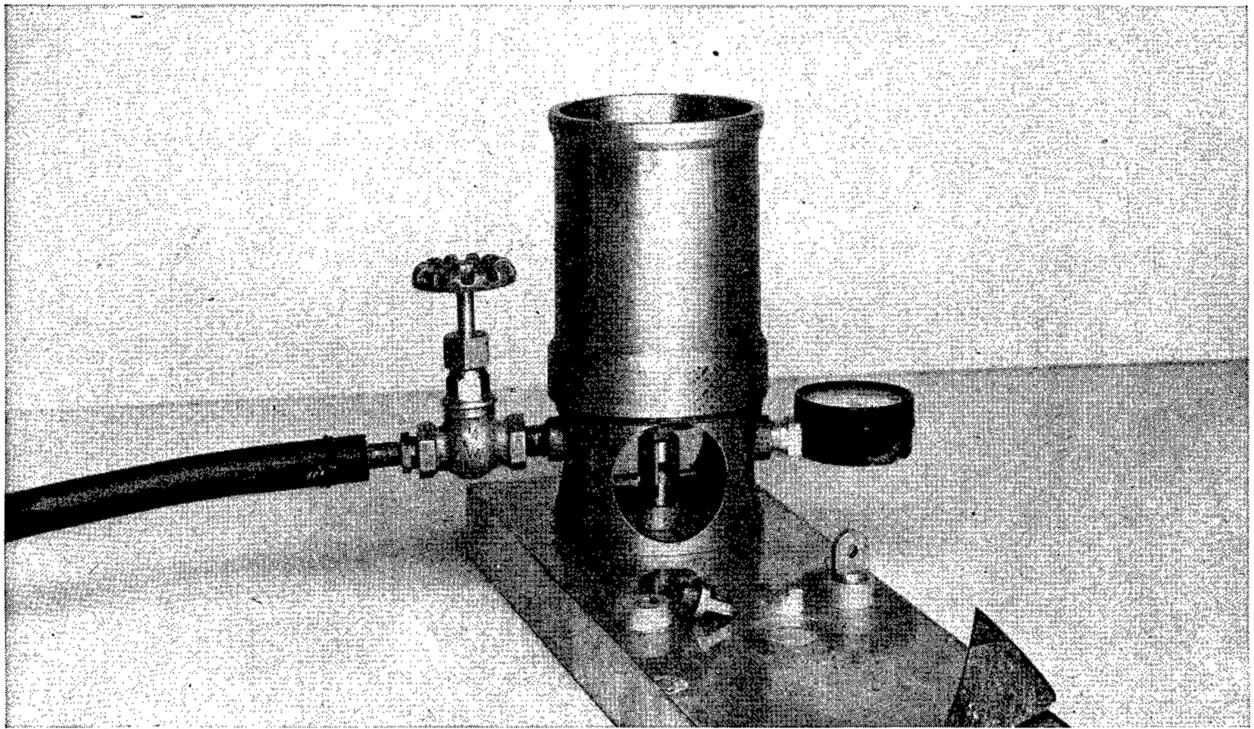

Figure 5–3. Two similar button tension-testing devices. The device shown in the top view employs a calibrated spring puller; and that in the lower view, a pneumatic puller.

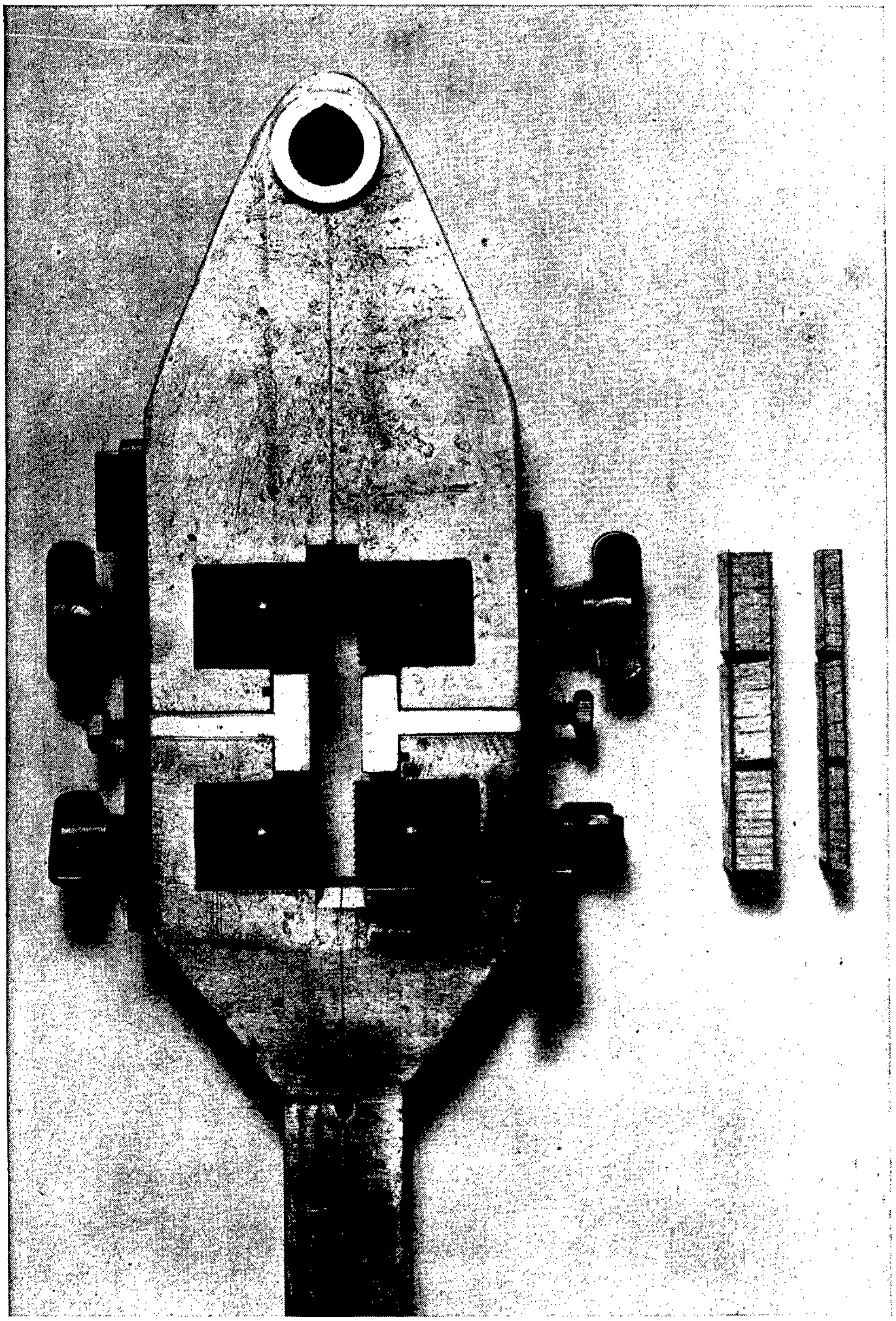

Figure 5–4. Plywood-type shear specimens and gripping jaws with special side-plate attachments.

5.3. Test Methods for Adhesives and for Bonded Joints

In addition to the tension-flatwise, bending-flatwise, and strip tests of sandwich construction described in Forest Products Laboratory Report No. 1556 (ref. 5–8) shear tests of bonded joints in plywood or in sandwich construction, lap-joint shear tests of bonded metal-to-metal joints, or block-shear tests of wood-to-wood or metal-to-metal joints have been used in evaluating adhesives for use in sandwich construction. The results of these tests are not intended for use in design, but are merely means of comparing the performance of various adhesive processes. Standard block-shear specimens of maple and plywood-type shear specimens of yellow birch veneer for evaluating woodworking adhesives are described in Specification MIL–A–397; ANC Bulletin 19, "Wood Aircraft Inspection and Fabrication" (ref. 5–5); in Federal Specification MMM–A–175 Adhesives, General Specifications, Test Methods (ref. 5–13); and in ASTM Standards D905–47T and D906–47T (ref. 5–1 and 5–2). Certain modifications of these wood joint specimens have been used for evaluating other types of adhesives. Specimens representative of the several types of such shear tests, that have been used in evaluating laminating resins and metal-bonding adhesives, are discussed in the following paragraphs.

5.30. Plywood-Type Specimen of Sandwich Construction. The plywood type of specimen of sandwich construction is fabricated by cutting 1- by 3¼-inch sections from sandwich panels. These sections are then notched by sawing from opposite facings so that a shear area of 1 square inch results as shown in figure 5–4. A plywood testing machine equipped with adjustable grips, as suggested for wood-to-wood joints in ANC Bulletin 19 (ref. 5–5), can be used for loading the specimens by applying a tension force of 600 to 1,000 pounds per minute. A modification of these testing grips made by placing retaining bars against the center areas of the specimen, as shown in figure 5–4, may be necessary to prevent excessive bending with specimens having thin facings.

Military Specification MIL–A–928 (Aer), "Adhesive; Synthetic Resin for Clad Aluminum Alloy to Wood" (ref. 5–14), specifies the use of a plywood-type shear specimen of clad aluminum alloy and yellow birch veneer for evaluating adhesives for bonding sandwich construction. This specimen consists of facings of 0.032-inch clad aluminimum alloy with a core of $\frac{1}{16}$-inch thick yellow birch veneer having its grain parallel to the longest dimension of the test specimen. The size of this specimen is 1 by 3¼ inches with saw cuts from one face to the inside of the opposite face and 1 inch apart so that 1 square inch of the specimen is under test.

5.31. Lap-Joint Shear Specimens of Metal to Metal. Adhesives of the types used for bonding metal facings to cores in sandwich construction can be evaluated by single lap-joint shear specimens of metal to metal. Clad aluminum alloy (0.064-inch) is used frequently in fabricating specimens of this type. USAF Specification 14164, "Adhesive, Metal to Metal, Structural" (ref. 5–12), specifies that the specimen shall consist of two pieces, 1 by 4 inches, of 0.064-inch clad aluminum alloy overlapped for one-half inch to result in a specimen having a total length of 7½ inches and a test area of 0.5 square inch. Variations of this type of specimen, however, have been used with thinner metal, greater overlap, and with various lengths of unsupported specimen between the tips of the grips. This specimen is tested by loading in tension in a universal testing machine and self-aligning test grips.

5.32. Lap-Joint Shear Specimens of Wood to Metal. Adhesives of the type used for bonding metal facings to cores in sandwich parts are also evaluated by the use of lap-joint specimens of wood and metal. A specimen representative of this type of specimen that has been used at the Forest Products Laboratory in evaluation tests is shown in figure 5–5. In this specimen three-ply $\frac{3}{16}$-inch yellow birch plywood is bonded to 0.032-inch clad aluminum alloy. The specimen is tested by loading in tension in a plywood testing machine at a rate of 600 to 1,000 pounds per minute.

5.33. Block-Shear Specimens of Metal to Metal. Certain fabricators have preferred a modification of the standard block-shear specimen used for evaluating woodworking adhesives (ANC Bulletin 19—ref. 5–5) to the metal-to-metal lap-joint specimens as a means of evaluating adhesives because of the large amount of bending and stress concentration that occurs when the latter specimen is loaded. In this modification two metal plates, usually ¼-inch aluminum, are bonded together to result in a block of standard dimensions (2 by 2 inches). These bonded-block assemblies are then notched from the outer face to the adhesive line one-fourth inch in opposite plies at the ends so that a bonded joint area of 1½ by 2 inches results. These specimens are then loaded by applying a compression force to the ends of the specimen with a suitable shearing tool at a rate of 3,000 pounds per minute so as to result in shear forces along the bonded joint. A modification of this specimen has been used whereby thin sheets of metal are bonded together with the adhesive under test, and subsequently maple blocks are bonded to both faces

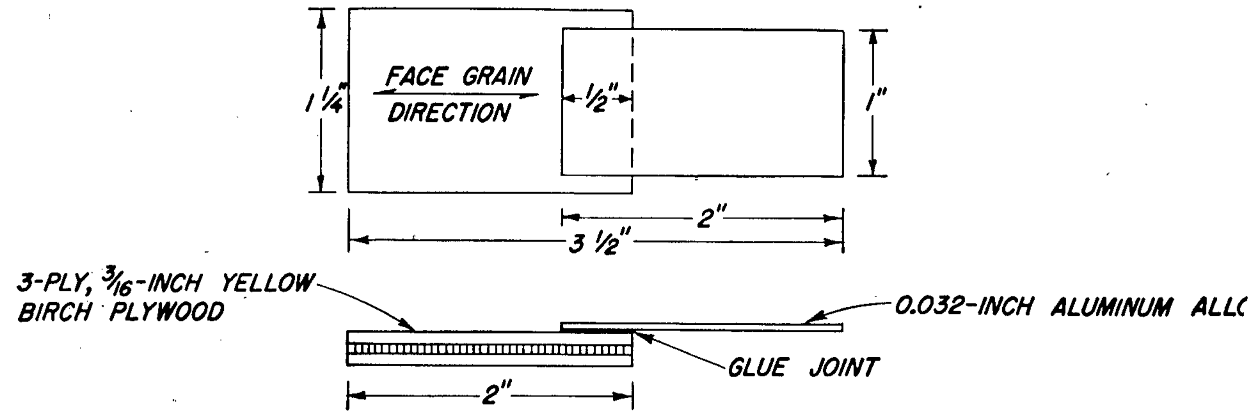

Figure 5–5. Plywood-to-metal lap-joint shear-test specimen.

of the laminated metal so that a conventional block-shear test can be made as prescribed for wood-to-wood joints. The block-shear test can also be used for the evaluating of laminating resins by cutting block-shear specimens from laminates prepared with the laminating resin.

REFERENCE FOR CHAPTER 5

(5–1) AMERICAN SOCIETY FOR TESTING MATERIALS. STANDARD D905–47–T.
1947. *Test for Shear-Strength Properties of Adhesives by Compression Loading.*

(5–2) AMERICAN SOCIETY FOR TESTING MATERIALS. STANDARD D906–47–T.
1947. *Test for Shear Test Properties of Adhesives in Plywood Type Construction by Tension Loading.*

(5–3) A. N. C. DOCUMENT 5a.
---- *Strength of Metal Aircraft Elements. Aircraft Committee of the Munitions Board.*

(5–4) A. N. C. BULLETIN 17.
---- *Plastics for Aircraft. Reinforced Plastic Facings.* (Currently being revised to include facing properties.) Aircraft Committee of the Munitions Board.

(5–5) A. N. C. BULLETIN 19.
1943. *Wood Aircraft Inspection and Fabrication.* Aircraft Committee of the Munitions Board.

(5–6) ARMY-NAVY-AERONAUTICAL SPECIFICATION, MIL–P–6069.
1946. *Plywood and Veneer; Aircraft Flat Panel.*

(5–7) FOREST PRODUCTS LABORATORY.
1948. *Methods of Test for Determining Strength Properties of Core Material for Sandwich Construction At Normal Temperatures.* Forest Products Laboratory Report No. 1555.

(5–8) FOREST PRODUCTS LABORATORY.
1948. *Methods for Conducting Mechanical Tests of Sandwich Constructions at Normal Temperature.* Forest Products Laboratory Report No. 1556.

(5–9) U. S. AIR FORCE SPECIFICATION NO. 12049.
1948. *Resin, Low-Pressure Laminating.*

(5–10) U. S. AIR FORCE SPECIFICATION NO. 12050.
1949. *Core Material: Laminated Glass-Fabric-Base Plastic Honeycomb.*

(5–11) U. S. AIR FORCE SPECIFICATION NO. 12051.
1949. *Plastic Materials: Laminated Glass-Fabric-Base, Low Pressure Molded.*

(5–12) U. S. AIR FORCE SPECIFICATION NO. 14164.
1949. *Adhesive, Metal to Metal, Structural.*

(5–13) U. S. AIR FORCE SPECIFICATION NO. 12053.
1949. *Plastic Molded Sandwich Construction, Honeycomb Core.*

(5–14) U. S. AIR FORCE SPECIFICATION NO. 1204–3A.
1947. *Plastic Parts, Molded, General Specification for Inspection.*

(5–15) U. S. AIR FORCE SPECIFICATION R26603.
1945. *Rubber Synthetic, Cellular Hard Board (for Sandwich Construction).*

(5–16) U. S. AIR FORCE SPECIFICATION R12046A.
1945. *Plastic; Molded Sandwich Construction, for Radomes. (Cellular Synthetic Rubber Core).*

(5–17) U. S. FEDERAL SPECIFICATION BOARD.
1950. *Federal Specification MMM–A–175 Adhesives, General Specifications, Test Methods.*

(5–18) U. S. NAVY MILITARY SPECIFICATION MIL–A–928 (Aer).
1949. *Adhesive; Synthetic Resin (for Clad Aluminum Alloy to Wood).*

CHAPTER 6

DURABILITY

6.0. General

An acceptable sandwich structure, in addition to possessing specified initial physical properties, must be relatively unaffected by continued exposure to conditions imposed by severe service. Obviously, with sandwich combinations involving new and untried materials it is impossible to provide the assurance of adequate service tests, and reliance must therefore be placed on tests conducted after artificial aging under conditions thought to be typical of severe service. Artificial-aging tests are time-consuming and often do not include all the possible combinations of exposure conditions that might be encountered in actual service.

Information is available from the results of tests made at the Forest Products Laboratory after exposure of a limited number of cores and sandwich combinations to controlled conditions. Additional specimens having core materials of the honeycomb type are currently being tested after similar exposures.

A summary of the results of tests, conducted principally at the Forest Products Laboratory, but including information from similar tests by the Services and industry, is presented in the following sections.

6.1. Tests on Core Materials

6.10. Exposure Conditions. End-grain balsa, cellular-hard-rubber, and cellular-cellulose-acetate specimens were conditioned to equilibrium at a relative humidity of 65 percent and a temperature of 75° F., and then subjected to the following treatments: (1) Immersion in running tap water for (*a*) 24 hours, (*b*) 40 days, (*c*) 40 days, and then reconditioned at 75° F. and 65 percent relative humidity; (2) (*a*) conditioned to equilibrium at a relative humidity of 97 percent and a temperature of 80° F., (*b*) treatment (2) (*a*) followed by reconditioning at 75° F. and 65 percent relative humidity; (3) (*a*) heated for 240 hours at a temperature of 200° F., (*b*) treatment (3) (*a*) followed by reconditioning at 75° F. and 65 percent relative humidity; and (4) exposed to (*a*) one, (*b*) five, and (*c*) 10 cycles of high-low temperatures, with each cycle consisting of 24 hours at a temperature of 175° F. and 75 percent relative humidity, 24 hours at a temperature of −20° F., 24 hours at 175° F. dry heat, and 24 hours at −20° F. At the end of the last cycle the specimens were reconditioned at 75° F. and 65 percent relative humidity.

6.11. Results of Tests. The results of the tests showed that of the three materials, balsa had the poorest weight and dimensional stability when immersed in water (table 6–1), heated for long periods (table 6–2), or subjected to high humidities (table 6–3). It retained its compressive strength at high temperatures, but lost considerable strength when immersed in water or subjected to high humidities. The elastic properties conformed to the strength properties, increasing slightly when dry and decreasing when wet. The results thus follow the general strength-moisture relations as found for native wood species.

