TECHNICAL REPORT 4240

PROGRESS REPORT OF COOPERATIVE PROGRAM
FOR
DESIGN, FABRICATION, AND TESTING
OF
GRAPHITE/EPOXY COMPOSITE
HELICOPTER SHAFTING

BY
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OCTOBER 1971

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Technical Report 4240

PROGRESS REPORT OF COOPERATIVE PROGRAM FOR DESIGN, FABRICATION, AND TESTING OF GRAPHITE/EPOXY COMPOSITE HELICOPTER SHAFTING

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ABSTRACT

Picatinny Arsenal, NASA/Langley Research Center, and the U. S. Army Air Mobility Research and Development Laboratory have cooperated in a joint effort to demonstrate the applicability of graphite/epoxy composite technology to the fabrication of a UH-1 helicopter tail rotor drive shaft. Progress thus far has produced seven tubes in the preliminary fabrication phase of the work, and partial testing has been accomplished on three shafts made from these preliminary tubes. Fabrication techniques have been sufficiently improved to eliminate wrinkles due to lack of precure compaction. Although not conclusive, test results are encouraging, since they tend to confirm design analysis of the adhesive bond between aluminum end couplings and the composite tube, and to indicate that tests of later, improved shafts will confirm that composite shafting can meet performance requirements. The ultimate program objective is to confirm predicted weight savings by flight testing a standard length shaft specimen and a longer one built to the design extreme of the best composite commercially available.
INTRODUCTION

The Army Materiel Command is interested in composites of graphite fiber and epoxy resin because this class of materials possesses properties unattainable in structural materials commonly used today. Graphite fiber/epoxy composites, now commercially available, are significantly stiffer on an equivalent weight basis than metals commonly used in structural applications. High thermal and electrical conductivity, a damping capacity greater than that of aluminum, and ease of fabrication and machining are other important physical properties which add to the value of graphite/epoxy composites as materials for military items.

The actual performance of this material can, of course, be best demonstrated by fabricating a part and testing it in actual application. To this end, the Materials Engineering Laboratory (MEL) at Picatinny Arsenal has teamed up with NASA/Langley Research Center and the Langley and Eustis Directorates of the U. S. Army Air Mobility Research and Development Laboratory (AAMRDL). In April 1970, a cooperative program was initiated to demonstrate the applicability of the state of the art in composite technology to an existing helicopter tail rotor drive shaft. To accomplish this, it was planned to design, fabricate, and test a number of graphite/epoxy and graphite/epoxy reinforced aluminum shafts for the UH-1 helicopter.

The design and testing functions are being accomplished by NASA, and the tubes are being fabricated by Picatinny Arsenal. The design requirements are being furnished by AAMRDL. Final testing will be flight experience to demonstrate graphite/epoxy composite suitability to future helicopter designers. Once this assurance level is attained, a natural next step will be the construction and testing of an even longer shaft to the design limitations of the material so as to confirm predicted weight savings. As funds and time permit, additional testing of shaft segments after outdoor exposure is planned.

As Army fabrication expertise has been gained, the quality of commercially available fiber has been upgraded, and its price has been reduced. Consequently, even newer and improved weight savings at still lower cost can be predicted. These newer savings would be demonstrated in the same manner as described above.
Fig 1  All-composite, No. 5 THORNEL 50S/ERLA 4617 drive shaft segment with adhesively bonded aluminum end couplings
Three shaft design cycles have been performed, and at least one more is planned for minimum weight optimization purposes. One practice E glass/polyester, five THORNEL® 50S(graphite)/epoxy, and one MODMOR® I/epoxy shafts have been fabricated to identify the problems associated with fabrication of a tube over a male mandrel. Graphite prepreg materials have been provided to MEL by the Army Materials and Mechanics Research Center (AMMRC). As of this writing, an additional quantity of MODMOR I prepreg is being procured by AMMRC in order that the projected program may be completed.

As of 1 May 1971, three shafts have been furnished to Langley Research Center (LRC): One fiber glass/polyester and two made from THORNEL 50S/epoxy. Bench tests of the glass/polyester and the No. 1 THORNEL 50S shafts confirm the adequacy of the adhesive bond between the aluminum end coupling and the composite tube and give encouragement that all performance requirements will be met in later specimens.

The fiber glass/polyester and No. 1 THORNEL 50S shafts have been nondestructive evaluation (NDE) inspected and loaded to failure in torsion. The No. 5 THORNEL 50S shaft, shown in Figure 1, has been NDE inspected, vibrated to determine its natural frequency, and is currently undergoing instrumentation for determining the compression and shear moduli. After determining the moduli, a cyclic loading of 0 to 3,600 in. -lb will be applied for $10^7$ cycles.

EXPERIMENTAL PROCEDURE

Composite Shaft Design

Shaft performance criteria were provided in preliminary form by Eustis/AAMRDL in their letter of 27 March 1970, and by Bell Helicopter Company in June 1970 telephone conversations. Later, Eustis/AAMRDL provided more definitive guidelines in their letter of 28 January 1971. Initial composite tube design by LRC was based on the Bell Helicopter Company guidance and THORNEL 50S/ERLA 4617/MDA^1 composite. This design was changed to reflect the Eustis/AAMRDL

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^1 Union Carbide Corp. graphite fiber and epoxy resin cured with methylene dianiline (MDA)
letter of 28 January 1971, as well as a changeover in composite material to MODMOR I/ERLA 4617/MDA, but also to facilitate fabrication procedure. Most recently, LRC has begun to optimize the design for minimum weight. Total helicopter weight saving resulting from substitution of graphite composite shafting for aluminum is expected to derive from three sources: Elimination of bearing supports, of fuselage reinforcement where bearing supports are now used, and of nose ballast required now to counterbalance the weight behind the center of gravity. Preliminary studies of potential weight savings show that a graphite composite shaft train is attractive if the current $55 \times 10^6$ psi modulus fiber (MODMOR I) is used, and even more so if $75 \times 10^6$ modulus fiber is considered.

The UH-1D helicopter tail rotor drive shaft has two different length segments of 23.0 and 63.0 inches between supports. The longer shaft segment is critical in all design conditions; consequently, both length segments are being fabricated to the requirements for the long one. Original aluminum design requirements as outlined by Eustis/AAMRDL and Bell Helicopter Company were that the shaft would not fail prior to gearbox failure (575 horsepower) and would be free of vibration at 4,300 rpm. The outside diameter of the composite tube, if made to the same diameter as the aluminum one, could be adhesively bonded to the same aluminum end coupling which is currently being riveted to the aluminum tubing. Stress analysis of an adhesively bonded joint confirmed that it had a safety factor of about 9.0. Such a design would have the further advantage that a standard length composite shaft could be installed in a helicopter with the same ease as making a maintenance replacement with the current aluminum part. Copy of Figure 193 in TM-55-1520-210-35P, contained in Appendix A as Figure A1, depicts the tail rotor drive shaft train and coupling details of the current UH-1 helicopter.

Incorporation of a spring segment in each bearing/coupling assembly essentially eliminates axial tension and compression forces so that critical design parameters are reduced to shaft windup and torsional buckling. Based on material properties of THORNEL 50S/ERLA 4617/MDA and Bell Helicopter's performance requirements, LRC used a computer program to make a recommendation to MEL for the composite tube ply configuration. Using laminate code as described in

2Developed by Cheng and Ho, Case Western Reserve University
the AFML "Design Guide", angularity of ply orientation in degrees is described as \((90/45/0/-45/90)_{T}\). Reading from left to right, the ply sequence proceeds from the outside to the inside of the tube layup. Zero degrees of ply orientation describes a ply whose fibers run parallel to the axis of the tube, 90° one whose fibers run circumferentially or perpendicularly to that axis. Reconsideration of the unidirectional composite properties used to derive this configuration prompted a change in the input data, and the program was rerun. The corrected configuration then became a six-ply laminate of \((90/45/0/0/-45/90)_{T}\).

Program design discussions had earlier established the desirability of evaluating a graphite overwrap configuration where approximately half the wall thickness of an existing tube would be milled from the outside of the tube and replaced with the higher modulus graphite composite. Running of the Cheng and Ho torsional buckling program and other design mode checks yielded an orientation for this reinforced aluminum concept of \((60/-60/0/0.020"\text{ aluminum})_{T}\).

When MEL encountered wrinkling problems in the graphite tube fabrication, the ply configuration of the all-composite version was changed to \((80/-45/15/-15/45/80)_{T}\) to accommodate filament winding of the entire tube.

In January 1971, Eustis/AAMRDL furnished the following design criteria:

1. The critical shaft speed should be at least 5,400 rpm, which is 1.25 times the design maximum rotor speed, 4,300 rpm, power on and off. This provides a 15 percent margin at the design limit, power off, rotor speed of 4,830 rpm; thus the critical speed mode should be adequately damped.

2. A rotating shaft test is considered mandatory.

3. The shaft and couplings should be free of catastrophic failure for all statically applied torques to 6,950 in.-lb.

4. The shaft windup, under the limit torque of 4,620 in.-lb, should be within ± 5 percent of 3.91 degrees.

5. To substantiate fatigue life, a constant amplitude fatigue test of \(10^7\), on-off load cycles of a torque of 3,620 in.-lb would be sufficient.
6. An additional requirement used in this design was suggested by Bell Helicopter Company. It specified that the shaft must carry 600 horsepower (9,152 in.-lb of torque).

