PROCESSING COMPOSITE MATERIALS

R. M. Baucom
NASA Langley Research Center
Hampton, Virginia

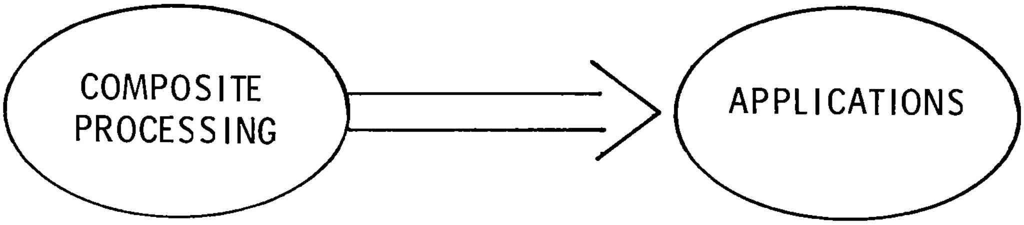
INTRODUCTION

Langley Research Center has an active role in the development of composite materials for aerospace applications. This activity was initiated over ten years ago and has included a variety of study efforts that have led to several production commitments to use composite materials in structural components. The overall composites program at Langley includes basic polymer studies, composites processing research, materials evaluation, analysis, and applications. In order to support the composite research activities, the current annual consumption of graphite, Kevlar and fiberglass reinforced polymer materials is approximately 1000, 400, and 800 pounds, respectively. An additional 50 pounds of fiber reinforced metal matrix composite materials are also consumed. Annually, approximately 300 structural laminates ranging in size up to 20 square feet and in thickness up to 1.2 inches are fabricated from these materials. Structural articles weighing up to several hundred pounds are also frequently fabricated. In addition to conventional vacuum molding capability, 12 heated platen presses, 4 research autoclaves, 2 thermoforming machines and a pultruder are available for composites fabrication. This paper will review composite processing methods and illustrate selected examples of components produced by Langley as well as components produced by our aerospace contractors.

COMPOSITE PROCESSING AND APPLICATIONS

Fiber reinforced polymer composite materials can be processed into structural articles by a vareity of different methods. The application of pressure or force to composite materials to shape and cure is accomplished by means of the application of vacuum, autoclave pressurization, trapped rubber expansion or hydraulic presses. Vacuum molding is a widely used method for the fabrication of large production, non-aerospace articles from general use composite materials such as fiberglass reinforced polyester and epoxy. Advanced composite materials such as Kevlar and graphite reinforced epoxies and polyimides are generally processed by autoclave molding, by trapped rubber expansion, or by hydraulic presses. To complete the processing cycle the articles fabricated by these methods are normally subjected to nondestructive inspection to verify the structural integrity of the finished part.

This presentation will feature the fabrication of several composite structural articles including DC-10 upper aft rudders, L-1011 vertical fins and composite biomedical appliances. Also, a discussion on innovative composite processing methods will be included.



COMPOSITE PROCESSING

APPLICATIONS

CONVENTIONAL

- VACUUM MOLDING
- AUTOCLAVE
- TRAPPED RUBBER
- PRESS MOLDING
- INSPECTION

ADVANCED

- INTEGRATED LAMINATING CENTER
- HOT MELT FUSION

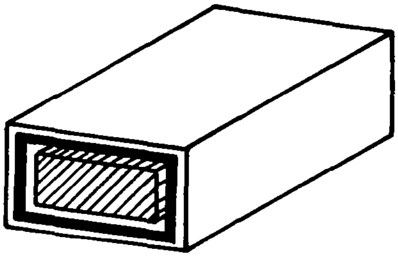
- DC-10 UPPER AFT RUDDER
- L-1011 VERTICAL FIN
- BIOMEDICAL APPLIANCES

COMPOSITE MOLDING METHODS

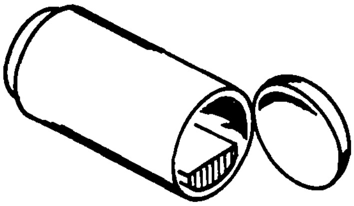
The three most widely used methods for applying pressure to mold composites are thermal expansion of trapped rubber, autoclave pressurization, and hydraulic presses. The selection of the appropriate molding method depends primarily on the structural article size and maximum cure temperature and pressure. The trapped rubber or thermal expansion molding technique has the capability of developing very high pressures during composite cure and care must be exercised in the design of the tooling in order to maintain the selected pressures. This method is utilized in composite processing where uniform pressure application in complex shapes is difficult with other methods. Composite article size is limited only by oven size and tool mass with the thermal expansion molding technique. Autoclave processing of composite materials is widely used due to the precise control of pressure and temperature offered by the method.

Structural article size and maximum pressure are limited by the design of the autoclave pressure vessel. Hydraulic presses equipped with heated platens are generally utilized for applications which require high pressures and fast cycle times during composite molding. Hydraulic presses are widely used to fabricate small, intricate parts in matched metal tooling.

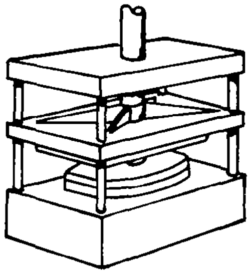
THERMAL EXPANSION



AUTOCLAVE



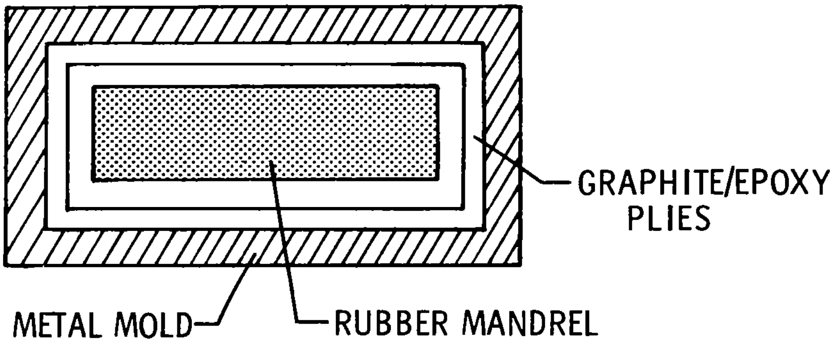
HYDRAULIC PRESS



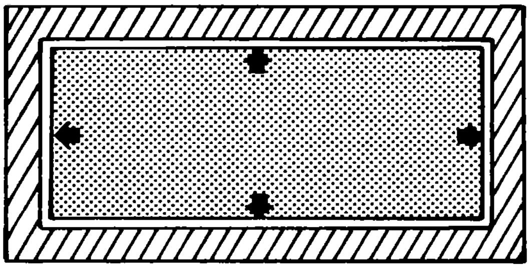
COMPOSITE MOLDING BY THERMAL EXPANSION

Most rubber compounds possess the physical characteristic of expanding upon the application of heat. This characteristic can be used to apply uniform pressure to composite materials to form and cure a structural article. Typically, a block or plug of rubber is cast into the desired shape with appropriate allowances for expansion prior to contacting the mold cavity during heat up. The composite material is applied over the rubber plug and the assembly is placed in the mold cavity which serves as the pressure containment chamber during cure. As the temperature is increased the composite material is forced against the mold. Since the rubber expands uniformly, the composite material is subjected to near-hydrostatic pressure as the temperature approaches the cure temperature. After an appropriate dwell time at the cure temperature the assembly is cooled and the part is removed. The cast rubber mold is then removed from the part and the assembly is prepared for the next fabrication cycle. The cast rubber block can be used for several cycles without degrading the material or losing its pressurization capability which, in turn, reduces the tooling costs.