Table 6–1. Some properties [1] of low-density core materials for sandwich-type constructions at 75° F. and 65 percent relative humidity, after immersion in water at 60° F., and after reconditioning at 75° F. and 65 percent relative humidity following immersion

Material	Treatment [2] of specimens before test	Range of values	Compression (Flatwise) [3]								Shear	Tension (Flatwise) [5]				Dimensional stability [6]			
			Specific gravity [1]	Ultimate strength	Proportional limit		Modulus of elasticity		Yield at 0.7 percent strain		Modulus of rigidity [4]	Specific gravity [1]	Ultimate strength	Failure area		Change based on original observations made at 75° F.—65 percent relative humidity			
					¼" strain gage length	Dials between heads	¼" strain gage length	Dials between heads	¼" strain gage length	Dials between heads				Core	Bond	Length	Width	Thickness	Weight
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
				Lb. per sq. in.	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*		*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Balsa (end grain)	Conditioned to equilibrium with 75° F.—65 percent relative humidity (Controls).	Minimum	0.104	851	223	447	328,220	36,556	794	249	17,632	0.100	1,040	--------	--------	--------	--------	--------	--------
		Average	.113	935	404	485	415,115	46,080	895	317	19,308	.104	1,455	36	64	0	0	0	0
		Maximum	.120	990	474	521	531,190	55,876	969	384	21,412	.116	1,891	--------	--------	--------	--------	--------	--------
	Immersed in running tap water for 24 hours and tested immediately.	Minimum	.093	313	113	205	65,266	15,141	244	103	10,371	.100	1,372	--------	--------	+2.16	+1.20	+0.19	+120
		Average	.118	469	234	291	270,500	22,506	405	155	12,456	.104	1,673	37	63	+2.54	+1.72	+.43	+153.5
		Maximum	.145	663	300	362	427,600	30,527	506	208	13,594	.116	1,988	--------	--------	+2.95	+2.65	+.80	+275.7
	Immersed in running tap water for 40 days and tested immediately.	Minimum	.097	448	120	189	166,168	18,759	308	130	12,069	.090	1,069	--------	--------	+2.49	+1.25	+.59	+278.2
		Average	.133	546	189	303	361,327	26,221	406	180	14,149	.103	1,570	41	59	+3.37	+1.98	+.79	+327.1
		Maximum	.163	641	249	409	499,000	39,797	476	277	15,620	.116	1,995	--------	--------	+3.89	+2.65	+.99	+395.2
	Immersed in running tap water for 40 days and conditioned to equilibrium with 75° F.—65 percent relative humidity.	Minimum	.095	608	298	423	282,960	22,535	580	157	16,079	.090	1,031	--------	--------	+.20	+.10	0	+1.0
		Average	.110	769	361	522	344,894	30,474	725	211	17,289	.103	1,280	3	97	+.39	+.30	+.32	+1.4
		Maximum	.126	992	522	646	452,056	39,468	946	276	19,196	.116	1,773	--------	--------	+.60	+.65	+.59	+1.6
Cellular hard rubber (expanded type) (Sponge Rubber Products).	Conditioned to equilibrium with 75° F.—65 percent relative humidity (Controls).	Minimum	.102	151	65	80	11,049	7,227	77	48	3,330	--------	305	--------	--------	--------	--------	--------	--------
		Average	.111	199	89	127	22,445	7,345	134	50	3,379	.115	331	100	0	0	0	0	0
		Maximum	.115	224	121	156	28,186	7,534	152	52	3,424	--------	358	--------	--------	--------	--------	--------	--------
	Immersed in running tap water for 24 hours and tested immediately.	Minimum	.101	126	65	80	15,523	5,772	101	39	3,210	--------	157	--------	--------	−.05	−.10	−.78	+21.1
		Average	.105	157	80	100	18,509	6,726	114	46	3,390	.109	187	100	0	−.13	−.11	−1.17	+28.4
		Maximum	.109	184	95	118	28,595	8,170	149	56	3,533	--------	208	--------	--------	−.20	−.15	−1.94	+33.2
	Immersed in running tap water for 40 days and tested immediately.	Minimum	.103	122	50	90	13,810	6,403	90	44	3,124	--------	145	--------	--------	+.10	+.05	−.39	+38.0
		Average	.108	148	78	104	25,441	7,282	124	50	3,282	.106	187	100	0	+.13	+.11	−.66	+44.1
		Maximum	.113	177	116	131	50,226	8,174	140	55	3,387	--------	208	--------	--------	+.20	+.15	−.98	+50.4
	Immersed in running tap water for 40 days and conditioned to equilibrium with 75° F.—65 percent relative humidity.	Minimum	.091	96	55	68	11,514	4,788	77	33	2,855	--------	244	--------	--------	−.05	0	−1.34	+.4
		Average	.104	144	94	98	15,602	6,799	104	46	3,004	.105	262	100	0	−.15	−.05	−1.71	+.6
		Maximum	.114	184	174	133	19,741	8,323	124	58	3,248	--------	275	--------	--------	−.30	−.10	−2.33	+.8
Cellular cellulose acetate (extruded type) (Du Pont).	Conditioned to equilibrium with 75° F.—65 percent relative humidity (Controls).	Minimum	.096	138	54	64	21,075	5,317	126	35	4,274	.096	274	--------	--------	--------	--------	--------	--------
		Average	.099	164	79	105	30,605	6,461	152	44	4,394	.098	316	100	0	0	0	0	0
		Maximum	.105	201	130	118	38,502	9,639	187	68	4,481	.101	358	--------	--------	--------	--------	--------	--------
	Immersed in running tap water for 24 hours and tested immediately.	Minimum	.096	74	20	50	9,926	1,937	58	13	2,683	.096	147	--------	--------	+1.14	+.40	0	+40.2
		Average	.102	88	44	56	19,485	3,015	77	20	2,879	.098	184	100	0	+1.40	+.47	+.19	+43.6
		Maximum	.108	94	62	59	36,670	3,592	94	24	3,261	.101	210	--------	--------	+1.63	+.55	+.39	+56.1
	Immersed in running tap water for 40 days and tested immediately.	Minimum	.098	70	20	44	15,594	2,626	70	18	3,454	.097	140	--------	--------	+1.44	+.60	+.39	+64.4
		Average	.103	83	43	53	23,702	3,385	80	23	3,544	.098	149	94	6	+1.65	+.72	+.62	+77.1
		Maximum	.109	88	69	59	36,670	3,838	84	26	3,716	.100	162	--------	--------	+1.89	+.80	+1.36	+99.2
	Immersed in running tap water for 40 days and conditioned to equilibrium with 75° F.—65 percent relative humidity.	Minimum	.095	140	32	77	22,472	5,022	131	34	3,367	.097	216	--------	--------	−.74	−.60	−.97	+.2
		Average	.102	162	74	104	38,382	6,857	144	46	4,096	.098	287	100	0	−.95	−.82	−1.39	−.1
		Maximum	.106	173	101	128	71,506	8,146	156	55	4,474	.100	348	--------	--------	−1.04	−1.00	−1.56	−.4

[1] Based on dimensions and weights when in equilibrium with 75° F.—65 percent relative humidity prior to immersion in water.

[2] All immersed specimens were conditioned to equilibrium with 75° F.—65 percent relative humidity prior to immersion treatment.

[3] Average of five tests, specimen size 2 inches square by ½ inch long, load applied parallel to ½-inch dimension.

[4] Modulus associated with shear distortion in planes parallel to the length-thickness plane of the original material (lengthwise-radial or tangential plane for balsa). See FPL Report No. 1301 for plate-shear-test method. Average of three tests. Specimen 16 by 16 by ½ inches.

[5] Average of six tests, specimen size 1 inch square by ½ inch thick. Aluminum loading blocks were bonded to balsa, and plywood loading blocks were bonded to cellular-hard-rubber and cellular-cellulose-acetate core materials. Load was applied parallel to ½-inch dimension.

[6] Data obtained from compression specimens prior to test.

Table 6–2. Some properties [1] of low-density core materials for sandwich-type constructions at normal and elevated temperatures

Material	Temperature at time of test	Treatment of specimens before test [2]	Range of values	Compression (flat wise) [3]								Shear	Tension (flatwise) [5]				Dimensional stability [6]			
				Specific gravity [1]	Ultimate strength	Proportional limit		Modulus of elasticity		Yield at 0.7 percent strain		Modulus of rigidity [4]	Specific gravity	Ultimate strength	Failure area		Change based on original observations made at 75° F.—65 percent relative humidity			
						¼-inch strain gage length	Dials between heads	¼-inch strain gage length	Dials between heads	¼-inch strain gage length	Dials between heads				Core	Bond	Length	Width	Thickness	Weight
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)
	(°F.)				*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*		*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Balsa (end grain).	75	Conditioned to equilibrium with 75° F.—65 percent relative humidity (controls).	Minimum.	0.104	851	223	447	328, 220	36, 556	794	249	14, 459	0.100	1, 040	------	------	------	------	------	------
			Average	.113	935	404	485	415, 115	46, 080	895	317	16, 133	.104	1, 455	36	64	0	0	0	0
			Maximum.	.120	990	474	521	531, 190	55, 876	969	384	17, 947	.116	1, 891	------	------	------	------	------	------
	200	Heated continuously for 240 hours at 200° F. dry heat.	Minimum.	.114	999	322	520	301, 416	46, 726	1, 047	323	13, 397	.090	596	------	------	−1.05	−0.94	−0.19	−9.72
			Average	.124	1, 148	483	599	548, 157	52, 316	1, 109	358	14, 227	.094	982	34	66	−1.19	−1.03	−.20	−9.82
			Maximum.	.129	1, 270	893	743	827, 119	58, 060	1, 171	395	15, 821	.103	1, 342	------	------	−1.29	−1.24	−.20	−9.93
	75	Heated continuously for 240 hours at 200° F. dry heat and conditioned to equilibrium with 75° F.—65 percent relative humidity.	Minimum.	.095	666	299	447	320, 175	30, 647	664	212	14, 200	.091	1, 141	------	------	0	.05	.20	−1.12
			Average	.102	766	348	504	387, 118	36, 455	716	251	15, 496	.100	1, 717	21	79	−.05	.07	.34	−1.19
			Maximum.	.110	874	397	635	525, 328	44, 422	771	305	17, 560	.111	2, 208	------	------	−.10	.10	.39	−1.29
Cellular hard rubber (expanded type) (Sponge Rubber Products).	75	Conditioned to equilibrium with 75° F.—65 percent relative humidity (controls).	Minimum	.102	151	65	80	11, 049	7, 227	77	48	3, 132	------	305	------	------	------	------	------	------
			Average	.111	199	89	127	22, 445	7, 345	134	50	3, 300	.115	331	100	0	0	0	0	0
			Maximum	.115	224	121	156	28, 186	7, 534	152	52	3, 406	------	358	------	------	------	------	------	------
	200	Heated continuously for 240 hours at 200° F. dry heat.	Minimum.	.102	59	11	25	11, 764	1, 990	39	14	1, 187	------	95	------	------	.70	0	0	−3.00
			Average	.108	68	24	45	15, 037	2, 290	48	16	1, 250	.100	102	100	0	1.47	−.12	−1.57	−3.26
			Maximum.	.116	84	42	66	21, 754	2, 621	65	18	1, 312	------	112	------	------	2.36	−.20	−2.36	−3.45
	75	Heated continuously for 240 hours at 200° F. dry heat and conditioned to equilibrium with 75° F.—65 percent relative humidity.	Minimum.	.096	120	55	98	23, 139	4, 610	104	34	3, 287	------	180	------	------	1.10	−.05	−.58	−1.43
			Average	.108	171	92	123	27, 947	6, 348	124	44	3, 495	.114	196	100	0	1.49	−.23	−.98	−1.57
			Maximum.	.114	211	129	166	36, 648	7, 474	156	52	3, 681	------	214	------	------	1.76	−.65	−1.79	−1.67
Cellular cellulose acetate (extruded type) (Du Pont).	75	Conditioned to equilibrium with 75° F.—65 percent relative humidity (controls).	Minimum.	.096	138	54	64	21, 075	5, 317	126	35	4, 329	.096	274	------	------	------	------	------	------
			Average	.099	164	79	105	30, 605	6, 461	152	44	4, 353	.098	316	100	0	0	0	0	0
			Maximum.	.105	201	130	118	38, 502	9, 639	187	68	4, 391	.101	358	------	------	------	------	------	------
	200	Heated continuously for 240 hours at 200° F. dry heat.	Minimum.	.096	135	29	89	14, 649	4, 940	102	34	4, 153	.099	235	------	------	−.69	−.30	−.39	−5.18
			Average	.101	160	73	110	28, 613	5, 830	130	40	4, 246	.104	266	99	1	−1.00	−.62	−.70	−6.06
			Maximum.	.108	173	149	139	61, 757	6, 623	158	46	4, 432	.108	329	------	------	−1.24	−.90	−1.17	−6.97
	75	Heated continuously for 240 hours at 200° F. dry heat and conditioned to equilibrium with 75° F—65 percent relative humidity.	Minimum.	.095	143	94	79	20, 525	6, 321	132	43	4, 606	.099	178	------	------	0	0	0	−.43
			Average	.102	166	106	111	30, 981	7, 290	154	50	4, 823	.104	232	99	1	−.17	−.07	+.16	−.94
			Maximum.	.109	177	117	139	37, 865	8, 013	171	54	5, 091	.108	285	------	------	−.30	−.25	+.20	−1.19

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[1] Based on dimensions and weights when in equilibrium with 75° F.—65 percent relative humidity prior to heating at 200° F.

[2] Specimens which were subsequently heated for 240 hours were first conditioned to equilibrium with 75° F.—65 percent relative humidity.

[3] Specimen size 2 inches square by ½ inch long, load applied parallel to ½-inch dimension, average of 4 to 9 tests.

[4] Modulus associated with shear distortion in planes parallel to the length-thickness plane of the original material (lengthwise-radial or tangential plane for balsa). See FPL Report No. 1301 for plate-shear-test method. Specimen size 16 inches square by ½ inch thick. Average results from three specimens.

[5] Average of six tests, specimen size 1 inch square by ½ inch thick. Aluminum loading blocks were bonded to balsa, and plywood loading blocks were bonded to cellular-hard-rubber and cellular-cellulose-acetate core materials. Load applied parallel to ½-inch dimension.

[6] Data obtained from compression specimens prior to test.

Table 6–3. Some properties [1] *of low-density core materials for sandwich-type constructions at 75° F.—65 percent relative humidity, at 80° F.—97 percent relative humidity, and after conditioning at 75° F.—65 percent relative humidity following exposure to 80° F.—97 percent relative humidity*

Material	Treatment [2] of specimens before test	Range of values	Compression (flatwise) [3]								Shear	Tension (flatwise) [5]				Dimensional stability [6]			
			Specific gravity [1]	Ultimate strength	Proportional limit		Modulus of elasticity		Yield at 0.7 percent strain		Modulus of rigidity [4]	Specific gravity [1]	Ultimate strength	Failure area		Change based on original observations made at 75° F.—65 percent relative humidity			
					¼-inch strain gage length	Dials between heads	¼-inch strain gage length	Dials between heads	¼-inch strain gage length	Dials between heads				Core	Bond	Length	Width	Thickness	Weight
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
				Lb. per sq. in.	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*		*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Balsa (end grain)	Conditioned to equilibrium with 75° F.—65 percent relative humidity (Controls).	Minimum	0.104	851	223	447	328,220	36,556	794	249	17,340	0.100	1,040	---	---	---	---	---	---
		Average	.113	935	404	485	415,115	46,080	895	317	17,977	.104	1,455	36	64	0	0	0	0
		Maximum	.120	990	474	521	531,190	55,876	969	384	19,151	.116	1,891	---	---	---	---	---	---
	Conditioned to equilibrium with 80° F.—97 percent relative humidity.	Minimum	.105	383	254	274	145,464	18,281	380	127	12,969	.090	747	---	---	+2.14	+1.34	+1.77	+14.14
		Average	.149	629	283	441	239,949	28,511	577	197	13,663	.100	1,038	51	49	+2.78	+1.57	+1.90	+14.58
		Maximum	.209	930	312	662	372,575	44,218	884	303	14,615	.111	1,368	---	---	+3.30	+2.15	+2.00	+14.98
	Conditioned to equilibrium with 80° F.—97 percent relative humidity followed by conditioning to equilibrium with 75° F.—65 percent relative humidity.	Minimum	.097	476	261	324	114,432	29,286	---	202	16,971	.090	660	---	---	+.10	+.20	+.98	−1.14
		Average	.133	890	286	457	367,296	47,352	1,033	326	17,772	.100	856	33	67	+.27	+.33	+1.30	−1.52
		Maximum	.189	1,551	311	745	642,162	67,318	---	463	19,081	.116	1,158	---	---	+.40	+.55	+1.78	−1.75
Cellular hard rubber (expanded type) (Sponge Rubber Products).	Conditioned to equilibrium with 75° F.—65 percent relative humidity (Controls).	Minimum	.102	151	65	80	11,049	7,227	77	48	2,862	---	305	---	---	---	---	---	---
		Average	.111	199	89	127	22,445	7,345	134	50	3,029	.115	331	100	0	0	0	0	0
		Maximum	.115	224	121	156	28,186	7,534	152	52	3,321	---	358	---	---	---	---	---	---
	Conditioned to equilibrium with 80° F.—97 percent relative humidity.	Minimum	.108	106	33	80	10,749	6,396	76	36	2,757	---	171	---	---	+.25	+.20	−.19	+4.29
		Average	.112	155	82	100	17,755	7,420	106	47	2,914	.111	210	100	0	+.37	+.26	−.29	+4.58
		Maximum	.116	196	146	123	26,288	7,984	125	55	3,023	---	242	---	---	+.60	+.30	−.39	+5.17
	Conditioned to equilibrium with 80° F.—97 percent relative humidity followed by conditioning to equilibrium with 75° F.—65 percent relative humidity.	Minimum	.104	154	35	105	15,955	6,721	111	46	3,630	---	257	---	---	0	0	−.57	+.89
		Average	.110	188	90	130	39,482	7,914	149	54	3,716	.116	288	100	0	+.04	+.04	−.66	+.93
		Maximum	.114	198	146	141	62,751	9,001	188	62	3,838	---	330	---	---	+.05	+.10	−.78	+.99
Cellular cellulose acetate (extruded type) (Du Pont).	Conditioned to equilibrium with 75° F.—65 percent relative humidity (Controls).	Minimum	.096	138	54	64	21,075	5,317	126	35	4,117	.096	274	---	---	---	---	---	---
		Average	.099	164	79	105	30,605	6,461	152	44	4,228	.098	316	100	0	0	0	0	0
		Maximum	.105	201	130	118	38,502	9,639	187	68	4,404	.101	358	---	---	---	---	---	---
	Conditioned to equilibrium with 80° F.—97 percent relative humidity.	Minimum	.094	100	44	64	16,280	4,065	88	28	2,557	.099	177	---	---	+.99	+.40	+.39	+7.21
		Average	.099	114	59	71	23,519	4,555	98	31	2,799	.106	218	91	9	+1.32	+.55	+.62	+7.96
		Maximum	.107	127	72	84	40,242	5,293	124	36	3,025	.110	257	---	---	+1.54	+.64	+1.17	+8.78
	Conditioned to equilibrium with 80° F.—97 percent relative humidity followed by conditioning to equilibrium with 75° F.—65 percent relative humidity.	Minimum	.097	148	59	96	21,573	5,625	130	39	3,671	.099	238	---	---	−.40	−.30	0	−.51
		Average	.102	167	85	113	34,064	6,639	137	46	4,038	.104	274	98	2	−.53	−.42	−.24	−.89
		Maximum	.108	180	103	139	63,134	7,989	143	55	4,392	.110	340	---	---	−.75	−.55	−.79	−1.14

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[1] Based on dimensions and weights when in equilibrium with 75° F.—65 percent relative humidity prior to exposure to 80° F.—97 percent relative humidity.

[2] All specimens were initially conditioned to equilibrium with 75° F.—65 percent relative humidity.

[3] Average of 5 tests, specimen size 2 inches square by ½ inch long, load applied parallel to ½-inch dimension (parallel to grain for balsa).

[4] Modulus associated with shear distortion in planes parallel to the length-thickness plane of the original material (lengthwise-radial or tangential plane for balsa). See FPL Report No. 1555 for plate-shear-test method. Average of three tests, specimen size 16 inches square by ½ inch thick.

[5] Average of 5 to 8 tests, specimen size 1 inch square by ½ inch thick. Aluminum loading blocks were bonded to balsa, and plywood loading blocks were bonded to cellular-hard-rubber and cellular-cellulose-acetate core materials. Load applied parallel to ½-inch dimension.

[6] Data obtained from compression specimens prior to test.

Of the three materials, the cellular hard rubber when immersed in water had good dimensional and weight stability and retained its compressive strength better than the other two materials, but it was permanently weakened. The balsa and cellular cellulose acetate had better recovery characteristics than the cellular hard rubber when reconditioned at 75° F. and 65 percent relative humidity after immersion. The cellular hard rubber had very poor strength properties when heated to 200° F. for 240 hours, and retained only one-third of the original values. It did not recover well when reconditioned. It was likewise most affected by the cyclic exposures and decreased in all properties except modulus of rigidity. The loss in strength might have been due to the high-temperature portion of the cyclic exposure.

In general, the cellular cellulose acetate had the best properties of the three materials. Although it was inferior to the other materials in a few individual exposures, it had the best weight and dimensional stability under a majority of them. It was the least affected by the cyclic exposures (table 6–4) and maintained a better portion of its tensile strength under dry heat (table 6–2). While the material was reduced considerably in strength when immersed in water or subjected to high humidities, its strength recovery after it was reconditioned was very good.

Rated on a specific-gravity basis, the balsa had much higher strength and elastic properties than either the rubber or acetate. The unsatisfactory characteristic of balsa was its very great change in weight when equilibrium moisture conditions were varied. Even with its increase in weight when wet, however, the balsa had greater strength and stiffness than the other two materials on a strength-weight ratio.