This changed the design problem from being buckling critical to torsional windup critical. The ± 0.2° on the torsional windup put a severe restriction on the shear stiffness ((thickness (t) x modulus of rigidity (G)) tolerance, which required a redesign of the shaft. Furthermore, the material to be used in the evaluation test specimens was changed to MODMOR I/ERLA 4617/MDA. Since the shear stiffness of the composite must match that of the aluminum shaft, it was decided to begin with a composite orientation that would produce the maximum composite shear stiffness and still be close to that of the aluminum shaft. The Cheng and Ho program predicted four ± 45° plies of the MODMOR I/4617 composite would yield a shear stiffness of 210,000 lb/in. and an allowable buckling torque of 1,850 in.-lb. This compared with 196,000 lb/in. of shear stiffness for the aluminum shaft and a torsional buckling requirement of 9,152 in.-lb. To improve the shaft buckling strength, various combinations of 0° and 90° plies were added to the above basic orientation. By repeated use of the Cheng and Ho program, the torsional buckling initiation surface described by the lines AB, BC, and CA in Figure 2 was produced as a function of the number of 0° or 90° plies added to the basic four ply ± 45° layup. Figure 3 shows curves made by the intersection of constant torsional load planes with the solid body of unbuckled laminates of Figure 2. Buckling calculations were made for laminates with the 0° plies added to the interior surface of the shaft and 90° plies added to its exterior surface.

From Figure 3 it is obvious that the minimum weight shaft that meets the minimum torsional requirements has a configuration of (90°3/45°/-45°2/45°/0°3)T. In a later run of the program, the shear stiffness of this configuration was reduced from 237,000 lb/in. to 197,000 lb/in. by changing the 45° plies to 58°. This also produced an allowable buckling torque of 12,500 in.-lb and a material (shear) strength allowable of 18,500 in.-lb. At MEL's request, the configuration of

\[ A = 0.715 \text{ reduction factor (test theoretical)} \text{ is used with the Cheng and Ho program} \]
(90_3/58/0/-58/0/-58/0/58)_T was investigated to facilitate fabrication by filament winding. This configuration produced an allowable buckling torque of 18,700 in.-lb. From this it appears possible to reduce the 10 ply layup by choosing the optimum stacking sequence. A computer optimization program (AFML-TR-69-251) written by Chao has been requested from Case Western Reserve University and will be applied in the next reporting period in an effort to select an optimum tube design.

In support of MEL's projection of future work, LRC made a preliminary study to determine the weight savings in the application of 75 million psi modulus graphite fiber. Predictions from this study were that the drive train could be made from this stiffer material in three pieces: Two of 94 inches and one of 87 inches. The ply configuration required was (Og/±30_2)_T, while the reinforced aluminum shaft orientation was (O12/0.020 Aluminum)_T. From the above optimization efforts with the MODMOR I/4617 composite, it would appear that use of the Chao optimization program might produce even more favorable results from use of the 75 million psi modulus fiber.

Test Program

A test program has been designed to give the maximum information on shaft performance under simulated flight conditions. In the interest of conserving expensive graphite fiber, most of the bench testing will be performed on short shaft segments (23.0 inches between supports, 18.651 inches from end to end of couplings, and 17.2 inches of composite tubing). A summary of the test program is shown in Table 1. The data listed in that table do, however, not include those pertaining to the preliminary shafts made to date. Concurrently with the composite and reinforced aluminum shaft testing, identical aluminum parts will be tested to provide a standard for data evaluation. All shafts will receive NDE inspection prior to any testing to verify continuity of the end coupling adhesive bond and to discover any voids in the composite, which could cause premature failure.
Fig 2  Design surface of torsional buckling initiation for basic ± 45° four-ply laminate strengthened with additional plies at 0° and 90°.
Fig 3  Torsional buckling response of basic ±45° four-ply laminate strengthened with additional plies at 0° and 90° for constant torsional load or for constant weight.
### TABLE 1

**Shaft test program**

<table>
<thead>
<tr>
<th>Number of Specimens</th>
<th>Shaft Length</th>
<th>Tests to be Performed (in Order of Sequence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Short</td>
<td>(a) Natural frequency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b) Measure axial compression modulus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(c) Measure shear modulus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(d) Torsion test to failure</td>
</tr>
<tr>
<td>3</td>
<td>Short</td>
<td>(a) Measure moduli</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b) Natural frequency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(c) Fatigue cycling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(d) Natural frequency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(e) Measure moduli</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(f) Torsion - failure</td>
</tr>
<tr>
<td>3</td>
<td>Short</td>
<td>(a) Sustained loading</td>
</tr>
<tr>
<td>1</td>
<td>Long</td>
<td>(a) Natural frequency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b) Torsion - failure</td>
</tr>
<tr>
<td>1</td>
<td>Long</td>
<td>(a) Natural frequency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b) Rotational test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(c) Torsion - failure</td>
</tr>
</tbody>
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Assuming the data generated in this testing confirms the suitability of either or both the all-composite or the reinforced aluminum shaft, efforts will be directed toward having a standard or "long" specimen flight tested in a UH-1 helicopter. Figure 4 delineates time frame sequencing of project events. Time zero is the point when MEL receives the necessary MODMOR I/ERLB 4617/MDA graphite prepreg. At this writing, a potential supplier has responded to a request for quotation, but the order has not been issued as yet.

**Tube Fabrication**

Fabrication of the graphite composite tube on a male mandrel was selected as the preferred method because it required the simplest tooling and offered the prospect of being the lowest cost technique in volume.
Fig 4  Development program for graphite composite helicopter shaft
production operation. Several misadventures were encountered in the process of producing a successful wrinkle-free part; but changing from a hand layup of pieces cut from broadgoods prepreg to a tape wrapped product and use of a heat shrinkable nylon tape proved the means to the end of better precure compaction, lack of which had been the cause of most of the wrinkling problem. Experience in winding excessively sticky prepreg tape prompted the development of a prepreg tape specification; and this, in turn, is now, hopefully, the means for procurement of additional tape wholly suited for this application. Curing the laid-up tube proved to be a bit of a problem since an autoclave consistent with Picatinny safety regulations was not available. Substitution of a vacuum bag/oven cure schedule is apparently satisfactory. Although a small amount of data from Fiberite, Inc., suggests the properties of an autoclave cured part to be superior to those of a vacuum bag/oven cured part, the small amount of shaft testing accomplished thus far indicates that the vacuum bag/oven cure is satisfactory for this application. Figure 5 is a chart showing both cure schedules. Temperatures shown are from a thermocouple taped to the outside of the nylon film vacuum bag. Figure 6 is a sketch of the mandrel assembly used. Figures 7 and 8 are photos of the assembled and disassembled mandrel with threaded rod for mounting in a filament winding machine. Although this mandrel was used in the fabrication of tubes for "short" shafts, the same kind of a mandrel in greater length will be used for fabrication of tubes for "long" shafts.

E Glass Practice Tube

In order to conserve expensive graphite prepreg, a practice shaft was first made from E glass cloth and polyester resin in prepreg form. The exact shape and size of each ply was calculated and laid out on polyethylene sheeting (10-mil thickness) which then was used as a template for cutting the desired piece of prepreg. The template also was useful as a carrier for the prepreg while it was being applied to the mandrel or the previously applied ply. The layup for the glass/polyester tube consisted of six plies of 45° alternated plus and minus in direction. Following layup and removal of the mandrel from the filament winding machine, the threaded rod and end pieces were removed from the mandrel to prepare for curing. Pieces of silicone rubber cut to the proper size were plugged into each end of the mandrel, one of the plugs having previously been fitted with a glass tube to which the vacuum hose was attached. The plugged mandrel was wrapped in polyvinyl alcohol (PVA) film and clamped at each end around the silicone
rubber plugs by means of hose clamps. This assembly then was placed in a 260° F oven for one hour, while a vacuum of about 27 inches of mercury was applied.

After cooling the cured part to room temperature, it could not be stripped from the mandrel even though the mandrel, prior to layup, had been sprayed liberally with Teflon release agent. Stripping finally was accomplished by first placing the tube and mandrel in a dry-ice box for one hour, followed by warming of the tube with a heat gun. Expansion of the tube due to warming produced sufficient difference in diameter between it and the mandrel to allow easy removal.

No. 1 THORNEL 50S Tube

In an effort to avoid the tube stripping problem encountered with the glass/polyester tube, the mandrel was acetone cleaned, degreased with spray degreaser, and again liberally sprayed with Teflon release spray. Before beginning the graphite layups, one layer of Teflon coated fiber glass cloth\(^4\) was taped to the mandrel. Dimensions of polyethylene templates were calculated as in the making of the glass/polyester tube, and plies were cut from THORNEL 50S broadgoods (warmed to room temperature from -40° F storage in a sealed plastic bag). Ply configuration was \((90/+45/0/0/-45/90^\circ)\) where \(0^\circ\) is parallel to the tube shaft, and the first \(90^\circ\) ply is the outside of the tube. The \(90^\circ\) plies were applied by cutting them in one-inch-wide strips in order to stagger the joints. In effect, each \(90^\circ\) ply was a series of 18 one-inch-wide bands of prepreg butted next to each other. Trouble was encountered in applying \(0^\circ\) plies because of the prepreg tackiness. Once the piece was stuck to the previous ply, it was virtually impossible to take it up again (to correct a slight misplacement). The negligible transverse strength of the broadgoods made smoothing in this direction difficult. The result was to have two plies which were not well compacted and fitted to the previous plies at all places.

