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PROGRESS REPORT III OF COOPERATIVE PROGRAM FOR DESIGN, FABRICATION, AND TESTING OF HIGH MODULUS COMPOSITE HELICOPTER SHAFTING

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JUNE 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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Picatinny Arsenal (later U.S. Army ARRADCOM), NASA/Langley Research Center, and the U.S. Army Air Mobility Research and Development Laboratory continued their cooperative efforts to demonstrate the applicability of high modulus composite technology to the fabrication of a UH-1 helicopter tail rotor drive shaft. The objective of the latest work phase was to overcome the excessive brittleness of the previously developed drive shaft design which demonstrated a shaft train weight savings for the H Model UH-1 of 53.1% over

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the current 2024-T3 aluminum shaft train. A materials impact screening program demonstrated exceptionally noteworthy performance of two woven constructions containing E-glass and PRD 49-III (designation later changed to KEVLAR 49) fibers in an epoxy resin matrix. Also noteworthy was the contribution of thermoplastic matrices and PRD 49-III fiber in providing impact resistance at low weight which was superior to composites having the same fiber in a thermoset resin matrix.

A design, fabrication, and test program of five types of short shaft specimens showed that shaft impact resistance could be improved over the previously developed graphite composite design at a cost in shaft train weight savings. All shaft specimens having mixed fibers had greater post-impact strength than the all-THORNEL 50-S design but the alternating plies of THORNEL 50-S and S-1014 glass had the greatest impact durability (98.6% residual strength). The shaft train weight savings of the most impact tolerant construction was 4.0% over the current aluminum shaft train. One of the most significant findings was that alternating plies of graphite and glass appear to provide substantially greater tube impact durability than that provided by hybridization of the two fibers into one tape wound to a ply design equivalent in strength and stiffness to that of the alternating ply design.

Recommendations were made to continue research and development work to exploit the potential for more impact-durable structures through the use of KEVLAR 49 fiber, woven structures, thermoplastic matrices, and THORNEL 50-S/KEVLAR 49 blends with thermoset matrices. Should this work provide lighter weight, more impact durable shaft segments yielding significant shaft train weight savings, they should be flight service tested.

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Donna Ripplemeier - For torque testing the cylindrical test specimens.

SUMMARY

This report describes the third phase of work performed under a cooperative program involving Picatinny Arsenal, Dover, NJ, the Army Air Mobility Research and Development Laboratory (AAMRDL), Hampton, VA, and the National Aeronautics and Space Administration, NASA, Langley Research Center, Hampton, VA. The objective of this phase of the program was to overcome the excessive brittleness of the previously developed UH-1 helicopter tail rotor drive shaft design which demonstrated a shaft train weight savings of 53.1% over the current 2024-T3 aluminum shaft train.

The first step in the latest work was to evaluate the impact damage tolerance of 36 candidate material constructions. This group of 36 included the bench mark materials 2024-T3 aluminum and the high stiffness-low weight graphite composite GY70-S/ERLB 4617/MDA. Of the candidate material constructions tested, exceptionally noteworthy was the performance of two woven constructions containing E-glass and PRD 49-III fibers in an epoxy resin matrix. These constructions gave a combined performance of high strength, low weight, and impact resistance superior to all others tested. Also noteworthy was the contribution of thermoplastic matrices and PRD 49-III fiber in providing impact resistance at low weight superior to composites having the same fiber in a thermoset resin matrix.

A design, fabrication, and test program of five types of short shaft specimens showed that impact resistance could be improved over the previously developed graphite composite design at a cost in shaft train weight savings. All shaft specimens having mixed fibers had greater post-impact strength than the all-THORNEL 50-S design but the alternating plies of THORNEL 50-S and S-1014 glass had the greatest impact durability (98.6% residual strength). Surprisingly, the all-THORNEL 50-S construction had the second best impact durability at 83.5%. When all tube types were normalized to an equivalent fiber content and the factors of post-impact strength, percent residual strength, and low weight were combined into one numerical score, the type 3 (alternating plies of THORNEL 50-S and S-1014 glass) ranked highest.

The shaft train weight savings of the most impact tolerant construction (type 3 tube) was 4.0% over the current aluminum shaft train. The all-THORNEL 50-S (type 1) had the highest shaft train weight savings (24.1%), demonstrating the advantage of the stiffer fiber to achieve longer shaft segments, thus eliminating some of the bearing assembly weight.

All shaft specimens tested were made to custom ply designs developed by AAMRDL using their own minimum weight optimization computer programs. Operation of these programs showed that ply angle variations

in optimum sequence can provide longer tubes for a given minimum stiffness requirement than a tube having only one ply angle but the same number of plies.

One of the most significant findings was that alternating plies of graphite and glass appear to provide substantially greater tube impact durability than that provided by a hybridization of the two fibers into one tape wound to a ply design equivalent in strength and stiffness to that of the alternating ply design.

Recommendations were made to continue research and development work to exploit the potential for more impact-durable structures through the use of KEVLAR 49 fiber, woven structures, thermoplastic matrices, and THORNEL 50-S/KEVLAR 49 blends with thermoset matrices. Should this work provide lighter weight, more impact durable shaft segments yielding significant shaft train weight savings, they should be flight service tested.

Recommendations were also made to pursue efforts to upgrade the quality assurance of end coupling-to-tube adhesive bonds, develop an alternate integral end coupling to obviate the need for an adhesively bonded end coupling, and test the accuracy of the acid digestion fiber content test method for high strength structures containing KEVLAR 49 fiber. If the current digestion method is found to be insufficiently accurate, a more satisfactory one should be developed. If an integral composite end coupling could be devised, it could yield an important shaft train weight saving.

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INTRODUCTION

Picatinny Arsenal, Dover, NJ in cooperation with NASA, Hampton, VA, and U.S. Army Air Mobility Research and Development Laboratory (AAMRDL), Hampton, VA, designed the program to demonstrate the suitability of high modulus composite material for helicopter application by flight testing a composite tail rotor drive shaft in the UH-1H helicopter. Reference 1 describes the plans, program and progress through 15 May 1971. Reference 2 describes work conducted from 15 May 1971 through 1 May 1973.

The work conducted during phase II (ref 2) of this program revealed that shaft segments initially developed would meet the strength and stiffness requirements of the application; however, they would very likely not survive the normal Army impact environment (for example, the impact of a falling wrench). Consequently, attention was focused on possible means of compromising the competing demands of stiffness and impact resistance while maintaining a respectable system weight saving compared to the existing aluminum system.

The thrust of the FY 73 effort was to establish one or more candidate materials and/or configurations which would provide the necessary balance of impact resistance, stiffness, and low weight. Assuming success in achieving such a configuration from a flat specimen screening program, shaft specimens were to be fabricated from the likely flat specimen materials and tested to confirm design predictions. Assuming success in this phase of the program, composite potential was to be demonstrated further by fabricating a complete drive shaft designed to the limit of the optimum material's properties. This drive shaft would then be flight tested.

The forward program was followed generally as outlined with three exceptions; one, an analytical parametric study of low velocity impact on composite structures was conducted to better aid the design of tubular specimens; two, ballistic testing was not accomplished, and three, execution of the program plan beyond the testing of short length shaft specimens was terminated because of lack of funds.

FLAT SPECIMEN SCREENING PROGRAM

The object of this work phase was to study the impact potential of fiber reinforced plastic (FRP) composite materials in one specific construction (fiber orientation), i.e., plus and minus (+ and -) 45 degrees. Flat specimens 5.08 x 22.86 cm (2 x 9 in.) in size were prepared in thicknesses likely to yield a tensile strength comparable to that of the currently used 2024-T3 aluminum. The aluminum specimens tested for comparative purposes were 1.397 mm (0.055 in.) thick with a tolerance of $\pm$ 0.127 mm (0.005 in.). Figure 1 is a sketch of this specimen. Composite test materials were prepared in panels 38.1 x 48.3 cm (15 x 19 in.) and 14 test specimens 5.08 x 22.86 cm (2 x 9 in.) were cut from each panel as diagrammed in figure 2. Six replicates of each test material varient were sent to LRC for tensile testing. These were identified as "baseline" data and were retained for comparison with results of tensile tests of other replicates which were impacted by means of a falling ball or "tup". A residual strength value was obtained by computing the impacted strength as a percentage of the un-impacted (baseline) specimen, thus yielding a means for ranking, with the aid of density data, all materials tested with each other.

Test Laminates

All of the test materials were procured from commercial sources with the aid of specifications which detailed the physical size of the panel, its fiber ply orientations, reinforcing fiber, its matrix resin, and the specific resin cure schedule to be used. Appendix A documents the specifications for the 35 varient test materials procured and tables A-1, A-2, and A-3 provide additional construction details of each configuration.