COLD

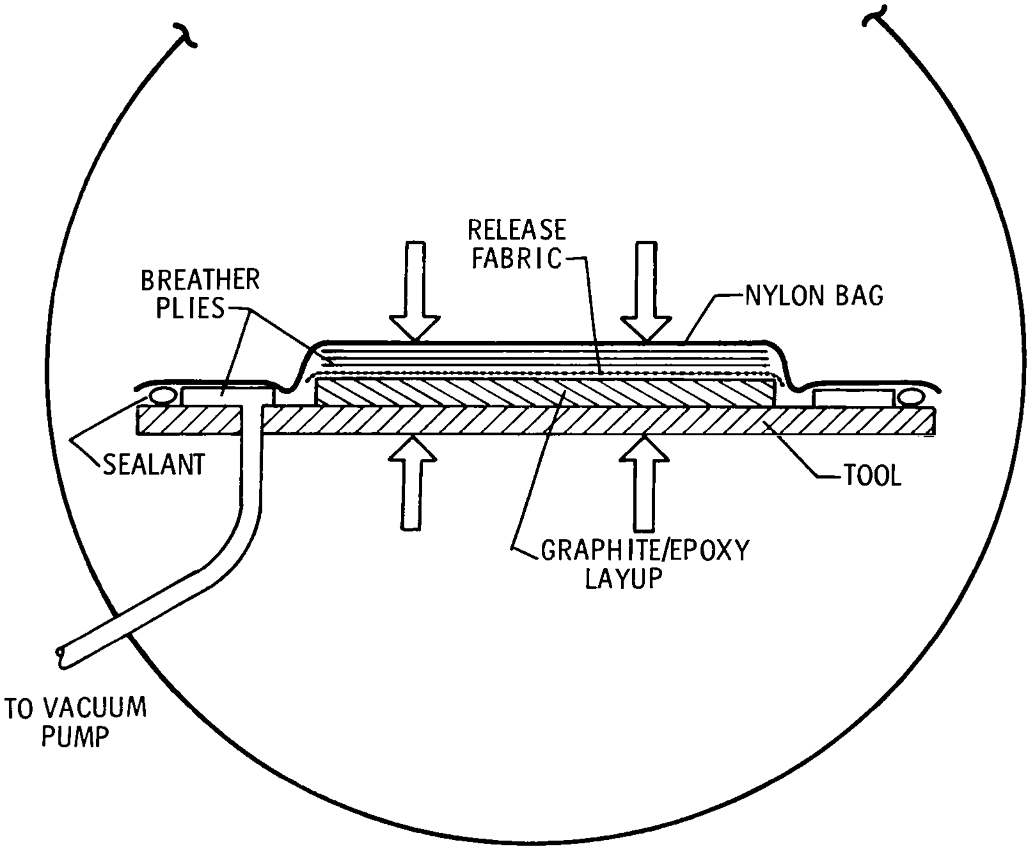


HOT



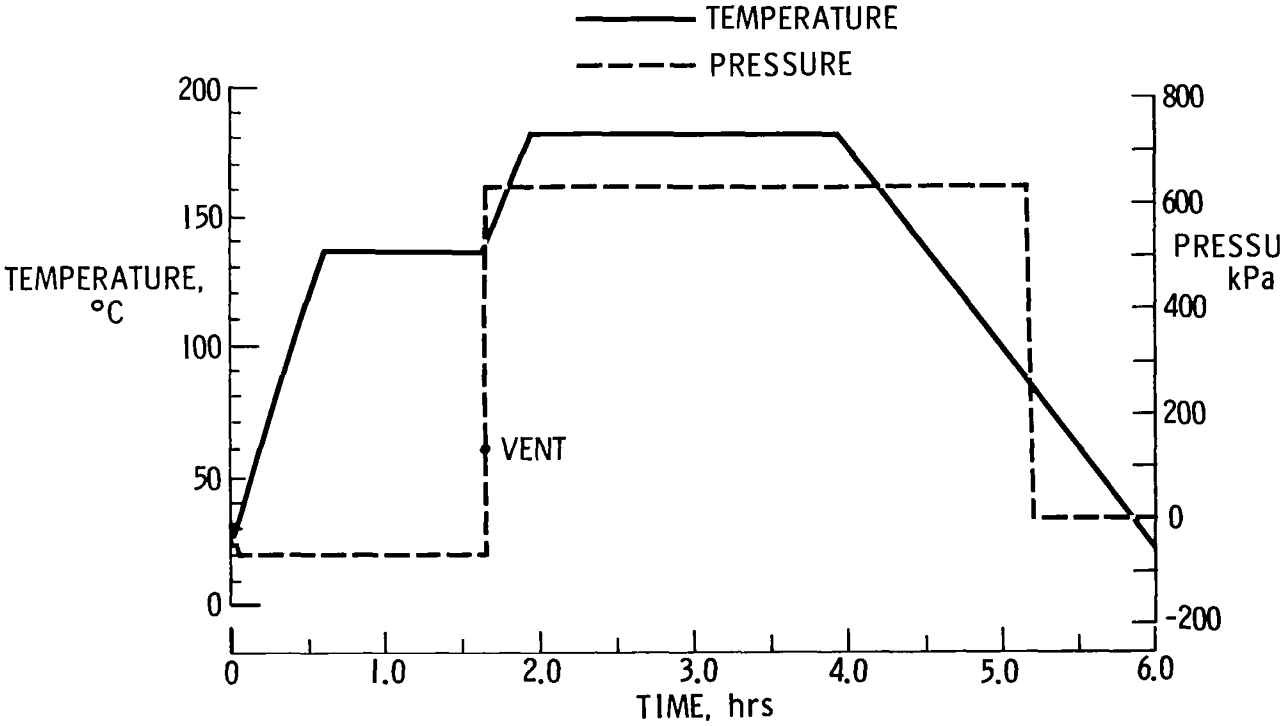
AUTOCLAVE MOLDING OF COMPOSITES

Autoclaves are utilized for processing a wide variety of composite materials into flat laminates and structural shapes. A typical autoclave process begins with assembling the part from the appropriate composite prepreg material. This assembly, commonly referred to as the layup, is placed on a metal caul plate that has been coated with spray release agent or a nonporous release film. The composite material is then covered with a porous release film and the required number of plies of breather material. A vacuum bag is then installed over the assembly and sealed around its periphery with gasket sealant material. A vacuum line is attached to the caul plate, vacuum is applied to the part, and the entire assembly is inserted into the autoclave. During heat-up to the composite cure temperature the viscosity of the resin in the prepreg material is lowered and the excess resin is drawn into the breather plies through the porous release fabric. Volatile products generated during cure are also removed in the same manner. After the temperature and autoclave pressure are held for the appropriate time to cure the prepreg, the vacuum bag assembly is removed from the autoclave, the vacuum bag is stripped away, and the fully cured part is removed. The materials utilized in this fabrication process are selected to withstand the temperature and pressure required for the particular composite material being processed. Autoclave molding is the most widely used process in the aerospace industry for manufacture of large graphite/epoxy and graphite/polyimide structural articles.



TYPICAL COMPOSITE CURE CYCLE

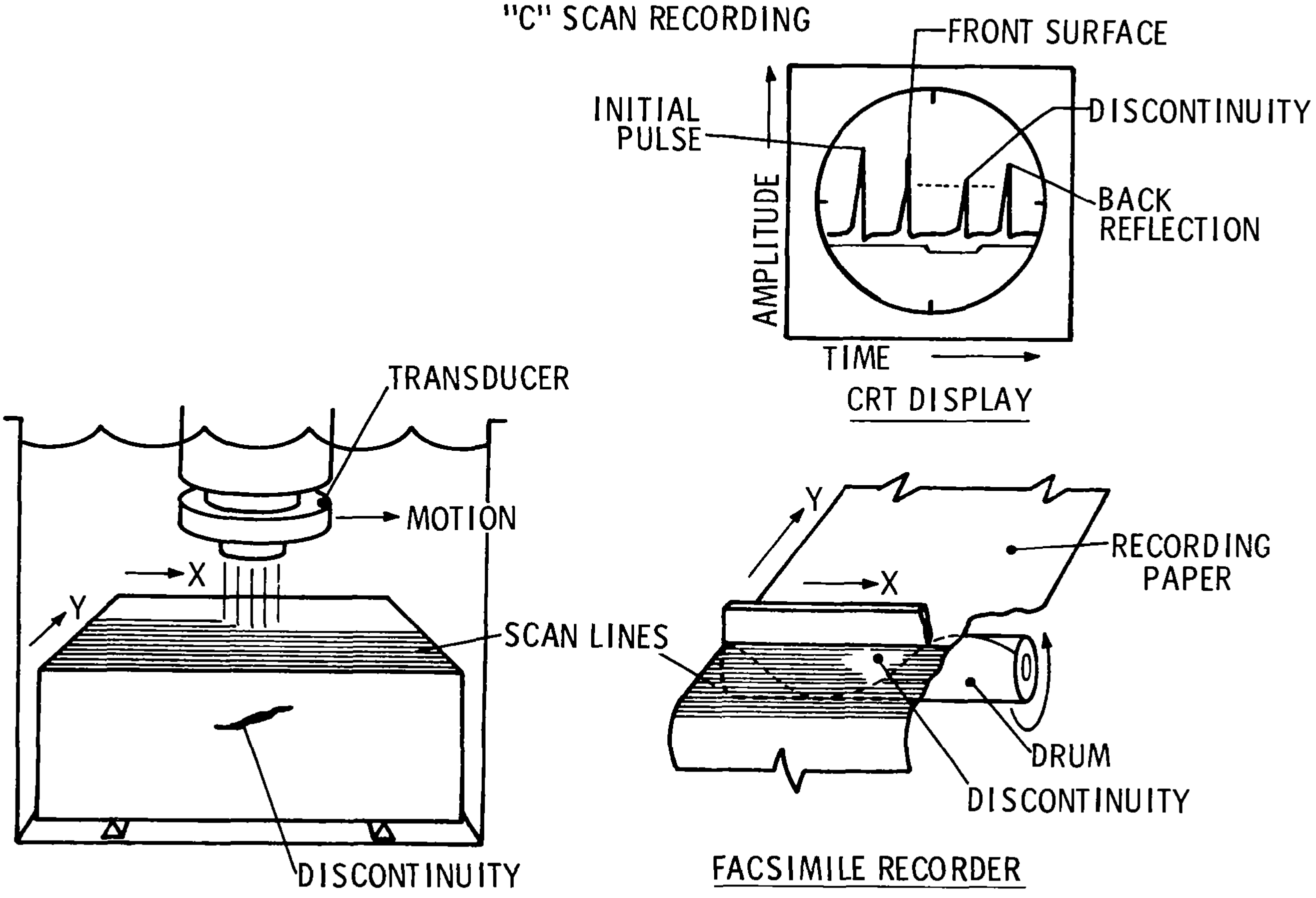
Polymer matrices for fiber reinforced composite materials generate reaction by-products during cure. In addition, the viscosity of the polymer matrix varies substantially during cure. In order to accommodate these physical phenomena during composite processing, the application of heat, vacuum, and pressure must be precisely controlled to avoid incomplete cures, voids, delaminations, and excess resin and fiber movement. A typical cure cycle for fabricating graphite/epoxy is shown in the figure. Vacuum is applied to the composite material and it is heated to an intermediate temperature of approximately 250-275°F. This condition is held for a period of time to allow excess solvent, water and reaction by-products to be removed. Prior to matrix gellation, the vacuum is removed and positive pressure is applied. The composite material is heated to the cure temperature, typically 350°F, and allowed to soak for 1 to 2 hours to effect a complete matrix cure. The part is then cooled to room temperature, the pressure is vented, and the part is removed. With minor variations to accommodate different composite material combinations, this profile is representative of most engineering composite material cure cycles.