After layup of the six plies described above, one ply of Teflon coated fiber glass\(^4\) (bleeder cloth) was taped on to allow for excess resin bleed-off. One ply of No. 181 fiber glass cloth was taped on top of the bleeder cloth to allow for additional bleed-off.

\(^4\) Fluoropeel No. 3 from Dodge Industries, Inc., Hoosick Falls, New York
Fig 5  Autoclave and oven cure schedules, ERLA/ERLB 4617/MDA
MACHINE DIAMETER TO 2.5 + 0.000, - 0.010, 2 PLACES. NOTE: END PCS. & ALUM. TUBING TO SLIDE FIT.

CHAMFER ALL EDGES

3/4 THREADED STEEL ROD, 10 THREADS/IN.
NOTE: SUPPLY 2 HEX NUTS & 2 WASHERS

DRILL FOR SLIDE FIT WITH 3/4 THREADED ROD

MACHINE FROM APPROPRIATE ALUMINUM ROD

3 IN. ALUMINUM TUBING WITH 0.250 WALL. MACHINE O.D. TO 2.865, + 0.000, - 0.010; I.D. TO SLIDE FIT WITH END PIECES.

CONICAL HOLE, 1/2 DEEP x 60° TAPER

Fig 6 Mandrel assembly
Fig 7  Aluminum mandrel assembly ready for prepreg layup when mounted in filament winding machine
Fig 8. Aluminum mandrel assembly disassembled to show ends and threaded rod for mounting in filament winding machine.
A nominal three-inch diameter, heat shrinkable Teflon tube was slipped over the layup and shrunk on to it by means of a heat gun. The Teflon tubing, by clamping hose clamps over its ends and the silicone rubber plugs as was done in curing the fiber glass/polyester tube, was made to serve in lieu of PVA film as a vacuum bag. This scheme, however, did not work satisfactorily in the autoclave because the combination of vacuum on the inside of the bag and 100 psi pressure on the outside forced the rubber plugs inside the mandrel, thus breaking the pressure differential which existed between the outside and inside of the shrink tubing. Cure of the shaft was accomplished in Sikorsky Aircraft Company's autoclave at their Bridgeport plant because, as stated above, an autoclave consistent with applicable safety regulations was not available at Picatinny. Except for the implosion of the silicone rubber plugs approximately 55 minutes into the cure schedule and slightly higher than planned temperature in the latter part of the schedule, the cure followed that shown for an autoclave cure in Figure 5.

Difficulty was experienced in stripping the tube from the mandrel in spite of precautions taken. Even the chilling-heating treatment was unsuccessful. Separation finally was achieved by pounding the mandrel through the tube while it was held by an aluminum ring machined to hold the tube, but pass the mandrel. The ring rested on a pipe which also was larger in diameter than the mandrel. Stripping resistance was attributed mainly to a gathering of the inner ply of Teflon coated fiber glass which created a wedging action between the tube and the mandrel.

Several large wrinkles on the outside of the cured tube and oriented parallel to the axis of the tube gave visual evidence that the tube probably would fail at less than design loads. Figures 9 and 10 are close-up photos of these wrinkles, which were attributed primarily to the 0°ply compaction problem described earlier. Data taken on the trimmed 17'' length were:

<table>
<thead>
<tr>
<th>Diameter Measurements, each end</th>
<th>Weight</th>
</tr>
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<tbody>
<tr>
<td>ID (inches)</td>
<td>OD (inches)</td>
</tr>
<tr>
<td>2.869</td>
<td>2.965</td>
</tr>
<tr>
<td>2.863</td>
<td>2.975</td>
</tr>
</tbody>
</table>

5From Penn Dixon Corp., Holley Street and Madison Avenue, Clifton Heights, Pennsylvania 19018
Improvement objectives in the making of this tube were to (a) facilitate removal of the tube from the shaft, and (b) eliminate the wrinkles. Heat shrinking a nominal three-inch Teflon tube on the mandrel was the proposed solution for the tube removal problems, and careful application of the 0° plies in one-inch-wide strips that for the problem of eliminating the wrinkling. In order to reduce the number of strips to be applied, LRC was consulted for an alternate ply orientation to eliminate the 90° plies. Their recommended equivalent performance alternate was (+60/-60/0/0/+60/-60°). Layup procedure involving polyethylene templates was followed in the same manner as in the case of the No. 1 THORNEL 50S tube, except for the above mentioned technique for handling 0° plies. Plies 3 and 4 went down much better than had been the case in the previous tube. Although somewhat slower, progress was certain and sure. Sufficient confidence was gained in applying these plies to prompt a change in plan and apply the No. 5 and No. 6 ply in the same manner. Only the orientation of the first one-inch strip at a 60° angle was difficult.

Fluoropeel No. 3 and No. 181 glass cloth were applied for resin bleed-out purposes as in the previous tube. This was followed by a heat shrinkable polyethylene tubing (irradiated to give cross-linking of the polymer) in lieu of the previously used heat shrinkable Teflon tubing because the former was much cheaper than the latter. Unfortunately (and contrary to experience with Teflon tubing), the polyethylene tubing shrank in the lengthwise direction as well as circumferentially, thus leaving both ends of the tube uncovered by about 3/4". Some difficulty was experienced in getting a uniform shrinkage of the tubing, probably because the tubing used was four inches in diameter. (The nominal three-inch diameter size was not as large in diameter as the nominal three-inch Teflon tubing and would not slip over the tube layup.)

Mandrel end caps machined from aluminum and fitted with a brass nipple for attachment to a vacuum hose were used this time to overcome the problem of imploding silicone rubber plugs. Figure 11 is a sketch of these caps, Figure 12 a photo showing them in relation to the mandrel. Bleeder cloth outside the prepreg layup, loose fitting end cap, vacuum holes in the conical end cap, and a hollow mandrel combine to provide a vacuum path for excess resin bleed-out when PVA film is sealed around a whole assembly.
Fig 9 Closeup photo of left end of No. 1 THORNEL 50S/ERLA 4617/MDA graphite composite tube showing wrinkles caused by inadequate compaction of plies during layup.
Fig 10 Closeup photo of right end, No. 1 THORNEL 50S/ERLA 4617/MDA graphite composite tube showing wrinkles caused by inadequate compaction of plies during layup
This assembly (including film and sealant) was taken to the Army Materials and Mechanics Research Center (AMMRC) where it was cured in their autoclave according to the autoclave schedule shown in Figure 5. After completing the autoclave cure and removing the vacuum bag and bleeder plies, the part was easily stripped from the Teflon tube covered mandrel. Subsequently, it was postcured in a 330°F oven for 3 1/2 hours. Figure 13 is a photo of the No. 2 THORNEL 50S cured tube showing one of the two small wrinkles running roughly parallel to the axis of the tube. The need for further improvement in compaction during layup was indicated.

Dimensions of the tube pictured in Figure 13 are as follows: The outside diameter varied from 2.997 inches at one end to 3.006 inches at the other. Similarly, the inside diameters were 2.905 and 2.904 inches, respectively. By difference, the wall thickness varied from 0.046 to 0.051 inches.

No. 3 THORNEL 50S Tube

The next step taken to improve ply compaction was to fabricate this tube by tension winding 0.25-inch-wide THORNEL 50S prepreg tape on the mandrel in the model W-1 McClean-Anderson filament winding machine. The part was made of six alternating plus and minus 60° plies in an effort to demonstrate the feasibility of making a wrinkle-free part in this type of machine.

The mandrel was covered with heat shrinkable Teflon tubing as in the case of the No. 2 shaft. A helical pattern at an angle of 61.165° and an advancement rate of 0.253 inches was used. In order to avoid tape crossovers, only one-half of the pattern was used, the graphite tape being cut and the end taped (with masking tape) to the mandrel end piece each time the winding eye came to the end of the mandrel. The eye was moved through the rest of the pattern cycle without graphite, and the cycle repeated until enough lengths of graphite tape had been laid down to cover the mandrel completely. Tape lay-down then was shifted to the other half of the cycle to achieve a negative 60° ply.

Some gaps appeared between tape widths. These were attributed to the machine setting (0.253") and tape hangup in the chrome plated winding eye due to the adhesive tendency of the prepreg toward the
Fig 11  Mandrel end caps for heat cure
chrome surface. Insertion of a polyethylene funnel as a liner in the chrome winding eye abated this problem considerably, but later use of a machined Teflon winding eye proved to be still much superior.

Two plies of Fluoropeel No. 3 Teflon coated glass fabric were wrapped around the tube prior to heat shrinking Teflon tubing over the tube and mandrel.

Mandrel end caps were used as in the case of the No. 2 tube. The assembly was vacuum bagged in PVA film and cured in an oven. Autoclave pressure was deliberately omitted to eliminate another variable in a systematic search for wrinkle sources. Except for the pressure, the autoclave cure schedule of Figure 5 was followed.

After curing, the tube was stripped from the mandrel with ease at room temperature, and subsequently postcured in a 330°F oven for three hours. The part measured 22.5 inches in length and weighed 246 grams (0.542 lb). The outside diameter varied from 3.012 inches at one end to 3.015 inches at the other. The inside diameter measured 2.915 inches at one end and 2.914 inches at the other.