Table 6–4. The effect of 1, 5, and 10 cycles [1] *of exposure to high and low temperatures and humidities on several properties* [2] *of low-density core materials for sandwich-type construction*

Material	Treatment [3] of specimens before test	Range of values	Compression (flatwise) [4]								Shear	Tension (flatwise) [6]				Dimensional stability [7]			
			Specific gravity [2]	Ultimate strength	Proportional limit		Modulus of elasticity		Yield at 0.7 percent strain		Modulus of rigidity [5]	Specific gravity [2]	Ultimate strength	Failure area		Change based on original observations made at 75° F.—65 percent R. H.			
					¼ inch strain gage length	Dials between heads	¼ inch strain gage length	Dials between heads	¼ inch strain gage length	Dials between heads				Core	Bond	Length	Width	Thickness	Weight
				P. s. i.	*P. s. i.*	*P. s. i.*	*P. s. i.*	*P. s. i.*	*P. s. i.*	*P. s. i.*	*P. s. i.*		*P. s. i.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Balsa (end grain).	Conditioned to equilibrium with 75° F.—65 percent relative humidity (controls).	Minimum	0.104	851	223	447	328,220	36,556	794	249	16,849	0.100	1,040	--------	--------	--------	--------	--------	--------
		Average	.113	935	404	485	415,115	46,080	895	317	18,834	.104	1,455	36	64	0	0	0	0
		Maximum	.120	990	474	521	531,190	55,876	969	384	22,641	.116	1,891	--------	--------	--------	--------	--------	--------
	Exposed to 1 cycle followed by conditioning to equilibrium with 75° F.—65 percent relative humidity.	Minimum	0.100	724	309	395	181,909	31,729	663	215	--------	0.090	1,240	--------	--------	−0.20	0	+0.19	−0.91
		Average	.110	876	404	552	307,428	38,348	833	260	24,042	.100	1,632	59	41	−0.28	−0.11	+0.24	−1.06
		Maximum	.130	1,089	507	643	532,469	44,482	1,003	302	--------	.116	1,954	--------	--------	−0.40	−0.25	+0.38	−1.14
	Exposed to 5 cycles followed by conditioning to equilibrium with 75° F.—65 percent relative humidity.	Minimum	0.105	918	444	396	447,649	35,951	904	243	--------	0.091	1,013	--------	--------	−0.25	−0.05	−0.39	−1.97
		Average	.123	1,097	569	495	718,134	76,953	1,062	445	18,349	.098	1,384	73	27	−0.32	−0.13	0	−2.01
		Maximum	.145	1,203	767	598	949,554	156,428	1,147	663	--------	.101	2,000	--------	--------	−0.40	−0.20	+0.20	−2.05
	Exposed to 10 cycles followed by conditioning to equilibrium with 75° F.—65 percent relative humidity.	Minimum	0.095	695	309	421	113,881	26,180	662	179	--------	0.091	866	--------	--------	−0.35	−0.20	−0.98	−2.09
		Average	.105	852	523	572	390,075	39,129	819	268	16,548	.097	1,205	77	23	−0.63	−0.33	−1.21	−1.34
		Maximum	.120	1,068	793	694	784,072	46,310	979	316	--------	.103	1,571	--------	--------	−0.79	−0.45	−1.56	+0.89
Cellular hard rubber (expanded type). (Sponge Rubber Products)	Conditioned to equilibrium with 75° F.—65 percent relative humidity (controls).	Minimum	0.102	151	65	80	11,049	7,227	77	48	3,125	--------	305	--------	--------	--------	--------	--------	--------
		Average	.111	199	89	127	22,445	7,345	134	50	3,845	0.115	331	100	0	0	0	0	0
		Maximum	.115	224	121	156	28,186	7,534	152	52	4,416	--------	358	--------	--------	--------	--------	--------	--------
	Exposed to 1 cycle followed by conditioning to equilibrium with 75° F.—65 percent relative humidity.	Minimum	0.106	1,581	73	108	--------	5,233	133	36	3,405	--------	248	--------	--------	0.55	0.20	−0.98	−0.77
		Average	.111	179	83	131	--------	6,487	156	45	3,801	0.118	273	100	0	2.29	1.68	−0.48	−0.94
		Maximum	.116	201	95	149	--------	7,380	173	51	4,197	--------	296	--------	--------	3.71	3.46	+0.57	−1.17
	Exposed to 5 cycles followed by conditioning to equilibrium with 75° F.—65 percent relative humidity.	Minimum	0.108	147	75	93	22,534	5.802	124	39	3,443	--------	227	--------	--------	0.25	−0.10	−0.19	−1.67
		Average	.111	176	77	123	28,148	7,010	146	48	4,190	0.119	250	100	0	1.55	1.93	−0.78	−1.79
		Maximum	.115	205	78	143	33,763	8,920	158	62	4,571	--------	275	--------	--------	3.35	3.46	−1.16	−1.97
	Exposed to 10 cycles followed by conditioning to equilibrium with 75° F.—65 percent relative humidity.	Minimum	0.103	136	118	105	11,035	6,215	110	43	3,296	--------	261	--------	--------	−0.10	−0.20	−0.99	−1.77
		Average	.106	161	126	128	20,788	6,889	142	48	4,027	0.119	302	100	0	1.22	0.96	−2.01	−2.07
		Maximum	.112	196	135	148	34,490	7,509	172	52	4,617	--------	337	--------	--------	2.55	2.90	−2.94	−2.40
Cellular cellulose acetate (extruded type). (Dupont)	Conditioned to equilibrium with 75° F.—65 percent relative humidity (controls).	Minimum	0.096	138	54	64	21,075	5,317	126	35	4,003	0.096	274	--------	--------	--------	--------	--------	--------
		Average	.099	164	79	105	30,605	6,461	152	44	4,225	.098	316	100	0	0	0	0	0
		Maximum	.105	201	130	118	38,502	9,639	187	68	4,368	.101	358	--------	--------	--------	--------	--------	--------
	Exposed to 1 cycle followed by conditioning to equilibrium with 75° F.—65 percent relative humidity.	Minimum	0.094	143	47	86	15,983	6,289	115	43	--------	0.098	254	--------	--------	−0.25	−0.15	−0.19	0
		Average	.100	164	113	113	24,021	7,201	136	49	4,687	.103	284	100	0	−0.10	−0.27	−0.45	−0.50
		Maximum	.106	181	144	136	30,818	8,993	164	61	--------	.108	316	--------	--------	+0.05	−0.45	−0.77	−1.01
	Exposed to 5 cycles followed by conditioning to equilibrium with 75° F.— 65 percent relative humidity.	Minimum	0.095	149	42	79	16,700	6,355	113	43	--------	0.098	208	--------	--------	−0.30	−0.05	0	−1.24
		Average	.101	165	89	111	44,446	7.823	142	54	4,470	.103	251	100	0	−0.13	−0.16	−0.16	−0.47
		Maximum	.106	174	117	130	90,050	8,786	173	61	--------	.108	308	--------	--------	+0.05	−0.20	−0.39	+0.54

Exposed to 10 cycles followed by conditioning to equilibrium with 75° F.—65 percent relative humidity.	Minimum	0.095	150	70	99	12,821	6,389	90	43	--------	0.090	232	--------	--------	0.65	−0.64	−1.16	−0.29
	Average	.102	169	105	124	40,389	7,068	145	48	4,652	.095	259	97	3	−0.28	−0.31	−1.58	−0.84
	Maximum	.106	180	133	138	75,417	8,142	175	55	--------	.099	291	--------	--------	+0.75	+0.60	−1.76	−1.20

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[1] One cycle consisted of the following consecutive treatments: 24 hours at 175° F.—75 percent relative humidity, 24 hours at —20° F., 24 hours at 175° F., and 24 hours at —20° F.

[2] Based on dimensions and weights when in equilibrium with 75° F.—65 percent relative humidity prior to cyclic exposures.

[3] All specimens were initially conditioned to equilibrium with 75° F.—65 percent relative humidity.

[4] Average of five tests, specimen size 2 inches square by ½ inch long, load applied parallel to ½-inch dimension (parallel to grain for balsa).

[5] Modulus associated with shear distortion in planes parallel to length-thickness plane of the original material (lengthwise-radial or tangential plane for balsa). See Forest Products Laboratory mimeograph 1555 for plate-shear method. Average of 1–3 tests, specimen size 16 inches square by ½-inch thick.

[6] Average 5–8 tests, specimen size 1 inch square by ½ inch thick. Aluminum loading blocks were bonded to balsa, and plywood loading blocks were bonded to cellular-hard-rubber and cellular-cellulose-acetate core materials. Load was applied parallel to ½-inch dimension.

[7] Data obtained from compression specimens prior to test.

The cellular cellulose acetate had approximately the same strength-weight properties as the cellular hard rubber and appeared to be a good material under severe exposures. The rubber had good properties when wet, but lost considerable strength when subjected to the high temperatures that may be encountered in aircraft structures. A summary of the relative characteristics of these three core materials after exposure to these conditions is presented in table 6–5.

In bottle decay tests, untreated balsa was severely decayed (as measured by percentage loss in weight) when exposed to *Poria microspora* (No. 106), *Poria incrassata* (No. 563), and *Polyporus versicolor* (No. 72074) for periods of 1, 2, and 3 months, and when exposed in soil. Under the same conditions, cellulose acetate and cellular hard rubber sustained no weight losses. Treatment of the balsa with 2.0 percent pentachlorophenol in acetone was required to prevent decay. Results of these tests are presented in table 6–6.

Flame tests made in accordance with Method No. 2021 of L–P–406a, "Federal Specification for Plastics, Organic: General Specifications, Test Methods," gave an average rate of burning, in inches per minute, of 34 for cellular hard rubber, 30 for balsa, and 10 for cellular cellulose acetate (table 6–7).

Table 6–5. Some properties [1] of low-density core materials for sandwich constructions after various exposures [2]

Treatment of specimens	Material	Compression (flatwise)								Shear modulus of rigidity	Tension (flatwise)		Dimensional stability average of length, width, and thickness	Weight
		Specific gravity [1]	Ultimate strength	Proportional limit		Modulus of elasticity		Yield at 0.7 percent strain			Specific gravity [1]	Ultimate strength		
				¼ inch strain gage length	Dials between heads	¼ inch strain gage length	Dials between heads	¼ inch strain gage length	Dials between heads					
Immersed in running tap water for 24 hours.	Balsa	1. 044	0. 502	0. 578	0. 600	0. 652	0. 488	0. 453	0. 488	0. 645	1. 000	1. 150	1. 015	7. 535
	C. H. R.[3]	. 946	. 788	. 899	. 788	. 825	. 915	. 851	. 920	1. 002	. 948	. 565	. 995	1. 284
	C. C. A.[4]	1. 030	. 536	. 557	. 533	. 636	. 466	. 507	. 455	. 538	1. 000	. 582	1. 007	1. 436
Immersed in running tap water for 40 days.	Balsa	1. 177	. 585	. 467	. 625	. 869	. 570	. 454	. 568	. 733	. 991	1. 078	1. 020	4. 271
	C. H. R.[3]	. 973	. 743	. 876	. 819	1. 134	. 991	. 926	1. 000	. 972	. 922	. 565	1. 001	1. 441
	C. C. A.[4]	1. 040	. 506	. 544	. 505	. 775	. 524	. 527	. 522	. 719	1. 000	. 472	1. 010	1. 771
Immersed in running tap water for 40 days and reconditioned.[5]	Balsa	. 973	. 821	. 893	1. 077	. 830	. 661	. 810	. 666	. 894	. 991	. 880	1. 003	1. 014
	C. H. R.[3]	. 937	. 723	1. 057	. 772	. 695	. 925	. 776	. 920	. 890	. 913	. 792	. 994	1. 006
	C. C. A.[4]	1. 030	. 988	. 937	. 991	1. 252	1. 061	. 948	1. 045	. 829	1. 000	. 909	. 989	. 999
Conditioned to equilibrium with 80° F.—97 percent relative humidity.	Balsa	1. 319	. 673	. 700	. 910	. 576	. 617	. 645	. 621	. 770	. 962	. 714	1. 021	1. 146
	C. H. R.[3]	1. 009	. 780	. 922	. 788	. 790	1. 010	. 791	. 940	. 962	. 965	. 635	1. 001	1. 046
	C. C. A.[4]	1. 000	. 695	. 747	. 676	. 767	. 705	. 645	. 705	. 662	1. 081	. 688	1. 008	1. 080
Conditioned to equilibrium with 80° F.—97 percent relative humidity and reconditioned.[5]	Balsa	1. 177	. 952	. 708	. 943	. 885	1. 026	1. 155	1. 029	. 986	. 962	. 589	1. 006	. 985
	C. H. R.[3]	. 991	. 945	1. 012	1. 022	1. 760	1. 079	1. 111	1. 080	1. 225	1. 009	. 871	. 998	1. 009
	C. C. A.[4]	1. 030	1. 018	1. 076	1. 075	1. 115	1. 027	. 902	1. 045	. 955	1. 061	. 865	. 996	. 991
Heated for 240 hours at 200° F. dry heat.	Balsa	1. 097	1. 230	1. 195	1. 235	1. 320	1. 135	1. 239	1. 130	. 882	. 903	. 675	. 992	. 902
	C. H. R.[3]	. 973	. 342	. 270	. 355	. 669	. 312	. 358	. 320	. 379	. 870	. 302	. 999	. 967
	C. C. A.[4]	1. 020	. 975	. 924	1. 047	. 935	. 903	. 855	. 909	. 974	1. 061	. 842	. 992	. 939
Heated for 240 hours at 200° F. dry heat and reconditioned.[5]	Balsa	. 903	. 820	. 862	1. 040	. 932	. 791	. 800	. 792	. 959	. 962	1. 180	1. 001	. 988
	C. H. R.[3]	. 973	. 860	1. 023	. 968	1. 243	. 864	. 926	. 880	1. 058	. 992	. 592	1. 001	. 984
	C. C. A.[4]	1. 030	1. 012	1. 342	1. 056	1. 010	1. 130	1. 013	1. 136	1. 107	1. 061	. 735	1. 000	. 991
Exposed to 1 cycle of temperatures and humidities.[6]	Balsa	. 973	. 936	1. 000	1. 138	. 739	. 832	. 930	. 820	1. 279	. 962	1. 121	. 999	. 989
	C. H. R.[3]	1. 000	. 900	. 933	1. 031	-------	. 883	1. 163	. 900	. 989	1. 026	. 825	1. 012	. 991
	C. C. A.[4]	1. 010	1. 000	1. 430	1. 077	. 786	1. 116	. 894	1. 113	1. 102	1. 051	. 899	. 997	. 995
Exposed to 5 cycles of temperatures and humidities.[6]	Balsa	1. 088	1. 130	1. 410	1. 021	1. 730	1. 670	1. 187	1. 404	. 975	. 942	. 951	. 998	. 980
	C. H. R.[3]	1. 000	. 884	. 865	. 968	1. 252	. 955	1. 090	. 960	1. 089	1. 035	. 755	1. 009	. 982
	C. C. A.[4]	1. 020	1. 005	1. 127	1. 058	1. 451	1. 211	. 934	1. 227	1. 051	1. 051	. 794	. 998	. 995
Exposed to 10 cycles of temperatures and humidities.[6]	Balsa	. 929	. 911	1. 295	1. 180	. 940	. 848	. 915	. 845	. 878	. 932	. 828	. 993	. 987
	C. H. R.[3]	. 955	. 808	1. 417	1. 008	. 924	. 937	1. 060	. 960	1. 047	1. 035	. 912	1. 001	. 979
	C. C. A.[4]	1. 030	1. 030	1. 330	1. 181	1. 318	1. 093	. 954	1. 091	1. 088	. 969	. 820	. 993	. 992

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[1] Based on dimensions and weights when in equilibrium with 75° F.—65 percent relative humidity prior to exposure.

[2] All figures are ratios of the average test values after exposure to the average control values prior to exposure.

[3] Cellular hard rubber (expanded butadiene-acrylenitrile type) (Sponge Rubber Products).

[4] Cellular cellulose acetate (extruded type) (DuPont).

[5] Reconditioned to equilibrium with 75° F.—65 percent relative humidity.

[6] One cycle consisted of the following consecutive treatments: 24 hours at 175° F.—75 percent relative humidity, 24 hours at −20° F., 24 hours at 175° F., and 24 hours at −20° F.

NOTE.—See tables 6–1 to 6–4 for detailed results.

Table 6–6. *Change in weight*[1] *of low-density core materials for sandwich type constructions when tested for resistance to decay*

Material	Exposures					
	No. 106 *Poria microspora*	No. 563 *Poria incrassata*	No. 72074 *Polyporus versicolor*	Soil	Sterile agar[2]	65 percent relative humidity[3]
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1 month's exposure:						
Balsa—no preservative	−23.4	−15.5	−21.3	−5.4	+0.68	−0.53
Balsa—0.1 percent pentachlorophenol	−1.21	−8.4	−8.8	−.12	−.2	−1.0
Balsa—1.0 percent pentachlorophenol	+.03	−4.3	−1.6	−.15	−.1	−1.3
Balsa—2.0 percent pentachlorophenol	−.44	−.46	−.72	+.19	−.37	−1.7
Cellular cellulose acetate[4]	+.64	+.66	+.34	+1.30	+.4	−.6
Cellular hard rubber[5]	+1.3	+1.1	+.54	+2.7	+.5	+.15
2 months' exposure:						
Balsa—no preservative	−22.6	−28.7	−34.9	−10.3	−.18	−.66
Balsa—0.1 percent pentachlorophenol	−1.0	−24.3	−30.1	−3.1	−.70	−1.30
Balsa—1.0 percent pentachlorophenol	−.8	−8.2	−14.7	−.71	−.6	−1.40
Balsa—2.0 percent pentachlorophenol	−.88	−1.4	−1.1	+.56	−.97	−1.10
Cellular cellulose acetate[4]	+.56	+1.2	+.04	+2.60	+.20	−.45
Cellular hard rubber[5]	+1.0	+.94	+.60	+4.9	+.6	+.35
3 months' exposure:						
Balsa—no preservative	−32.5	−34.8	−43.4	−19.8	+.05	−.35
Balsa—0.1 percent pentachlorophenol	−13.8	−33.9	−41.0	−12.0	−.77	−1.10
Balsa—1.0 percent pentachlorophenol	−.7	−16.9	−16.9	−5.8	−.70	−1.10
Balsa—2.0 percent pentachlorophenol	−.92	−1.0	−.84	+4.4	−.43	−1.30
Cellular cellulose acetate[4]	+.13	+1.1	−.36	+7.7	+.27	−.20
Cellular hard rubber[5]	+1.1	+1.1	+.52	+10.7	+.4	+.55

[1] Based on conditioned weights at 65 percent relative humidity and 80° F. before and after exposure. Weight of preservative included where present. Average of 5 specimens except where otherwise stated. Minus sign indicates loss in weight, plus sign a gain in weight.

[2] Average of 3 specimens.

[3] Average of 2 specimens.

[4] Du Pont.

[5] Sponge Rubber Products.

Table 6–7. Flammability tests on core materials

Core material	Average rate of burning (inches per minute)	Remarks
Balsa	30	Odor and flame characteristic of dry wood.
Cellular hard rubber (Sponge Rubber Products).	34	Burned with smoky, sputtering flame. Shrank but did not melt. Odor of burning rubber. Specimen remained intact after burning.
Cellular cellulose acetate (Du Pont).	10	Burned with clean, sputtering flame. Shrank, melted, charred, and dripped. Very slight odor similar to burnt sugar. Specimen entirely consumed.

The same three core materials were immersed in the following aircraft liquids: isopropyl alcohol, ethylene glycol, 3580 oleo fluid, 3586 oleo fluid, 100 octane gasoline, used crankcase oil, and distilled water. None of the core materials was greatly affected by the 7-day immersion, except balsa, which materially increased in weight and dimensions when immersed in water, ethylene glycol, 3586 oleo fluid, and alcohol (table 6–8). After being reconditioned for 39 days most test specimens returned essentially to their original weight and dimensions, but an appreciable weight increase was retained by specimens immersed in 3580 and 3586 oleo fluids and used crankcase oil, particularly by the balsa specimens. A slight amount of permanent shrinkage in dimensions was noted after reconditioning acetate and rubber cores, while balsa, notably the specimens exposed to ethylene glycol, retained a small amount of permanent swelling.

6.2. Tests on Sandwich Parts

6.20. EXPOSURE CONDITIONS. Nine sandwich constructions (made by combining three facing materials, aluminum, glass cloth-resin, and plywood, with the three core materials, balsa, cellular hard rubber, and cellular cellulose acetate) were conditioned to equilibrium at a relative humidity of 65 percent and a temperature of 75° F. They were then subjected to various exposures to determine, by tension tests, weight and dimensional measurements, and observation, the relative durability of each construction. The details of these exposure conditions were the same as those described in section 6.10, with the addition of exposure to a salt-water spray.

Table 6–8. Weight and dimensional changes of core materials exposed to various aircraft liquids

Core material [1]	Liquid	Average gain in weight [2]			Average gain in thickness [3]		Average gain in width [3]		Average gain in length [3]	
		After soaking for 7 days	After soaking 7 days and conditioning for—		After soaking for 7 days	After soaking 7 days and conditioning for 39 days	After soaking for 7 days	After soaking 7 days and conditioning for 39 days	After soaking for 7 days	After soaking 7 days and conditioning for 39 days
			7 days	39 days						
		Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Cellular hard rubber [4]	Iso-propyl alcohol.	29. 45	0. 22	0. 15	0. 14	−0. 37	−0. 17	−0. 28	−0. 03	−0. 03
Balsa		181. 96	2. 01	2. 00	. 13	−. 20	1. 62	. 08	. 79	. 01
Cellular cellulose acetate [5]		45. 46	2. 52	1. 86	1. 20	−. 33	. 53	. 18	1. 03	−. 54
Cellular hard rubber	Ethylene glycol	10. 95	. 27	. 22	−. 34	−. 47	−. 21	−. 33	−. 06	−. 02
Balsa		219. 20	125. 11	14. 30	. 39	. 23	3. 34	1. 79	2. 15	1. 14
Cellular cellulose acetate		54. 34	5. 22	3. 31	. 86	−. 53	. 56	−. 48	1. 00	−. 48
Cellular hard rubber	3580-oleo fluid (petroleum base).	37. 08	10. 91	7. 57	. 14	−. 17	−. 17	−. 03	−. 07	−. 09
Balsa		117. 26	75. 11	62. 68	. 46	. 16	. 33	. 13	. 30	. 06
Cellular cellulose acetate		38. 52	14. 52	9. 72	. 13	−. 36	. 03	−. 21	. 11	. 02
Cellular hard rubber	3586-oleo fluid (castor-oil base).	45. 22	18. 42	17. 46	−. 20	−. 27	−. 17	−. 09	−. 03	−. 02
Balsa		148. 05	69. 29	62. 73	. 34	. 33	1. 85	1. 22	1. 18	. 73
Cellular cellulose acetate		63. 91	26. 75	24. 34	. 19	−. 36	. 46	−. 48	. 55	−. 54
Cellular hard rubber	100-octane gasoline.	25. 68	−. 09	−. 05	−. 07	0	−. 21	−. 17	. 02	−. 04
Balsa		159. 98	0	. 48	−. 39	−. 29	−. 13	−. 15	−. 06	−. 06
Cellular cellulose acetate		28. 92	. 17	. 40	. 26	−. 13	0	. 10	−. 18	−. 09
Cellular hard rubber	Used crankcase oil.	28. 82	22. 93	19. 47	−. 41	−. 68	−. 14	−. 23	−. 03	−. 06
Balsa		92. 48	84. 26	82. 83	. 07	−. 26	0	−. 43	. 11	−. 03
Cellular cellulose acetate		34. 48	28. 50	23. 55	−. 07	−. 40	. 13	−. 16	0	−. 01
Cellular hard rubber	Water	21. 35	. 67	. 67	. 07	−. 58	. 07	−. 28	. 21	−. 01
Balsa		536. 55	. 96	. 78	. 07	. 00	4. 00	. 61	2. 44	. 31
Cellular cellulose acetate		65. 30	. 84	. 79	. 60	−. 73	. 89	−. 80	1. 79	−. 67

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[1] Dimensions of test specimens—thickness ½-inch, width 1 inch, length 3 inches. Balsa ½-inch dimension in grain direction (thickness).

[2] Based on weight of specimens, conditioned to equilibrium at 75° F., 50 percent relative humidity before immersion. Each value is the average for 3 specimens.

[3] Based on dimension of specimens, conditioned to equilibrium at 75° F., 50 percent relative humidity before immersion. Each value is the average for 3 specimens.

[4] Obtained from Sponge Rubber Products Co.

[5] Obtained from DuPont.