ULTRASONIC INSPECTION OF COMPOSITES

After composite articles are fabricated it is necessary to establish the structural integrity of the finished part. An initial visual examination is performed to identify areas of gross disbonding, delamination, fiber misalignment, laminate cracking, warped areas, etc. This inspection is normally followed by nondestructive ultrasonic evaluation of the article to ensure that the article is free of internal defects. This method requires that the article be acoustically coupled to the ultrasound transducer. The most convenient way to establish positive acoustic coupling is to immerse the article in a water tank equipped with a traveling bridge for attachment of the transducer. As the transducer travels along the bridge, sound is directed through the water and into the article. When a discontinuity is detected in the composite, the decibel level of the sound transmitted back to the transducer is reduced. This data can be displayed on an oscilloscope in the form of signal amplitude changes or on a printer which highlights the defect area. Voids, delaminations, cracks and porosity absorb the sound transmitted by the transducer and can be readily identified by this inspection process. Transducer frequency, focal distances, and focal diameters are selected to accommodate article thickness, shape, and fiber and resin type.

"C" SCAN RECORDING

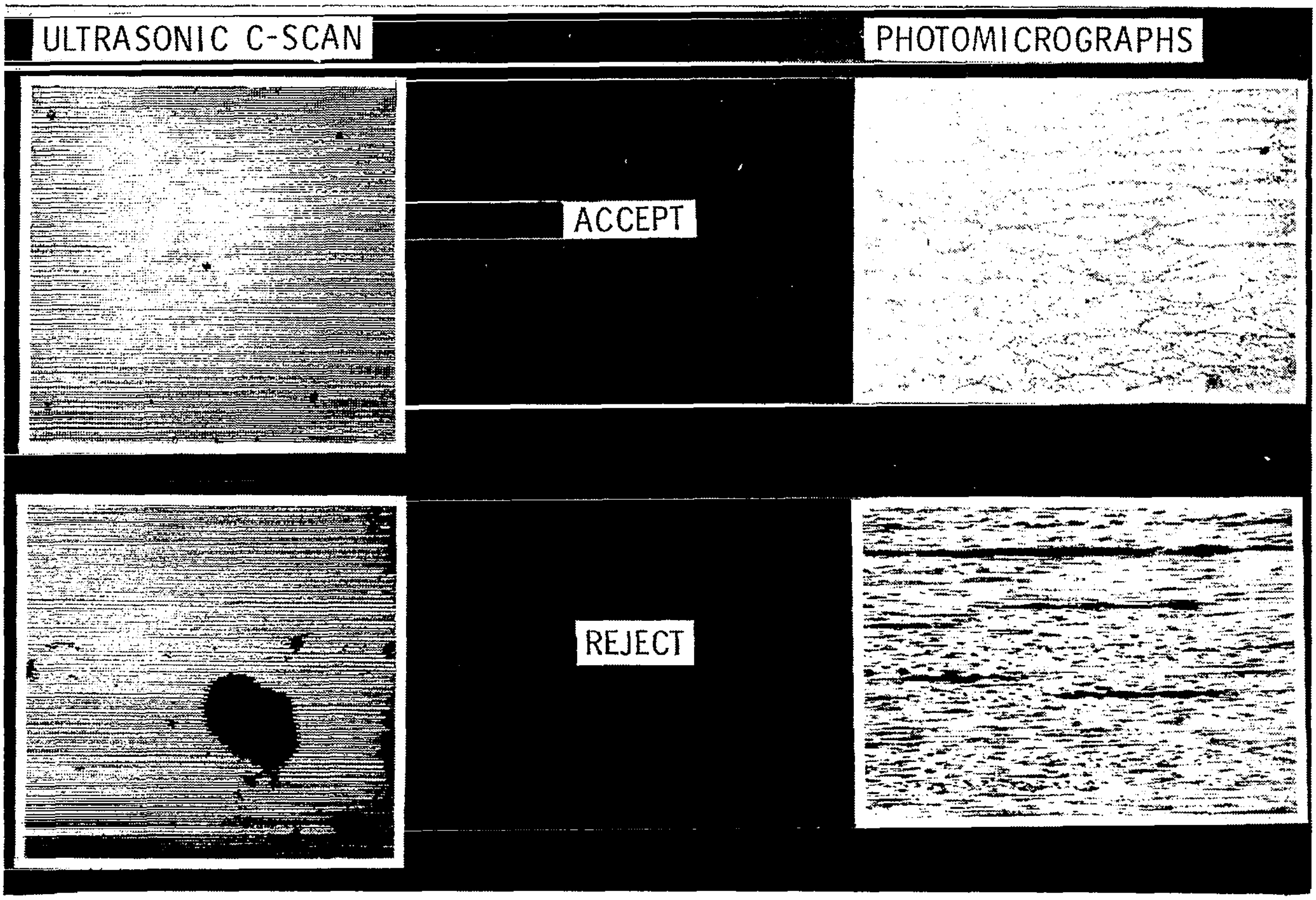


CRT DISPLAY

FACSIMILE RECORDER

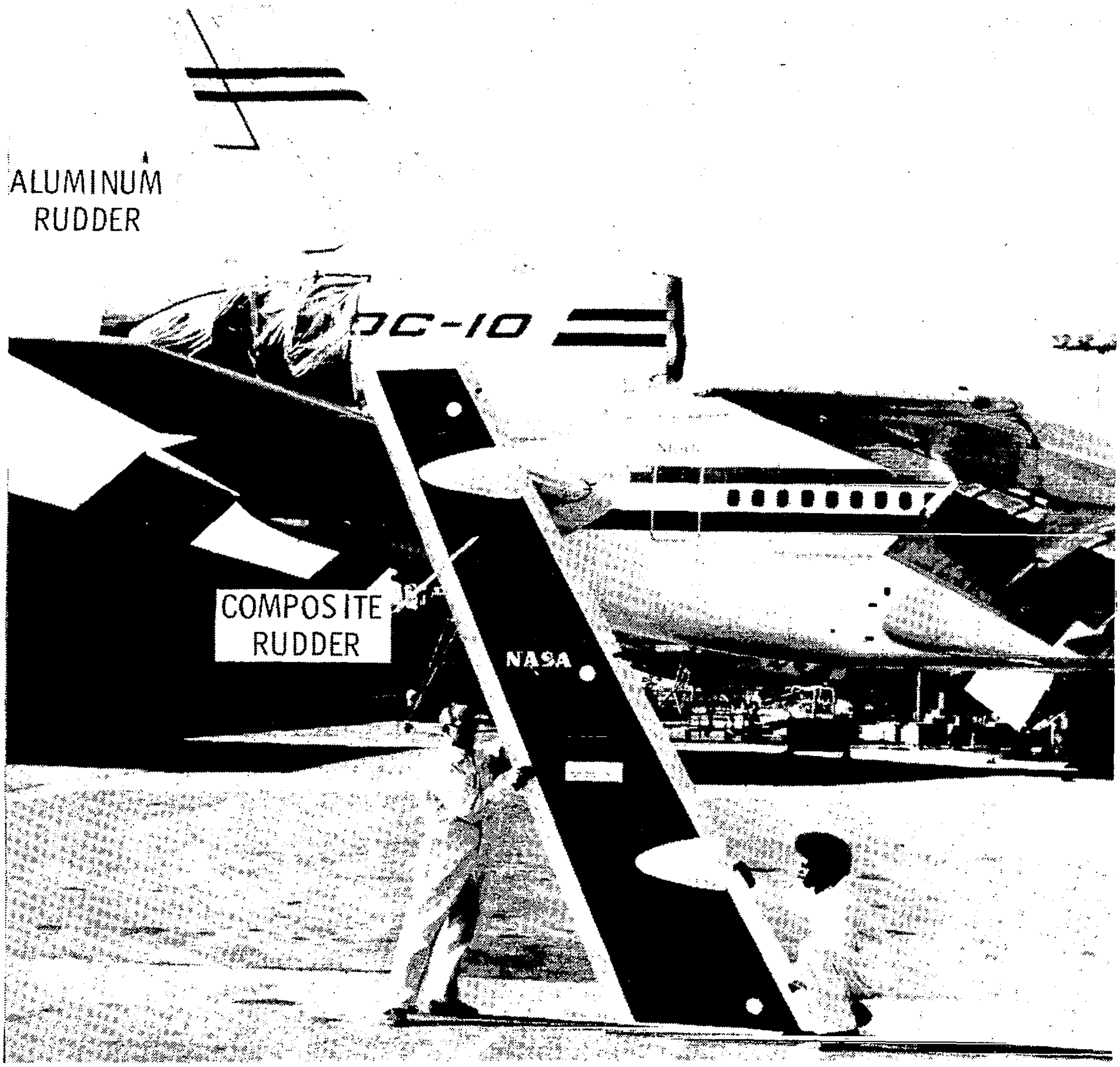
INSPECTION TECHNIQUES

The capability of ultrasonic inspection to verify the structural integrity composites has been demonstrated by machining, polishing, and visually inspecting the suspected defect areas. The ultrasonic C-scan image, shown in the upper left of the figure, indicates a structurally sound laminate. The small black dots on the C-scan represent the metal support pins used to elevate the laminate off the base of the water immersion tank to avoid undesirable artifacts in the C-scans. The photomicrograph of the laminate shown in the upper right of the figure verified the assessment. The ultrasonic C-scan in the lower left portion of the figure shows evidence of internal voids which absorbed the sound beam during inspection. This laminate was also sectioned, polished and visually inspected to verify the ultrasonic display of voids. Large discontinuities between laminate plies are evident in the defective areas indicated by ultrasonic inspection. The criteria for accept/reject of a composite article vary widely as a function of the data base generated for the particular composite system and the mission for the composite article. In particular, the criticality of void size, type, and location plays a major role in establishing the acceptable limits for anomalies discovered by ultrasonic inspection.