After careful examination of the slight wrinkles visible in Figure 14, it was concluded that they had been caused by wrinkling of the bleeder cloth when the Teflon heat shrinkable tubing had been slipped on. The very slight wrinkle at left center, which runs roughly parallel to the axis of the tube, also is attributed to mark-off and wrinkling of the bleeder cloth.

**No. 4 THORNEL 50S Tube**

Fabrication of this shaft followed the same procedure as in the case of the No. 3 tube, with the following exceptions:

1. Ply orientation was +60/-60/0/0/+60/-60.

2. McClean-Anderson gear ratios were recalculated to yield a winding angle of 59.28° (instead of 61.16°) and an advancement rate (tape width) of 0.238 inches (instead of 0.253).
3. 0° plies were cut from broadgoods and laid on by hand in one-inch strips, and tape was wound under approximately six pounds tension.

4. Two plies of bleeder cloth (Fluoropeel No. 3) in tape form (approximately one-inch wide) were wrapped over the completed lay-up under hand tension (approximating six pounds). Teflon tubing was heat shrunk over this prior to vacuum bagging in two-mil-thick nylon film. \(^6\)

5. A winding eye "doughnut" machined from Teflon was used. It worked quite well.

6. A different cure schedule, recommended by Fiberite, Inc. (oven cure schedule, Figure 5), was used in an attempt to achieve a low void content part without the use of the 100 psi pressure recommended by Union Carbide Corporation.

Figure 15 is a photo of the No. 4 tube following cure. The horizontal wrinkle typical of those seen previously is the longest of five major ones. Since the No. 3 tube had been virtually free of this type wrinkle, it was assumed that they were caused by insufficient compaction of the 0° plies prior to cure. The angular lines are marks from the bleeder cloth tape. This mark-off is not a pronounced surface effect; consequently, it is considered a minor problem. If necessary, the marks can be easily removed with light sanding.

**No. 5 THORNEL 50S Tube**

This tube was fabricated in the same manner as the No. 4 tube, with the following changes:

1. Ply orientation was changed in order to use 15° plies which could be tape wrapped under tension. This was done in order to eliminate the wrinkling caused by poor precure compaction of the 0° plies. On recommendation from LRC, the ply orientation was changed to (-80/+45/-15/+15/-45/+80°).

2. Tape tension was increased to approximately ten pounds.

\(^{6}\)CAPRAN 80 from Allied Chemical Co.
Fig 14  No. 3 THORNEL 50S/ERLA 4617/MDA tape wound tube showing slight wrinkles caused by wrinkling of bleeder cloth when heat shrinkable tubing was slipped over it
3. One-inch-wide woven nylon heat shrinkable tape\(^7\) was wrapped under hand tension after each of the last four plies (-80/45/-15/+15\(^f\)). A layer of Teflon coated glass bleeder cloth was hand wrapped as before (one-inch-wide tape) on top of the nylon tape, and held in place with masking tape.

4. The heat shrinkable Teflon was omitted, the assembly being put in a nylon film vacuum bag as before and cured in the same way as the No. 4 tube.

Following cure, the part was easily stripped of its glass and nylon tapes and from the mandrel. The nylon tape functioned as a bleeder layer and stripped clean from the composite surface. There were no wrinkles; hence, this tube was considered suitable for test at NASA/Langley. It seemed desirable to sand the surface to provide a smooth base for strain gaging because the mark-off from the nylon tape was rather pronounced. The tube was remounted on the mandrel and chucked in a lathe for sanding, first with 120 grit then 240 grit aluminum oxide abrasive cloth. The tube fit so loosely on the mandrel that it had to be taped to it during sanding. The left-hand portion of the tube in Figure 16 is unsanded. The variegated pattern of the right-hand portion of the tube is caused by parts of the +45° ply showing through the -80° ply -- the result of a slightly overzealous sanding job. The variegations were not sensible to the touch.

The data, after sanding and before bonding of metal end couplings, were:

- **Length:** 17 7/32 (17.217) inches
- **I D (either end):** 2.915, 2.914\(^\text{in}\); **O D (3 places):** 2.992 inches
- **Weight:** 165 g (0.364 lb)

**MODMOR I/ERLA 4617 Fabrication**

The fabrication techniques proven successful in making the No. 5 THORNEL 50S tube were next applied to the No. 1 MODMOR I tube, and eventually proved successful again, as can be seen from the photo of this tube shown in Figure 17.

\(^7\)Pattern No. 7282 from Bally Ribbon Mills, 23 North Seventh Street, Bally, Pennsylvania 19503
Fig 16  No. 5 THORNEL 50S/ERLA 4617/MDA tube chucked in lathe on mandrel during sanding
No. 1 MODMOR 1/ERLA 4617/MDA graphite/epoxy composite tube
Since the ply thickness of the MODMOR I prepreg is only 0.0065 inches (compared with 0.008 inches for THORNEL 50S), seven plies were used instead of six, i.e., (+60/0/-60/0/-60/0/+60). The zero plies were purposely alternated as shown, in an effort to determine whether the 60° plies could provide the same compaction of 0° plies as was accomplished with the nylon tape. If they could, it should be possible to eliminate the need for nylon tape, except for the outer wrap after ply No. 7.

A high incidence of tape breakage forced a reduction in winding tension to about six pounds.

The resulting compaction from the 60° plies appeared inadequate, and the plan was changed to revert to the nylon tape wrapping after each ply.

The tape breakage at an 11-pound tension was attributed primarily to excessive handling; i.e., because the tape was wound at low tension on manufacture, it was necessary to pass it over a capstanlike device with the aid of two tensioning devices plus two guide rollers. Passage over so much surface caused progressive fraying and weakening. Part of the breakage incidence was attributed to the extra handling caused by the manufacturer's reprocessing of the tape. Original attempts to wind it were immediately frustrated because of its excessive stickiness. Figure 18 is a photo showing fiber pickup on the tensioning device rollers. The manufacturer's reprocessing reduced the resin and volatiles content of the tape to a workable level, but is thought to have weakened it some from repassage over their rollers.

Concurrently with the manufacturer's reprocessing of this tape, MEL and manufacturer personnel developed a tape specification deemed suitable for the application and practical for future procurement (copy of specification in Appendix B). AMMRC will use this specification to procure approximately 25 pounds of the 35 pounds MEL requested as their estimate of prepreg tape required for making the specimens itemized in Figure 4.

**Graphite Fiber Content**

From accumulated data, Northrop Corporation has determined that the maximum modulus of graphite fiber reinforced ERLA 4617 structures is achieved when the fiber content is in the range of 58-60%.

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8Telephone conversation, C. C. Wright and B. Bowen, Northrop.

See also Table XIV, p 147, Vol I, AFML TR 7-207
by volume. They have found this to hold for MODMOR I, Courtaulds HMS, HT, and Type A fiber.

Portions of each of the THORNEL 50S tubes were tested for fiber content in accordance with the method proposed by Steingeiser and Hanna of Monsanto Research Corporation, Dayton, Ohio (copy in Appendix C). Results of these tests are compiled in Table 2.

**TABLE 2**

Fiber content THORNEL 50S/ERLA 4617/MDA tubes

<table>
<thead>
<tr>
<th>Thornel 50S/ERLA 4617 Tube Number</th>
<th>Specific Gravity</th>
<th>Weight % Fiber by Acid Digestion</th>
<th>Volume % Fiber by Calculation</th>
<th>Average Volume % Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.45</td>
<td>62</td>
<td>55</td>
<td>55.0</td>
</tr>
<tr>
<td>2</td>
<td>1.47</td>
<td>69</td>
<td>63</td>
<td>62.3</td>
</tr>
<tr>
<td>3</td>
<td>1.42</td>
<td>66</td>
<td>58</td>
<td>56.0</td>
</tr>
<tr>
<td>4</td>
<td>1.44</td>
<td>64</td>
<td>57</td>
<td>57.7</td>
</tr>
<tr>
<td>5</td>
<td>1.45</td>
<td>66</td>
<td>59</td>
<td>59.0</td>
</tr>
</tbody>
</table>

Average 1.45

*Density of THORNEL 50S fiber taken as 1.62 g/cc*
From the No. 5 tube fiber volume, it is concluded that the choice of amount of bleeder cloth for the prepreg resin content used was fortuitous.

**Metal End Coupling Bonding**

Initial efforts to bond the aluminum end couplings\(^9\) to a composite tube were begun with the fiber glass/polyester tube described earlier. Hope for use of an epoxy film adhesive was abandoned when it was found impossible to slip the coupling over the adhesive film without buckling it. Success was achieved, however, when using a paste adhesive\(^{10}\) applied to each surface (description in Appendix D). The high flex version was used in the first shafts (fiber glass/polyester THORNEL 50S numbers one and five); but after voids were detected by ultrasonic and X-ray examination of the cured parts, the high density version was procured for subsequent use.

Couplings were surface treated according to the following procedure:

1. Wash couplings with acetone and air dry.
2. Immerse couplings in acid solution of 150-155° F temperature for 10 minutes.
   
   Acid Solution: 1 pbw sodium dichromate  
   10 pbw sulfuric acid (98% reagent grade)  
   30 pbw water
3. Rinse with clean tap water.
4. Spray rinse with deionized water.
5. Dry one-half hour at 140-150° F.