6.21. Preparation of Specimens. All test parts were in the form of panels nominally ½ by 6 by 6 inches, and four panels were prepared for each exposure condition, two with unprotected edges and two with well-painted edges. Eight tension specimens, of the type described in chapter 5, were prepared for each exposure, except for weathering.

6.210. *Plywood-balsa.* Panels with end-grain balsa cores and plywood faces were bonded with an intermediate-temperature-setting melamine-resin adhesive. The adhesive was spread on the 0.070-inch three-ply birch aircraft plywood by brush. Twenty-four grams of wet adhesive were spread per square foot. After an open assembly period of 1 to 7 days the panels were assembled and bag-molded on a flat aluminum mold. The curing cycle was 15 minutes at a pressure of 50 pounds per square inch and a temperature of 300° F.

6.211. *Aluminum-balsa.* A two-step bonding process was used on all aluminum combinations. The primed and cured aluminum faces were bonded to the balsa cores with a room-temperature-setting resorcinol-resin adhesive.

6.212. *Glass cloth-balsa.* Panels with glass-cloth faces and balsa cores were assembled and cured in one operation with no additional adhesive between the faces and the core.

The normal procedure was to cover the flat caul with a parting film of cellophane. The glass cloth for one face (eight sheets), impregnated with a viscous laminating resin to 43 percent, was laid, one sheet at a time, cross-laminated, on the cellophane-covered caul. This procedure was repeated for the other face on the matching caul or on a piece of cellophane taped to a flat surface. The balsa core was then laid on one of the cauls and covered with the lay-up for the opposite face. This procedure, rather than laying the glass cloth directly on the core, was found necessary to avoid blisters and wrinkles.

Due to the slight waviness of the balsa-core surfaces, fluid pressure or its equivalent was necessary to assure intimate contact between the glass cloth and the core.

The panels were cured at a temperature of 220° F. and a pressure of 13 pounds per square inch for 1½ hours and were then removed from the press while hot.

6.213. *Plywood-cellulose acetate.* These panels were made by brushing a room-temperature-setting resorcinal adhesive (35 grams per square foot) on the plywood faces only, and pressing the panels in a vacuum bag at room temperature for a minimum period of 4 hours.

6.214. *Aluminum-cellulose acetate.* The normal technique for producing these panels was the same as that used on the aluminum-balsa durability panels.

6.215. *Glass cloth-cellulose acetate.* This combination was fabricated by the same technique as that used on the glass cloth-balsa combination.

6.216. *Plywood-cellular rubber.* This combination was made by the same process that was used on the plywood-cellulose acetate combination.

6.217. *Aluminum-cellular rubber.* The same process was used on this combination as on aluminum-cellulose acetate.

6.218. *Glass cloth-cellular rubber.* Cellular rubber inhibits the cure of the contact-pressure laminating resin when the two are in intimate contact during the curing cycle. Therefore, the normal wet-laminating process, as used on balsa and cellulose-acetate cores, could not be used. If, however, a suspension (about 15 percent concentration) of the catalyst (benzoyl peroxide) in water were sprayed or brushed on the cellular rubber and allowed to dry, the normal laminating process could be used with fair results.

6.22. Results of Tests. The test results presented in tables 6–9 to 6–13 in general revealed considerable variation. It is difficult, therefore, to present clearly and concisely the effect of the different exposure conditions on the nine sandwich combinations. Certain fairly well established effects, however, can be summarized.

In water immersion (table 6–9), the weight gain of each sandwich construction was controlled partly by the characteristics of the core and facing material and partly by the quality of the edge seal. Unsealed glass cloth-balsa panels gained about 92 percent, whereas, edge-coated rubber-aluminum panels gained about 2.5 percent. The wet laminated glass-cloth faces were poorer vapor barriers than the $\frac{1}{16}$-inch birch plywood faces, but they absorbed loss moisture. Void-free laminate facings would undoubtedly be more impervious.

Tensile strengths were generally lower in the soaked conditions than at room conditions, but regained most of this loss upon reconditioning.

Transverse dimensional changes under all exposures reflected the properties of the faces only, and those for plywood were usually two to three time those for either glass cloth or aluminum.

Changes in thickness followed the same trends exhibited by the respective core materials in the tests described in section 6.11.

The effects of exposure to high humidity (table 6–10) resembled, on a reduced scale, those of immersion in water.

Table 6–9. Effect of water immersion on the weight, dimensions, and tensile strength of nine sandwich constructions

Sandwich construction		Edge condition	Conditioned to equilibrium with 75° F. and 65 percent relative humidity (controls)			Immersed in water for 24 hours and tested immediately						Immersed in water for 40 days and tested immediately						Immersed in water for 40 days and conditioned to equilibrium with 75° F. and 65 percent relative humidity					
			Tension			Dimensional change [1]			Tension			Dimensional change [1]			Tension			Dimensional change [1]			Tension		
Core	Face		Strength	Material failure	Adhesive failure [2]	Weight	Average of length and width	Thickness	Strength	Material failure	Adhesive failure [2]	Weight	Average of length and width	Thickness	Strength	Material failure	Adhesive failure [2]	Weight	Average of length and width	Thickness	Strength	Material failure	Adhesive failure [2]
			P. s. i.	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*P. s. i.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*P. s. i.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*P. s. i.*	*Percent*	*Percent*
Balsa	Plywood	Unpainted	753.2	15	85	20.90	0.20	1.42	388.4	5.7	94.3	67.28	0.25	1.74	428.3	0	100	2.32	0.02	0.95	664.2	6.8	93.2
		Painted				12.63	.90	1.58				41.69	.23	1.82				3.00	.02	1.26			
Balsa	Aluminum	Unpainted	425.6	4.2	95.8	7.02	.14	.28	366.5	0	100	29.46	.17	−.10	457.2	0	100	−.64	.05	.28	521.1	0	100
		Painted				1.40	−.02	.00				5.52	.02	−.18				.84	.00	.37			
Balsa	Glass cloth	Unpainted	626.6	3.6	96.4	22.30	.10	.28	278.4	0	100	92.42	.10	−.10	132.5	0	100	.76	−.07	.28	312.8	0	100
		Painted				20.54	.07	−.10				76.60	.08	−.37				.36	−.10	.00			
Rubber [3]	Plywood	Unpainted	256.5	100	0	16.05	.16	1.16	233.2	100	0	40.73	.22	1.54	261.6	100	0	.80	.01	.46	278.0	100	0
		Painted				12.38	.07	.70				40.94	.19	1.16				1.55	.01	.08			
Rubber	Aluminum	Unpainted	166.6	100	0	2.08	.00	−.46	164.4	100	0	5.74	.03	−.82	179.9	98.4	1.6	−.67	.06	−.18	162.2	81.3	18.7
		Painted				.51	−.02	−.28				2.44	.04	−.46				−.03	.04	.19			
Rubber	Glass cloth	Unpainted	174.2	90	10	1.68	.01	−.09	135.7	83.3	16.7	5.66	.06	−.18	113.0	15	85	−.40	−.05	.36	220.7	87.5	12.5
		Painted				.31	.00	.00				5.10	.07	−.18				.00	.06	.37			
Acetate [4]	Plywood	Unpainted	253.9	98	2	19.14	.23	1.16	177.7	99.3	.7	54.26	.31	1.78	175.4	99.2	.8	−.19	−.01	−.70	281.1	100	0
		Painted				15.76	.17	1.56				53.82	.32	2.04				1.52	.03	−.46			
Acetate	Aluminum	Unpainted	240.2	37.5	62.5	3.07	.10	−.18	203.3	64.1	35.8	16.00	.14	−.36	95.3	26.3	73.7	−.66	.02	−1.89	259.0	69.2	30.8
		Painted				2.56	.04	−.18				18.02	.10	.19				−.15	−.03	−1.12			
Acetate	Glass cloth	Unpainted	242.5	96.4	3.6	4.78	.15	−.28	180.8	13.8	86.2	17.92	.14	.00	103.1	0	100	.31	−.10	−1.19	223.1	34.1	65.9
		Painted				3.82	.05	.29				16.00	.11	.20				.40	−.02	−.76			

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[1] Based on dimensions and weights when in equilibrium with 75° F. and 65 percent relative humidity prior to exposure.

[2] No attempt was made to classify the type of bond-line failure; that is, adhesive, cohesive, or failure etween primary and secondary adhesive. Miscellaneous types of failures, such as failures between face and grip, were not recorded. Delamination in glass-cloth faces was classified as bond-line failure.

[3] Cellular hard rubber from Sponge Rubber Products Co.

[4] Cellular cellulose acetate from DuPont.

Table 6–10. Effect of high humidity on the weight, dimensions, and tensile strength of nine sandwich constructions

Sandwich construction		Edge condition	Conditioned to equilibrium with 75° F. and 65 percent relative humidity (controls)			Conditioned to equilibrium with 80° F. and 97 percent relative humidity						Conditioned to equilibrium with 80° F. and 97 percent relative humidity followed by conditioning to equilibrium with 75° F. and 65 percent relative humidity					
Core	Face		Tension			Dimensional change [1]			Tension			Dimensional change [1]			Tension		
			Strength	Material failure	Adhesive failure [2]	Weight	Average of length and width	Thickness	Strength	Material failure	Adhesive failure [2]	Weight	Average of length and width	Thickness	Strength	Material failure	Adhesive failure [2]
			P. s. i.	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*P. s. i.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*P. s. i.*	*Percent*	*Percent*
Balsa	Plywood	Unpainted	753.2	15	85	11.50	0.15	1.67	633.4	0	100	0.72	−0.02	0.47	589.6	18.5	81.5
		Painted				17.42	.22	1.59				2.44	.07	.55			
Balsa	Aluminum	Unpainted	425.6	4.2	95.8	3.47	.16	−.09	355.2	20	80	−.39	.04	.27	387.2	25	75
		Painted				2.99	.01	.19				.37	.02	.46			
Balsa	Glass cloth	Unpainted	626.6	3.6	96.4				210.6	0	100	−.99	−.03	.27	446.8	0	100
		Painted										.27	−.02	.37			
Rubber [3]	Plywood	Unpainted	256.5	100	0	9.30	.18	1.54	284.8	100	0	.80	−.01	.46	216.0	0	100
		Painted				9.16	.20	1.86				1.29	.03	1.31			
Rubber	Aluminum	Unpainted	166.6	100	0	.80	.05	−.28	154.6	98.3	1.7	.25	−.01	−.18	97.2	100	0
		Painted				.19	.10	.00				−.34	.05	.47			
Rubber	Glass cloth	Unpainted	174.2	90	10	3.11	.05	.66	101.7	23.4	76.6	.80	.01	.75	152.2	77	23
		Painted				2.21	.09	.55				.29	.20	.36			
Acetate [4]	Plywood	Unpainted	253.9	98	2	10.10	.22	1.16	226.9	98	2	−.35	−.04	−.39	245.1	100	0
		Painted				11.40	.21	2.03				1.04	−.02	−.08			
Acetate	Aluminum	Unpainted	240.2	37.5	62.5	2.32	.06	−.81	50.7	10	90	−1.01	−.01	−1.89	147.2	0	100
		Painted				2.15	.09	.85				.40	.03	−.56			
Acetate	Glass cloth	Unpainted	242.5	96.4	3.6	3.41	.06	.47	67.3	5	95	.50	−.05	−.19	202.9	19.3	80.7
		Painted				3.39	.08	.92				.46	−.01	.18			

[1] Based on dimensions and weights when in equilibrium with 75° F. and 65 percent relative humidity prior to exposure.

[2] No attempt was made to classify the type of bond-line failure; that is, adhesive, cohesive, or failure between primary and secondary adhesive. 100 percent−(percent core+percent bond-line failure)=miscellaneous types of failures, such as failures between face and grip or delamination of face.

[3] Cellular hard rubber from Sponge Rubber Products Co.

[4] Cellular cellulose acetate from du Pont.

All sandwich combinations lost weight in the exposure to high temperature (table 6–11). The unprotected acetate-plywood specimens lost the most (about 9 percent), and the rubber-glass cloth, the least (about 1.5 percent). A retained loss of weight in some combinations (bonded with resorcinol adhesive) upon their being reconditioned was attributed to a loss of retained solvent in the adhesive lines. Dimensionally, the glass cloth-acetate panels were the most stable in this exposure.

Ten cycles of high and low temperatures and humidities had relatively little effect on the weight and dimensions. Tensile strengths, however, of the nine sandwich combinations after exposure and reconditioning presented considerable variation as shown in table 6–12.

An exposure of 1 year to the weather, as shown in figure 6–1, with inspection after 4, 8, and 12 months' exposure produced little deterioration on edge-protected sandwich parts other than fading of the glass-cloth faces, checking of the unprotected plywood, and slight corrosion of the aluminum (table 6–13). Parts with unprotected edges exhibited some delamination between the faces and the cores. Unprotected cellular-cellulose-acetate edges shrank considerably and were in poorer condition than either the balsa or cellular hard rubber.

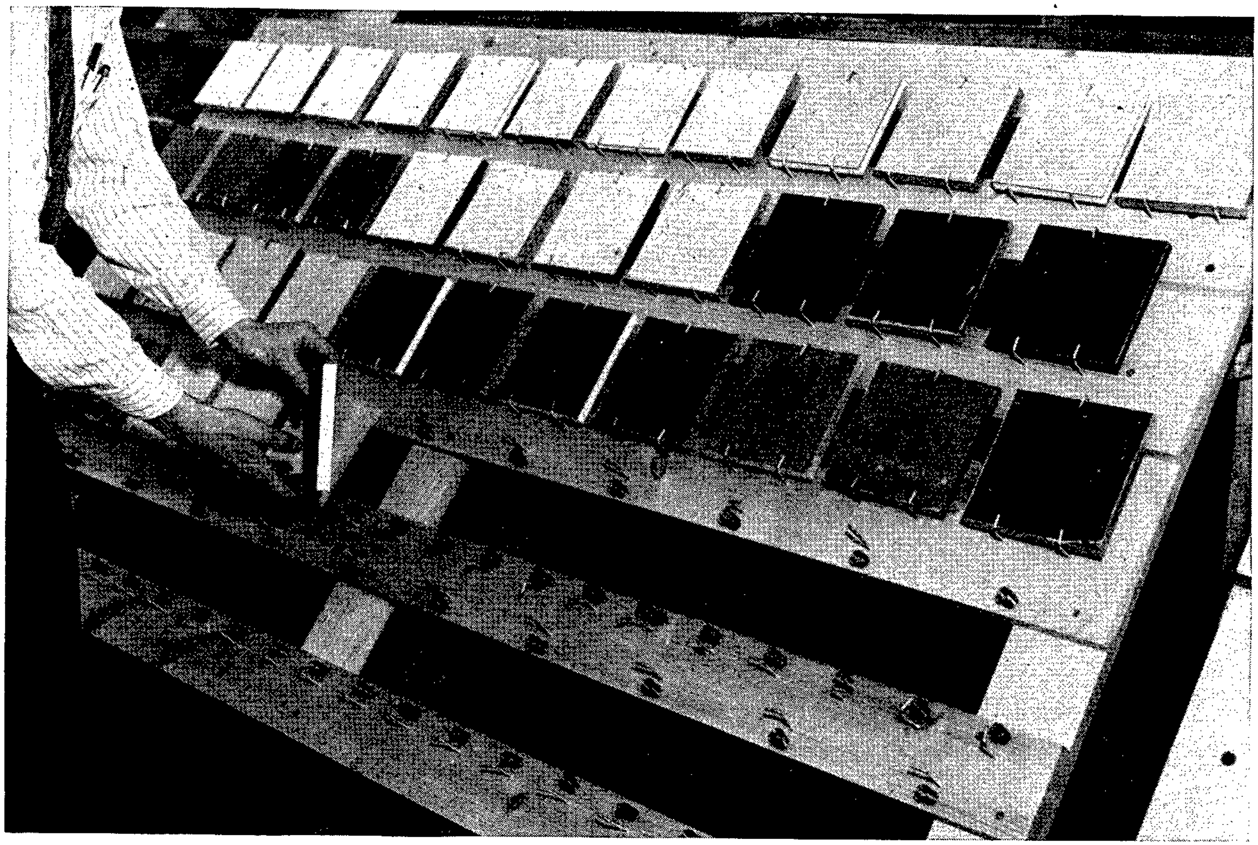

Figure 6–1. Racks used for mounting sandwich parts for exposure to weather, showing the method of attaching specimens.

Aluminum-balsa sandwich parts bonded by a two-step process (a cured film of a modified thermosetting priming resin plus a high-temperature-setting phenolic resin) are reported to be relatively unaffected when exposed with protected edges for a month to a cycle including high and low temperature (200° to −65° F.) and a 20-percent salt spray. Similar parts exposed with unprotected edges showed considerable evidence of corrosion.

Table 6–11. Effect of high temperature (200° F.) on the weight, dimensions, and tensile strength of nine sandwich constructions

Sandwich construction		Edge condition	Conditioned to equilibrium with 75° F. and 65 percent relative humidity (controls)			Heated continuously for 240 hours at 200° F. dry heat						Heated continuously for 240 hours at 200° F. dry heat and conditioned to equilibrium with 75° F. and 65 percent relative humidity					
Core	Face		Tension			Dimensional change [1]			Tension			Dimensional change [1]			Tension		
			Strength	Material failure	Adhesive failure [2]	Weight	Average of length and width	Thickness	Strength	Material failure	Adhesive failure [2]	Weight	Average of length and width	Thickness	Strength	Materia failure	Adhesive failure [2]
			P. s. i.	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*P. s. i.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*P. s. i.*	*Percent*	*Percent*
Balsa	Plywood	Unpainted	753.2	15	85	−7.08	−0.25	−1.33	332.7	14	86	0.43	0.01	−0.32	479.4	10.8	89.2
		Painted				−5.98	−.18	−1.10				.82	−.37	.16			
Balsa	Aluminum	Unpainted	425.6	4.2	95.8	−5.11	.03	−.76	996.7	0	100	−1.87	.04	−.66	791.2	2.5	97.5
		Painted				−4.24	.07	−1.22				−2.40	.06	−.10			
Balsa	Glass cloth	Unpainted	626.6	3.6	96.4	−3.69	−.13	−.28	267.3	1.2	98.8	.30	−.02	.09	514.2	0	100
		Painted					.09	−.18				.00	−.01	.37			
Rubber [3]	Plywood	Unpainted	256.5	100	0	−6.92	−.15	.77	93.8	92.1	7.9	−.93	.15	2.08	187.8	100	0
		Painted				−6.16	.11	2.01				−.22	.26	3.16			
Rubber	Aluminum	Unpainted	166.6	100	0	−4.02	.08	4.86	127.2	96.6	3.4	−3.00	.04	5.51	257.4	96.6	3.4
		Painted				−3.32	.30	6.14				−2.68	.22	7.72			
Rubber	Glass cloth	Unpainted	174.2	90	10	−1.44	−.03	2.16	93.0	58.3	41.7	.08	.02	1.69	146.3	49.1	50.9
		Painted				−2.00	.34	−.45				−.37	.34	−.36			
Acetate [4]	Plywood	Unpainted	253.9	98	2	−8.96	−.29	−2.80	218.2	100	0	−1.68	−.02	−.86	207.5	100	0
		Painted				−7.14	−.25	−2.66				−.10	.02	−.78			
Acetate	Aluminum	Unpainted	240.2	37.5	62.5	−3.16	.05	−2.64	260.4	67.5	32.5	−.69	.03	−1.55	257.7	100	0
		Painted				−3.89	.07	−2.11				−1.19	.09	−1.19			
Acetate	Glass cloth	Unpainted	242.5	96.4	3.6	−2.68	−.08	−.86	142.0	15	85	.22	−.05	−.47	132.1	41.4	58.6
		Painted				−3.19	−.01	−.92				−.13	.05	.00			

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[1] Based on dimensions and weights when in equilibrium with 75° F. and 65 percent relative humidity prior to exposure.

[2] No attempt was made to classify the type of bond-line failure, that is, adhesive, cohesive, or failure between primary and secondary adhesive. 100 percent − (percent core failure + percent bond-line failure)=miscellaneous types of failures such as failure between face and grip, or delamination of face.

[3] Cellular hard rubber from Sponge Rubber Products Co.

[4] Cellular cellulose acetate from DuPont.