Composite panels 38.1 x 48.3 cm (15 x 19 in.) were procured from the following:

Whittaker Corporation
Research and Development Division
3540 Aero Court
San Diego County, California 92123

EXXON Enterprises Incorporated
(COMTEK Project)
242-A St. Nicholas Avenue
South Plainfield, New Jersey 07080

Fiber Science Incorporated
245 East 157Th Street
Gardena, California 90248

General Structures Corporation
2142 Miramar Drive
Balboa, California 92661

The panels procured from EXXON Enterprises, Inc. had thermoplastic matrix resins; those from the others had thermosetting matrix resins.

In addition to the evaluation of several types of reinforcing fibers for impact resistance and stiffness, another objective of this program was to obtain some measure of the role of the matrix resin in composite structures in resisting impact and aiding or degrading specimen stiffness.

Impact and Tensile Testing

The 5.08 x 22.86 cm (2 x 9 in.) specimens were impacted by a falling ball or tup while mounted in a fixture as depicted in figure 3. All edges were supported and restrained. The falling tup which impacted the specimen is shown in figure 4 and weighed 2.42 kg (5.34 lb) with the guide pins in place.

The goal for satisfactory impact resistance was established as thirty minutes of helicopter operation after having sustained an impact of 13.56 joules (J), (10 ft-lb) from an object having a radius of curvature of 2.54 cm (1 in.). See reference 2 for design requirements.

In order to determine as nearly as possible the onset of catastrophic damage in terms of an ascending scale of impact force, a routine sequence of testing was adopted. The first specimen was impacted with 6.78 J (5.0 ft-lb). If the specimen broke, another replicate was impacted with 2.712 J (2 ft-lb). If the first replicate did not break, the second replicate was impacted with 9.49 J (7 ft-lb) and checked for damage. As soon as a replicate survived 13.56 J (10 ft-lb) without catastrophic damage, the balance of the replicates was impacted with 13.56 J (10 ft-lb). All specimens falling into this latter category were sent to NASA for tensile testing. Of the 36 configurations impacted, 23 were sent to NASA for tensile testing and 13 were retained as having damage too great to be useful for residual strength evaluation.

Tensile testing of all specimens was performed at NASA on a Baldwin hydraulic test machine at 224 N/min (500 lb/min). All of the un-impacted configurations were tested in replicates of six, but the uncertainty of the impact testing caused the replication of the impacted configuration tensile testing to vary from three to six specimens. Thicker specimens such as specimens D1 through D4 (table 1) were too thick to be tensile tested in conventional jaw grips, therefore were tested in a four point sandwich beam loading fixture. The distance between load points on the top side of the specimen was 5.08 cm (2 in.) and the distance between load points on the bottom side of the

specimen was 20.32 cm (8 in.). Compressive loading was provided by an Instron test machine at a crosshead speed of 0.127 cm/min (0.005 in./min).

Table 1 shows the average specimen thickness, average density, fiber content, and construction description of each material configuration procured and tested. Table 2 shows the impact causing catastrophic damage under 13.56 J (10 ft-lb) of impact, the pre-impact average tensile strength, the post-impact average tensile strength, and the percent residual tensile strength.

DISCUSSION AND CONCLUSIONS

From the information in tables 1 and 2, it can be seen that none of the "all CELION GY70" fiber specimens possessed sufficient impact resistance to warrant tensile testing after impact. All specimens were 0.127 cm (0.050 in.) thick or less, hence doubling the thickness could conceivably have qualified some or all. However, the added weight penalty would very likely have cancelled much of the potential weight saving as compared to the current aluminum tube.

From the data in table 2, it can be noted that residual strength, in general, appears to increase with decreasing fiber modulus; e.g., specimen B2 (MODMOR I-S) at 57.5% fiber content has greater residual strength than specimen A2 (CELION GY70-S) which was so severely damaged by the impact that its post-impact strength could not be measured. Specimens B4 (MAGNAMITE A-S) at 86.4% and B5 (MAGNAMITE A-U) at 74.2% both have greater residual strength than specimens A2, B2, and B6 (CELION GY70-S, MODMOR I-S, and THORNEL 75-S respectively). One notable exception to this observation is the comparison of specimens B6 and B2, where the former exceeds the latter in residual strength in spite of the greater modulus of the B6. The average specimen thickness for B6 was 0.104 cm (0.041 in.) and that of B2 was 0.099 cm (0.039 in.). It is considered unlikely that the difference in thickness (alone) between the two types (5%) would produce a 108% difference in residual strength.

Of all the specimens receiving 13.56 J (10.0 ft-lb) of impact, only the all-PRD 49-III and the MAGNAMITE A-S fiber reinforced specimens survived without broken fibers. All other graphite fiber specimens suffered fiber breakage to some degree, even when plied with glass or PRD 49-III.

Mixtures of low and high modulus fibers appear to offer significant improvement in residual strength as can be noted by comparing:

1. The 61.7% strength of C2 (MODMOR I-U w/PELLON Veil) as compared with the 40.4% strength of B3 (MODMOR I-U).

2. The 58.8% strength of C3-2 (CELION GY70-S w/Glass Fabric) and the negligible strength of A2 (CELION GY70-S).

3. The 57.5% strength of C3-1 (CELION GY70-S w/Glass Fabric) and the negligible strength of A2 (CELION GY70-S).

4. The 50.6% strengths of C4-1 and C4-2 (CELION GY70-S w/PRD 49-III) and the negligible strength of A2 (CELION GY70-S).

The most promising of all the table 2 specimens, in terms of residual strength, have been listed in table 3 along with their densities in order to rank them in terms of their relative "high strength-to-low weight" quality. Since the A1 configuration (CELION GY70-S, ERLB 4617, MDA) gave the best system weight saving in the earlier work (ref 2), it would have been interesting to compare its strength-to-low weight ratio with that of the other promising candidates. Since this was not possible because A1 had insufficient impact resistance to yield a residual strength, the desired "percent residual strength/density" ratio was computed for those candidates which did have residual strengths in order to provide the desired ranking.

Similarly, since the fiber contents of these specimens varied considerably, one from the other, it was desirable to compare all specimens on the basis of equivalent fiber content. Broutman (ref 7, p. 111) teaches that the longitudinal modulus of a composite varies directly with the modulus of the component fiber and its volume fraction. Because the stiffness and impact resistance of composite tubes was the primary objective of this work, it was of great interest to compare the specimens of table 3 when their residual strengths had been modified by the volume fraction element of the stiffness equation. Since a 55 $\pm$ 5% volume fraction was a goal adopted at program outset, the constant 55 divided by the particular specimen's fiber volume fraction (expressed as a percent) was chosen as the ratio to be multiplied times the score obtained from density modification to obtain a stiffness modified score. Thus, the 86.4% residual strength of specimen B4 was density modified by dividing it by 1.63 to get a score of 53.0. When this was multiplied by the ratio of 55/63.0, its stiffness modified score became 46.3. From a ranking of these scores, it was possible to select the most promising candidate on the basis of the three primary factors of interest; the candidate having the highest numerical score was the most promising one.

From a study of these normalized data, it became apparent that:

1. The woven specimens, J' and K' rank highest in the final combined performance ranking.

2. The presence of PRD 49-III fiber in a specimen is a very powerful influence in providing impact resistance at low weight, since specimens with both thermoplastic and thermoset matrices scored high in this ranking.

3. A thermoplastic matrix appears to be making a significant contribution to impact resistance; e.g., specimens A', B' and C' scored higher than specimens D5 and D6 even before the density factor was applied.

4. MAGNAMITE A-S is the only graphite fiber to appraoch PRD 49-III in providing composite impact resistance at low weight.

Chamis (ref 8) teaches that less than 5% of the longitudinal impact resistance is derived from the matrix when the fiber-to-matrix modulus ratio is 20. The effect of the resin matrix on residual strength is difficult to assess without experimental resin content data, but at least one comparison from the table 3 data suggests that the matrix is playing a much larger role in impact resistance than theory would predict; i.e., specimens D6 and A' differ only in matrix resin and fiber volume fraction, the latter having a significantly lower fiber fraction, yet A' ranks significantly higher in residual strength than D6.

SHAFT SEGMENT DESIGN

Parametric Study

Concurrent with the flat specimen residual strength screening program, it became apparent that a more thorough understanding was needed of the variables controlling impact resistance of composites. Accordingly, a contract was let to Whittaker Corporation to elucidate these variables. The objective of this work was to evaluate the parametric sensitivities associated with impact on orthotropic composite materials in geometries typical of helicopter structural components in order to establish a basic understanding of the influence of the material, geometric configurations, and energy levels involved in impact resistance.Generated data will be used as a guide for subsequent design efforts to maximize stiffness, impact resistance, and low structural density of helicopter components. Reference 4 is the final report of this effort.