After coating each faying surface with adhesive (tube was covered with masking tape immediately adjacent to the band of adhesive on each tube end), the couplings were slipped on the composite tube, and the assembly was mounted into a curing fixture. Subsequently, the

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\(^9\) Bell Helicopter P/N 204-040-619-3 
\(^{10}\) Scotchweld 2214 from the 3M Company, St. Paul, Minnesota
assembly with fixture was placed in a 250° F oven for 1 1/2 hours. Figure 19 is a photo of the curing fixture, Figure 20 a photo of the No. 5 THORNEL 50S shaft with metal ends bonded and mounted in the curing fixture. Aluminum end couplings were machined on the inside to allow for an adhesive film thickness of approximately 0.015 inches. The No. 5 THORNEL 50S tube with metal ends bonded weighed 433 grams (0.955 lb). The tube before bonding weighed 165 grams (0.364 lb). A production aluminum shaft (including riveted couplings) of the same length as the No. 5 THORNEL 50S shaft weighed 654 grams (1.44 lb).

RESULTS AND DISCUSSION

Although data obtained thus far are restricted to two completed graphite composite shafts, results are encouraging in that the adhesive bond appears adequate in spite of existing voids; and the composite structure appears satisfactory since even a wrinkled tube (No. 1 THORNEL 50S) surpassed the static torque requirement set by Eustis/AAMRDL.

All test setups are currently ready for use, and completion of the full set of tests on the No. 5 THORNEL 50S shaft will serve to confirm their suitability.

Vibration Tests

Vibration tests have been conducted on two aluminum shafts (flight items for purposes of comparison,) and the No. 5 THORNEL 50S graphite-epoxy shaft. The natural frequency, \( f_n \), and damping coefficient, \( C/C_C \), of the lowest frequency structural mode were measured for shafts under the following test conditions:

1. Shaft suspended by strings to simulate free boundary conditions.

2. Shaft mounted in bearings to simulate helicopter supports (Figure 21).

3. Shaft mounted in bearings with motor attached for rotational tests.
The tests reported here were conducted primarily to check out the test setup and to aid in evaluation of any future analytical techniques. The measured natural frequencies and damping coefficients are presented in Table 3.
## TABLE 3
Vibration test results

<table>
<thead>
<tr>
<th>Test Specimen</th>
<th>Test Condition 1</th>
<th>Test Condition 2</th>
<th>Test Condition 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f_n</td>
<td>C/C_c</td>
<td>f_n</td>
</tr>
<tr>
<td>Graphite-Epoxy Shaft No. 5 L = 13.5 in. a</td>
<td>932.6</td>
<td>1.8</td>
<td>1036.5</td>
</tr>
<tr>
<td>Aluminum Shaft L = 13.5 in.</td>
<td>---</td>
<td>---</td>
<td>858</td>
</tr>
<tr>
<td>Aluminum Shaft L = 53.5 in.</td>
<td>---</td>
<td>---</td>
<td>96.8</td>
</tr>
</tbody>
</table>

a Shaft lengths listed above are basic tubular sections between end fittings
Fig 19  Fixture used for holding aluminum couplings in proper position relative to the composite tube while the epoxy adhesive cures
Fig. 20  No. 5 THORNEL 50S/ERLA 4617/MDA tube with aluminum ends bonded and mounted in adhesive curing fixture
Fig 21  Aluminum shaft with test condition 2
These data indicate that the graphite-epoxy shaft has a higher natural frequency than the comparative flight-item aluminum shaft. Damping coefficients measured are similar in magnitude to values published in the open literature for filamentary boron-epoxy and aluminum panels.

The rotational test setup is essentially complete. Only a calibration of the instrumentation for measuring shaft deflections is necessary before tests can be conducted. This setup will be discussed in detail in the next progress report.

**Fatigue Testing**

A torsional fatigue fixture has been fabricated, installed, and checked out on an SF-1U fatigue machine, as shown in Figure 22.

- **Capability:** Torque: ±6,000 in.-lb
  - Deflection: ±.06 radians
  - Frequency: 1,800 cpm
  - Max. specimen length: 19 in. (including end fittings (14 in. basic section between end fittings))

If necessary, longer tubes can be accommodated by installing these fixtures on other fatigue machines. The No. 5 THORNEL 50S graphite shaft will be in fatigue testing early in June 1971.

**Torsion Testing**

The torsional testing will be accomplished on a 60,000 in.-lb capacity Baldwin-Lima-Hamilton testing machine. The glass and No. 1 THORNEL 50S graphite shafts have been tested to failure as part of the preliminary checkout of equipment, bonded end fittings, and test techniques. The glass shaft failed by buckling at 8,200 in.-lb of torque, and the graphite shaft experienced a material failure at 8,500 in.-lb of torque. The sustained loading tests will be performed by applying a static load (limit load) for a period of 1,000 hours.
Fig 22  Torsional fatigue testing machine
Nondestructive Evaluation

**Apparatus and Procedure**

Radiographic and ultrasonic methods were used for the nondestructive evaluation of the fiber glass and the No. 1 and No. 5 THORNEL 50S graphite drive shafts. The radiography was performed using Picker Corporation model 575F (110KVP, 5 ma) X-ray equipment. The tubes were mounted on a fixture which permitted rotation about their longitudinal axes, and the X-ray beam was oriented perpendicular to the axis at the centerline. The film, with lead shielding to prevent back exposure, was placed inside the tubes. A device containing a slit of adjustable width was fabricated from lead and located 2.5 cm from the tubes, in line with the X-ray equipment. The X-ray energy, exposure time, focal film distance, and film were varied as shown in Table 4. It should be noted that some radiographs were obtained with the drive shaft being rotated and others from sequential exposures.

The ultrasonic evaluation was performed using through transmission "C" scan in an immersion system. The equipment consisted of a model 724 Special Budd Immerscope, a Sonofax SR 130 Recorder Adapter and Bridge, and a model 319A Alden Helix Recorder using wet paper. The drive shafts were mounted vertically on a turntable in the water tank. The receiver transducer was mounted vertically within the drive shafts with a 45° reflector to reflect the signal from the transmitter transducer to the receiver. The transmitter transducer was mounted horizontally outside the drive shafts and aligned with the reflector-receiver assembly. The total path distance between transducers was 15 cm. The transducers and parameters for ultrasonic evaluation are listed in Table 5.

All transducers were 1.9 cm diameter focused type except for the 3LXP, which was a nonfocused type 1 cm diameter. It should be noted that the testing frequency was changed to 5MH\(_z\) for the No. 5 THORNEL 50S drive shaft because of shaft vibration at 10 MH\(_z\).

Radiographs and ultrasonic "C" scans revealed several flaws in the drive shafts. Visible in the radiographs of the fiber glass tube are a few high density inclusions about 0.08 cm diameter, a void in the adhesive bonding the end fittings to the tube, and overlaps of cloth layers. The adhesive void was detected also in the ultrasonic scans.
<table>
<thead>
<tr>
<th>Fiber Glass</th>
<th>Graphite No. 1</th>
<th>Graphite No. 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage, KVP</td>
<td>37-38</td>
<td>37-40</td>
</tr>
<tr>
<td>Amperage, ma</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Focal film distance, cm</td>
<td>61</td>
<td>76</td>
</tr>
<tr>
<td>Slit width, cm</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Rotation, rpm</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Exposure time, min</td>
<td>105</td>
<td>120</td>
</tr>
<tr>
<td>Film type</td>
<td>du Pont Cronar 506</td>
<td>Kodak Type M Cronax 510</td>
</tr>
<tr>
<td>Film density</td>
<td>2.4-2.8</td>
<td>0.8-0.9 1.3-1.6</td>
</tr>
</tbody>
</table>

**TABLE 4**

X-ray parameters for drive shaft NDE
<table>
<thead>
<tr>
<th>Fiber Glass</th>
<th>No. 1 THORNEL 50S</th>
<th>No. 5 THORNEL 50S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter transducer</td>
<td>10 MHz, 6LXP-FS</td>
<td>10 MHz, 6LXP-FS</td>
</tr>
<tr>
<td>Receiver transducer</td>
<td>10 MHz, S-64</td>
<td>10 MHz, S-64</td>
</tr>
<tr>
<td>Pulse frequency, pps</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Gate setting</td>
<td>Front face</td>
<td>075 to 007</td>
</tr>
<tr>
<td>Nominal gain setting</td>
<td>1220</td>
<td>5130</td>
</tr>
</tbody>
</table>
The wrinkles that were visually apparent in the No. 1 THORNEL 50S drive shaft were visible also in the radiographs. Large wrinkles were oriented longitudinally and at 45°, small wrinkles circumferentially. Also visible in the radiographs were a large number of dense inclusions (probably metal), indications of some larger diameter fibers with random orientation, and large void areas in the adhesive bonding the end fittings to the shaft. The adhesive voids and wrinkles were detected also in the ultrasonic scans.