Table 6–12. Effect of 1, 5, and 10 cycles [1] of exposure to high and low temperatures and humidities on the weight, dimensions, and tensile strength of nine sandwich constructions

Sandwich construction		Edge condition	Conditioned to equilibrium with 75° F. and 65 percent relative humidity (controls)			After 1 cycle followed by conditioning to equilibrium with 75° F. and 65 percent relative humidity						After 5 cycles followed by conditioning to equilibrium with 75° F. and 65 percent relative humidity						After 10 cycles followed by conditioning to equilibrium with 75° F. and 65 percent relative humidity					
Core	Face		Tension			Dimensional change [2]			Tension			Dimensional change [2]			Tension			Dimensional change [2]			Tension		
			Strength	Material failure	Adhesive failure [3]	Weight	Average of length and width	Thickness	Strength	Material failure	Adhesive failure [3]	Weight	Average of length and width	Thickness	Strength	Material failure	Adhesive failure [3]	Weight	Average of length and width	Thickness	Strength	Material failure	Adhesive failure [3]
			P. s. i.	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*P. s. i.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*P. s. i.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*P. s. i.*	*Percent*	*Percent*
Balsa	Plywood	Unpainted	753.2	15	85	0.76	0.03	0.08	675.0	27.8	72.2	0.13	−0.02	0.00	450.1	96.2	3.8	0.22	−0.02	0.16	413.5	4.5	94.5
		Painted				1.52	.04	.48				.40	.04	.16				.30	.02	.24			
Balsa	Aluminum	Unpainted	425.6	4.2	95.8	−1.39	.02	−.28	596.3	20	80	−2.06	−.01	−.10	563.4	5	95	−2.20	.05	−.10	871.2	33.1	66.9
		Painted				−.74	.03	.18				−1.59	.02	−.18				−2.12	.07	.19			
Balsa	Glass cloth	Unpainted	626.6	3.6	96.4	.34	−.03	.10	465.2	3.3	96.7	−.36	−.02	.18	456.8	4.1	95.9	−1.18	.03	.10	424.8	27.2	72.8
		Painted				−.07	−.02	.18				−.60	.01	−.09				−1.64	.04	−.18			
Rubber [4]	Plywood	Unpainted	256.5	100	0	−.26	.17	3.32	147.0	92.8	7.2	−1.26	.09	3.41	121.2	54.2	45.8	−1.60	−.01	1.56	210.2	100	0
		Painted				.48	.23	3.26				−.70	.30	1.16				−.75	.19	2.86			
Rubber	Aluminum	Unpainted	166.6	100	0	−.52	.28	11.60	116.5	83.3	16.7	−2.40	.03	4.06	209.4	100	0	−2.80	.04	8.25	238.1	100	0
		Painted				−.60	.21	3.19				−2.63	.48	4.94				−2.90	.34	3.46			
Rubber	Glass cloth	Unpainted	174.2	90	10	.75	.04	1.69	147.5	60.8	39.2	.57	.08	2.76	46.2	2.5	97.5	.06	.13	1.10	106.8	7.5	92.5
		Painted				.30	.21	.64				−.10	.34	2.58				−.88	.32	9.19			
Acetate [5]	Plywood	Unpainted	253.9	98	2	−1.08	−.05	−.08	243.4	100	0	−2.36	−.07	−.96	225.3	97.1	2.9	−2.63	−.10	−1.01	239.1	96.7	3.3
		Painted				−.14	.04	.08				−.92	−.01	−.62				−1.36	−.08	−.70			
Acetate	Aluminum	Unpainted	240.2	37.5	62.5	−.83	01	−1.46	204.3	71.6	28.4	−1.73	.01	−2.47	226.9	100	0	−1.58	.04	−2.22	288.7	100	0
		Painted				−.77	.04	−.28				−.90	−.01	−.46				−.93	.04	−.46			
Acetate	Glass cloth	Unpainted	242.5	96.4	3.6	.24	−.01	−.10	233.5	52.1	47.9	.27	−.01	−.36	82.7	2.8	97.2	.04	.04	.10	115.9	2	98
		Painted				.24	.05	.09				.08	.07	.00				−.18	.18	−.08			

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[1] One cycle consisted of the following consecutive treatments: 24 hours at 175° F. and 75 percent relative humidity, 24 hours at −20° F., 24 hours at 175° F., and 24 hours at −20° F.

[2] Based on dimensions and weights when in equilibrium with 75° F. and 65 percent relative humidity prior to exposure.

[3] No attempt was made to classify the type of bond-line failure; that is, adhesive, cohesive, or failure between primary and secondary adhesive. 100 percent−(percent core failure +percent bond-line failure) = miscellaneous types of failures, such as failure between face and grip or delamination of face.

[4] Cellular hard rubber from Sponge Rubber Products Co.

[5] Cellular cellulose acetate from DuPont.

Table 6–13. The condition of nine sandwich constructions after weathering

Sandwich construction		Edge condition	After 4 months			After 8 months			After 12 months		
Core	Faces		End coat condition	Bonded-joint integrity	General appearance	End coat condition	Bonded-joint integrity	General appearance	End coat condition	Bonded-joint integrity	General appearance
Balsa	Plywood	Unpainted		Good	Good		Good	Plywood checked		Good	Plywood checked.
		Painted	Good	Good	Good	Good	Good	Plywood checked	Good	Good	Plywood checked.
Balsa	Aluminum	Unpainted		Good	Good		Good	Good		Good	Good.
		Painted	Good	Good	Good	Good	Good	Good	Good	Good	Good.
Balsa	Glass cloth	Unpainted		Good	Good		Good	Glass cloth faded		Fair	Glass cloth faded, core checked.
		Painted	Good	Good	Good	Good	Good	Glass cloth faded	Good	Fair	Glass cloth faded.
Rubber[1]	Plywood	Unpainted		Good	Good		Good	Good		Good	Plywood checked, plastic deformation.
		Painted	Fair	Good	Good	Fair	Good	Good	Fair	Good	Plywood checked.
Rubber	Aluminum	Unpainted		Good	Good		Good	Good		Good	Good.
		Painted	Fair	Good	Good	Fair	Good	Good	Fair	Good	Good.
Rubber	Glass cloth	Unpainted		Good	Plastic deformation.		Good	Glass cloth faded		Fair	Glass cloth faded, plastic deformation.
		Painted	Fair	Good	Good	Fair	Good	Glass cloth faded	Fair	Good	Glass cloth faded, plastic deformation.
Acetate[2]	Plywood	Unpainted		Good	Plastic deformation.		Good	Plywood checked		Good	Plywood checked, plastic deformation, core shrinkage.
		Painted	Fair	Good	Good	Fair	Good	Plywood checked	Fair	Good	Plywood checked.
Acetate	Aluminum	Unpainted		Good	Good		Fair	Good		Fair	Plastic deformation, core shrinkage.
		Painted	Fair	Good	Good	Fair	Good		Fair	Good	Good.
Acetate	Glass cloth	Unpainted		Good	Plastic deformation.		Good	Plastic deformation.		Good	Plastic deformation, glass cloth faded.
		Painted	Fair	Good	Good	Fair	Good	Plactic deformation.	Fair	Good	Plastic deformation, glass cloth faded.

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[1] Cellular hard rubber from Sponge Rubber Products Co.

[2] Cellular cellulose acetate from DuPont.

6.3. Results of Service Tests

Only limited information is available on the performance of sandwich constructions under service conditions. In general, no serious deterioration nor serious basic weaknesses have been reported with the exception of rapid rain erosion of unprotected reinforced-plastic facings under high-speed conditions. A summary of U. S. Air Force service experience is given in Institute of Aeronautical Sciences Preprint 165, "Theory and Practice of Sandwich Construction in Aircraft."

Radomes constructed of glass-cloth-reinforced-plastic facings on foamed-synthetic-rubber or glass-cloth honeycomb cores have been in wide use and have been generally satisfactory when properly protected against rain erosion.

Specific tests that appear worthy of mention are summarized in the following sections.

6.30. Low-Temperature Service Tests. A rear fuselage section of sandwich monocoque construction was substituted for the standard metal section on a training plane and flown approximately 48 hours (including 150 landings) over a period of about 1 month under typical winter conditions in Alaska. The sandwich structure consisted of glass-cloth facings on a glass-cloth honeycomb core impregnated with a typical high-viscosity contact-pressure laminating resin. No detrimental effects, as judged by visual inspection and hardness tests, were reported as a result of the cold-weather exposure.

Service experience under low temperature conditions could not readily be obtained, but sandwich stabilizers (aluminum facings bonded to end-grain balsa core) were tested by the Navy under repeat-load and vibratory conditions in the laboratory at a temperature of −70° F. Loading cycles were applied between minimum values of approximately 30 percent and maximum values of approximately 60 percent of the ultimate strength of the structure, while at the same time, the stabilizer was vibrated at a resonance frequency of 1,620 c. p. m. with a double amplitude at the tip of 0.03 inch. No failures or deterioration of the bonded sandwich structure was experienced in two tests in which 30,574 and 26,899 cycles of loading were applied, the tests being terminated in each case for other reasons.

6.31. Operational Service Test. Sandwich construction, consisting of thin aluminum alloy facings with balsa wood core, assembled by bonding, was used in 193 sets of stabilizers for a Navy fighter airplane. Records were maintained of the hours of flight of each stabilizer panel, and after certain specified amounts of service, representative parts were returned to the manufacturer for examinations and static tests. The results of the examinations were compared with records of the inspections of each part prior to delivery, and the static test results were compared with results obtained on similar unused parts. No evidence of deterioration, corrosion, or impairment of strength was observed after 1,800 hours of flight during 3 years of service operation.

6.4. Preliminary Test Results on Durability of Honeycomb Cores

6.40. Compression Tests on Cores. Durability tests have been conducted at the Forest Products Laboratory on honeycomb cores as described in table 6–14. The results are given in detail in FPL Report 1573–B.

Exposure conditions were the same as those described in section 6.10. Compression tests on specimens similar to that shown in figure 5–7 were conducted before exposure, immediately after exposure, and after reconditioning. A summary of the effect of the exposure conditions on compressive strength is presented in table 6–15.

6.41. Tensile Tests on Sandwich Specimens. Preliminary tensile values before and after exposure are also available on a limited number of sandwich combinations having honeycomb cores of the type described in section 6.40. Aluminum facings were bonded to these cores with six typical metal-to-metal adhesive systems. In addition, glass-cloth facings impregnated with five typical laminating resins were wet-laminated to the similar cores.

Table 6–14. Descriptions of honeycomb cores under durability test at Forest Products Laboratory

Base material	Impregnating resin	Cell size (approximate)
Glass cloth [1]	Polyester type	3/16 inch.
Cotton cloth [2]	Phenolic type	7/16 inch.
Kraft paper [3]	10 percent phenolic + 55 percent polyester	1/8 inch.
Aluminum foil [4]	(Corrugated sheets bonded with a typical metal-to-metal adhesive).	3/8 inch.

[1] Core manufactured by Western Products, Inc.

[2] Core manufactured by U. S. Plywood Corp.

[3] Core fabricated by Forest Products Laboratory.

[4] Core manufactured by Glenn L. Martin.

Table 6–15. Effect of various controlled exposures on the compressive strength of honeycomb cores [1]

Core material	Exposure conditions [2]							
	Immersion 40 days	Immersion and reconditioned	Equilibrium at 97 percent relative humidity	97 percent relative humidity and reconditioned	200° F. 10 days	200° F. and reconditioned	10 cycles	10 cycles and reconditioned
Glass cloth (Western Products) [3]	0. 71	0. 98	0. 81	1. 04	0. 50	1. 14	0. 83	0. 74
Cotton cloth (U. S. Plywood)	. 80	. 98	. 84	1. 03	1. 04	1. 23	1. 03	1. 07
Paper (FPL)	. 30	. 76	. 44	. 85	. 53	1. 20	1. 15	. 97
Aluminum (Martin)	. 80	. 88	. 91	. 89	. 79	. 84	1. 01	No test

[1] Data from Forest Products Laboratory tests. All figures are ratios of the average test values after exposure to the average control values prior to exposure. Ends of specimens cast in plaster.

[2] A more detailed description of the exposure conditions is presented in sec. 6.10.

[3] Tested as received. Not dipped in thinned resin.

Tensile tests were made before and after exposure to the conditions described in section 6.10.

Test values are available in preliminary form for a few combinations. Table 6–16 presents results of tests on aluminum-faced panels bonded with one metal-to-metal adhesive, a phenolic liquid-vinyl powder composition; and on glass-cloth-faced panels impregnated with a high-viscosity laminating resin.

Inspection of the type of failure revealed that when glass-cloth cores were used the failure was confined almost wholly to the bond between the core and facings. Panels having cotton cloth and paper cores in combination with glass-cloth facings failed in the core as well as in the bond, whereas with aluminum facings the failure was largely in the core.

6.5. Rain Erosion of Plastic Surfaces

High-speed flight through rain causes erosion damage to some exterior plastic parts of aircraft, particularly parts having leading edges. Several studies have been undertaken to determine the mechanism of this erosion and methods to prevent or retard it. The rate of rain erosion has been found to be greatly affected by the nature of the material under test, speed of flight, angle of incidence of rain, radius of curvature, and raindrop size and concentration. It appears to be relatively unaffected by the airfoil angle of attack or by water temperature. Although no plastic laminate has been found to date to resist rain erosion sufficiently for service use without protection, certain neoprene coating materials have been developed which give relatively good protection to the laminate, and are considered satisfactory for service use, pending further developments. More detailed information on this subject is available from the Air Matériel Command.

Table 6–16. Effect of various controlled exposures on the tensile strength of sandwiches having honeycomb cores [1]

Core material	Exposure conditions [2]							
	Immersion 40 days	Immersion and reconditioned	Equilibrium at 97 percent relative humidity	97 percent relative humidity and reconditioned	200° F. for 10 days	200° F. and reconditioned	10 cycles	10 cycles and reconditioned
GLASS-CLOTH FACINGS								
Glass cloth [3] (Western Products)	0. 62	0. 86	0. 58	0. 81	0. 79	0. 84	0. 66	0. 60
Cotton cloth (U. S. Plywood)	. 56	. 87	. 62	. 72	. 70	. 87	. 64	. 54
Paper (FPL)	. 55	. 86	. 57	. 87	. 69	. 83	. 86	. 70
ALUMINUM FACINGS								
Glass cloth [4] (Western Products)	. 87	1. 08	. 90	. 91	1. 12	1. 10	. 82	. 83
Cotton cloth (U. S. Plywood)	. 81	1. 12	. 73	. 72	. 94	1. 22	. 59	. 83
Paper (FPL)	. 86	1. 04	. 75	1. 04	. 74	. 88	. 87	. 73

[1] Data from Forest Products Laboratory tests. All figures are ratios of the average test values after exposure to the average control values prior to exposure.

[2] A more detailed description of the exposure conditions is presented in sec. 6.10.

[3] Extra resin roller-coated on the core.

[4] Used as received. Not dipped or coated with extra resin.

CHAPTER 7

REPAIR

7.0. General

With the current increasing application of sandwich construction in aircraft, it is inevitable that a certain amount of damage will occur. During the manufacturing stages, where hazards of dropped tools and equipment are encountered, serious damage to sandwich parts may be eliminated by temporary protective covers of rather stiff, rigid material. Proper precautions will minimize damages; but when damage does result, acceptable methods of repair must be available.

Only limited experience has been accumulated on the repair of sandwich structures, and it is therefore impossible at this time definitely to recommend detailed procedures. Methods that have been used and that have given reasonable results are presented in the following sections for some of the typical sandwich combinations. It is cautioned that inclusion of this information on repairs does not provide authorization for any repairs of defects in new parts, such requirements are given in specifications on contracts.

7.1. Principles of Repair

Repair procedures are developed with the objective of equaling as nearly as possible the strength of the original part. In order to eliminate dangerous stress concentrations, abrupt changes in cross-sectional areas must be avoided whenever practicable by tapering joints, making small patches round or oval-shaped instead of rectangular, and rounding corners of all large repairs. Smoothness of outside surfaces of high-speed aircraft is a necessity for proper performance, and consequently patches that project above the original surface must be avoided if at all possible. When this is impossible, the edges must be generously tapered. Uniformity of thickness and continuity of core are also important where radomes are involved. Repairs of punctured facings and fractured cores in radar housings, therefore, necessitate removal of all of the damaged material, followed by its replacement with the same type of material and in the same thicknesses as the original.

Cutting and treatment of the core should be done in accordance with the methods presented in chapter 4. Wherever plywood is involved, the repair tools and equipment discussed in sections 4 and 5 of AN-01-1A-7, "Repair of Wood Aircraft Structures," will be found applicable.

7.2. Classes of Repair

For convenience in presentation and for efficiency in designating repairs to sandwich constructions, damages are divided into groups or classes according to severity and possible effect upon the airplane structure. The following classes are used in presentation of the repair techniques in this bulletin:

Class 1: Small dents, scars, scratches, or erosion in the facings, not accompanied by a puncture or a fracture.
Class 2: Small punctures or fractures in one facing only, possibly accompanied by damage to the core but without damage to the opposite facing.
Class 3: Holes or damage extending completely through the sandwich, affecting both the facings and the core.
Class 4: Extensive damage requiring replacement of a complete sandwich part or parts.

7.3. Repair Techniques

The repairs shown in the following sections are of the permanent type. It is sometimes necessary or convenient to install over a minor damage a temporary repair that is later replaced by a permanent repair. These emergency or temporary repairs are normally devised to fit the application and are not considered here. The repairs listed in class 3 may be further subdivided according to the accessibility of the panel from both or from only one side. Repairs shown here are primarily of the type that can be installed when only one side of the part is accessible, such as in a thin wing section or horizontal stabilizer. If both sides are accessible, the procedure is somewhat more simple, but the same technique can be used.

7.30. ALUMINUM-FACED PARTS.

7.300. *Class 1 repairs.* Dents or scars in aluminum facings may be repaired by the use of either a suitable filling compound or a synthetic glazing putty. One of these materials of the putty type (SYE–12, Atlas Powder Co., Zapon Division), which was originally developed for the repair of dents and scars in metal propellers, has been used for repairs of aluminum-faced sandwiches. Repairs to dents have been made with this synthetic glazing putty, or its equivalent, by the following method:

> Remove all dirt and old finish from the dent. Apply the putty with a putty knife in coats not exceeding $\frac{3}{16}$-inch thickness. Permit a 2-hour drying period between applications. Fill the dent slightly above the surrounding level in the final application. Sand down the filler to the original level after a drying period of 3 hours or longer, being careful not to scratch the surrounding aluminum surface. When refinishing the surface, apply a prime coat of aluminum paint, because otherwise the putty will absorb the paint and leave a dull finish in contrast to the glossy finish produced on the surrounding area.

Repairs of this type have been subjected to 20 repetitions of a cycle consisting of 8 hours at 200° F., followed by 16 hours at −20° F. No deterioration of the putty was observed at the end of this period. The same panels were then exposed to 80° F. and 97 percent relative humidity for 3 months. At the end of this period slight scaling of the putty occurred where it was less than $\frac{1}{32}$ inch thick, which was apparently due to breakdown of the putty and to corrosion of the metal.

For certain applications where abrasion resistance is important, such as in floors, it may be advisable to bond a thin aluminum plate over the filled dent. This may be done by properly cleaning the area around the filled dent as well as the plate and by bonding the plate over the repaired area by any acceptable metal-to-metal adhesive. The heat required may be supplied by an electrically heated iron. The edges of the plate should be generously beveled before the bonding operation.

7.301. *Class 2 repairs.* Small punctures in only one facing have been repaired by the method described in section 7.300, provided holes are drilled at the ends of the cracks produced by the puncture in order to avoid severe concentration of stress.

Larger punctures or damages to one facing and the core require trimming of the punctured area, preferably to a circular- or oval-shaped opening. This trimming of only one facing is a rather difficult operation, and it is therefore sometimes advisable to cut completely through the sandwich and repair as illustrated in section 7.302. If one facing and the core are removed, however, the repair may proceed as illustrated in section 7.302 by inserting a new piece of core and an overlapping facing plate.

7.302. *Class 3 repairs.*

7.3020. *Repairs to lightly stressed parts.* Figure 7–1 shows diagrammatically a method that has been used for repairing class 3 damages to nonstructural parts, such as floors and bulkheads. If the part is installed in the airplane in such a location that either top or bottom is inaccessible, it will be necessary to remove the part for proper repair. For damages smaller than one-half inch in diameter, no core filler is required. When a filler is required, it should be of the same material as the existing core and of the exact thickness of the total part thickness so that both patch plates make complete contact with the filler and with the bordering part area.

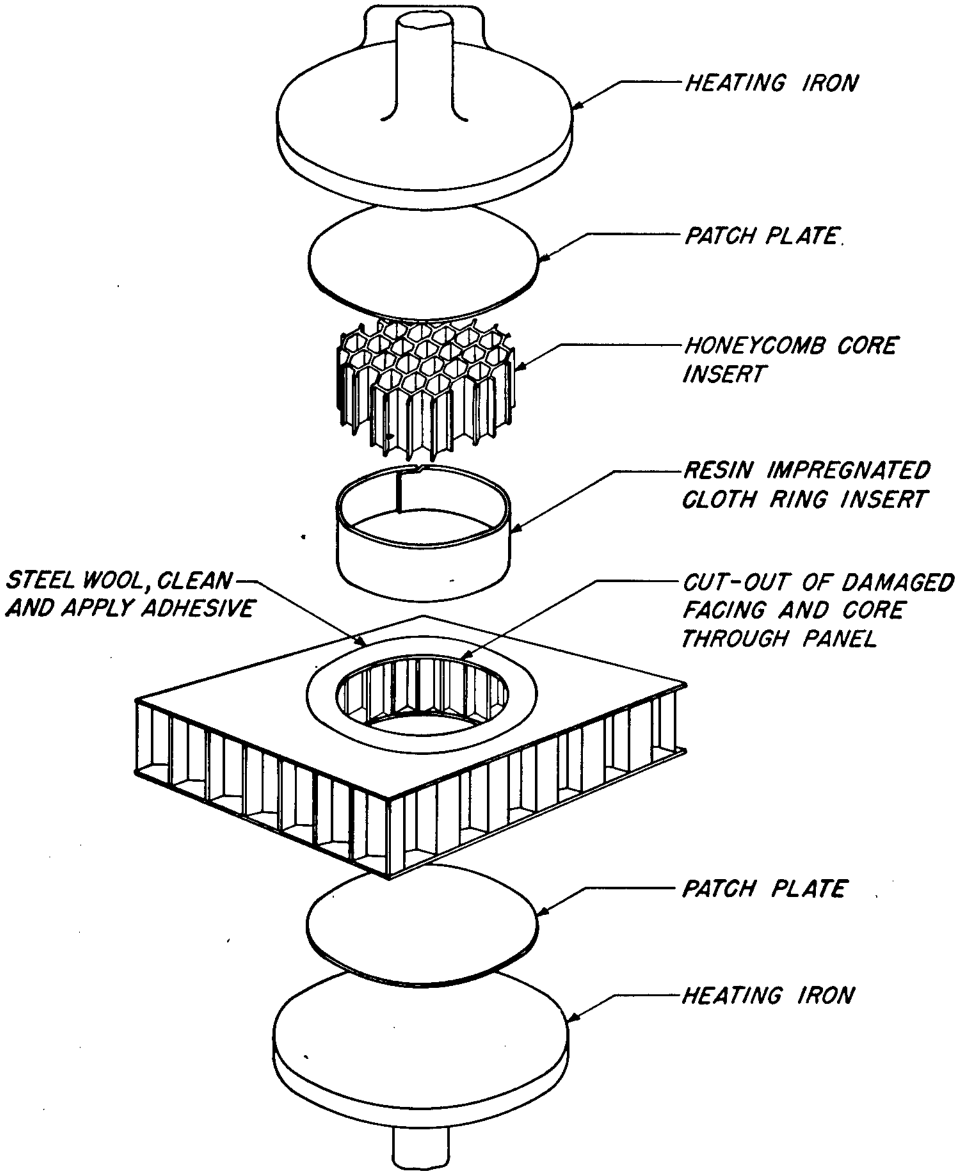


Figure 7–1. Method for repairing class 3 damages to lightly stressed sandwich parts.