DC-10 UPPER AFT RUDDERS

One of the composite structural components developed under the NASA ACEE (Aircraft Energy Efficiency) program is the upper aft rudder for the DC-10 aircraft. The component is approximately 13 feet in length. The aluminum production design weighs 93 pounds whereas the composite rudder weighs only 61 pounds. The structural box was fabricated from graphite/epoxy material. The leading and trailing edges were fabricated from glass/epoxy material.



COMPOSITE DC-10 UPPER AFT RUDDER ADVANTAGES

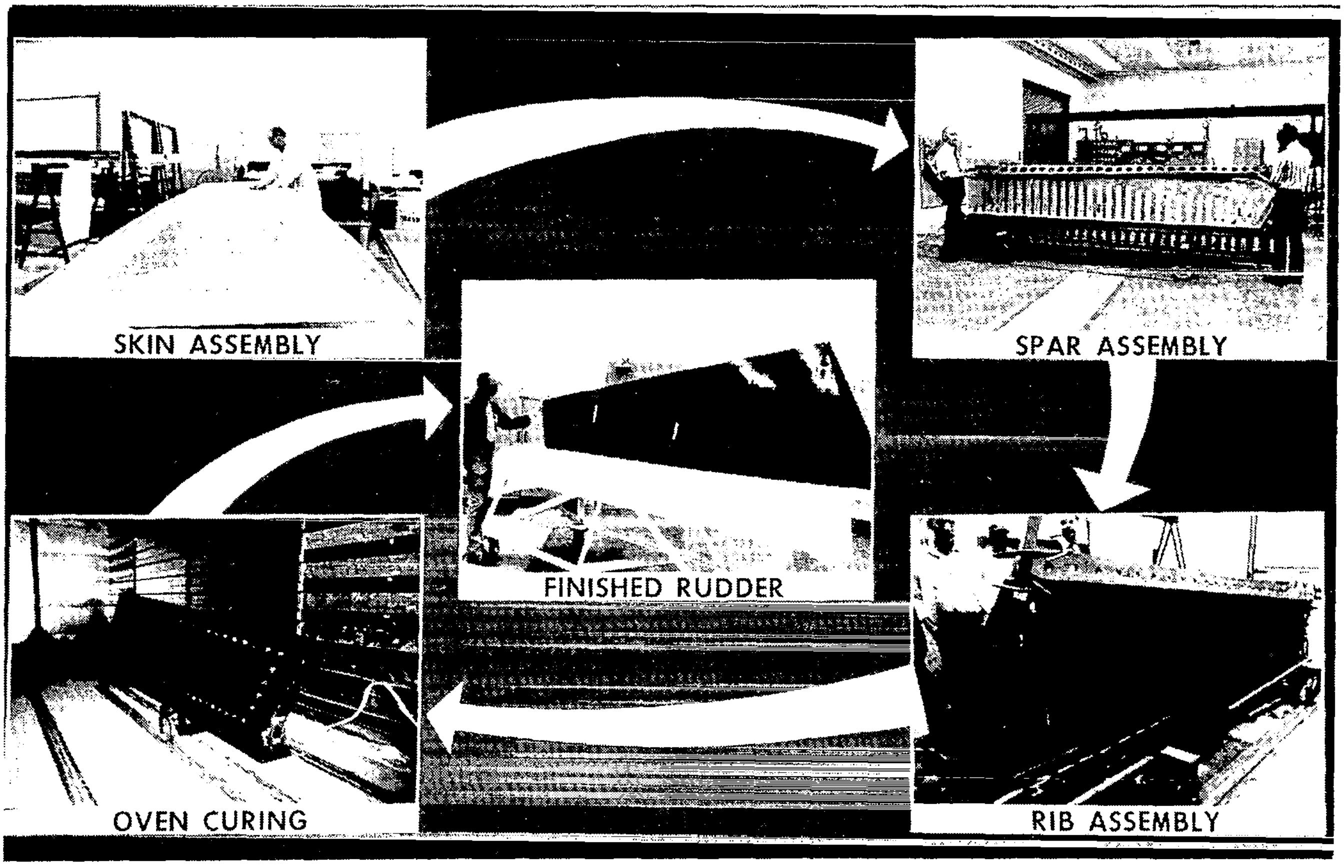
The graphite/epoxy upper aft rudder for the DC-10 was fabricated using the trapped rubber thermal expansion technique. Principal advantages of using this fabrication procedure were: (1) the component was molded to net size and machining operations were minimized, (2) the complete assembly was cured in one cycle thereby saving costs and limiting exposure time of the composite to 350°F temperatures, and (3) the requirement for secondary bonding of subassemblies was eliminated. Composite rudders fabricated in this manner weigh approximately 30 percent less than the production aluminum rudders.

GRAPHITE/EPOXY COCURED COMPONENT

- MOLDED NET TO SIZE
- CURED IN ONE CYCLE
- NO SECONDARY BONDING
- SIGNIFICANT WEIGHT REDUCTION OVER METAL CONFUGURATION

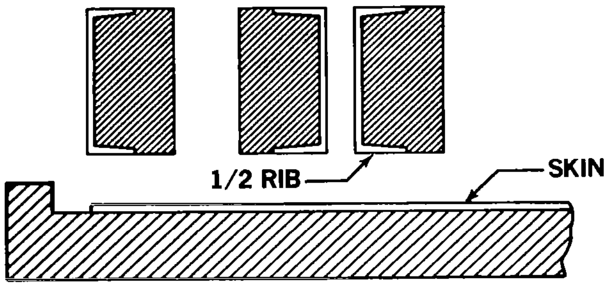
DC-10 UPPER AFT RUDDER MANUFACTURING SEQUENCE

Fabrication of the DC-10 graphite/epoxy upper aft rudder began with layup and predensification of the skins, front and rear spars and ribs from unidirectional tape and broadgoods. These parts were then loaded into the rubber molding tool along with the internal metal and rubber mandrels. Steel side plates were bolted into place and the assembly was placed in the oven. The assembly was heated to 350°F and held for 2 hours and 15 minutes to fully cure the graphite/epoxy. The finished rudder was removed from the tool.

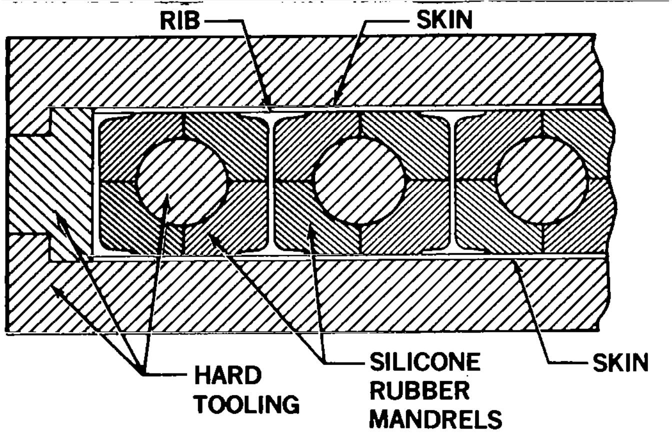


THERMAL EXPANSION MOLDING TECHNIQUE

Thermal expansion molding technique (trapped rubber processing) is predicated on the fact that silicone rubber, when confined within a vessel and subjected to heat, thermally expands and generates internal pressure. As in the case of the upper aft rudder of the DC-10, graphite/epoxy details are laid up, densified on wooden form blocks, trimmed and prepared for freezer storage. The formed details are then loaded into the rudder tool, the rubber mandrel is properly positioned, and the tool vessel is closed. The loaded tool is then placed in an oven and cured for 2 hours at 350°F after initial heat-up. Advantages of the process include elimination of the autoclave and vacuum bagging operations.