Composite Tube Design Philosophy

Results of the fixed support flat specimen impact testing showed that the A type (low modulus) graphite composite is the only graphite type showing promise of resisting 13.56 J (10 ft-lb) of impact when the composite tube wall is in the 0.127 to 0.254 cm (0.050 to 0.100 in.) range. This wall thickness range is required for the tube to be equal to or less than the weight per unit of length of the current aluminum tube. Further, NASA learned from running tube design computer programs described in reference 2 that the stiffness requirements for a 218.44 cm (86 in.) long tube are such that a reinforcing fiber having a minimum modulus of 345×10^9 Pa (50×10^6 psi) is required to meet the design requirements of critical speed and/or buckling strength. Reference 4 studies show that a tube can absorb impact by bending (beam bending along the tube axis) and also by deforming from a circular to an oval cross section. Thus, the results from the flat specimen testing are probably unrealistically pessimistic when used as an indicator of impact resistance of a tube made from the same material configuration.

The decision was made to pursue the search for an optimum material configuration by making a series of short shaft specimens, approximately 25.4 cm (10 in.) long, in a number of different material configurations and test for residual torsional strength after impact in a manner analogous to the flat specimen program. The tubes were designed to an inside diameter of 8.128 cm (3.2 in.) so they could be bonded to the outer surface of the end coupling and at the same time gain the benefit of slightly greater stiffness due to the greater section modulus when compared with that of the tubes bonded to the inner surface of the end coupling. Further, the larger tube diameter would provide for greater impact energy absorption without material failure because of its greater freedom to bend without exceeding the unit strain level at break. The methodology adopted was to design a number of tubes in different materials, using the NASA computer programs, to meet the drive train requirements when the shaft segments are of equal length and only two intermediate bearing support assemblies are required. Figure 5 illustrates the proposed composite drive train using adhesively bonded aluminum end couplings (same as those currently in use).

In accordance with this philosophy, it was planned to fabricate short shaft lengths in each material/ply varient. Two replicates were to be torqued to failure without having been exposed to impact and two additional replicates were to be torqued to failure after receiving 13.56 J (10 ft-lb) of impact from the same falling tup as was used for the flat specimen screening program.

It was recognized that, although the design requirements of reference 2 call for 30 minutes of helicopter operation after sustaining a fully tumbled 0.30 caliber ball or untumbled 0.50 caliber impact, the initial shaft development work would be tasked only with the low energy impact requirement of 13.56 J (10 ft-lb) of impact absorption without loss of helicopter operation for at least 30 minutes.

It was also decided that, contrary to the practice of tube making reported in references 1 and 2, the tubes would be wound on a mandrel having rounded ends so that a continuous, rather than a discontinuous, winding process could be used. Based on the NASA computer design programs, it was decided to wind tubes from prepreg tapes having the following material varients:

Continuous Fiber Types

1. THORNEL 50-S[1] graphite.
2. CELION GY70-S[2] graphite.
3. Alternating double plies of Ferro S-1014[3] glass and THORNEL 50-S
4. Alternating double plies of KEVLAR 49[4] polyaramid and THORNEL 50-S.
5. Alternating double plies of Ferro S-1014 glass and CELION GY70-S.
6. Alternating double plies of KEVLAR 49 and CELION GY70-S.
7. Uniform winding of hybrid tape having a 1:1 volume ratio of S-1014 glass and THORNEL 50-S.
8. Uniform winding of hybrid tape having a 1:1 volume ratio of S-1014 glass and CELION GY70-S.
9. Uniform winding of hybrid tape having a 1:1 volume ratio of KEVLAR 49 and THORNEL 50-S.
10. Uniform winding of hybrid tape having a 1:1 volume ratio of KEVLAR 49 and CELION GY70-S.

A prepreg specification was written to provide the necessary eight types of tapes and bids were solicited (appendix B).

[1] Trade name of the Union Carbide Corporation, 270 Park Ave., New York, N.Y. 10017.
[2] Trade name of the Celanese Corporation, Morris Court, Summit, NJ 07901.
[3] S-1014 glass is a product of the Ferro Corporation, Fiber Glass Division, Fiber Glass Road, Nashville, Tennessee 37211.
[4] New trade name for PRD 49, Ex: E.I. duPont de Nemours and Co., Inc., Wilmington, Delaware 19898.

Because of the limited project funding and the high cost of the prepreg tape, it was necessary to curtail the number of material varients and reduce the tube length from 25.4 cm (10 in.) to 20.955 cm (8.25 in.), thus making the overall length of the short shaft test specimen (including two aluminum end couplings) 25.095 cm (9.880 in.) (fig 6).

The successful prepreg tape bidder was the Ferro Corporation, 3512-20 Helms Avenue, Culver City, California 90230. However, the material actually received was not exactly in accord with the solicited specification (appendix B). The exceptions to this specification and the physical test results on the materials shipped are recorded in appendix C.

Composite Tube Ply Design

AAMRDL's computer programs were used to develop individual ply designs for each tube configuration. The constraints on these programs were as follows:

1. Tube inside diameter of 8.128 cm (3.2 in.).
2. The tube must meet the strength and stiffness requirements for helicopter operation when the modular shaft segment is 2.184 m (86 in.) long.
3. The tube design of interest is that which has the minimum weight when the materials properties provided by the Ferro Corporation are used.

The computer output, based on the above, for a type 1 tube (CE9015 resin system and THORNEL 50-S) was, $(\pm 10/\pm 50/\pm 10/\pm 10/\pm 10/\pm 15)_{1S}$, where reading from left to right, the ply sequence is the same as reading the tube from the innermost to the outermost ply. Construction and performance information for each type of shaft fabricated is summarized in table 4.

From operation of the computer optimization programs on the variants planned for test, the value of computer optimized ply design was learned. Table 5 compares the segment lengths for optimized angle designs with tubes having the classical + and - 45 degree single angle design for maximum torsional strength. The predicted lengths are quite different, yet the same number of plies and the same materials are considered in each case. Fortunately, tape winding of composite structures provides the opportunity to place load bearing fibers in a spatial arrangement where their maximum properties are best arrayed to meet the strength and stiffness requirements of the particular component under consideration.

Conspicuous by their absence in the above listed tube/shaft specimens to be evaluated are the three dimensional woven type (General Structures Corporation) and tubes having thermoplastic matrices. Since flat specimens of these materials ranked above all others it is logical to expect that tubes made from the same materials/configurations should perform well. Unfortunately, the available computer optimization programs were not amenable to use in designing a shaft module in the woven, three dimensional type and the technology for fabricating tubes from composites having thermoplastic matrices was not available to the author in 1975 and 1976 when it was needed. Therefore, the work went forward without them. Hopefully, some day, tubes of these types can be evaluated in the same fashion.

COMPOSITE TUBE FABRICATION

Prepreg Tape Winding

Initial program plans called for tape winding of the composite tubes in the Goldsworthy electronic winding machine because of the facility with which winding angles could be changed. Accordingly, the mandrel was designed for the one end support demanded by this machine and the drawings in figures 7 through 11 reflect this. Trial windings on this machine with dry glass roving revealed a problem of slippage on the end domes and erratic angle laydown of the roving. After a thorough debugging of the machine, it was concluded that the cost of correcting the electronic circuitry would be well beyond the limits of the program funding and the mandrel assembly was appropriately modified for use in the W-1 model McClean-Anderson winding machine.

As previously mentioned, tape winding of these tubes was of the usual continuous method as opposed to the discontinuous method described in reference 2. The mandrel was first covered with heat shrinkable TEFLON tubing as also described in reference 2, pages 11 and 12. Figure 12 is a photo of a typical prepreg tape winding setup. Of particular importance in achieving a satisfactory winding when small angles (under 30°) were required was the spring loaded multi-rolled structural device immediately above the TEFLON winding eye. For 45° or higher angles, the CTC[5] tensioning device was adequate for maintaining uniform tension on the tape throughout the carriage round trip. However, at low winding angles the carriage traverse beyond each mandrel end dome was so great the tape takeup capacity of the CTC device was inadequate to cope with the excess tape length between the winding eye and the mandrel end dome the instant that the carriage reversed direction. It was at this point that the auxiliary spring loaded swinging arm type takeup was critically needed. It was also very valuable during the tape compacting and final bleeder tape wrapping which will be described later. Figure 13 is a photograph of a typical nylon

[5]Compensating Tension Controls, Inc., Orange N.J.

tape wrapping setup. Note the function of the auxiliary takeup device in providing the means for additional tension on the nylon tape; i.e., the extra friction introduced by the nylon tape passing over two non-rotating rolls before passing over the final roller to the mandrel through the winding eye holder. Also of particular importance was the use of TEFLON covered rollers and the machined TEFLON "doughnut" winding eye above the mandrel as can be seen in figure 12. Without the non-stick nature of TEFLON, maintenance of the integrity of the slightly sticky prepreg tape would have been impossible. Even with the advantage of the TEFLON surfaces, there were times when the winding room temperature exceeded 29°C (85°F) and the only way to prevent the prepreg tape from sticking to the TEFLON was to continuously cool the tape while winding. Reference 6, pages 26 and 27 contain a detailed description of the technique used to blow cold air on the tape.