In bonding the plates over a honeycomb-core filler the pressure must be accurately controlled within limits of 15 to 25 pounds per square inch, based upon the plate area. Insufficient pressure will result in incomplete contact of the patch plates, and excessive pressure is likely to crush the core. Heat and pressure should be applied to both patch plates simultaneously. After the surfaces to be bonded have been properly cleaned, any metal-to-metal adhesive that is compatible with the cleaning method, may be used.

7.3021. *Minor Structural Repair.* For damages up to about 8 inches in maximum dimension, repairs have been made by the method shown in figures 7–2 and 7–3.

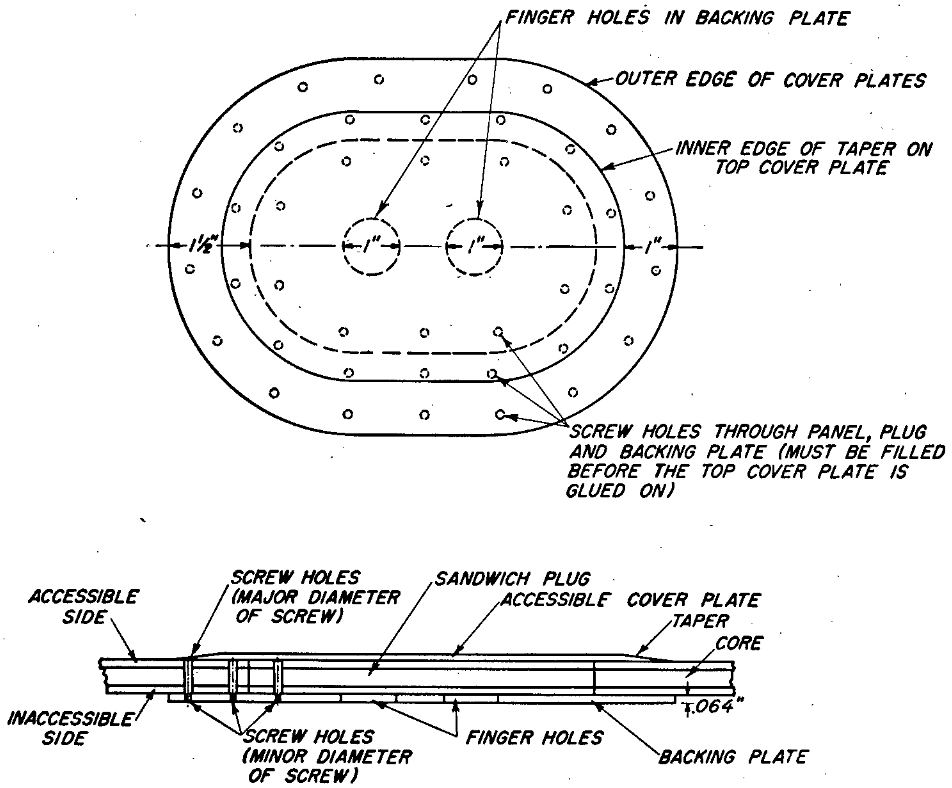


Figure 7–2. Oval patch assembly used in aluminum-faced parts when one side only is accessible.

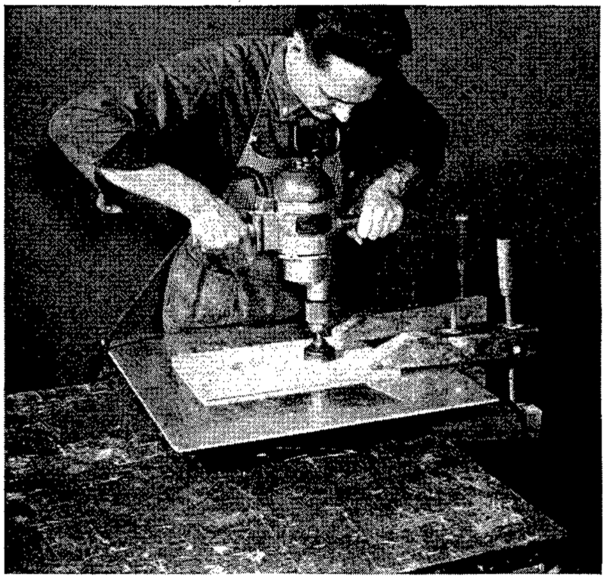


Figure 7–3. Steps in making an oval-shaped repair in a sandwich part having aluminum facings on end-grain balsa core.

A—cutting holes at the ends of the oval-shaped hole.

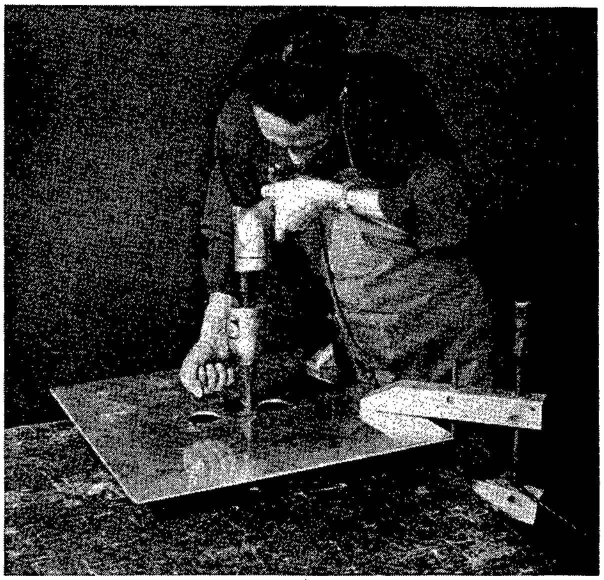


Figure 7–3.—Continued.

B—sawing out the damaged area, using a reciprocating-saw attachment for an electrical drill.

Figure 7–3.—Continued.

C—removing the burr on the sawn aluminum edges.

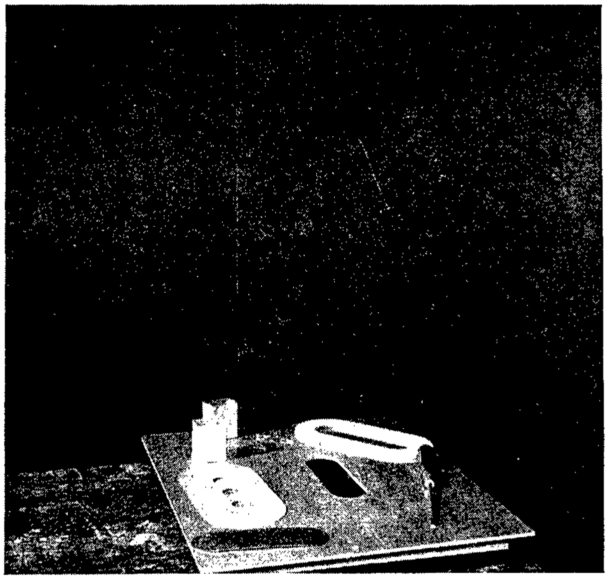


Figure 7–3.—Continued.

D—screw holes drilled in area around hole (note aluminum backing plate with finger holes and plywood caul ring).

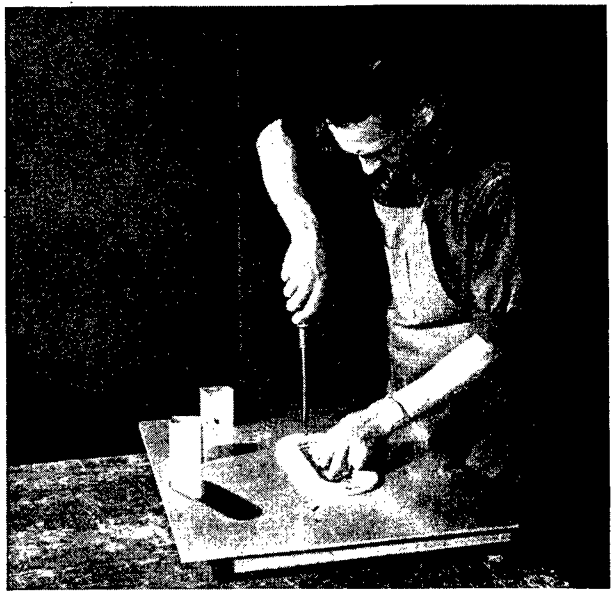


Figure 7–3.—Continued.

E—backing plate being screwed in place, using self-tapping screws through plywood caul ring.

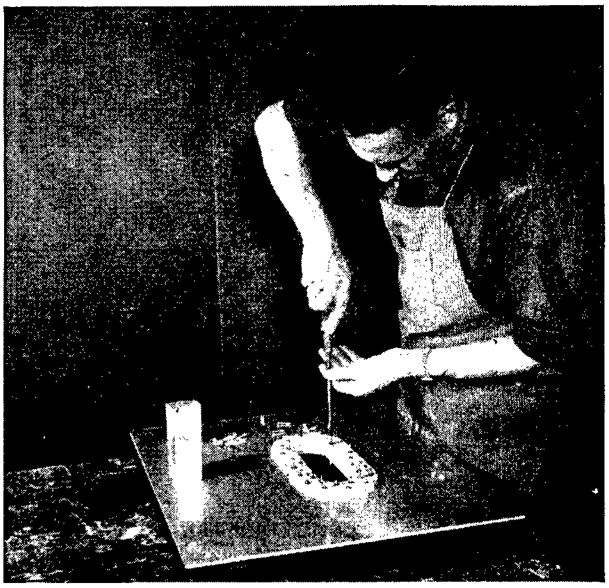


Figure 7–3.—Continued.

F—continuing to screw backing plate in place (protector plate has been dropped in place to cover holes in backing plate increasing heat transfer to bond line).

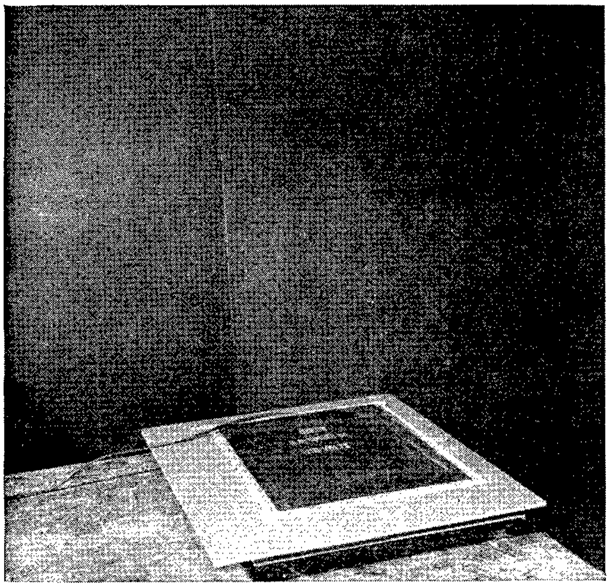


Figure 7–3.—Continued.

G—electrically heated blanket taped in place over patch to provide heat for curing adhesive.

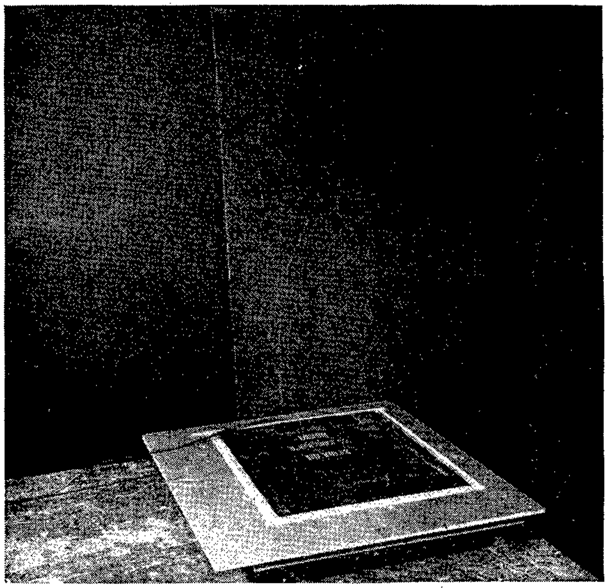


Figure 7–3.—Continued.

I—heated blanket again taped over patch to cure adhesive between plug and backing plate.

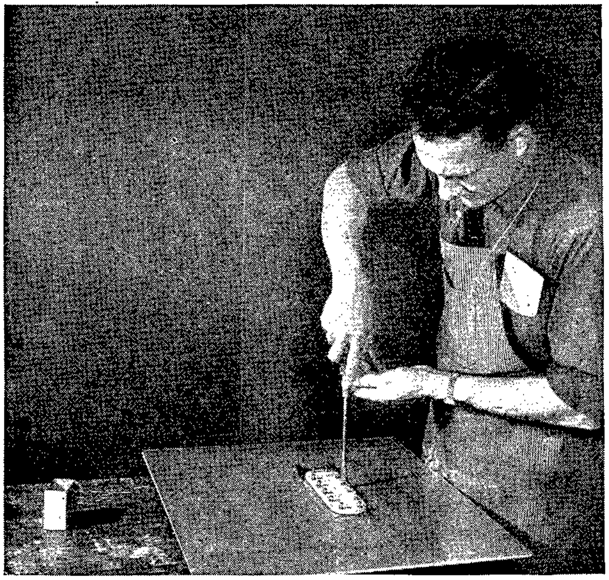


Figure 7–3.—Continued.

H—plug patch being screwed in place, using self-tapping screws through a plywood caul.

Figure 7–3.—Continued.

J—plugging screw holes with special filler to prevent leakage.

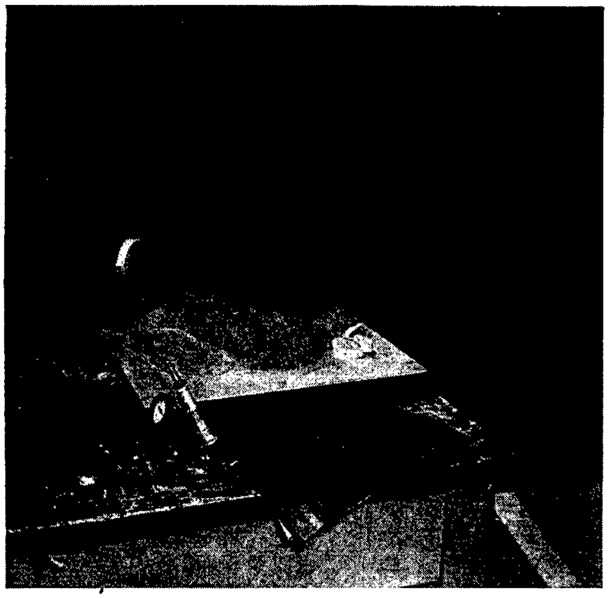


Figure 7–3.—Continued.

K—adhesive spread on patched area and surface plate preparatory to bonding surface plate in place.

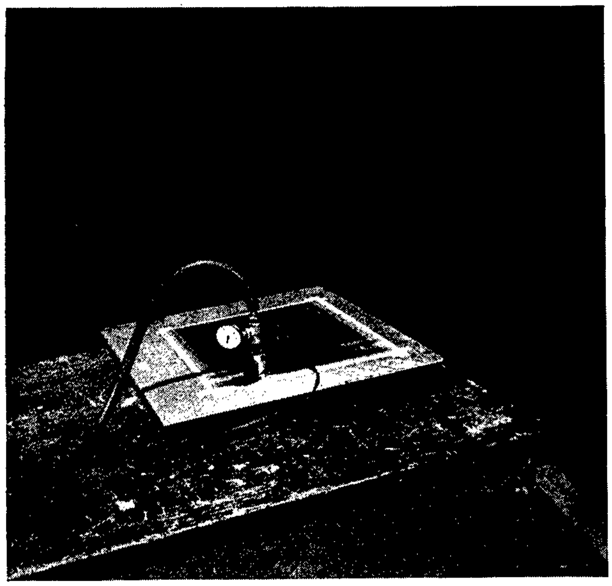


Figure 7–3.—Continued.

L—electrically heated vacuum blanket in place over patch in final bonding operation. (Later, adhesive squeeze-out was cleaned off preparatory to finishing.)

Cutting of the parts may be accomplished with a plug cutter on round cuts, with use of a template whenever possible, and with a reciprocating-saw attachment for a small electric drill on straight cuts. A 24- or 32-tooth hacksaw blade should be used to avoid excessively rough cuts.

A backing plate of 0.064-inch 24 ST aluminum is used on the back and a thinner-gage aluminum plate (0.012 to 0.020 inch) on the front face. The edges of the thinner plate are tapered with a file before application. Three major steps are required to complete the patch. First, the backing plate is bonded to the back facing. Self-tapping screws (sheet-metal screws) with lock washers under the heads may be used to apply pressure and a rubber electric heating blanket to supply the heat. Second, the sandwich plug is bonded to the backing ring. Self-tapping screws are used for pressure as in step 1. Heat is again supplied by an electrically heated blanket. Third, the front cover is bonded to the plug and to the original facing. A heated rubber vacuum blanket is used to supply pressure and heat.

7.3022. *Major structural repairs.* The following two procedures have been used for the repair of class 3 damages of any size in sandwich parts having aluminum facings and a balsa core. Procedure A is a flush-surface repair, whereas procedure B has a slight projection on the surface.

In both procedures care must be taken in cutting away the damaged area to form a hole of such proportions that the repair plates can be inserted from one side.

7.30220. *Procedure A—flush-surface repair.* Cut away damaged area to a hole of contour and dimensions as specified in table 7–1. Cut back inner metal facing of the sandwich as shown in figure 7–4. Drill two rows of holes for flush-head bolts or rivets as shown in figure 7–5. Prepare two patch plates of 24ST aluminum of the proper over-all dimension for sufficient overlap as shown in figure 7–5. Drill necessary holes for attachment and assemble as shown in figure 7–5. After the filler has been prepared, insert the individual parts of the patch through the hole to be prepared as shown in figure 7–6. If repair is accessible from one side only, blind rivets must be used in accordance with standard procedure.

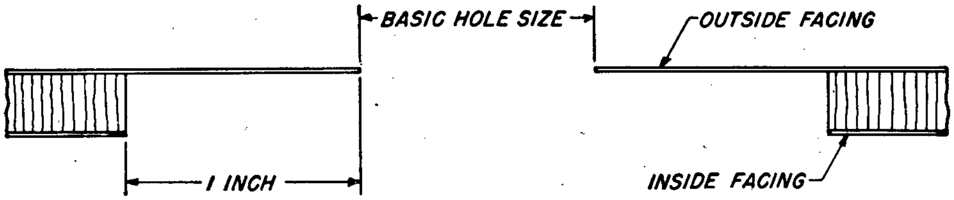


Figure 7–4. Procedure for flush-surface repair to class 3 damages of any size in sandwich parts having aluminum facings and a balsa core.

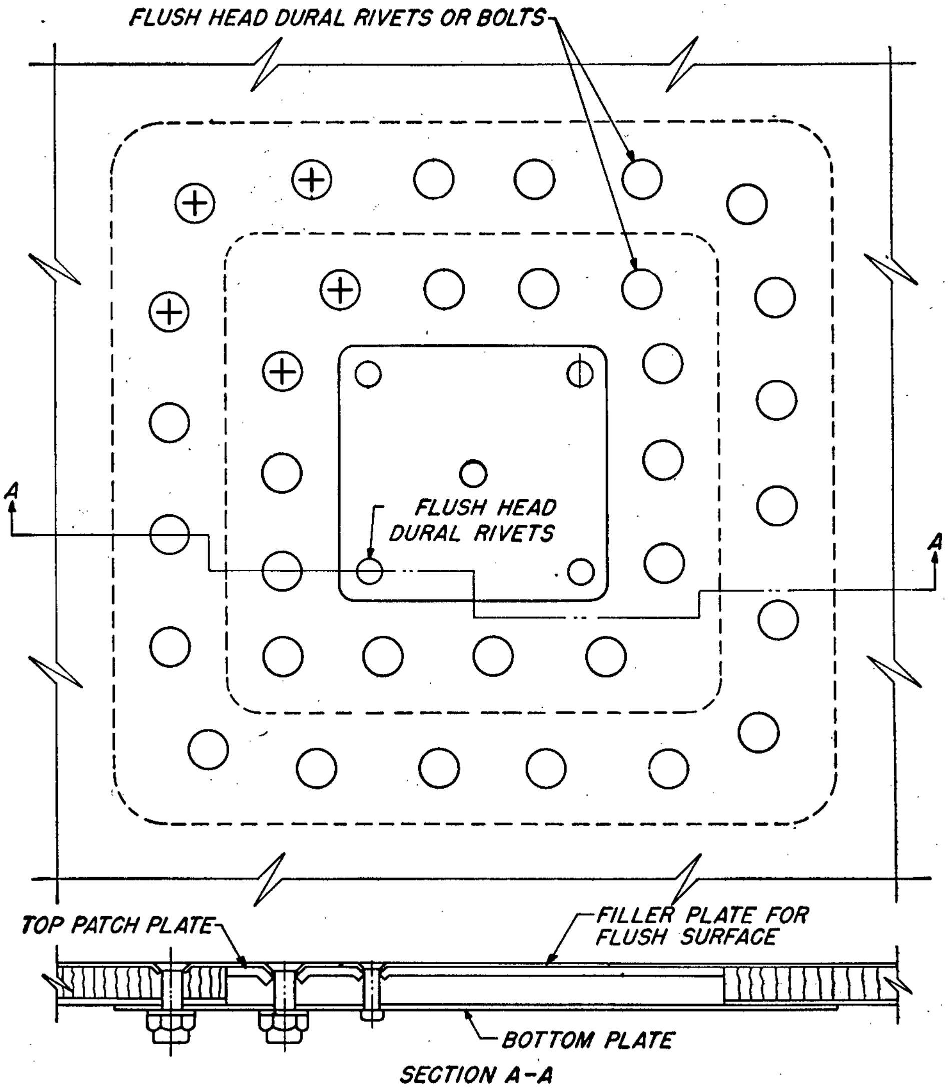


Figure 7–5. Typical flush repair in sandwich parts having aluminum facings and a wood core.