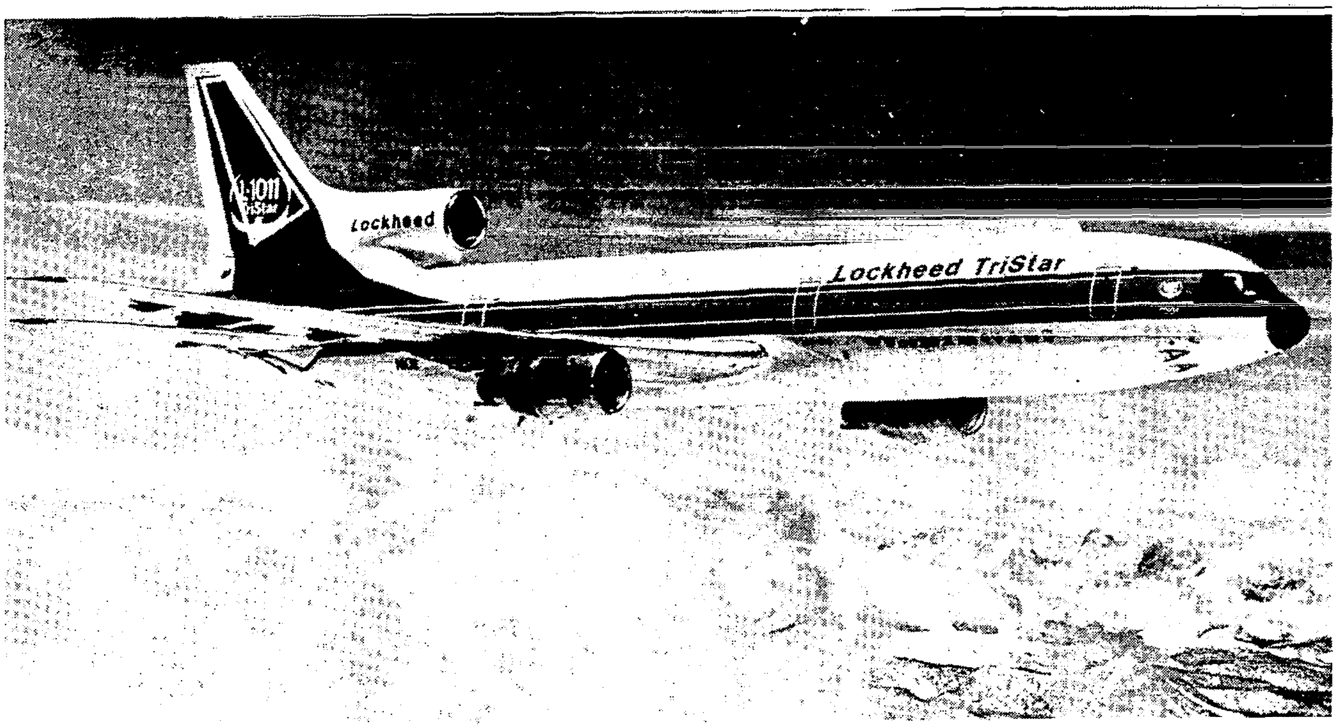
- **LAYUP INDIVIDUAL PIECES ON ANCILLARY TOOLS**
- **DENSIFY**
- **TRIM TO SIZE**
- **STORE IN FREEZER**



- **ASSEMBLE PIECES IN CURE TOOL**
- **APPLY HEAT**
- **PRESSURE SUPPLIED BY EXPANSION OF SILICONE RUBBER WITHIN TOOL CAVITY**
- **NO BAGGING, BLEED-OFF, OR ADHESIVE REQUIRED**

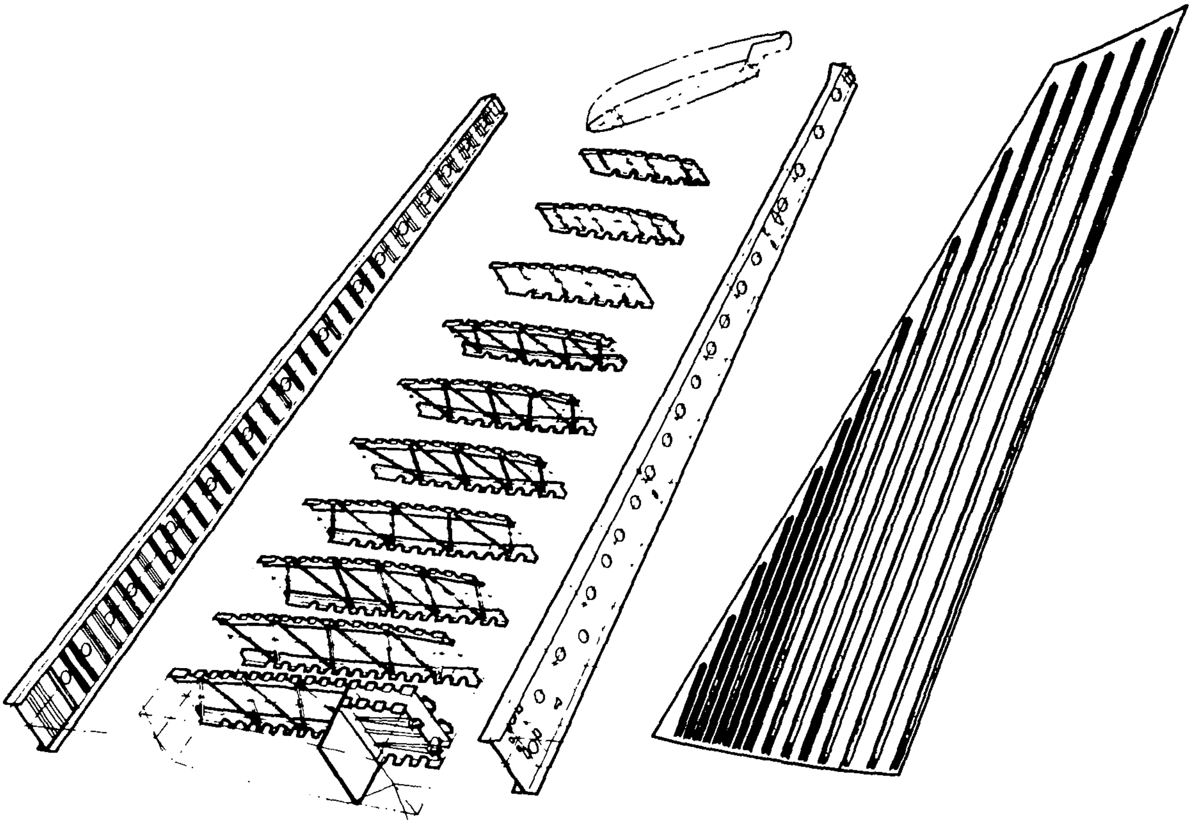
L-1011 ADVANCED COMPOSITE VERTICAL FIN

Two structural components on the L-1011 airplane were selected for fabrication from graphite/epoxy composite as part of the NASA ACEE program. One component, the vertical fin, is a primary load-carrying structural element. The objectives of the Advanced Composite Vertical Fin (ACVF) research were to develop low-cost manufacturing processes for large composite structural aircraft articles and to verify the structural integrity and durability of the article.



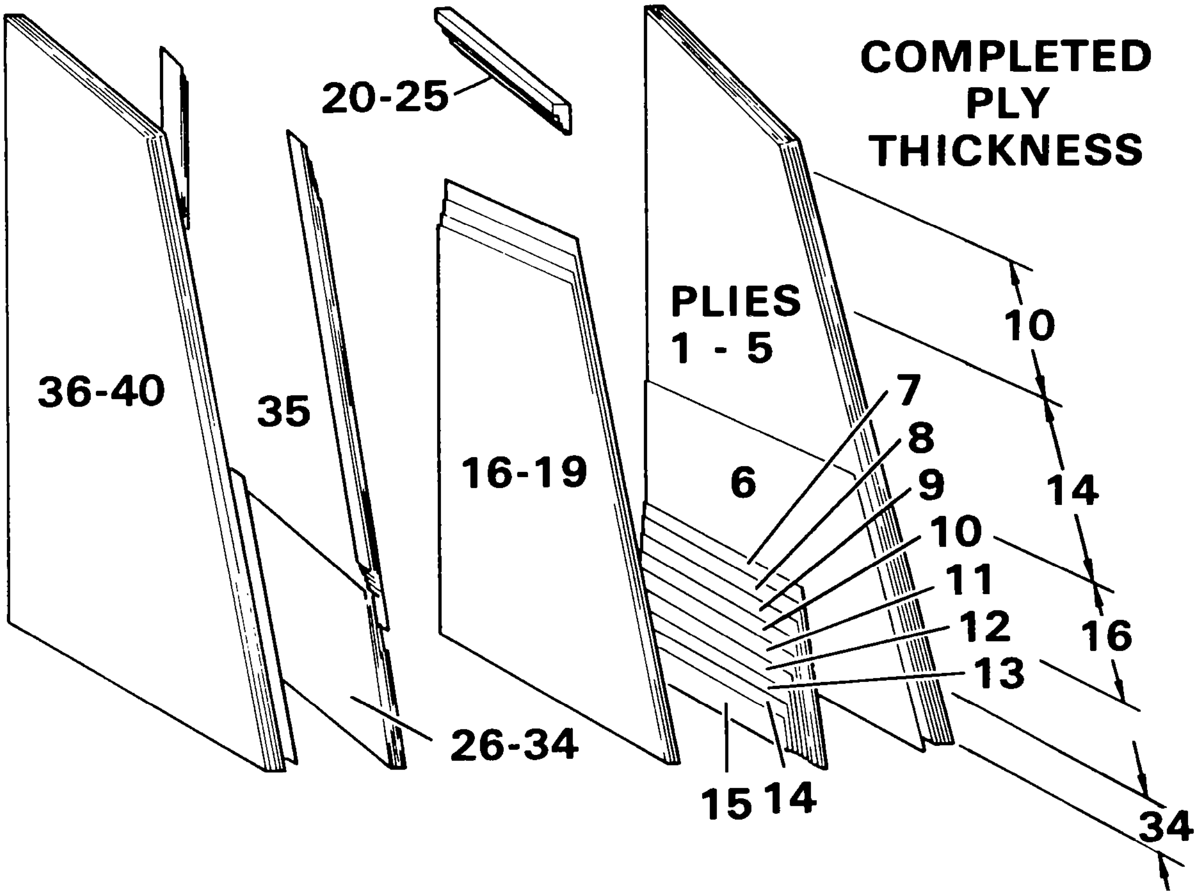
L-1011 ACVF STRUCTURAL CONFIGURATION

The ACVF is 25 feet long, 9 feet wide at the root, and weighs 622 pounds. It is comprised of 10 ribs, front and rear spars, and hat-stiffened cover skins. Unidirectional and woven graphite/epoxy prepreg is utilized in the construction of the ACVF subassemblies.