The typical winding cycle was to alternately wind a double ply of tape and compact this with a circumferential winding of nylon tape until all plies were wound. A double ply was one plus and one minus angle laydown of tape repeated until the entire surface of the 39.37 cm (17.5 in.) long tube (sufficient for two replicate test specimens) was completely covered. The number of carriage round trips required to accomplish this varied with the angle being laid down.

After winding a double ply, the prepreg tape was cut to allow for the compaction phase. This was accomplished by wrapping 2.54 cm (1.0 in.) wide woven nylon heat-shrinkable tape[6] circumferentially around the previous double ply of prepreg while the nylon tape was under tension estimated to be in the range of 67 to 89N (15 to 20 lbf). The carriage was taken out of gear so that it could be manually moved from left to right while the machine turned the mandrel. Care was taken to provide an overlap of up to 50% of the nylon tape width to avoid gaps between wrappings which could "pinch" the prepreg into ridges. As soon as the prepreg surface was completely wrapped with the nylon tape, it was removed in preparation for the next double ply winding. After all double plies were wound and compacted, the wound prepreg was machine wrapped with nylon tape preparatory to cure. This final wrap was a machine programmed one calculated to provide the appropriate amount of resin bleedout as well as material consolidation during cure. Reference 2, page 14 describes this dual function of the woven nylon tape and appendix D of this report describes the rationale for obtaining the desired wrap for each tape type.

Following final nylon tape overwrapping, the prepreg tape on the end domes was parted from the main cylindrical portion of the wound mandrel by manually cutting it off with a razor blade knife or very carefully cutting a circumference at the tangent point with a power

[6] Pattern no. 7282, Bally Ribbon Mills, 23 North Seventh Street, Bally, Pennsylvania 19503

band saw. The winding end domes were removed and "curing" end domes as shown in figures 14 and 15 were affixed to the mandrel preparatory to curing the wound composite in a vacuum bag.

Change in Tube Design Plan

The original program plans called for making tubes with ply configurations as shown below:

Tube type	Tube material description
1	All plies of THORNEL 50-S (type 1 tape)
2	All plies of CELION GY70-S (type 2 tape)
3	Alternating double plies of type 1 tape with double plies of S-1014 glass (type 3 tape)
4	Alternating double plies of type 1 tape with double plies of KEVLAR 49 (type 4 tape)
5	All plies of hybrid THORNEL 50-S/S-1014 glass (type 5 tape)
6	All plies of hybrid THORNEL 50-S/KEVLAR 49 (type 6 tape)

Unfortunately, the type 1 tape supply was exhausted during the winding of the number three of the type 3 tubes, and it became necessary to substitute type 2 tape for type 1 tape. This occurred 32% of the way through the winding of the last graphite ply. This shortfall of type 1 tape made necessary the use of type 2 tape also in the type 4 tubes which further shortened its supply, thus making it necessary to cancel the fabrication of type 2 tubes.

Another deviation from the original program plan was in the winding of the no. 4, type 4 tube. Since it became apparent there would be insufficient type 2 tape to make enough replicates of tubes having alternating double plies of GY70-S and S-1014 glass (a type "3A", which would provide a comparison with type 3 tubes), it was decided to make one more type 4 tube. The supply of GY70-S tape was exhausted just before the first double ply of GY70-S tape was completed. The final carriage round trip was completed using KEVLAR 49 tape. The winding was then completed by applying only the KEVLAR 49 tape. Thus the ply design

for the no.4, type 4 tube was:

$$(\pm 15 \pm GY70\text{-}S/\pm 45\ K\text{-}49/\pm 20\ K\text{-}49/\pm 45\ K\text{-}49)_8 .$$

The last roll of type 5 tape was very nearly exhausted after the no. 2 double ply on the no. 3, type 5 tube, hence it was decided to wrap this tube with its final nylon shrink tape wrap and cure it at this stage. Thus, the ply design for the no. 3, type 5 tube was:

$$(\pm 30 \text{ type } 5/\pm 30 \text{ type } 5)_4 .$$

The rest of the tubes shown in table 4 were wound as designed. Thus, table 4 reflects the revised designs as made with the exception of the deviations just described. Details of the winding machine gear calculations, machine setup, and winding experience for all tubes wound may be found in reference 5 and reference 6.

Composite Tube Curing

Preparation of the vacuum bag was accomplished in the same manner as described in reference 2, pages 15 and 16 with the exceptions of the cold trap in the vacuum line and the cure schedule. In the tube curing described in reference 2, a vacuum accumulator/resin condenser was used in the vacuum line, but it was found that sufficient resin in vapor form was passing through this accumulator/condenser as to be injurious to the vacuum pump, hence a cold trap (glass condenser) was placed in the vacuum line just ahead of the vacuum pump. This condenser was immersed in a Dewar flask filled with a mixture of dry ice (solid CO_2) and acetone. No vacuum pump problems were experienced thereafter. The cure schedule used was essentially the same as that described for the Ferro test panels in appendix C. Actual tube temperatures and vacuum pressures as they varied with time were recorded in reference 6. Description of the method and equipment used for curing the type 1 tubes is typical of all the tube curings and is recorded in reference 6, pages 3 and 4. Following cure, the tube was stripped from its bag, weighed and measured. Presented in table 6 is a summary of all cured tubes as stripped from the vacuum bag. Temperature and pressure data for each cured tube are recorded in reference 6.

SHAFT FABRICATION

Composite Tube Machining

The approximately 43.81 cm (17.25 in.) long composite tubes were cut into two equal length tubes for adhesive bonding to aluminum end couplings as follows:

1. The composite tube was mounted on an aluminum mandrel and chucked into a lathe.

2. A small "squaring" cut was taken off of one end (approximately 0.317 cm (0.125 in.)).

3. A length of 20.955 cm (8.25 in.) was measured from the squared end and another cut was made, thus completing the machining of one tube specimen.

4. Machining of the second tube specimen was performed as described in steps 2 and 3 above, thus creating rings from the center and ends of the original wound tube which were saved for fiber content analysis by acid digestion.

End Coupling Bonding

A total of 32 nominally 25.095 cm (9.88 in.) long drive shaft specimens were prepared by bonding two aluminum end couplings (Bell Helicopter part number 204-040-619-3) to each 20.955 cm (8.25 in.) tube specimen (fig 6). This adhesive bonding was performed as described in appendix E. Following adhesive bonding, the 32 specimens were measured by the Product Assurance Directorate, ARRADCOM. Their measurements are shown in table 7.

FIBER CONTENT DETERMINATION

Fiber content determinations were made in triplicate from the trimmings of each of the "as wound" 39.37 cm (17.5 in.) long composite tubes by the acid digestion method. These data were related to the shaft serial numbers of table 7 and presented in table 10. ASTM Test Methods D3171 and D792 were used for fiber content and density determinations.

It is important to note that the ASTM D3171 test method for determining composite fiber content is based on digesting the matrix resin with nitric acid, thus leaving the fiber for weight determination. Unfortunately, nitric acid also attacks graphite fiber

to a small extent and KEVLAR 49 fiber to a much greater extent. A correction factor was developed to overcome this source of error. It consists of determining the amount of fiber digestion experienced by a sample of fiber-without-resin. Thus, the amount of fiber-without-resin digested, expressed as a percentage and used as a correction fraction, is applied to the result from the composite digestion to get the total "true" fiber content. By the very nature of this method, its accuracy to a very precise degree is open to question. It is believed that an optical/computer integration technique may offer the best hope for a fool proof fiber content analysis method.

IMPACT TESTING

Shaft specimens with serial numbers ending in "A" were not impacted, but were sent directly to AAMRDL for torque-to-failure testing. Those specimens having a serial number ending in "B" were impacted prior to torque-to-failure testing with 13.56 J (10 ft-lb) of energy from a falling tup.

Figure 16 is a photograph of the falling tup impact tester with a shaft specimen mounted in the "V"-block support. The essential features of this impact tester are: (1) the free falling tup (see figure 4 for details of construction), (2) the movable electro-magnetic head for supporting the tup prior to intended release, (3) the fall height measurement assembly, (4) the rebound catcher, and (5) the "V"-block specimen support. Figure 17 is another view of the tester showing the adjustable electro-magnetic tup support, the test specimen restrained by wire springs, and the rebound catcher in its distended position. Figure 18 is a close-up photograph showing the electric switch box, the rebound catcher in the tup-catching position, and the machine screw with the ground head which was used as a guide or bench mark to assure that each tube was impacted at the same point in relation to the end of the shaft. The rebound catcher was manually operated by the test technician, the purpose being to make sure that each specimen received only one impact from the tup. Being spring loaded, the catcher was easily operated. In all cases, there was sufficient bounce to the tup so that the operator could release the catcher as soon as he heard the tup strike the specimen and the catcher retracted fast enough to catch the tup.