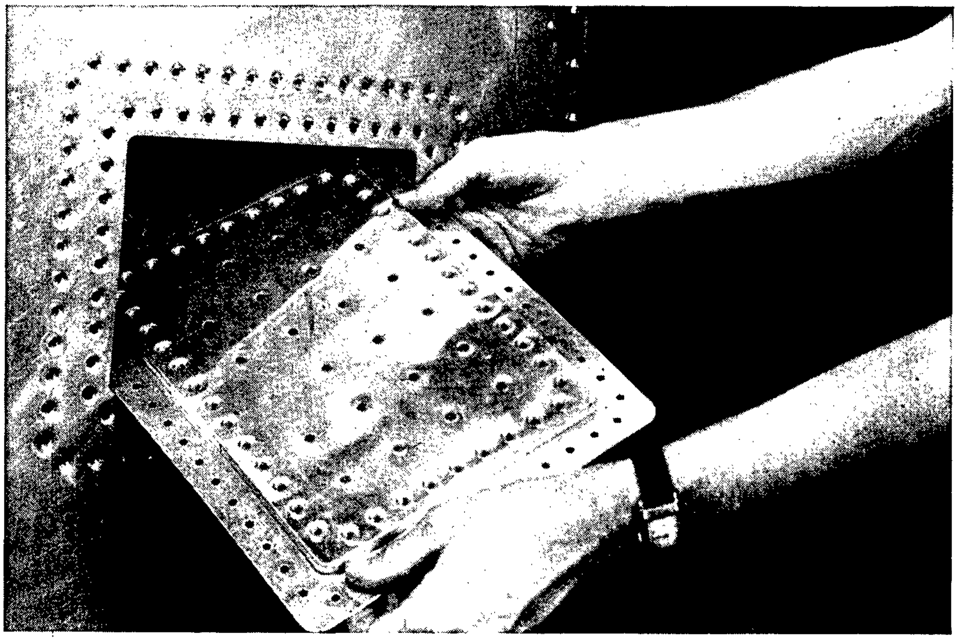


Figure 7–6. Procedure for inserting preassembled patch in prepared hole.

Table 7–1. Flush-repair dimensions

Approximate maximum dimension of hole (inches)	Top patch plate thickness (inch)	Bottom patch plate thickness (inch)	Corner radius (inches)
1– 5	Same as original facing.	0. 040	¾
5–10		. 040	1¼
10–15		. 051	1½
15–20		. 064	1½

Table 7–2. Patch-plate dimensions

Approximate maximum dimension of hole (inches)	Top patch plate thickness (inch)	Bottom patch plate thickness (inch)	Corner radius (inches)
1– 5	0. 012	0. 032	¾
5–10	. 020	. 040	1¼
10–20	. 032	. 051	1¼

7.30221. *Procedure B—patch-plate repair.* Cut away damaged area to a hole of proper contour and dimensions, smooth the edges, and provide a radius at all corners as specified in table 7–2. Drill two staggered rows of holes for flush-head bolts or rivets as shown in figure 7–7. Prepare two patch plates of 24ST aluminum, the thickness of which is to be determined from the approximate maximum dimension of the hole as shown in table 7–2, and with an overlap of 1½ inches around the edge of the hole. Drill holes required for attachment and assemble as shown in figure 7–7.

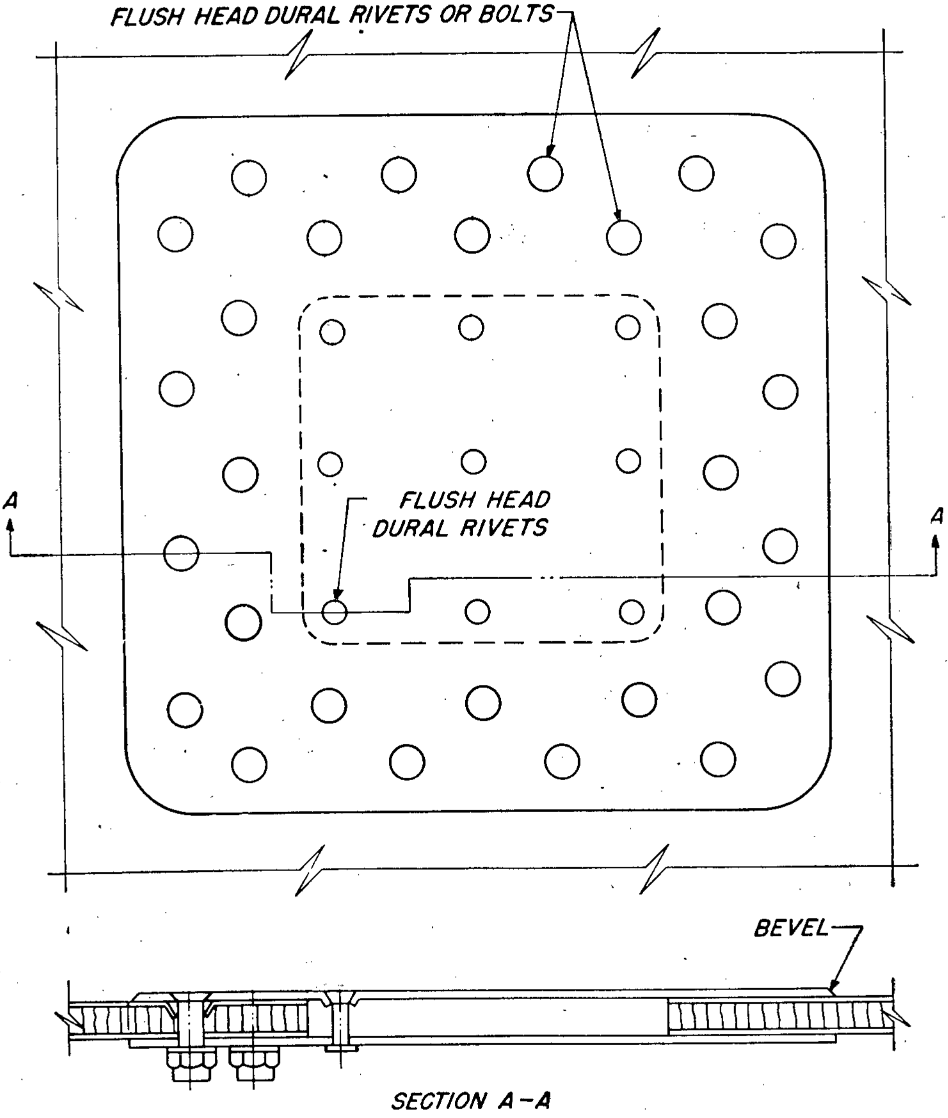


Figure 7–7. Typical patch-plate repair in sandwich parts having aluminum facings and a balsa core.

A damaged horizontal stabilizer repaired by procedures A and B above is shown before repair in figure 7–8, and after repair in figure 7–9.

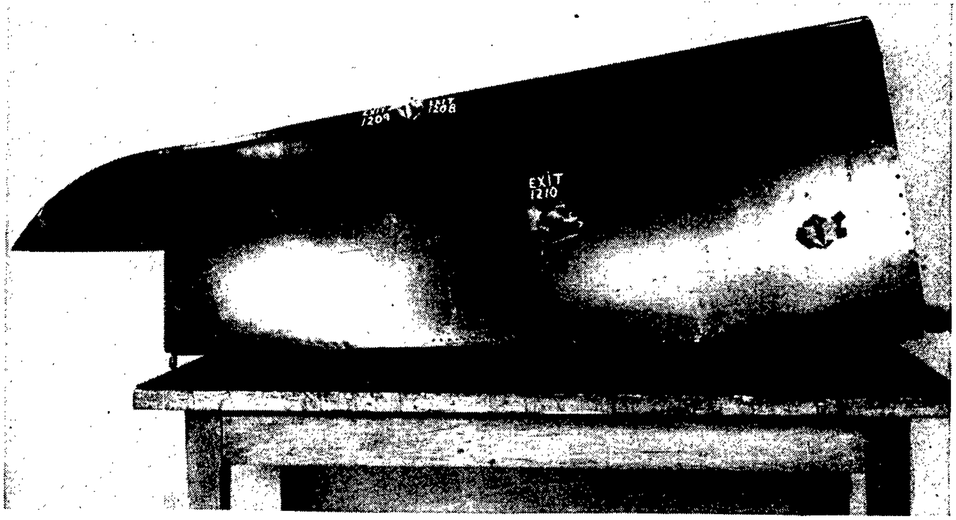


Figure 7–8. Damage to horizontal stabilizer before repair. General view.

Figure 7–8—Continued—close-up view.

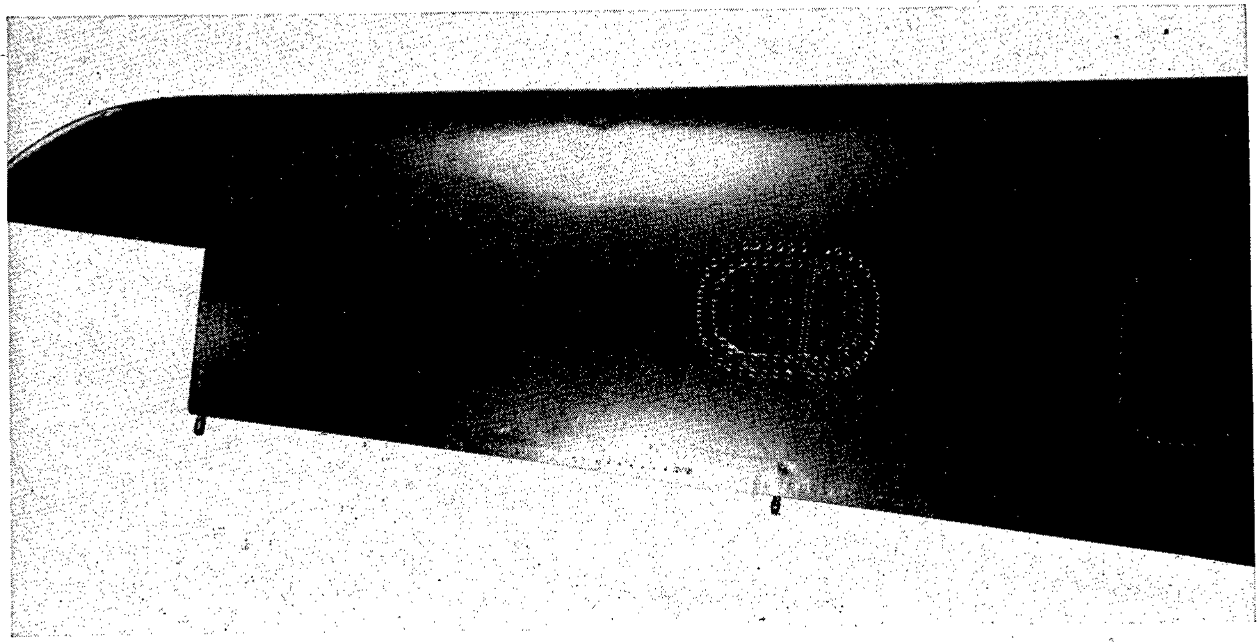


Figure 7–9. Horizontal stabilizer after repair.

7.31. Glass-Fabric-Base, Laminated, Plastic Parts.

7.310. *Class 1 repairs.* Due to the characteristics of glass-cloth laminates, class 1 damages (dents and scratches) are limited to minor imperfections that can either be disregarded or filled with suitable filler. A blow that will merely dent an aluminum facing, will normally either have no effect on the glass-cloth plastic facing or will fracture it so as to necessitate more extensive repair. However, such a blow may damage the core material on the bond to the core.

7.311. *Class 2 repairs.* Minor fractures in glass-cloth facings (not more than 2 inches in maximum dimension) have been repaired as follows:

(1) Clean the area immediately surrounding the damage with emery cloth and a solvent to remove paint or contamination and to roughen the surface slightly.

(2) Fill the depression accompanying the fracture with scraps of the glass cloth impregnated with any suitable low-pressure laminating resin and build it up to slightly higher than the surrounding surface.

(3) Cover the repaired area with one or two layers of fine-weave resin-impregnated glass cloth, being sure to overlap the undamaged facing about one-half inch.

(4) Cure the foregoing filler in place under a cellophane-covered aluminum-sheet caul. Heat and pressure may be supplied by means of an electrically heated vacuum blanket similar to that described in section 7.312.

Class 2 repairs more than 2 inches in maximum dimension have been repaired as described in section 7.312 for class 3 repairs after removal of the one damaged facing (and core if necessary).

7.312. *Class 3 repairs.* Suggested details for the repair of damages extending completely through the sandwich, when both sides are accessible, are shown in figure 7–10. The steps necessary in making the repair are shown in figure 7–11.

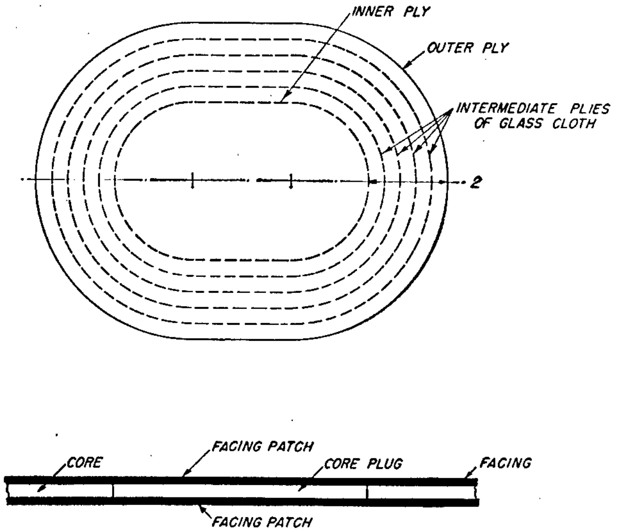


Figure 7–10. Oval patch assembly used in parts faced with glass cloth when both sides are accessible.

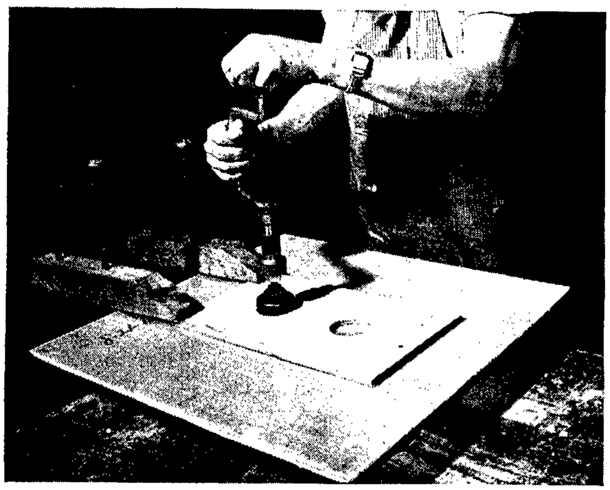


Figure 7–11. Steps in making an oval patch in a sandwich part having glass-cloth facings on glass-cloth honeycomb cores, with both sides accessible.

A—cutting holes at the end of the oval repair by means of a centerless hole saw in a hand brace.

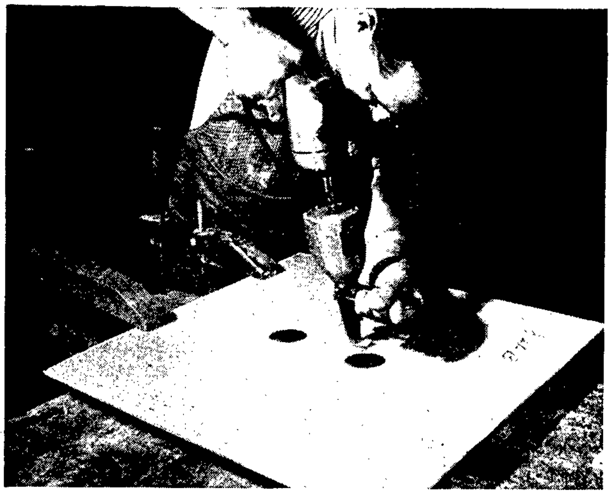


Figure 7–11.—Continued.

B—sawing out the damaged area with a reciprocating-saw attachment for an electric drill.

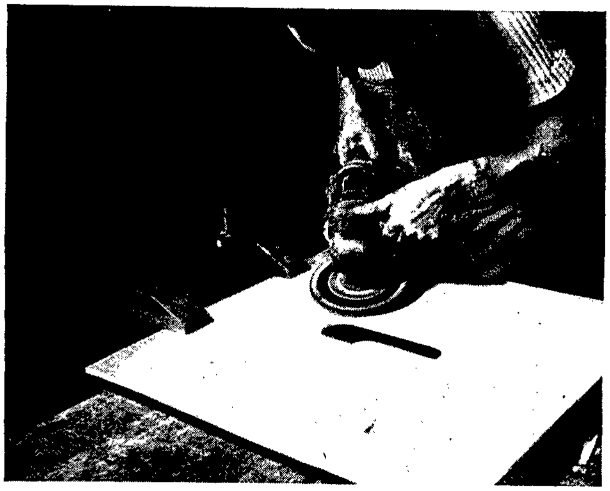


Figure 7–11.—Continued.

C—scarfing the area around the hole, using a flexible-disk sander.

Figure 7–11.—Continued.

D—core as been laid in place, and resin is being applied on scarfed face.

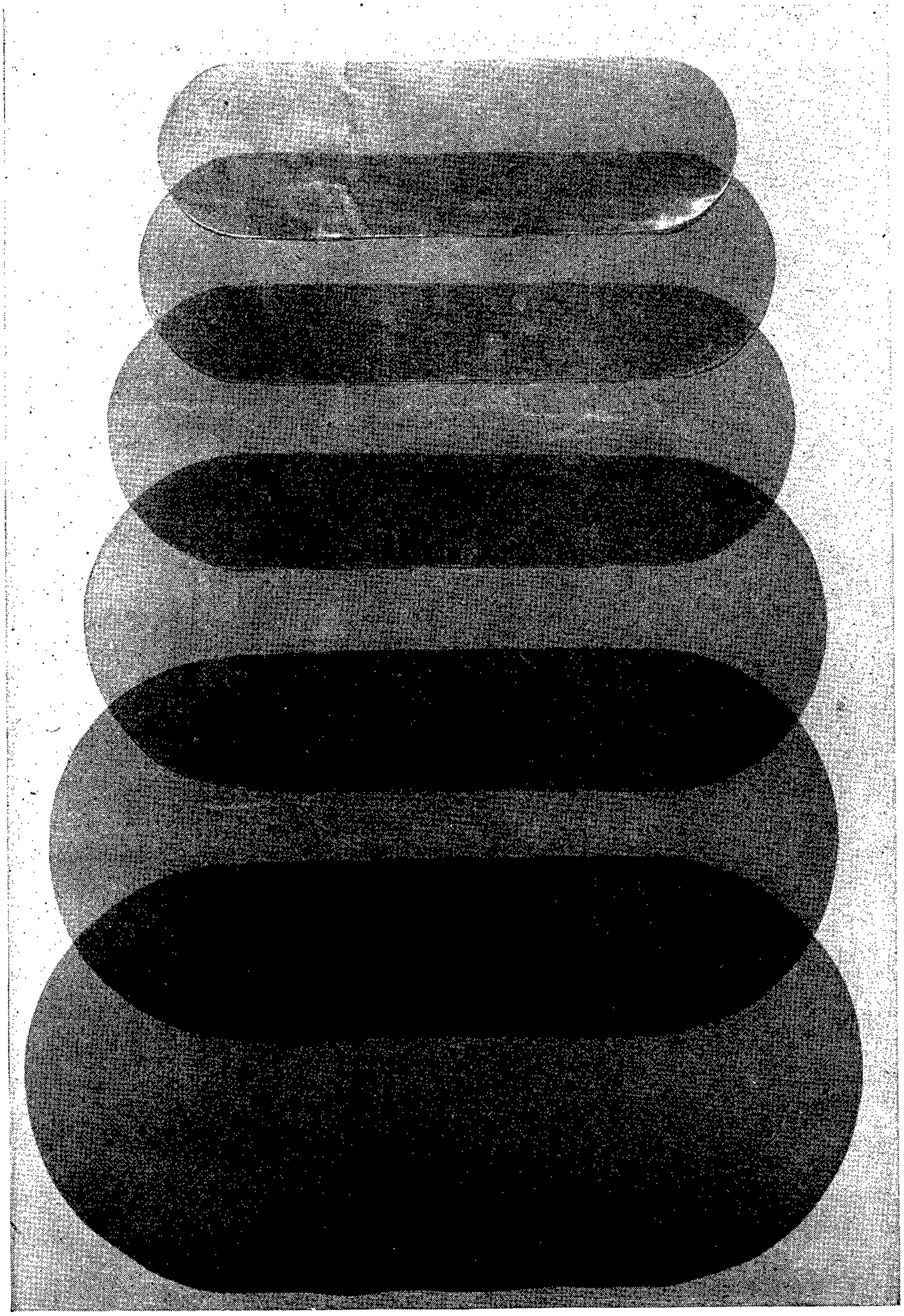


Figure 7-11.—Continued.

E—individual pieces of resin-impregnated, cellophane-covered glass cloth necessary to build up the repaired facing.

Figure 7-11.—Continued.

F—procedure of laying up the patch on a cellophane-covered aluminum caul.

Figure 7-11.—Continued.

H—pin-pricking the cellophane covering to aid in escape of entrapped air.

Figure 7-11.—Continued.

G—laying complete face lap-up in place over area to be repaired.