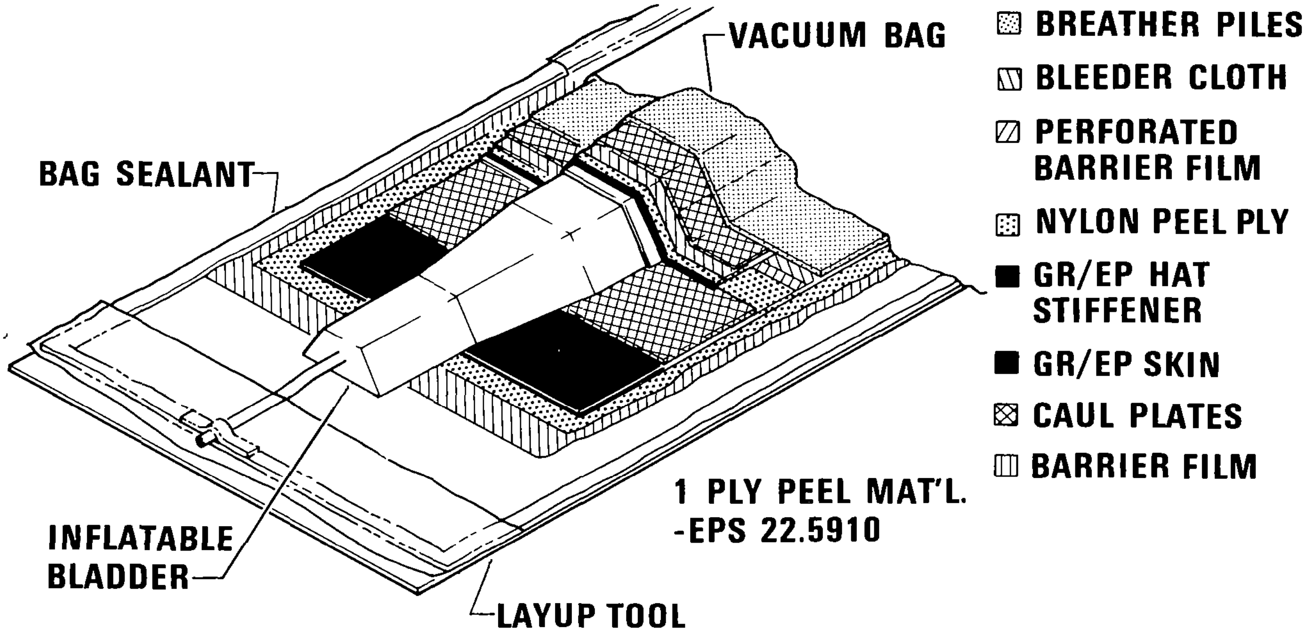
ACVF SKIN LAY-UP SCHEMATIC

The skin of the L-1011 composite fin (ACVF) is comprised of a ply buildup which is 34 plies at the root end (to match the existing L-1011 metallic mating structure) and tapers progressively to 16, 14, and 10 ply areas as shown. The buildup consists of five plies over the complete fin area, oriented ±45°, 0°, ∓45°. This is followed by 10 partial plies, principally 0° orientation, building up toward the root end, and a core of four ±45° plies at the midpoint in the symmetrical layup. Additional partial plies are included at the tip and along the front and rear spar attach areas to provide a reinforced bearing pad for fastening.



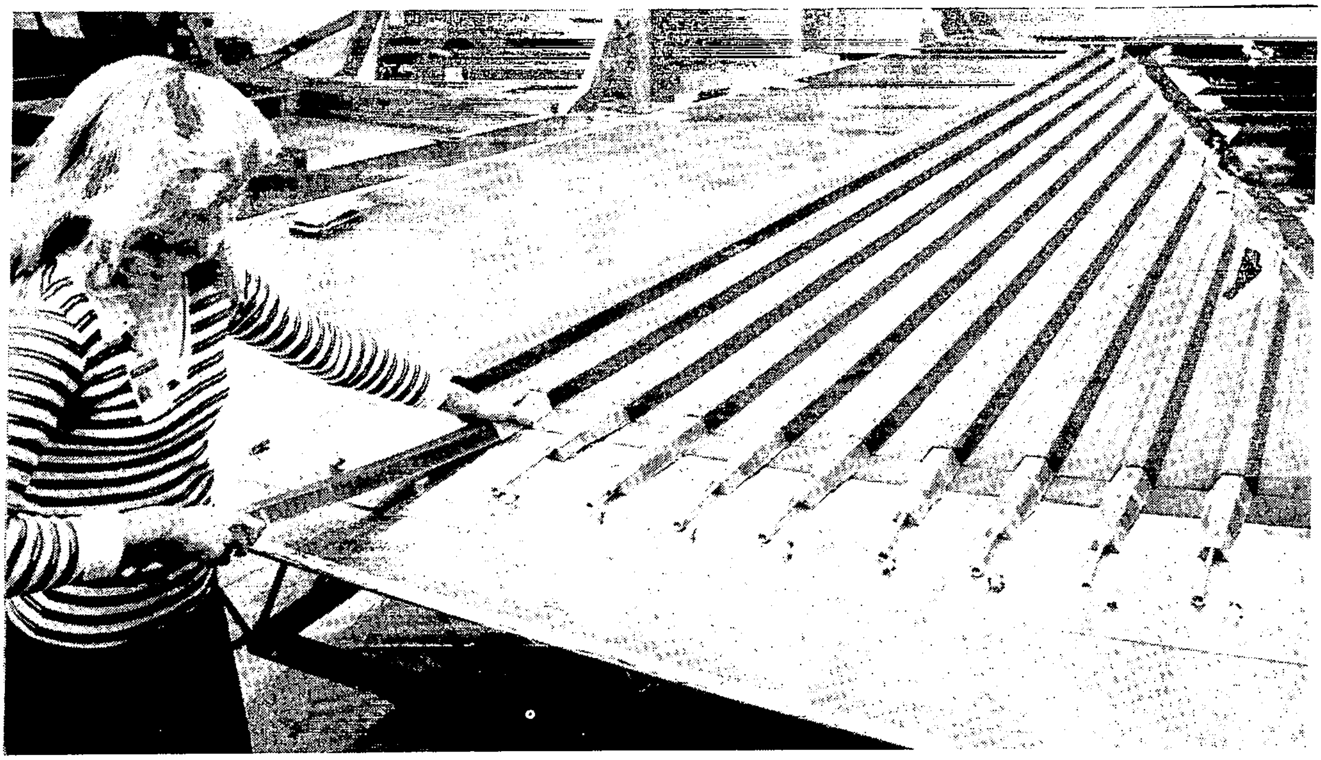
ACVF HAT/SKIN VACUUM BAG ASSEMBLY

The various types of materials which are used in the cure of a typical hat-stiffened bay of the ACVF cover assembly are shown in the figure. A barrier film is used next to the tool surface and also under the hat cauls to prevent resin adhesion to the tooling components. A nylon peel ply is placed immediately adjacent to the graphite layup, both on the tool side of the skin and over the hats and between hat flanges. Bleeder material is located between hat flanges and around the periphery of the part. Breather plies cover the completed stack to assure a continuous vacuum path to the vacuum ports located around the tool base. A vacuum bag covers the complete assembly and is sealed at the edges of the tool. The inflatable bladder penetrates the vacuum bag to admit autoclave pressure to the bladder interior.