Shaft Impact Resistance

Figures 19 through 27 are a partial pictorial record of the effect of the 13.56 J (10 ft-lb) impact on the 16 B-series of test specimens. Visually, shaft damage appears to be crippling in the case

of type 1 shafts and virtually nonexistent in the case of the type 6 shafts. Functionally, the data in table 8 summarizes the actual damage sustained by comparing the torsional strength of unimpacted specimens with that of the impacted specimens.

DISCUSSION OF RESULTS

From the data in table 8, the type 5 tubes had the greatest pre-impact and post-impact strength. However, this performance was tainted by the fact that type 5 tubes gave up next to the greatest amount of strength due to impact, thus leading to the conclusion that they rank low in durability, i.e., if one impact of 13.56 J (10 ft-lb) takes away 57% of the tube's torsional strength, one more equal blow could eliminate its load carrying capacity completely.

From the table 8 data, it is difficult to draw a conclusion about the best way to combine the attributes of two different fibers. If funds had allowed for the construction of tubes containing both type 1 and type 2 fibers in both alternating ply and hybrid combinations as originally planned, we would not now have to make the questionable (but simplifying) assumption that type 1 graphite is not very different from type 2. However, if we do make this assumption, one could say from the table 8 data that hybrid tape provides greater pre-impact and post-impact strength than an alternating ply configuration in the case of graphite and glass. This same bias would be correct for the pre-impact strength of graphite and KEVLAR 49 but incorrect for the post-impact strength of these two fibers when combined in hybrid tape form. On the basis of percentage residual strength, the results are conflicting; the alternating ply configuration being better for graphite and glass and the hybrid configuration being better for graphite and KEVLAR 49.

If we eliminate the anomaly of two different graphites by focussing only on the type 1 graphite-glass combinations, we are forced to conclude that an alternating ply configuration, on balance, is better since this configuration (type 3 tubes) provides the better, by a wide margin, percent residual strength than that provided by the hybrid configuration(type 5 tubes).

A more detailed analysis may be made of the performance of all candidates by referring to the numerical rankings in table 9. Since all tubes under test were designed to perform equally in the UH-1 helicopter service prior to impact, the only remaining questions to be answered about performance were:

1. How strong was the tube after impact?

2. How durable was it after one impact? Did one impact eliminate more than one half of its strength?

3. How heavy was each candidate shaft segment?

In table 9, the numbers in the column headed "Residual Strength/ Weight, Score" were obtained by dividing the "Percent Residual Strength" by the "Average Wt./Unit Length". Scores obtained from this division provided a means for comparing tube types on an equal weight basis; i.e., a residual strength per unit of weight. The numbers in the column headed "Residual Strength/Weight X Stiffness" were obtained by multiplying the equal weight score by a stiffness factor. The stiffness factor was obtained by the same philosophy used in the flat specimen analysis (the longitudinal modulus of a composite varies directly with the modulus of the component fiber and its volume fraction). Although the net equivalent fiber modulus varies from one tube type to another, at least all tubes are comparable on an equivalent fiber content basis. In the case of table 9 data, the stiffness factor was obtained by dividing 60 (the nominal fiber content we were seeking when the tubes were designed and fabricated) by the tube type average fiber content expressed as a percentage. Thus, the stiffness factor for tube type 1 was 60/59.69 or 1.0052.

From the table 9 rankings, type 5 tubes rank first in post-impact strength, type 3 tubes rank first in percent residual strength, type 4 tubes rank first in low weight per unit length, and type 3 tubes rank first when all three factors are combined in an arithmetic expression designed to discover the most favorable candidate by yielding the highest numerical score.

It was somewhat surprising to note that in the numerical combined performance ranking, the THORNEL 50-S tubes ranked highest, if only by 0.01 of a point. However, this numerical ranking does not recognize the post-impact strength of each tube type. If the "Percent Residual Strength/Weight X Stiffness" score were multiplied by the ratio "Post-Impact Strength" of each tube type/7,607, the new combined performance rankings would be as shown below:

Tube type	New combined score	New numerical rank
1	8.23	2
3	12.51	1
4	3.81	5
5	7.49	3
6	6.41	4

Another surprise was the poor performance of types 4, 5, and 6. Unfortunately, funds did not permit a detailed post mortem examination of specimens. However, from visual observation of the specimens prior to physical test, it was speculated that the tubes containing KEVLAR 49 did not perform as well as expected because the fibers were insufficiently wetted by the matrix resin to give a good fiber-to-resin bond. Although the fiber content data from table 10 do not seem to support this thesis, it is possible that the method for determining resin/fiber content is sufficiently inaccurate as to give critically misleading results.

Because impact durability is vital in providing flight structures with proper quality assurance and because it was the reason for conducting this most recent work phase, the most significant inference to be drawn from all the data is that the alternating graphite/glass plies of type 3 tubes appear to have provided a construction which is nearly impervious to the impact force prescribed for screening purposes. When the same materials were used in hybrid tape form (type 5), the tubes were superior in initial strength but less than half as good as the type 3 tubes in sustaining impact without damage (percent residual strength).

Rather surprising also was the fact that the percent residual strength for the hybrid tape tubes (types 5 and 6) ranked below the bench mark construction of all THORNEL 50-S (type 1 tape). Hence, it appears that hybridizing two fibers into one tape (in this case) not only failed to improve impact durability (percent residual strength), but actually acted as a detriment in this regard.

In addition to comparing the composite tube constructions of table 9 one with another, it is equally important to compare them with the bench marks of reference 2, i.e., 2024-T3 aluminum and the high stiffness-low weight graphite composite GY70-S/ERLB 4617/MDA. Data from reference 2 and the latest work have been combined to compute a "Percent Weight Savings Over Aluminum" in table 11. The aluminum referred to is the aluminum tail rotor drive shaft train used in the current UH-1H helicopter. By comparing the data in table 11 with the 53.1% weight saving of the best previous composite system (ref 2, p 10), it can be seen that the compromises used to improve impact resistance severely penalized weight savings. As in the case of the flat specimen screening program, the use of KEVLAR 49 fiber seems to offer the best chance for weight saving as witness the performance of the type 4 tubes which had the highest percent weight savings of all the nonhomogeneous fiber constructions. Of particular interest is the fact that the alternating ply construction ranked well above the hybrid tape construction (type 6). Similarly, the alternating ply construction was superior in weight saving to the hybrid tape construction in the case of graphite and glass.

CONCLUSIONS

1. The flat specimen testing program was very useful in elucidating the value of four means for upgrading the impact durability of high strength-low weight composite structures:

a. The woven E-Glass and PRD 49-III specimens with an epoxy matrix (specimens J and K) provided a combined performance of high strength, low weight, and impact resistance superior to all constructions tested.

b. The presence of PRD 49-III fiber in a composite specimen is a very powerful influence in providing impact resistance at low weight, since specimens with both thermoplastic and thermoset matrices scored high in this quality.

c. A thermoplastic matrix appears to be superior to a thermoset matrix in providing impact resistance.

d. MAGNAMITE A-S is the only graphite fiber to approach PRD 49-III in providing composite impact resistance at low weight.

2. NASA concluded from running tube design computer programs described in reference 2 that the stiffness requirements for a 218.44 cm (86 in.) long tube are such that a reinforcing fiber having a minimum modulus of 345×10^9 Pa (50×10^6 psi) is required to meet the design requirements of critical speed and/or buckling strength. This conclusion can also be reached from a consideration of the weight saving data in table 11.

3. From operation of the minimum weight computer optimization programs, AAMRDL concluded that ply angle variations in optimum sequence can have a very significant effect in providing maximum length tubes for a given minimum stiffness requirement. Table 5 demonstrates the advantages of computer optimization.

4. Alternating plies of graphite and glass appear to provide substantially greater tube impact durability than that provided by a tube wound from a hybrid tape of the two fibers, both tubes having been designed to be equal in strength and stiffness.

5. In view of the less-than expected performance (compared with the flat specimen test results) of composite tubes containing KEVLAR 49-III fiber, additional study is needed in the manufacture of prepreg tapes and tubes which contain this fiber.

6. Considering the "rash" of end coupling bond failures in the recent series of testing, compared with the failure-free performance of previous shaft tests, a restudy of the bonding procedure appears to be required.