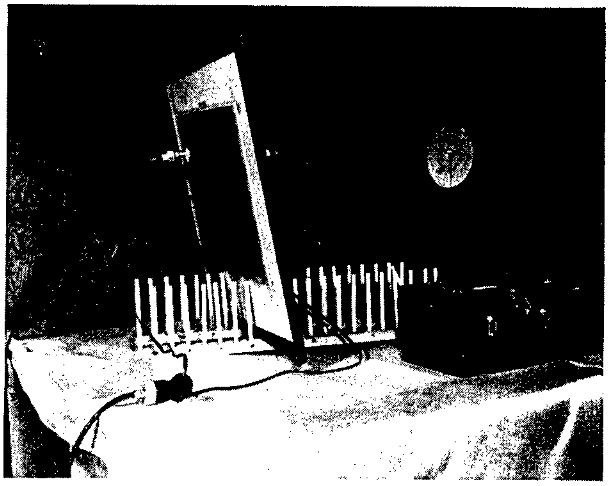


Figure 7-11.—Continued.

I—curing both faces of repair simultaneously under two electrically heated vacuum blankets.

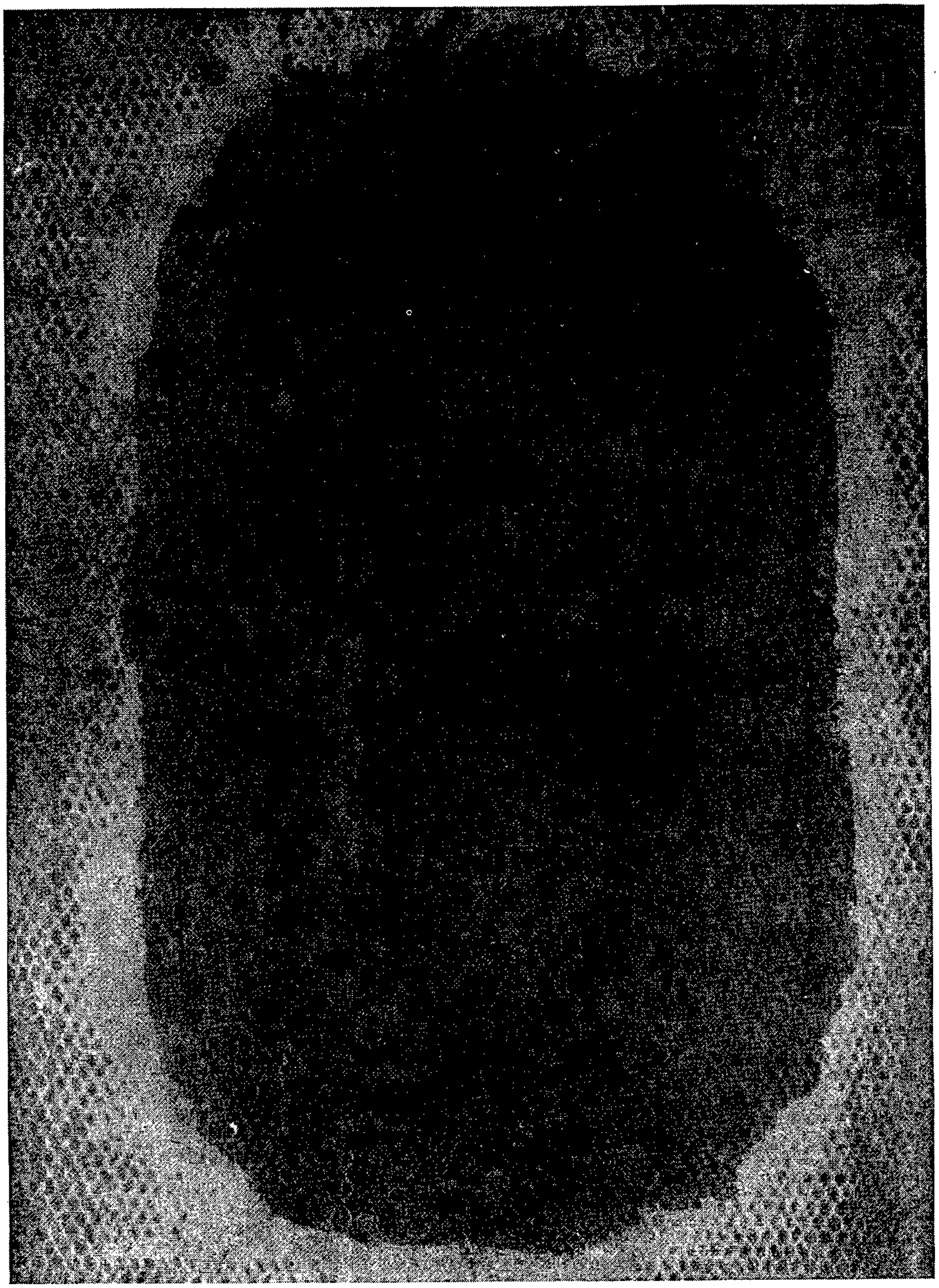


Figure 7–11.—Continued.
J—finished repair.

Round cuts, necessary in removing the damaged portion of a part, may be made with a plug cutter in a hand brace, as shown. A template should be used whenever possible. Straight cuts are most easily made with a fine-tooth hacksaw blade in a reciprocating-saw attachment for a portable electric drill. After trimming, the undamaged facings must be scarfed for a distance of at least 2 inches around the hole with a medium-grit cloth on a flexible-disk sander. Extreme care must be exercised to get the scarf uniform and not to gouge pieces out of the core. The core plug should be cut from material having the same thickness as the original core. Facing patches should be assembled to build up a thickness equal to or slightly thicker than the facing being repaired. Starting with a ply cut to a size about one-half inch larger than the opening, each successive ply should be slightly larger, with the final ply being at least 2 inches larger on all sides. Before the individual pieces of glass cloth shown in figure 7–11, E are cut, the cloth is to be impregnated with a resin of high viscosity and having a long assembly time. The impregnated cloth is to be sandwiched between two sheets of cellophane for ease in handling and storing. The outlines of the patches (two of each size) should then be drawn on the cellophane and the patches be cut with an ordinary shears.

The individual pieces of glass cloth composing the patch are then assembled as shown in figure 7–11, F and G. Before the assembled patch is applied to the area being repaired, the scarfed portion of the part around the hole should be coated with the same resin employed in the patch. It is also advisable to apply a light coat of resin to the core plug. The patch is then positioned over the core plug with the glass-cloth face down, and all air bubbles are carefully worked out by hand after the cellophane has been punctured at about 1-inch intervals. This procedure is to be repeated for the patch on the opposite side. Electrically heated vacuum blankets are then taped to both sides over the patches to supply the heat and pressure necessary for proper care (fig. 7–11, I). A typical completed repair in a sandwich part having glass-cloth honeycomb core is shown in figure 7–11, J.

Parts having single curvature have been repaired by the same method; but the operation is slightly more difficult. No satisfactory methods for the field repair of class 3 damages in parts of appreciable compound curvature have been developed to date.

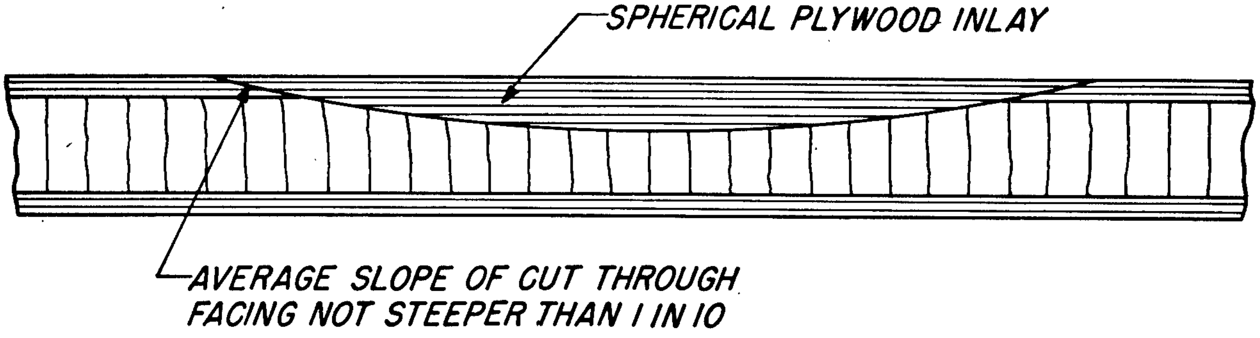


Figure 7–12. Cross section of a plywood inlay installed in a plywood-faced sandwich.

7.313. *Room-temperature-setting resins.* A number of room-temperature-setting resins have been developed that show promise for laminating glass cloth for repair purposes. These resins, in most cases, are contact pressure polyester resins to which special accelerators or promoters are added in addition to a catalyst to bring about a cure at room temperature or with the application of a small amount of heat. The use of room-temperature-setting resins reduces the necessity of having large and expensive equipment especially in the field where aircraft repair may be necessary. Repairs using the proper amount and type of accelerator or promoter can be made by methods similar to those discussed under class 1, 2, and 3 repairs. After making the repair, the patch is covered with cellophane and cured at room temperature within 24 hours. The time can be considerably reduced by the application of heat from a bank of infrared lamps or even by placing the repair in the sun.

7.32. Plywood-Faced Parts.

7.320. *Class 1 repairs.* Dents or scratches in plywood facings can be readily repaired with any durable commercial filler or a mixture of a room-temperature-setting resorcinol adhesive and wood flour. The methods shown in AN 01–1A–7, "Repair of Wood Aircraft Structures," are also applicable.

7.321. *Class 2 repairs.* Minor damages to one facing and the core only, such as fractures, not exceeding 4 inches in maximum dimension, may be repaired by means of plywood inlays in the facing, as shown in figure 7–12. These inlays are difficult to cut accurately by hand, but spherical-shaped inlays and the matching recesses can be readily and quickly cut with a set of spherically seated templates and a portable router. Sketches of these templates are shown in figure 7–13, and a repair by this means before and after installation of the inlay is shown in figure 7–14. Inlays may

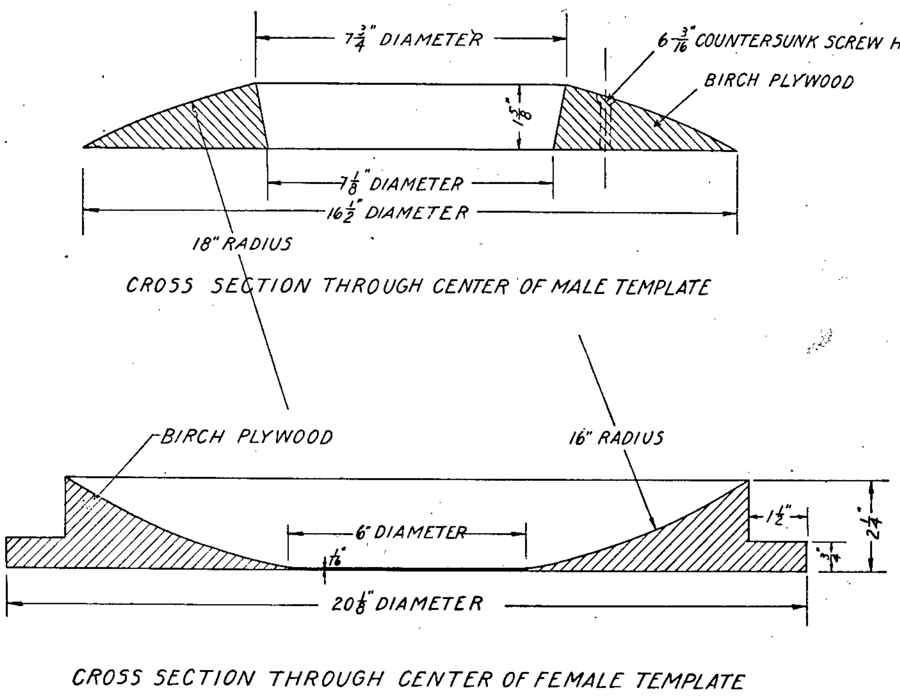


Figure 7–13. Cross section of a set of router templates for cutting inlays and inlay recesses.

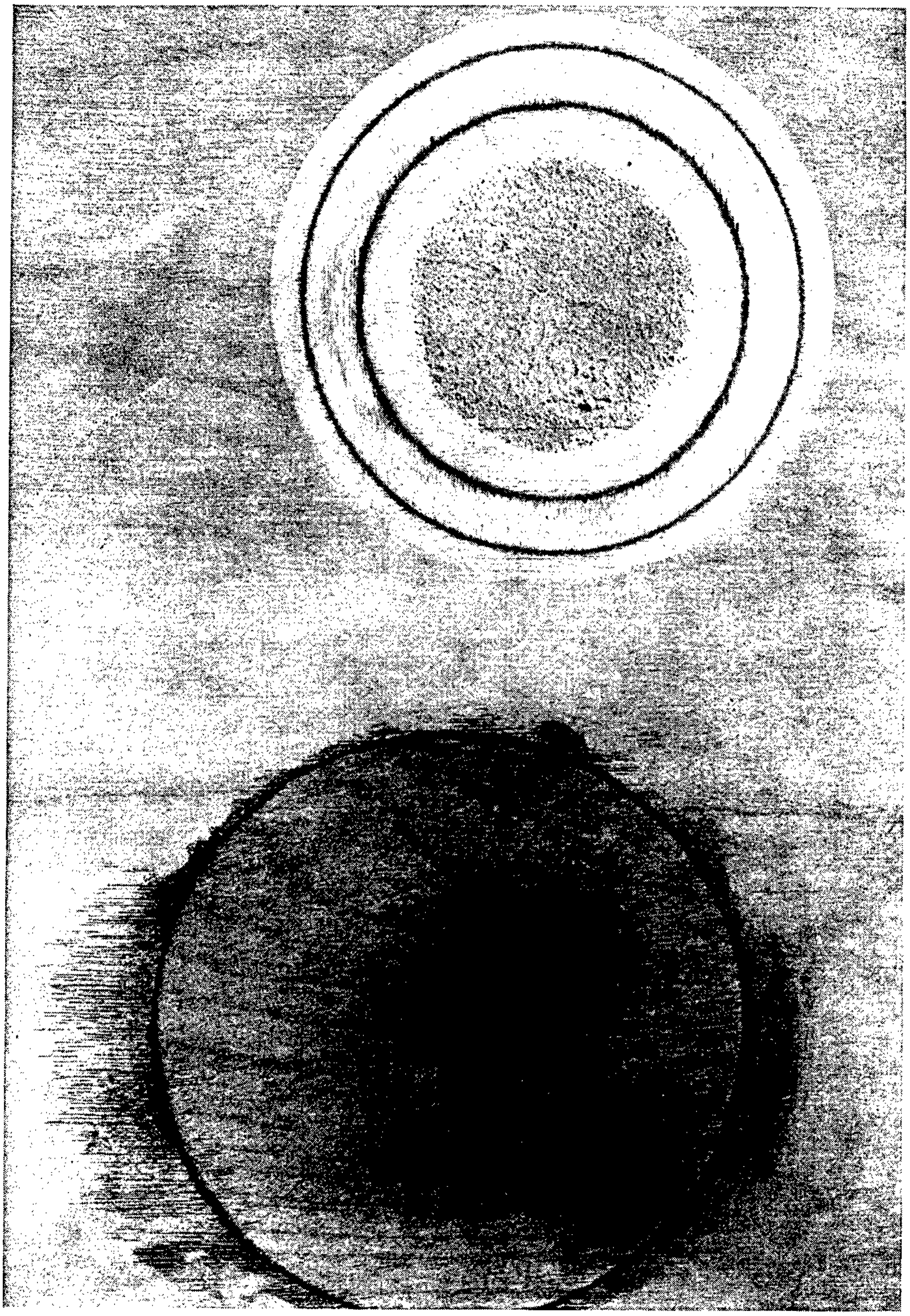
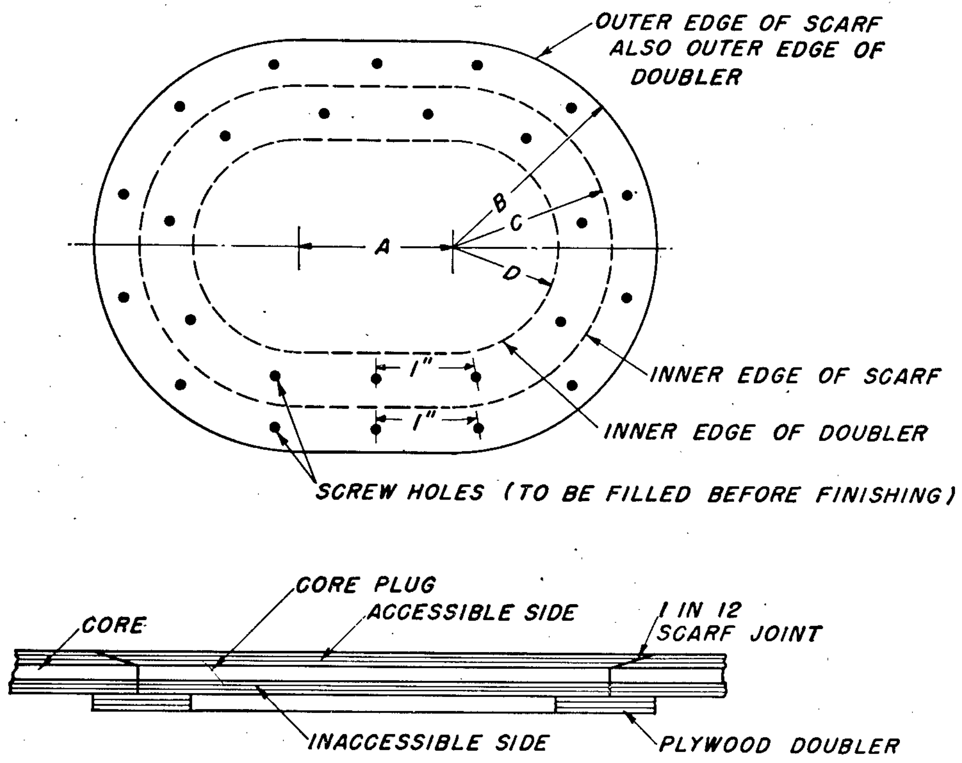


Figure 7–14. A small inlay recess (top) and completed inlay repair (bottom) in plywood-faced sandwich.

be bonded in place with a room-temperature-setting resorcinol adhesive with weights or a vacuum bag used for pressure.

More extensive class 2 damage should be treated as class 3 damage and repaired as described in section 7.322.

7.322. *Class 3 repairs.* Joints necessary in facings in repairing damages extending completely through the sandwich part should be of the scarfed type and have a slope not steeper than 1 in 12. Suggested details of oval- and square-shaped repairs of this type are shown in figures 7–15 and



DIMENSIONS (INCHES):	A	B	C	D
SMALL OVAL PATCH	$1\frac{1}{2}$	$2\frac{1}{4}$	$1\frac{1}{2}$	$\frac{3}{4}$
LARGE OVAL PATCH	2	$3\frac{1}{4}$	$2\frac{1}{2}$	$1\frac{3}{4}$

Figure 7–15. Oval-patch assembly used in plywood-faced parts when one side only is accessible.

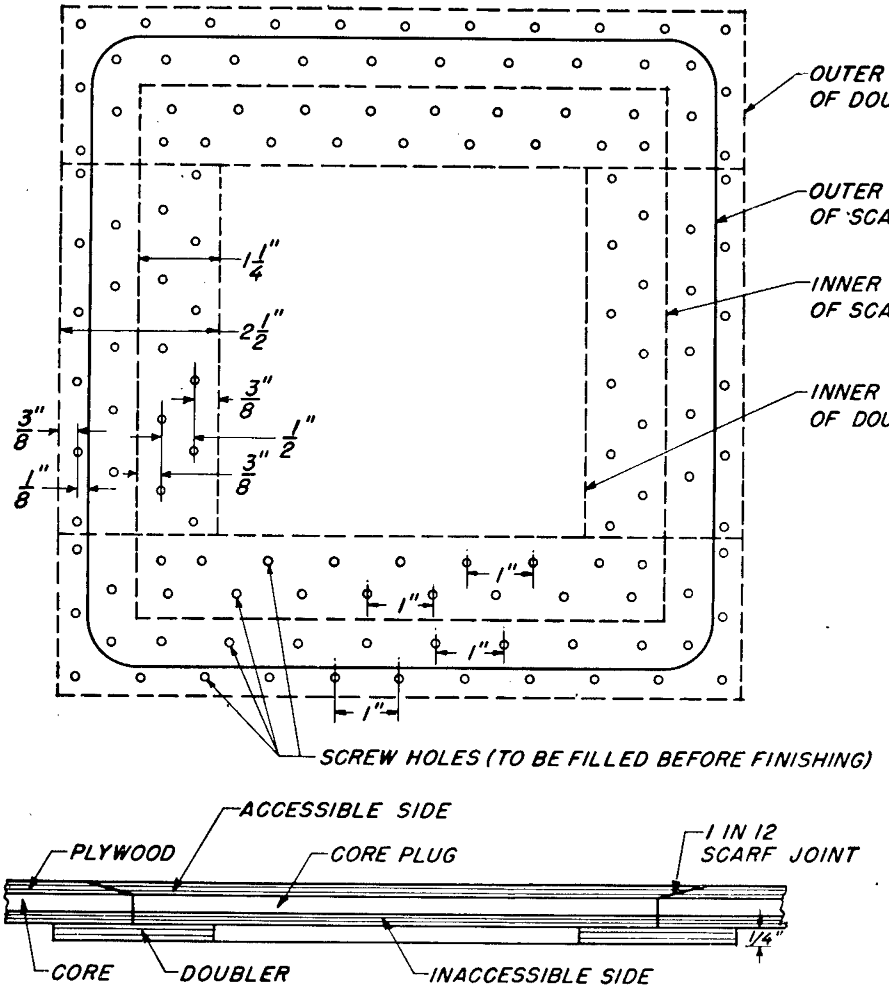


Figure 7–16. Square or rectangular patch assembly used in plywood-faced parts when one side only is accessible.

7–16. Pressure is applied to the scarf joint by round-head wood screws driven through 1/4-inch plywood pressure plates into backing strips. The grain direction of the patch must match that of the original facing. A room-temperature-setting resorcinol adhesive is recommended.

CHAPTER 8

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