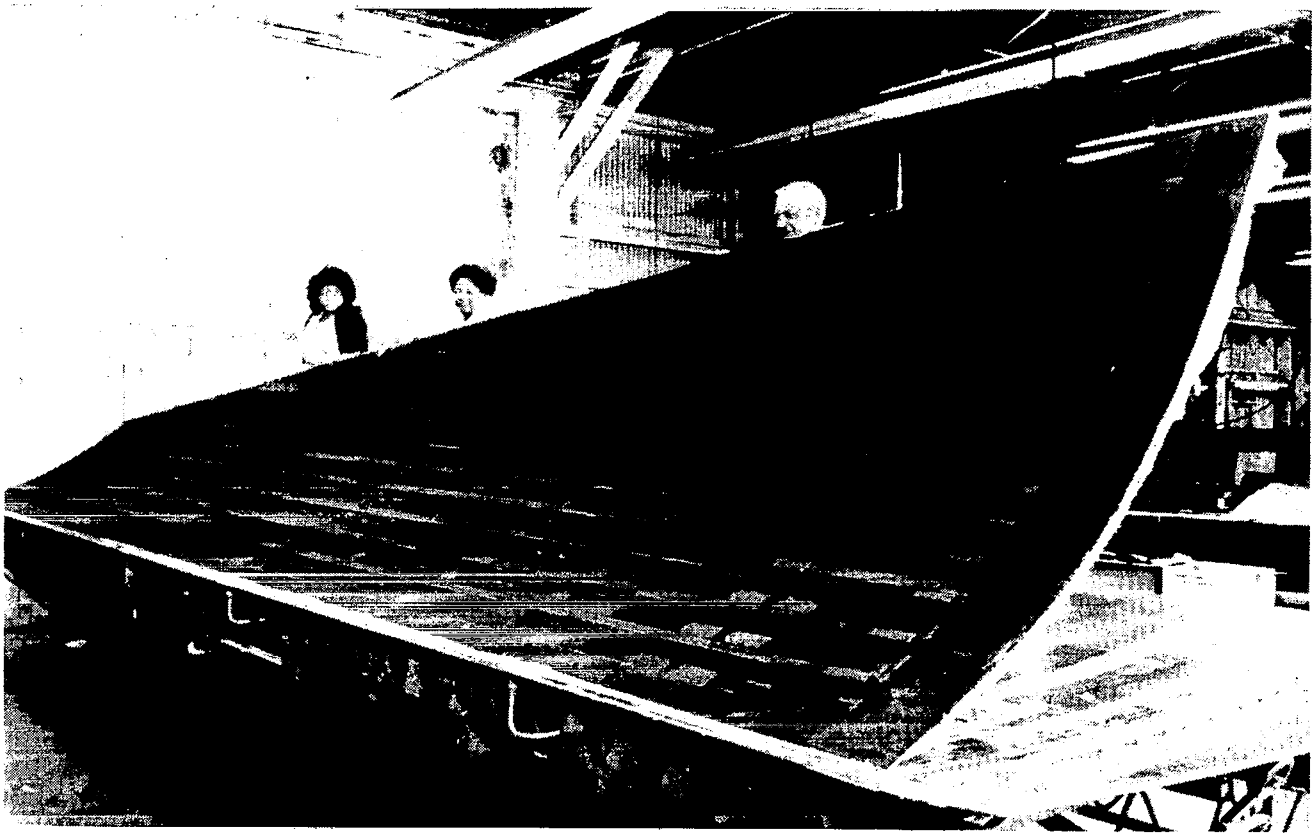
ACVF COVER FABRICATION

After the ACVF components are laid up, densified, and cured they are removed from the autoclave. The vacuum bag assembly for the fin cover shown in the figure has been removed and the inflatable rubber mandrels utilized for presurization of the hat stiffened elements during cure are being removed.



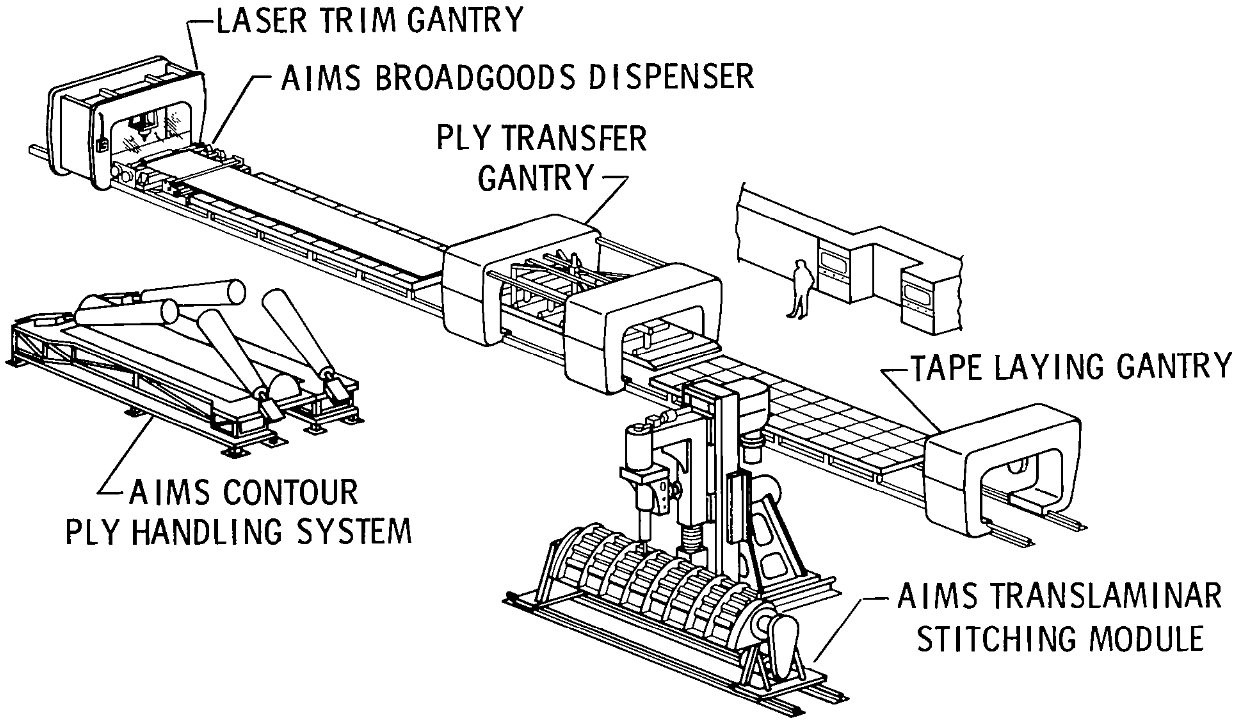
COMPLETE GRAPHITE/EPOXY ACVF COVER

The graphite/epoxy ACVF cover skin with integral cocured hat stiffener elements is shown being removed from the autoclave cure tool. After removal from the tool, the covers are subjected to a complete ultrasonic scan inspection to ensure that the part is free of voids, delaminations, or other anomalies that may affect structural integrity. The skins are then machined for mechanical attachment to the rib and spar assemblies.



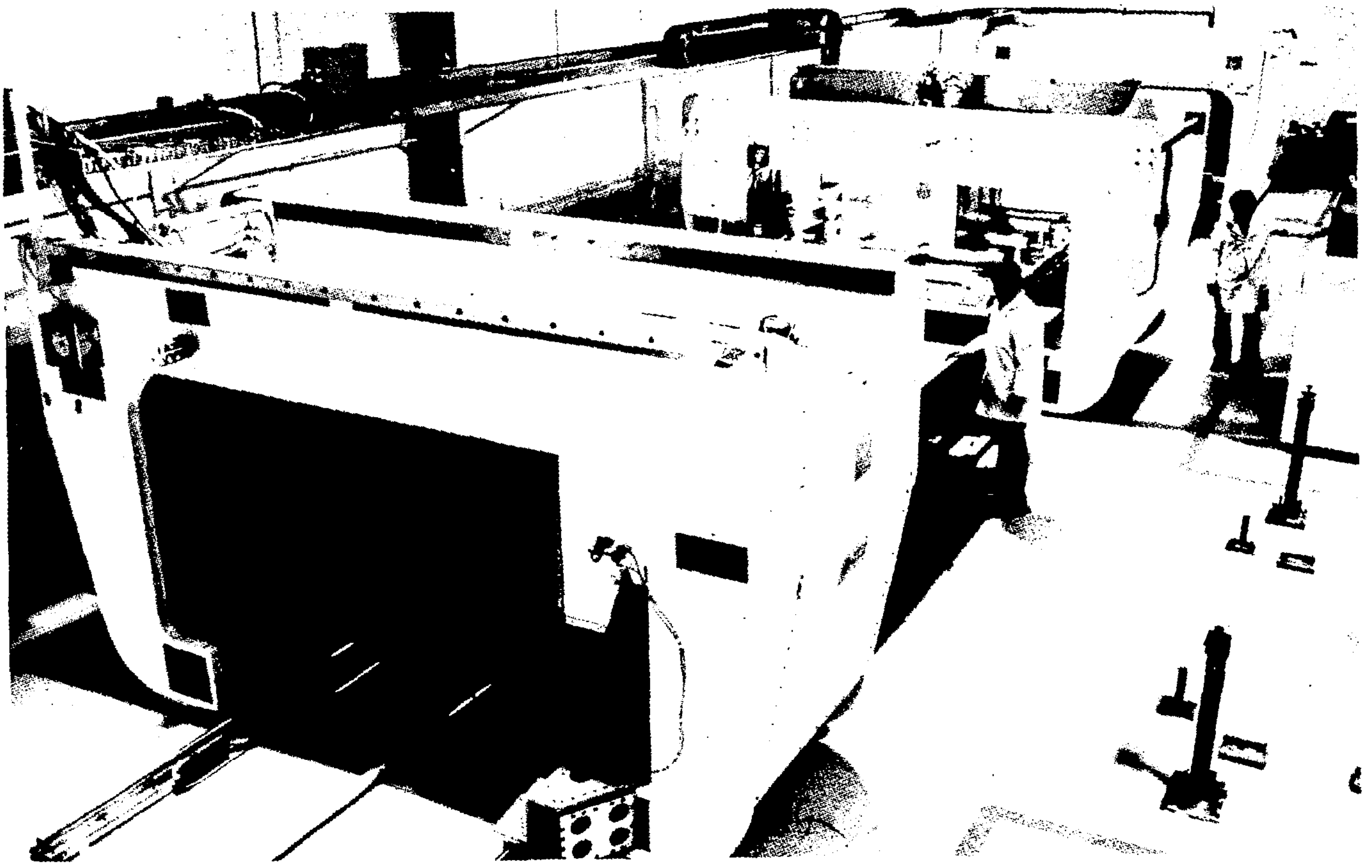
AUTOMATED INTEGRATED MANUFACTURING SYSTEM

During the 1970's, as composites became more generally accepted, the need for mechanized equipment to fabricate severely contoured, integrally stiffened, complex structures for aircraft was identified. This led to the development and implementation of a number of automated composites processing centers in the aircraft industry. The Automated Integrated Manufacturing System (AIMS) shown in the figure was developed by the Grumman Aerospace Corporation under Air Force sponsorship. This system has the capability to automatically dispense and laser trim composite tape and broadgoods. The prepreg details can then be automatically transferred to a contour ply handler or translaminar stitching machine for final layup and assembly into structural articles.