7. In view of the apparent sensing disagreement between the visual observation of very "dry" looking tubes (type 4) and "normal" fiber volume fraction data in table 10 for KEVLAR 49 tubes, it appears that further efforts are needed to develop a more accurate fiber content test method for composites containing this fiber.

8. Although a large weight saving penalty was paid in the process, efforts to upgrade the impact resistance of all-graphite tubes were successful in that the post-impact strengths of three of the alternate constructions exceeded that of the all-THORNEL 50-S tubes. However, in view of the promise of KEVLAR 49 fiber, woven structures, and thermoplastic matrices, much more potential for high strength and stiffness at low weight still exists.

RECOMMENDATIONS*

1. Additional research and development work, followed by shaft testing as described in this report, should be conducted to exploit the potential for more impact-durable structures through the use of KEVLAR 49 fiber, woven structures, thermoplastic matrices, and THORNEL 50-S/KEVLAR 49 blends with thermoset matrices. Of particular importance should be the work of improving the KEVLAR 49 fiber-to-matrix resin bond.

2. In future shaft test work, a minimum of five replicate specimens should be made and tested under the same conditions. This would give greater assurance of obtaining a valid statistical analysis of test results.

3. Research and development efforts should be pursued in order to understand what has to be done (or not done) to be sure that future end coupling-to-tube adhesive bonds do not fail. Concurrently, efforts should be pursued to develop an integral composite end coupling to obviate the need for an adhesively bonded end coupling. If such a coupling could be devised, it could yield an important shaft train weight saving.

*There are no current plans on the part of ARRADCOM to continue the work outlined in the recommendations.

4. Work should be done to test the accuracy of the acid digestion fiber content test method for composite structures containing KEVLAR 49 fiber. If the current method is found to be insufficiently accurate, a more satisfactory one should be developed.

5. When lighter weight impact durable composite shaft segments are available to provide significant system weight savings, they should be flight service tested so as to demonstrate their availability for production use.

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Table 1. Material configurations procured and tested*

Code number	Average thickness (cm/in.)	Average density g/cm³(lb/in.³)	Fiber content (% by vol.)	Construction description
A1	0.091/0.036	1.61(0.058)	56.6	GY 70-S/ERLB 4617/MDA
A2	0.099/0.039	1.80(0.065)	54.5	GY 70-S/ERX 67/MDA
A3	0.102/0.040	1.83(0.066)	52.5	GY 70-U/ERX 67/MDA
A4	0.104/0.041	1.38(0.050)	57.3	GY 70-S/RD2257-14A+14B
A5	0.112/0.044	1.69(0.061)	50.2	GY 70-S/ERX 67/MDA (80,45,0,0,45,80)
A6	0.109/0.043	1.77(0.064)	50.5	GY 70-S/ERX 67/MDA (90,0,0,0,0,90)
A7	0.124/0.049	1.41(0.051)	42.7	GY 70-S/APOGEN 101/230
B1	0.127/0.050	1.36(0.049)	48.3	GY 70-S/NR 150A
B2	0.099/0.039	1.58(0.057)	57.5	MODMOR I-S/ERX 67/MDA
B3	0.104/0.041	1.72(0.062)	56.9	MODMOR I-U/ERX 67/MDA
B4	0.104/0.041	1.63(0.059)	63.0	MAGNAMITE A-S/ERX 67/MDA
B5	0.117/0.046	1.69(0.061)	55.2	MAGNAMITE A-U/ERX 67/MDA
B6	0.104/0.041	1.72(0.062)	58.5	THORNEL 75-S/ERX 67/MDA
C1	0.114/0.045	1.63(0.059)	55.6 + 2.3	MODMOR I-U + 104 Glass Fabric/ERX 67/MDA
C2	0.122/0.048	1.58(0.057)	50.7 +15.0	MODMOR I-U + Pellon Veil/ERX 67/MDA
C3-1	0.142/0.056	1.88(0.068)	21.2 +43.5	GY 70-S + S-2 Glass/ERX 67/MDA
C3-2	0.140/0.055	1.88(0.068)	21.2 +43.5	GY 70-S + S-2 Glass/ERX 67/MDA
C4-1	0.091/0.036	1.58(0.057)	28.3 +24.1	GY 70-S/ERX 67/MDA + PRD 49-III/E702
C4-2	0.091/0.036	1.52(0.055)	28.3 +24.1	GY 70-S/ERX 67/MDA + PRD 49-III/E702
D1	0.358/0.141	0.61(0.022)	-	GY 70-S + NOMEX Honeycomb/ERX 67/MDA
D2	0.404/0.159	.0.80(0.029)	-	S-2 Glass + NOMEX Honeycomb + GY 70-S/ERX 67/MDA
D3	0.353/0.139	0.53(0.019)	-	PRD 49-III + NOMEX Honeycomb + GY 70-S/ERX 67/MDA + PRD 49-III/E702
D4	0.444/0.175	0.83(0.030)	-	GY 70-S + NOMEX Honeycomb/ERX 67/MDA
D5	0.127/0.050	1.52(0.055)	72.5	PRD 49-III/ERX 67/MDA
D6	0.084/0.033	1.30(0.047)	54.4	PRD 49-III/E702
A'	0.140/0.055	1.25(0.045)	40	PRD 49-III Style 181/ELVAMIDE 8061 Nylon
B'	0.155/0.061	1.16(0.042)	40	PRD 49-III Style 181/EXXON Polypropylene A11506
C'	0.137/0.054	1.33(0.048)	40	PRD 49-III Style 181/MERLON M40F Polycarbonate
D'	0.155/0.061	1.49(0.054)	55	Fiber Science, Inc. G-P-001- GY 70-S/FSI Resin
E'	0.145/0.057	1.52(0.055)	40	GY 70-S/ELVAMIDE 8061 Nylon
F'	0.112/0.044	1.63(0.059)	55	GY 70-S/ELVAMIDE 8061 Nylon
G'	0.132/0.052	1.55(0.056)	40	GY 70-S/MERLON M40F Polycarbonate
H'	0.142/0.056	1.41(0.051)	40	GY 70-S/EXXON Polypropylene A11506
J'	0.559/0.220	0.47(0.017)	55.2	GS-3002 PRD 49-III/E Glass/ ERX 67/MDA
K'	0.610/0.240	0.44(0.016)	62.6	GS-1002 E Glass/ERX 67/MDA
L'	0.137/0.054	2.68(0.097)	-	2024-T3 (Bare) Aluminum

*Details of construction and terminology may be found in appendix A.

Table 2. Impact and residual tensile strength test results

Specimen[a] code number	Impact causing catastrophic damage (joules)	(ft-lb)	Pre-impact Avg tensile strength (newtons)	(lb)	Post-impact Avg tensile strength (newtons)	(lb)	Residual strength (%)
A1	3.5	2.6	5196	1168	(b)	(b)	(b)
A2	3.5	2.6	4506	1013	(b)	(b)	(b)
A3	3.5	2.6	3585	806	(b)	(b)	(b)
A4	3.5	2.6	1882	423	(b)	(b)	(b)
A5	3.5	2.6	10137	2279	(b)	(b)	(b)
A6	3.5	2.6	16534	3717	(b)	(b)	(b)
A7	3.5	2.6	5631	1266	(b)	(b)	(b)
B1	3.5	2.6	3599	809	(b)	(b)	(b)
B2	(c)	(c)	3883	873	703	158	18.1
B3	(c)	(c)	3843	864	1552	349	40.4
B4	(c)	(c)	6961	1565	6014	1352	86.4
B5	(c)	(c)	5298	1191	3932	884	74.2
B6	(c)	(c)	4043	909	1526	343	37.7
C1	(c)	(c)	4168	937	1824	410	43.8
C2	(c)	(c)	3759	845	2318	521	61.7
C3-1	(c)	(c)	5373	1208	3087	694	57.5
C3-2	(c)	(c)	4951	1113	2909	654	58.8
C4-1	(c)	(c)	4226	950	2140	481	50.6
C4-2	(c)	(c)	4426	995	2237	503	50.6
D1	(c)	(c)	(d) (e)	(d) (e)	71(e)	16(e)	(d)
D2	(c)	(c)	1076(e)	242(e)	172(e)	38.6(e)	16.0
D3	(c)	(c)	(d) (e)	(d) (e)	183(e)	41.2(e)	(d)
D4	(c)	(c)	1499(e)	337(e)	289(e)	64.9(e)	19.3
D5	(c)	(c)	6103	1372	4986	1121	81.7
D6	(c)	(c)	6494	1460	5498	1236	84.7
A'	(c)	(c)	10164	2285	13856	3115	136.3
B'	(c)	(c)	7606	1710	9146	2056	120.2
C'	(c)	(c)	9319	2095	10467	2353	112.3
D'	6.8	5.0	7775	1748	(b)	(b)	(b)
E'	3.5	2.6	4217	948	(b)	(b)	(b)
F'	3.5	2.6	4075	916	(b)	(b)	(b)
G'	6.8	5.0	5787	1301	(b)	(b)	(b)
H'	3.5	2.6	3496	786	(b)	(b)	(b)
J'	(c)	(c)	725(e)	163(e)	609(e)	137(e)	84.0
K'	(c)	(c)	1392(e)	313(e)	1103(e)	248(e)	79.2
L'	(c)	(c)	31160	7005	31293	7035	100.4

[a]Test specimens were 5.08 x 22.86 cm (2 x 9 in.).