The primary flaws detected in the No. 5 THORNEL 50S drive shaft were voids in the adhesive bonding the end fittings to the tube and an apparent disbond or resin starved area in the composite near one end of the shaft. The adhesive voids were more noticeable in the radiographs, the disbond or resin starved area more in the ultrasonic scans. The disbond or resin starved area was generally "T" shaped, with the bar of the "T" (approximately 1.5 cm x 3 cm) under the end fitting, and the leg of the "T" (also approximately 1.5 cm x 3 cm) extending longitudinally down the tube. Radiographs also showed some dense inclusions (probably metal), indications of tape overlaps in some plies, and of small spacings between tape edges in a circumferential ply.

CONCLUSIONS AND RECOMMENDATIONS

A major effort should be made to reduce the weight of the aluminum end fittings now used on the graphite shafts. They are the same fittings as are riveted to the existing aluminum shafts and constitute approximately 60 percent of the total weight. A method of analysis would have to be developed to analyze a bonded torsional fitting with a reduced cross section. More testing would be necessary to demonstrate the adequacy of the redesigned end fitting.

In addition, as indicated in prior sections, future work should be conducted to develop analytically an optimum design computer program; design, fabricate, and test extra long shafts with graphite fibers having a modulus of 75 to 80 million psi; complete the ground test substantiation program; and seek approval for flight service of both standard length and extra long shafts.
APPENDIX A

Shaft Installation, Tail Rotor Drive, UH-1 Helicopter
Fig A1  Shaft installation, tail rotor drive
APPENDIX B

Specification, Graphite/Epoxy Prepreg Tape
1. **Acknowledgment:** Vendor shall mention this specification number and its revision letter in all quotations and when acknowledging purchase orders. Revisions to this specification when made a part of the purchase order will supersede the provisions of this specification.

2. **Purpose:** Primarily for molding into contoured laminates operating at temperatures to 300° F.

3. **Technical Requirements:**

   3.1 **Material**

   3.1.1 Graphite fibers shall be MODMOR I (Whittaker Corp.), Courtaulds HMS (Hercules, Inc.), or equivalent.

   3.1.2 The resin shall be Union Carbide Corp. ERLB 4617, with methylene dianiline (MDA) curing agent or equivalent.

3.2 **Prepreg**

   3.2.1 The prepreg shall consist of fibers per 3.1.1 and resin per 3.1.2 with the properties of Table I.

### TABLE I

**Prepreg Properties (Uncured)**

<table>
<thead>
<tr>
<th>Property</th>
<th>Specification</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatile Content, % by wt.</td>
<td>5.5 max.</td>
<td>4.6.1.1</td>
</tr>
<tr>
<td>Resin Content, % by wt.</td>
<td>32 ± 3</td>
<td>4.6.1.2</td>
</tr>
<tr>
<td>Gel Time, min.</td>
<td>25 ± 6</td>
<td>4.6.1.3</td>
</tr>
</tbody>
</table>
3.2.2 **Shelf Life and Workability of Preimpregnated Materials:**

Unless otherwise specified, the shelf life shall be not less than 3 months (desire 6 months) when material is stored in sealed package at a temperature not higher than 0°F. Each package withdrawn from storage shall be allowed to warm to room temperature prior to breaking its seal, and the material shall have a 4-day minimum period of workability at room temperature. The material may be tested at any time during the storage period for conformance to this specification.

4. **Quality Assurance Provisions:**

4.1 **Quality Control** - The supplier shall maintain, throughout the entire processing of the tape, all necessary quality controls and inspections of basic materials to demonstrate conformance to the requirements of this specification.

4.2 **Inspection and Test Requirements** - The supplier shall be responsible for the performance of all test and inspection requirements as specified by the procuring activity. Except as otherwise specified, the supplier may utilize his own or any other inspection facilities and testing laboratory services acceptable to the procuring activity.

4.2.1 **Inspection Records** - Inspection records shall be kept by the supplier, complete and available to the procuring activity, as specified by the contract or order, where such inspections are deemed necessary to assure that supplies conform to the prescribed requirements.

4.2.2 **Certification** - Each lot of material covered by this specification and delivered to the procuring activity shall be certified by the supplier stating that the components (graphite yarn, resin, and carrier) and processing used in the manufacture of the tape are substantially identical to those used for the preproduction sample.
4.2.3 Test Reports - Along with the certification required in paragraph 4.2.2, the supplier shall furnish with each lot a report stating the quantitative results of tests and inspections performed on representative samples. Both individual and average tests results shall be included. The reports shall include all necessary identification to correlate the inspections and test results with the roll and lot of material and with the purchase order or contract. Deviations from the specified test methods shall be reported and fully explained to the procuring activity.

4.2.4 Processing Data - The supplier shall furnish to the procuring activity all necessary information regarding curing and postcuring schedules, temperatures, and pressure conditions.

4.2.5 Defects - Defects apparent during use not detected during lot acceptance testing shall be cause for rejection of the unused portion of the roll, provided such defect is cause for rejection under the requirements of this specification and is not a result of mishandling, improper storage, or expiration of shelf life.

4.3 Definitions

4.3.1 Roll - For the purpose of this specification, a roll shall be defined as the continuous length material contained on a spool.

4.3.2 Lot - For the purpose of this specification, a lot shall consist of material produced in one manufacturing cycle, under substantially identical conditions, and offered for acceptance at one time. Lot numbers shall be designated by the supplier.

4.4 Sampling

4.4.1 Sampling Plan - Tests for gel time, tensile strength, tape thickness, and width shall be made on each lot of tape. All other tests called for in Table I shall be made in accordance with Table II below:

<table>
<thead>
<tr>
<th>Lot Size (No. of Rolls)</th>
<th>No. of Rolls to be Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>3</td>
</tr>
<tr>
<td>6-25</td>
<td>7</td>
</tr>
<tr>
<td>26-50</td>
<td>11</td>
</tr>
<tr>
<td>51-100</td>
<td>23</td>
</tr>
</tbody>
</table>
4.4.2 Sampling Procedure

4.4.2.1 Remove roll from cold storage, keep in moisture-proof bag, and allow to come to room temperature for a minimum of three hours.

4.4.2.2 Remove roll from moisture-proof bag.

4.4.2.3 Remove enough material from roll to conduct tests.

4.4.2.4 Replace in moisture-proof bag and reseal. Replace sealed roll in cold storage.

4.4.2.5 Test specimens shall be fabricated, and all required tests shall be initiated within 12 hours of sampling.

4.5 Classification of Tests

4.5.1 Classification - The test methods and procedures for the verification of the requirements of this specification shall be classified as follows:

4.5.1.1 Preproduction Tests - The preproduction tests shall consist of all tests listed in Table I.

4.5.1.2 Production Tests - The production tests shall consist of all tests listed in Table II.

4.6 Test Methods and Procedures

4.6.1 Methods of Test for Preimpregnated "B" Stage Material - The methods of test for preimpregnated "B" stage material are as listed in Table I and shall consist of the following:

4.6.1.1 Volatile Content - The volatile content loss percent by weight of the preimpregnated "B" stage material shall be determined as follows:

4.6.1.1.1 Construct a 2" diameter x 6" long tube by rolling a 6"x36" piece of Mylar film (du Pont 200A or equivalent) and stapling the ends. Precondition the tube in a forced air oven maintained at
163 ± 3° F for 20 minutes. Cool to ambient temperature in a desiccator, and weight to the nearest milligram (W₁).

4.6.1.1.2 Wind a minimum length of one yard of roving on the tube. Roving is secured by tucking the ends under the adjacent piece of roving. Do not overlap roving and maintain a minimum gap of 1/4" between adjacent turns of roving. Weigh specimen and tube to the nearest milligram (W₂).

4.6.1.1.3 Suspend tube and specimen in a forced air oven maintained at 163 ± 3°C for 20 ± 0.5 minutes.

4.6.1.1.4 Cool to ambient temperature in a desiccator, and weigh to the nearest milligram (W₃).

4.6.1.1.5 Calculate volatile content as follows:

\[
\text{Volatile content, percent} = \frac{W_2 - W_3}{W_2 - W_1} \times 100
\]

\(W_1\) = weight of preconditioned mylar tube.

\(W_2\) = weight of tube and specimen before volatile removal.

\(W_3\) = weight of tube and specimen after volatile removal.

4.6.1.1.6 Calculate the arithmetic mean of three determinations as volatile content of the sample. Report both individual results and the arithmetic mean.

4.6.1.2 Resin Content - The resin content percent by weight of the preimpregnated "B" stage material shall be determined as follows:

4.6.1.2.1 Run volatile content on a sample cut adjacent to the sample to be used for resin solids. The volatile procedure used shall be as specified in this specification (4.6.1.1).

4.6.1.2.2 Cut a sample of material approximately 3 grams in any convenient size.

4.6.1.2.3 Weigh the sample to the nearest 0.0001 gram. Record this as \(W_1\).
4. 6. 1. 2. 4 Place the sample in a 400 ml beaker. Add 200 ml of DMF (Dimethyl formamide). Boil for 5 minutes. (Time starts when the DMF starts to boil.)

4. 6. 1. 2. 5 Cool sample. Pour off the DMF. Wash sample twice with acetone.

4. 6. 1. 2. 6 Place sample in a tared aluminum foil pan. Dry sample for 30 minutes in an oven maintained at 163 ± 3°C.

4. 6. 1. 2. 7 Cool sample to ambient temperature in a desiccator.