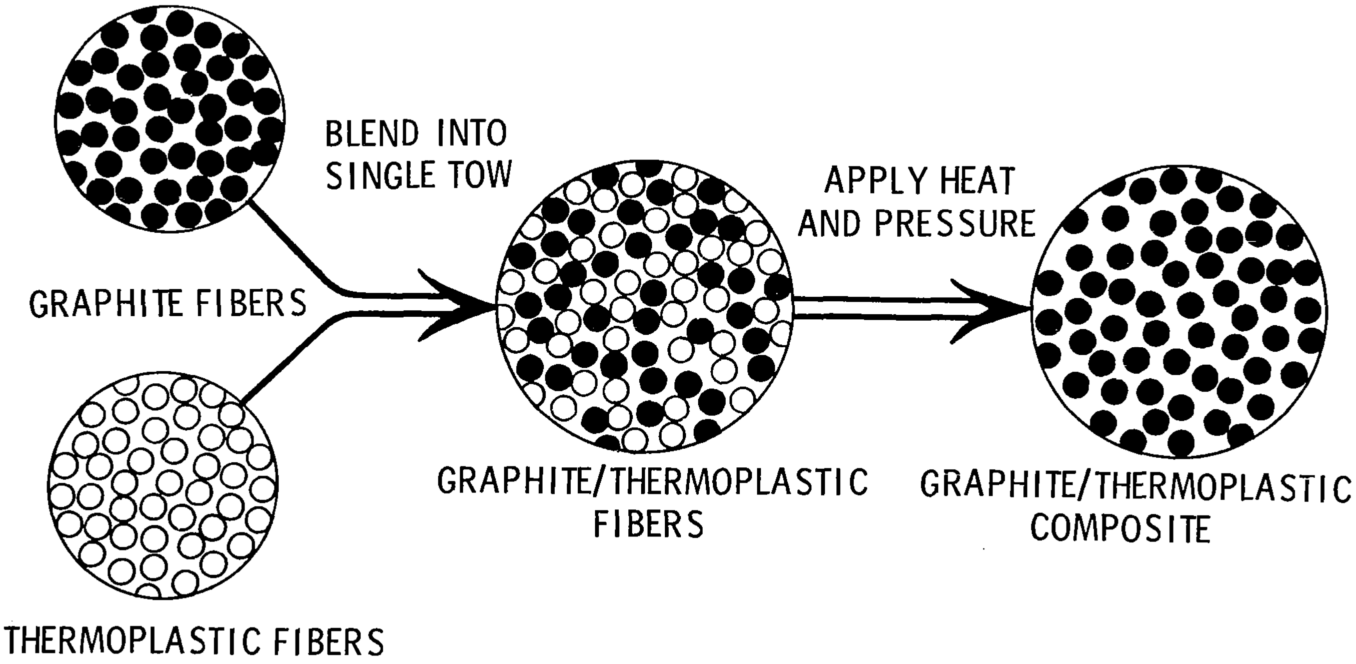
INTEGRATED LAMINATING CENTER

The heart of the Grumman AIMS is the Integrated Laminating Center which is comprised of three traveling gantrys and two separate layup racks. The composite tape or broadgoods are dispersed onto the appropriate rack and trimmed by the laser trim gantry. The composite details can then be removed by the ply transfer gantry and placed on the appropriate layup tool.



HOT MELT FUSION COMPOSITES

The state of the art for fabrication of fiber reinforced thermoplastic composite materials requires the impregnation of the reinforcement fiber with thermoplastic polymers that have been placed in solution with appropriate solvent systems. The matrix polymer materials that lend themselves to being placed in solution for impregnation naturally have limited resistance to exposure to various solvents after fabrication of a structural article. One obvious solution to this problem is to utilize a solvent-resistant polymer matrix material for impregnation of the composite. Since these matrix materials cannot be readily placed in solution, the reinforcing fibers must be impregnated by some form of hot-melt fusion of the matrix polymer. Performing this function by coating the fibers with films has met with limited success due to the inability to penetrate fiber bundles with the high-viscosity, solvent-resistant matrix materials. The technique of blending reinforcing fibers with nearly equal dimater thermoplastic matrix fibers is under investigation in the Materials Division at Langley Research Center. Preliminary results with laboratory-scale graphite/PBT thermoplastic composites fabricated in this manner indicate that very good wetting of the reinforcing fiber with the matrix fiber takes place during application of heat and pressure to form the composite. Work is under way to scale this technique up to fabricate broadgoods with graphite/thermoplastic PBT tows and subsequently manufacture structural articles from the graphite/PBT cloth.

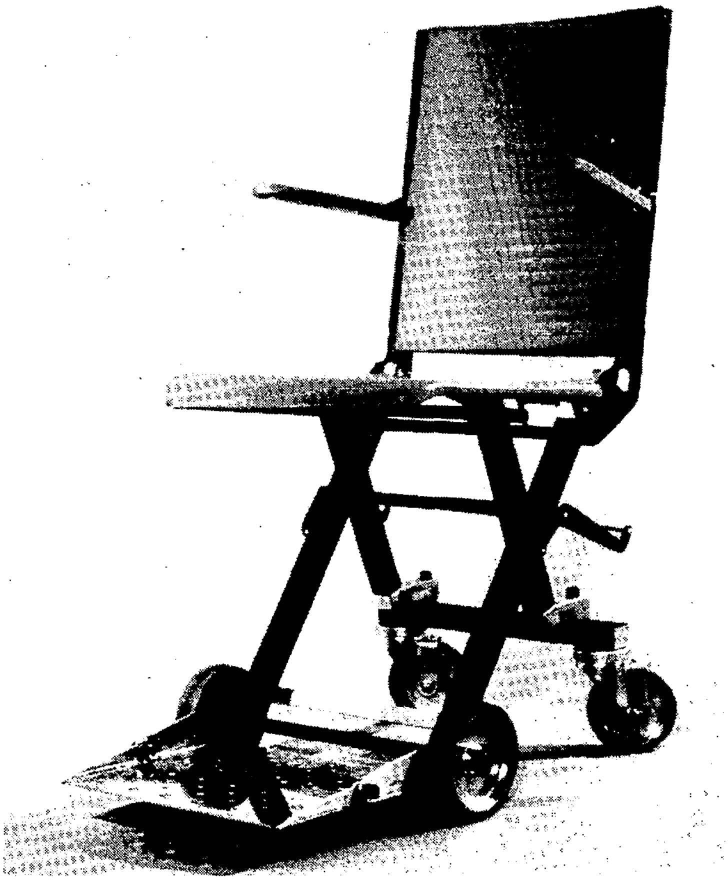


KEVLAR/EPOXY FACEGUARD

One physical impairment that frequently occurs as a result of cerebral palsy is the onset of seizures ranging from very mild to violent. Uncontrolled falls frequently result from these seizures which, without proper protection, can cause serious injury to the upper body and facial area of a person. One of the standard protection devices for uncontrolled falls is a helmet very similar to a football linemans' helmet. Due to the very heavy weight of this type of helmet, patients often refuse to wear them, which in turn eliminates the protection afforded by the helmet. A prototype Kevlar/epoxy protective face protection mask was fabricated at Langley for the boy shown in the figure. The mold for the mask was made from plaster and four plies of epoxy-impregnated Kevlar cloth were applied to the mold. After curing the mask it was removed from the plastic mold and the mouth and eye openings were cut. The resultant weight of this composite mask was 4 ounces compared to approximately 2 pounds for the football lineman's helmet. The patient in the figure has freely worn the Kevlar/epoxy mask for more than a year and has sustained no injuries in this time period. Prior uncontrolled falls without protection had resulted in several serious injuries to this patient including multiple jaw and nose breaks and loss of several permanent teeth.

COMPOSITE WHEELCHAIR PROJECT

NASA Langley Research Center and the University of Virginia Rehabilitation Engineering Center are working together to design, fabricate, and evaluate a durable, lightweight composite wheelchair for general use. The graphite/epoxy wheelchair shown in the figure was the forerunner for the current NASA/UVA effort. All of the major structural components for the wheelchair in the figure were fabricated from graphite/epoxy to develop confidence in the fabricability of wheelchair elements from composites. This wheelchair was designed to transport invalid passengers aboard aircraft. The current general-use wheelchair under development will employ a variety of composite materials in its construction. The side, seat, and foot rest elements will be fabricated from a composite system composed of graphite/epoxy and Kevlar/epoxy hybrid skins bonded to each side of a special high strength inert polyimide foam core. This structurally efficient composite system has been subjected to a variety of bending and flexural tests to identify the optimum combination of elements. The target weight for the composite wheelchair is 25 pounds, whereas conventional general-purpose metal wheelchairs weigh over 50 pounds. Three prototype composite wheelchairs are scheduled to be completed by March 1983 for structural and clinical evaluation.



SUMMARY

Composite materials processing at Langley Research Center encompasses a wide variety of concepts and applications ranging from the construction of exotic models for research to the computer-assisted identification of critical molecular changes in polymer systems during cure. Along with the research support functions performed by highly specialized technicians, research is continuing in composite materials processing to identify and provide the concepts necessary to fabricate low-cost, reliable, and efficient structures. Facilities are continually being updated to provide support for this research. New composite systems formulated in-house are assessed on a continuing basis to establish their utility for a variety of commercial and aerospace applications.

CURRENT TECHNOLOGY

- ESTABLISHED FABRICATION PROCEDURES
- FLIGHT QUALITY COMPONENTS PRODUCED

FUTURE EMPHASIS

- AUTOMATION OF COMPOSITE PROCESSING
- PROCESSING TECHNIQUES FOR ADVANCED RESINS

SPINOFF

- BIOMEDICAL
- SPORTS
- TRANSPORTATION