[b]This specimen sustained severe damage and was judged to have such minor residual strength that post-impact testing was unwarranted.

[c]This specimen sustained 13.56 joules (10 ft-lb) of impact with little or no visible damage.

[d]Specimen deflection exceeded the allowable on the fixture.

[e]This specimen was tested by the Four-Point Loading Sandwich Beam Test, where the distance between loading points was 5.08 cm (2 in.) on the top side of the specimen and 20.32 cm (8 in.) on the bottom side of the specimen. Loads shown were applied loads.

Table 3. Performance ranking for strength, low weight, and stiffness

Specimen code number	Construction description	Redisual strength (%)	Density (g/cm^3)	Strength/ density score	Calculated fiber content (volume %	Strength/ density X stiffness score	Numerical rank
B4	MAGNAMITE A/S/ERX 67/MDA	86.4	1.63	53.0	63.0	46.3	7
D5	PRD 49-III/ERX 67/MDA	81.7	1.52	53.7	72.5	40.7	8
D6	PRD 49-III/E 702	84.7	1.30	65.1	54.4	65.8	6
A'	PRD 49-III Style 181/ ELVAMIDE 8061 nylon	136.3	1.25	109.0	40.0	149.9	3
B'	PRD 49-III Style 181/ EXXON polypropylene A11506	120.2	1.16	103.6	40.0	142.4	4
C'	PRD 49-III Style 181/ MERLON M40F poly-carbonate	112.3	1.33	84.4	40.0	116.0	5
J'	GS-3002 PRD 49-III/E glass/ERX 67/MDA	84.0	0.47	178.7	55.2	178.0	1
K'	GS-1002 E Glass/ERX 67/MDA	79.2	0.44	180.0	62.6	158.1	2
L'	2024-T3 (bare) aluminum	100.4	2.68	37.5	—	37.5	9

Table 4. Composite tube design for test shafts

Tube type	Component tape description	Overall shaft[a] segment length for UH-1 stiffness strength, m (in.)	Ply sequence (inside to outside)
1	Type 1, THORNEL 50-S	2.184 (86)	$(\pm 10/\pm 50/\pm 10/\pm 10/\pm 10/\pm 15)_{12}$
3	Types 1/3, alternating[b] plies of T50-S and S1014 glass	1.702 (67)	$(\pm 20Gr/\pm 15Gl/\pm 45Gr/\pm 15Gl/\pm 45Gr/\pm 15Gl)_{12}$
4	Types 2/4, alternating plies of GY70-S and KEVLAR 49	1.956 (77)	$(\pm 15Gr/\pm 45K49/\pm 30Gr/\pm 20K49/\pm 15Gr/\pm 45K49)_{12}$
5	Type 5 hybrid tape,[c] T50-S and S1014 glass	1.778 (70)	$(\pm 30/\pm 30/\pm 15/\pm 45/\pm 10/\pm 10)_{12}$
6	Type 6 hybrid tape,[d] T50-S and KEVLAR 49	1.956 (77)	$(\pm 10/\pm 10/\pm 45/\pm 10/\pm 20/\pm 75/\pm 20/\pm 10/\pm 45)_{18}$

[a] Lengths listed are maximum for minimum weight shaft segments which meet UH-1 strength and stiffness requirements.
[b] Alternating plies means alternating double plies; e.g., ±15 means one double ply of prepreg tape wound at plus and minus 15° to the tube axis.
[c] A 1:1 volume ratio of THORNEL 50-S and S1014 glass in one tape.
[d] A 1:1 volume ratio of THORNEL 50-S and KEVLAR 49 in one tape.

Table 5. Comparison of computer optimized tube designs for minimum weight and maximum shaft segment length vs. single angle ply design

Tape type[a] description	Ply angle design, inside to outside	Predicted[b] maximum segment length, m (in.)	Single angle ply design, inside-to-outside	Predicted maximum segment length, m (in.)
1(T-50-S)	$(\pm 10/\pm 50/\pm 10/\pm 10/\pm 10/\pm 15)_{12}$	2.184 (86)	$(\pm 45)_{12}$	1.067 (42)
1/3(T-50-S and S-1014 glass)	$(\pm 20Gr/+15Gl/\pm 45Gr/\pm 15Gl/\pm 45Gr/\pm 15Gl)_{12}$	1.702 (67)	$(\pm 45Gr/+45Gl/\pm 45Gr/\pm 45Gl/\pm 45Gr/\pm 45Gl)_{12}$	1.092 (43)
2/4(GY70-S and KEVLAR 49)	$(\pm 15Gr/+45K/\pm 30Gr/\pm 20K/\pm 15Gr/\pm 45K)_{12}$	1.956 (77)	$(\pm 45Gr/+45K/\pm 45Gr/\pm 45K/\pm 45Gr/\pm 45K)_{12}$	1.143 (45)
5 (hybrid tape, T-50-S and S-1014 glass)	$(\pm 30/\pm 30/\pm 15/\pm 45/\pm 10/\pm 10)_{12}$	1.778 (70)	$(\pm 45)_{12}$	1.041 (41)
6 (hybrid tape, T-50-S and KEVLAR 49)	$(\pm 10/\pm 10/\pm 45/\pm 10/\pm 20/\pm 75/\pm 20/\pm 10/\pm 45)_{18}$	1.956 (77)	$(\pm 45)_{18}$	1.143 (45)

[a]Physical properties used in the computer programs were as reported by the Ferro Corp.
[b]Lengths are overall shaft segment lengths consisting of a composite tube with an aluminum end coupling bonded to the inside diameter of each end of the tube.

Table 6. Cured tube data summary

Type-tube number	Weight g (lb)	Length cm (in.)	Weight per unit length g/cm (lb/in.)	Average inside diameter cm (in.)	Average outside diameter cm (in.)
1-1	438 (0.97)	44.4 (17.5)	9.86 (0.055)	8.217 (3.235)	8.707 (3.428)
1-2	458 (1.01)	44.4 (17.5)	10.31 (0.058)	8.212 (3.233)	8.720 (3.433)
1-3	463 (1.02)	44.4 (17.5)	10.43 (0.058)	8.230 (3.240)	8.732 (3.438)
Avg	453 (1.00)	44.4 (17.5)	10.20 (0.057)	8.220 (3.233)	8.720 (3.433)
3-1	492 (1.08)	44.4 (17.5)	11.08 (0.062)	8.219 (3.236)	8.677 (3.416)
3-2	491 (1.08)	43.8 (17.2)	11.21 (0.063)	8.214 (3.234)	8.651 (3.406)
3-3	486 (1.07)	43.4 (17.1)	11.20 (0.063)	8.224 (3.238)	8.651 (3.406)
Avg	490 (1.08)	43.9 (17.3)	11.16 (0.063)	8.219 (3.236)	8.660 (3.409)
4-1	400 (0.88)	43.5 (17.1)	9.19 (0.051)	8.222 (3.237)	8.636 (3.400)
4-2	483 (1.06)	43.7 (17.2)	11.05 (0.062)	8.224 (3.238)	8.636 (3.400)
4-3	375 (0.83)	43.8 (17.2)	8.56 (0.048)	8.217 (3.235)	8.626 (3.396)
4-4	203 (0.45)	43.7 (17.2)	4.65 (0.026)	8.230 (3.240)	8.423 (3.316)
Avg	419 (0.92)[a]	43.7 (17.2)[a]	9.59 (0.053)[a]	8.221 (3.237)[a]	8.633 (3.399)[a]
5-1	537 (1.18)	43.9 (17.3)	12.23 (0.068)	8.219 (3.236)	8.715 (3.431)
5-2	526 (1.16)	43.8 (17.2)	12.01 (0.067)	8.217 (3.235)	8.674 (3.415)
5-3	163 (0.36)	43.8 (17.2)	3.72 (0.021)	8.227 (3.239)	8.334 (3.281)
Avg	531 (1.17)[b]	43.8 (17.2)[b]	12.12 (0.067)[b]	8.218 (3.235)[b]	8.694 (3.423)[b]
6-1	557 (1.23)	43.8 (17.2)	12.72 (0.071)	8.227 (3.239)	8.839 (3.480)
6-2	527 (1.16)	43.8 (17.2)	12.03 (0.067)	8.227 (3.239)	8.839 (3.480)
6-3	529 (1.17)	43.8 (17.2)	12.08 (0.068)	8.227 (3.239)	8.839 (3.480)
Avg	538 (1.19)	43.8 (17.2)	12.28 (0.069)	8.227 (3.239)	8.839 (3.480)

[a]Average of the first three replicates only.
[b]Average of the first two replicates only.