4. 6. 1. 2. 8 Reweigh the sample to the nearest 0.0001 gram. Record the weight as W2. Calculate resin content percent by weight as follows:

\[
\text{Resin Solids (\% by weight)} = \frac{(W_1 - W_1V) - W_2}{(W_1 - W_1V)} \times 100
\]

Where: \(W_1\) = Original sample weight.  
\(W_2\) = Weight of carrier remaining after extraction.  
\(V\) = Percent volatiles (Procedure as called out by the material specification).

4. 6. 1. 2. 9 Calculate the arithmetic mean of three determinations as resin content of the sample. Report both individual results and the arithmetic mean.

4. 6. 1. 3 Gel Time - The prepreg gel time shall be determined as follows:

4. 6. 1. 3. 1 Place about a 1/4"x1/4" sample sandwiched between 2 cover slips on a Fisher Johns melt point meter preset at 170°C.

4. 6. 1. 3. 2 Start timer, and probe specimen with a wooden pick. When resin gels, stop time; and report time to gel.

4. 6. 1. 3. 3 Report the average of 3 determinations.
4.6.1.4 **Tack** - A minimum amount of adhesive tack the prepreg tape should possess when it is warmed to room temperature shall be determined as follows:

4.6.1.4.1 Cut a 1" length of prepreg tape from the roll, and press it against a piece of 0.020" thick Teflon film using moderate finger pressure.

4.6.1.4.2 Hold up the tape/film lamination by the film. If the tape sticks to the film for at least 30 minutes, the tack is considered satisfactory. In the event a piece falls from the film before the end of the 30-minute period, it shall be judged satisfactory if it sticks to the film for 30 minutes upon repressing the same specimen with finger pressure. (Only one repress test permitted.) Failure to meet this test is cause for rejection of the roll from which the sample was taken and cause for increasing the frequency of the tack test to include all rolls within the lot under test.

4.6.1.5 **Tensile Strength** - This method is applicable to the determination of breaking strength of impregnated roving and shall be conducted as follows:

4.6.1.5.1 **Apparatus:**

1. A testing machine (Instron model TCC or equivalent) capable of measuring strength up to 200 lbf at an applied loading rate of 0.50 inches per minute.

2. A lower grip to clamp both ends of the test specimen without cutting the roving samples.

3. An upper 5 3/4 inch diameter X 1 1/4 inch wide steel jig. (One-half of an NOL ring testing fixture can be used.)

4.6.1.5.2 **Procedure:**

1. Cut the test specimen 54 inches long. Specimens with twists or broken ends shall be rejected.

2. Position the lower grip and upper 5 3/4 inch diameter jig so that the distance between the lower clamp, up over the upper jig, and back to the lower clamp is 48 inches.
(3) Position the test specimen in the testing machine with a piece of Teflon-glass film between the specimen and the 5 3/4 inch diameter steel jig. This will allow the specimen to slide over the jig without adhering to its metal surface. Pads should be placed in the lower clamp so the clamp faces will not cut the ends of the test specimen.

(4) Apply a constant loading rate of 0.50" per minute.

(5) Reject all readings obtained which break in the lower grip.

(6) Report the breaking strength in pounds.

Failure to meet this test is cause for rejection of the roll from which the sample was taken and cause for increasing the frequency of the tensile test to include all rolls within the lot under test.

4.6.1.6 **Width** - Prepreg tape width shall be determined in a manner which is generally representative of the situation which obtains when tape is wound around a male mandrel. Measurement methods shall be consistent with the degree of accuracy called for in Table I. Slight delinquencies from the tolerance are not expected to be grounds for material rejection but, at the U. S. Army's option, may serve as the basis for renegotiation of the lot contract price.

4.6.1.7 **Thickness** - Prepreg tape thickness shall be determined on the basis of a cured laminate as described below:

4.6.1.7.1 Cut four 3-inch square pieces of style 181 or 1581 glass bleeder and two 3-inch square pieces of porous TFE glass cloth.

4.6.1.7.2 Layup two plies of 2" square prepreg oriented 0° - 90°. Specimen shall consist of two layers of 181 glass, one layer of TFE glass, two plies (0°-90°) prepreg, one layer of TFE glass, and two layers of 181 glass.

4.6.1.7.3 Place specimen in a preheated 325 ± 3° F press at 100 psi for 35 ± 5 minutes, remove, and cool to room temperature.
4.6.1.7.4 Measure the laminate thickness with a micrometer having sufficient accuracy to determine thickness to the nearest ten thousandth of an inch. Divide the answer by two to obtain the single tape thickness. Report both individual results and the arithmetic mean of three determinations. Slight delinquencies from the tolerance are not expected to be grounds for material rejection but, at the U. S. Army's option, may serve as the basis for renegotiation of the lot contract price.

4.6.1.8 Length - Absence of prepreg tape breaks in any given roll is important to the fabrication process; hence, any roll having a continuous length less than the minimum prescribed in Table I is subject to rejection at the option of the U. S. Army and could, at the U. S. Army's option, serve as the basis for renegotiation of the lot contract price.

4.7 Retest - Upon failure of initial tests, additional tests may be performed. However, the retests must be conducted so as to provide a more comprehensive view of the behavior of the material. Material rejected on retest shall not be submitted again for test without written authorization of the procuring activity.

5. Identification - Unless otherwise specified, each roll shall be identified on the inside of the core such that even if the original package becomes separated from the roll, identification will still be present. Identification markings shall be legible, resistant to obliteration on normal handling, and thickness of a marking label (if such is used) shall be thin enough to avoid an interference problem when mounting the roll on the spindle of an unwinding device. Markings shall include the following information:

(1) Title: Tape, Graphite, Epoxy Resin. Impregnated.

(2) Specification number.

(3) Supplier's name.

(4) Supplier's code number and/or name of the graphite and resin system.

(5) Date of impregnation.

(6) Supplier's lot number.
6. **Packaging:**

6.1 **Rolls** - Tape shall be wound continuously with nonstick interleaves at least 0.001 in. in thickness on "movie film" style reels having a standard three-inch inside diameter core. Reels thus wound shall not exceed 13" in outside diameter nor one inch in width and shall be stable to uncoiling influences.

6.2 **Roll Cartons** - Wound rolls shall be protected from exposure to undesirable environment by a suitable tape sealed carton and subsequently encased in a moisture resistant casing equivalent to heat sealed 0.006 in. thick low density polyethylene sheeting. Roll cartons shall be marked as in 5.0 (above).

6.3 **Packaging for Environmental Control** - Material shall be so packaged with refrigerant in insulated cartons such that temperature of the product will not exceed 40°F during transit from supplier to purchaser. Responsibility for assuring this condition rests with the supplier until shipment is signed for by the purchaser on an appropriate bill of lading.
APPENDIX C

Test Method for Fiber Content, Graphite/Epoxy Composite
PROPOSED METHOD OF TEST FOR FIBER CONTENT OF REINFORCED RESIN COMPOSITES

1. SCOPE

1.1 This method covers the procedures for the determination of comparative fiber content of resin matrix composites. The technique used is based on the digestion of the matrix resin by a suitable digestion medium, which will not attack the fibers.

2. SIGNIFICANCE

2.1 The fiber content of a composite must be determined to calculate the apparent strength of the reinforcing fibers in the composite. It may be further used to evaluate the quality of a given specimen.

3. SUMMARY OF METHOD

3.1 The method consists of digesting the resin portion of a carefully weighed composite specimen in a hot digestion medium, usually an oxidizing solution. The residue is filtered, washed, dried and weighed. The weight percent of fiber can then be converted to a volume percent if the fiber density is known.

Two methods are given - Procedure A for resins digestible by HNO₃ and Procedure B for resins digestible in 50% H₂SO₄-H₂O₂. Examples of resins coming under Procedure A are epoxies and under Procedure B are polyimides.
4. APPARATUS

4.1 General

4.1.1 A 60-ml medium porosity fritted sintered-glass filter

4.1.2 A crucible holder

4.1.3 An analytical balance

4.1.4 A drying oven capable of attaining 100°C

4.1.5 A Pyrex vacuum filter flask: 500 ml

4.1.6 A vacuum source capable of at least 5 in. of Hg

4.2 Procedure A

4.2.1 A 200-ml round bottom flask with a 24/40 joint

4.2.2 A water reflux condenser with a 24/40 joint

4.2.3 A constant temperature water or oil bath with regulator unit

4.2.4 70% concentration reagent grade nitric acid

4.3 Procedure B

4.3.1 A tall form beaker

4.3.2 9"-long disposable capillary Pasteur pipettes

4.3.3 A hot plate

4.3.4 98% concentration reagent grade sulfuric acid

4.3.5 50% hydrogen peroxide
5. TEST SPECIMENS

5.1 At least five specimens approximately 0.30 g are cut from the sample of interest. The specimen may be of any convenient shape such that the specimen will fit into the beaker used in the test.

6. PROCEDURE

A. Epoxy resin matrices (and others which can be digested by nitric acid):

6.1.1 Each specimen is weighed on an analytical balance to four significant figures.

6.1.2 The volume of each specimen is determined by a liquid displacement technique.

6.1.3 Each specimen is placed in a separate flask containing 30 ml of 70% HNO₃.

6.1.4 The flasks are suspended in a constant temperature water or oil bath held at 75 ± 1°C, that is fitted with a reflux condenser.

6.1.5 After five hours, or when the digestion is complete, the contents of each flask are filtered onto a tared sintered-glass filter under a vacuum of 5 in. Hg. The fiber is then washed with excess water followed by acetone.

6.1.6 The filter and specimen are then placed in an oven at 100°C for one hour to remove residual water and acetone.

6.1.7 The filter containing the fiber residue is then cooled to room temperature in a desiccator and the sample is weighed accurately to four significant figures on an analytical balance.
7. **CALCULATIONS**

7.1 Weight of fiber in composite equals the weight of the filter plus the residue minus the tare of the filter.

7.2 Percent fiber in composite by weight, wt. % fiber

\[
\text{Wt. } \% \text{ fiber} = \frac{\text{Weight of fiber in composite}}{\text{Weight of initial composite specimen}} \times 100
\]

7.3 Percent fiber in composite by volume, vol. % fiber

\[
\text{Vol. } \% \text{ fiber} = \frac{\text{Weight of fiber/density}}{\text{Volume of specimen}} \times 100
\]

8. **REPORT**

8.1 The report shall include the following:

8.1.1 Complete identification of material tested including type, source, form, principal dimensions, and previous history.

8.1.2 Number of specimens measured per sample.

8.1.3 Average and standard deviation of weight percent of fiber in composite.

8.1.4 Average and standard deviation of volume percent of fiber in composite.

9. **PRECISION**

The following criteria should be used for judging the acceptability of results at a 95 percent confidence level:

9.1 Repeatability - Two results (each the average of duplicate determinations) obtained by the same analyst should be considered suspect if they differ by more than 1.0 percent, absolute.
9.2 Reproducibility - Two results (each the average of duplicate determinations) obtained by different laboratories should be considered suspect if they differ by more than 1.5 percent, absolute.
APPENDIX D

Product Specification, Epoxy Structural Adhesive
DESCRIPTION:

- An aluminum filled, one-part, heat curing structural adhesive that has been deaerated to provide dense, void free bond lines. Paste consistency and low temperature (250°F) curing properties offer many advantages for production use. High strength bonds are obtainable with clean metals, glass and some plastics.

PHYSICAL PROPERTIES

<table>
<thead>
<tr>
<th>BASE</th>
<th>CONSISTENCY</th>
<th>VISCOSITY (Press Flow) @ 75°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod. Epoxy</td>
<td>Paste</td>
<td>60-150 secs., 20 grams, 50 psi</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COLOR</th>
<th>SOLIDS</th>
<th>NET WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray</td>
<td>100%</td>
<td>12.8 pounds/gallon</td>
</tr>
</tbody>
</table>

APPLICATION CHARACTERISTICS

<table>
<thead>
<tr>
<th>METHOD</th>
<th>OPTIMUM BONDLINE THICKNESS</th>
<th>CURE CYCLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knife coat, Trowel, Pump,</td>
<td>2-5 mils</td>
<td>1) 40 min. @ 250°F.</td>
</tr>
<tr>
<td>High pressure injection</td>
<td></td>
<td>2) 30 sec. @ 400°F.</td>
</tr>
</tbody>
</table>

EQUIPMENT SUGGESTIONS

<table>
<thead>
<tr>
<th>PRODUCTION EXTRUSION EQUIPMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
</tr>
<tr>
<td>Ratio 50:1 with a chopping check</td>
</tr>
<tr>
<td>valve and priming piston</td>
</tr>
</tbody>
</table>

OUTPUT BASED ON ¼” TIP FLOW GUN (MATERIAL TEMPERATURE: 65°F)

<table>
<thead>
<tr>
<th>Hose Assembly</th>
<th>Material Pressure (PSI)</th>
<th>Output (lbs/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length—20', I.D.—⅛&quot;</td>
<td>4500 Pump air pressure for output is</td>
<td>.45</td>
</tr>
<tr>
<td>Length—20', I.D.—⅛&quot;</td>
<td>4500 material pressure + 50</td>
<td>.9</td>
</tr>
</tbody>
</table>

NOTE: Minimum Pumping temperature is 65°F for the material. These pressures will require special consideration during hose selection. They are actual working pressures.

DIRECTIONS FOR USE:

1. Surfaces must be clean, dry and free from paint, rust, oil, grease or wax. Surfaces can be cleaned by sanding with 3M Brand Coated Abrasives followed by solvent wiping.
2. For maximum bond strength apply evenly to both surfaces to be joined.
4. Keep parts from moving during cure. Contact pressure is necessary.
PERFORMANCE CHARACTERISTICS

1. Overlap Shear Strength (PSI) ASTM D-1002-64

<table>
<thead>
<tr>
<th>Test Temp.</th>
<th>Aluminum FPL Etch</th>
<th>Aluminum Alkaline Degrease</th>
<th>Steel Solvent Wipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40°F</td>
<td>3000</td>
<td>3600</td>
<td>3000</td>
</tr>
<tr>
<td>75°F</td>
<td>5000</td>
<td>4800</td>
<td>2800</td>
</tr>
<tr>
<td>180°F</td>
<td>1700</td>
<td>1500</td>
<td>1250</td>
</tr>
<tr>
<td>350°F</td>
<td>400</td>
<td>350</td>
<td>125</td>
</tr>
</tbody>
</table>

2. T-Peel Strength (PIW) ASTM D-1876-61T

<table>
<thead>
<tr>
<th>Test Temp.</th>
<th>Aluminum FPL Etch</th>
<th>Aluminum Alkaline Degrease</th>
<th>Steel Solvent Wipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40°F</td>
<td>5</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>75°F</td>
<td>9</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>180°F</td>
<td>16</td>
<td>9</td>
<td>34</td>
</tr>
<tr>
<td>250°F</td>
<td>1</td>
<td>16</td>
<td>27</td>
</tr>
<tr>
<td>350°F</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

NOTE: All data developed using hot press cure for 40 minutes @ 250°F, 25 psi.

STORAGE AND HANDLING

Store product at 40°F for maximum storage life. Higher temperatures reduce normal storage life. Lower temperatures than 75°F cause increased viscosity of a temporary nature. Rotate stock on a “first in-first out” basis. Upon request, your 3M Adhesives, Coatings and Sealers Sales Representative will be pleased to advise you of the anticipated shelf life of this product under the storage conditions in your plant.

Clean-up can be accomplished with Scotch Grip Brand Solvent No. 1. When using solvents for clean-up, it is essential that proper precautionary measures for handling such materials be observed.

ICC SHIPPING CLASSIFICATION: Cement, NOIBN, Liquid.

CAUTION! STRONG SENSITIZER. VAPOR HARMFUL.

Use only in well ventilated areas. Product may cause skin irritation. Avoid contact with skin and eyes. Remove from skin with soap and water promptly. In event of eye contact flush immediately with water and obtain medical attention. Keep container closed when not in use.

IMPORTANT NOTICE TO PURCHASER

All statements, technical information and recommendations contained herein are based on tests we believe to be reliable, but the accuracy or completeness thereof is not guaranteed, and the following is made in lieu of all warranties, express or implied:

Seller’s and manufacturer’s only obligation shall be to replace such quantity of the product proved to be defective. Neither seller nor manufacturer shall be liable for any injury, loss or damage, direct or consequential, arising out of the use of or the inability to use the product. Before using, user shall determine the suitability of the product for his intended use, and user assumes all risk and liability whatsoever in connection therewith.

No statement or recommendation not contained herein shall have any force or effect unless in an agreement signed by officers of seller and manufacturer.
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Non-Metallic Materials Branch
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Washington, D. C.

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Naval Air Systems Command
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Washington, D. C. 20360

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Monsanto Research Corporation  
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Winona, Minnesota 55987

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Department of the Navy  
Naval Underwater Weapons Research and  
Engineering Station  
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Celanese Corporation  
ATTN: Mr. W. D. Timmons  
Morris Court, Summit, New Jersey 07901

Grumman Aircraft Engineering Corporation  
ATTN: Mr. K. T. Marshall, Plant 12  
South Oyster Bay Road  
Bethpage, Long Island, New York 11714

Allied Chemical Corporation  
ATTN: Mr. William K. Stemple  
P. O. Box 309  
Morristown, New Jersey 07960
**Abstract**

Picatinny Arsenal, NASA/Langley Research Center, and the U. S. Army Air Mobility Research and Development Laboratory have cooperated in a joint effort to demonstrate the applicability of graphite/epoxy composite technology to the fabrication of a UH-1 helicopter tail rotor drive shaft. Progress thus far has produced seven tubes in the preliminary fabrication phase of the work, and partial testing has been accomplished on three shafts made from these preliminary tubes. Fabrication techniques have been sufficiently improved to eliminate wrinkles due to lack of precure compaction. Although not conclusive, test results are encouraging, since they tend to confirm design analysis of the adhesive bond between aluminum end couplings and the composite tube, and to indicate that tests of later, improved shafts will confirm that composite shafting can meet performance requirements. The ultimate program objective is to confirm predicted weight savings by flight testing a standard length shaft specimen and a longer one built to the design extreme of the best composite commercially available.
<table>
<thead>
<tr>
<th>KEY WORDS</th>
<th>LINK A</th>
<th>LINK B</th>
<th>LINK C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite fiber/epoxy composite</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Graphite reinforced epoxy resin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helicopter shafting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite tubes</td>
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<tr>
<td>Filament winding</td>
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<tr>
<td>Plastics</td>
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<td>Composite materials</td>
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