Table 7. Shaft test specimen measurements

Shaft* serial number	Made from type-tube number	L_1, overall shaft length cm (in.)	L_2, overall tube length cm (in.)	D, avg outside tube diameter cm (in.)	α, base line to ℄ angle degrees
11A	1-1	25.169 (9.909)	20.935 (8.242)	8.788 (3.460)	89.97
11B	1-1	25.376 (9.990)	20.914 (8.234)	8.872 (3.493)	89.89
12A	1-2	25.169 (9.909)	20.978 (8.259)	8.778 (3.456)	89.95
12B	1-2	25.174 (9.911)	21.021 (8.276)	8.776 (3.455)	89.91
13A	1-3	25.169 (9.909)	20.930 (8.240)	8.809 (3.468)	89.97
13B	1-3	25.169 (9.909)	20.742 (8.166)	8.806 (3.467)	89.95
31A	3-1	25.164 (9.907)	21.029 (8.279)	8.745 (3.443)	89.95
31B	3-1	25.159 (9.905)	20.902 (8.229)	8.756 (3.447)	89.92
32A	3-2	25.166 (9.908)	20.970 (8.256)	8.745 (3.443)	89.97
32B	3-2	25.164 (9.907)	20.991 (8.264)	8.745 (3.443)	89.95
33A	3-3	25.154 (9.903)	20.935 (8.242)	8.740 (3.441)	89.91
33B	3-3	25.413 (10.005)	21.001 (8.268)	8.771 (3.453)	89.59
41A	4-1	25.179 (9.913)	20.968 (8.255)	8.705 (3.427)	89.94
41B	4-1	25.174 (9.911)	20.978 (8.259)	8.710 (3.429)	89.97
42A	4-2	25.437 (10.015)	21.039 (8.283)	8.687 (3.420)	88.91
42B	4-2	25.173 (9.910)	20.968 (8.255)	8.697 (3.424)	89.92
43A	4-3	25.173 (9.910)	21.052 (8.228)	8.677 (3.416)	89.97
43B	4-3	25.185 (9.915)	20.874 (8.218)	8.672 (3.414)	89.95
44A	4-4	25.169 (9.909)	20.876 (8.219)	8.499 (3.346)	89.97
44B	4-4	25.179 (9.913)	21.018 (8.275)	8.494 (3.344)	89.94

Table 7 (Continued)

Shaft* serial number	Made from type-tube number	L_1, overall shaft length cm	(in.)	L_2, overall tube length cm	(in.)	D, avg outside tube diameter cm	(in.)	α, base line to ℄ angle degrees
51A	5-1	25.169	(9.909)	20.323	(8.001)	8.783	(3.458)	89.97
51B	5-1	25.173	(9.910)	20.841	(8.205)	8.776	(3.455)	89.97
52A	5-2	25.174	(9.911)	20.927	(8.239)	8.778	(3.456)	89.91
52B	5-2	25.169	(9.909)	20.874	(8.218)	8.781	(3.457)	89.97
53A	5-3	25.183	(9.914)	20.922	(8.237)	8.407	(3.310)	89.89
53B	5-3	25.185	(9.915)	20.937	(8.243)	8.420	(3.315)	89.89
61A	6-1	25.173	(9.910)	21.026	(8.278)	8.966	(3.530)	89.94
61B	6-1	25.173	(9.910)	20.960	(8.252)	8.956	(3.526)	89.95
62A	6-2	25.164	(9.907)	20.927	(8.239)	8.915	(3.510)	89.89
62B	6-2	25.159	(9.905)	20.861	(8.213)	8.915	(3.510)	89.83
63A	6-3	25.183	(9.914)	20.996	(8.266)	8.915	(3.510)	89.70
63B	6-3	25.174	(9.911)	20.988	(8.263)	8.923	(3.513)	89.95

*Serial numbers from the above list ending in "A" were not impacted. Those specimens having a serial number ending in "B" were impacted prior to torque to failure testing with 13.56 J (10 ft·lb) of energy from a falling tup.

Table 8. Shaft specimen strength data

Unimpacted specimens			Impacted specimes			
Shaft serial no.	Torsional load at failure lbf in.	N m	Shaft serial no.	Torsional load at failure lbf in.	N m	After impact residual torsion strength, %
11A	9,600	1,085	11B	7,000	791	
12A	7,000	791	12B	5,750	650	
13A	7,600	859	13B	7,450	842	
Type 1 average	8.067	911		6,733	761	83.5
31A	9,700	1,096	31B	8,400	1,062	
32A	11,350	1,282	32B	10,600	1,198	
33A	10,150	1,147	33B	10,750	1,215	
Type 3 average	10,400	1.175		10,250	1,158	98.6
41A	22,100	2,497	41B	8,100	915	36.7
42A	15,200[a]	1,717	42B	5,400	610	35.5
43A	8,500[a]	960	43B	6,300	712	74.1
44A	11,000[b]	1,243	44B	2,500[b]	282	22.7
Type 4[c] average						
51A	31,700	3,582	51B	13,100	1,480	41.3
52A	33,000	3,728	52B	14,600	1,650	44.2
53A	7,700[d]	870	53B	2,300	260	29.9
Type 5 average	32,350[e]	3,655[e]		13,850[e]	1,565[e]	42.8[e]
61A	8,200[a]	926	61B	10,500	1,186	--
62A	11,400	1,288	62B	7,300	825	64.0
63A	7,800	881	63B	6,500	734	83.3
Type 6 average	9,600[e]	1,085[e]		6,900[e]	780[e]	73.6

[a]Failure occurred in the bond between the end coupling and the composite tube. Thus, the load recorded is the maximum strength (in this specimen) of the adhesive bond.

[b]Since all of the type 2 graphite tape (GY70) was used up after the first ply of the no. 4 tube, the usual no. 3 double ply was replaced by the no. 4 double ply ($\pm 20°$, K-49) and the usual no. 4 double ply was replaced by the no. 6 double ply ($\pm 43°$, K-49). The no. 5 graphite double ply was omitted with no replacement.

[c]Because of bond line failures and construction alteration in one replicate, a type 4 average of the listed data was considered non-representative.

[d]All of the type 5 tape was used up after the no. 2 ply of the no. 3 tube, thus four double plies are missing.

[e]Only the two nearly replicable results were averaged.

Table 9. Combined performance ranking of composite tubes

Tube type	Post impact strength, N m	Percent residual strength	Average weight/unit length, g/cm	Residual strength/ weight, score	Fiber content, volume %	(Residual strength/ weight) X stiffness,[b] score	Numerical rank
1	761	83.5	10.20	8.19	59.69	8.23	1
3	1,138	98.6	11.16	8.83	64.49	8.22	2
4	762[a]	36.1[a]	9.59	3.76	50.32	3.80	4
5	1,565	42.8	12.12	3.53	58.13	3.64	5
6	780	73.6	12.28	5.99	57.48	6.25	3

[a]The average value was computed from the first two replicate values only from table 8.
[b]Stiffness factor = 60/tube type fiber content, expressed as a percent.

Table 10. Composite tube fiber content

Shaft serial number	Average[a] fiber content vol %	Average[b] fiber density g/cm^3	Average[b] composite density g/cm^3
11AB	59.51		
12AB	59.92	1.7197	1.4448
13AB	59.64		
31AB	64.77		
32AB	64.27	1.983	1.6810
33AB	64.44		
41AB	59.28		
42AB	59.36	1.6851	1.4280
43AB	61.39		
44AB	61.78		
51AB	58.93		
52AB	57.33	2.2090	1.6833
53AB	58.24		
61AB	56.72		
62.AB	57.82	1.4492	1.2976
63AB	57.90		

[a]Determined by Procedure A of ASTM Standard Test Method D3171, entitle, "Fiber Content of Reinforced Resin Composites" (ref. 9).
[b]Determined by Method A-1 of ASTM Standard Test Method D792, entitle, "Specific Gravity and Density of Plastics by Displacement" (ref. 10).

Table 11. Shaft train weight savings

Tube type	No. of shaft segments required[a]	Tube length required[b] m (in.)	Tube weight/unit length g/cm (lb/in.)	Total tube weight kg (lb)	Bearing assembly weight[c] kg (lb)	Shaft train weight kg (lb)	Percent weight savings over aluminum
2024 T3 aluminum	5	5.61 (220.789)	8.27 (0.0463)	4.64 (10.22)	9.78 (21.56)	14.42 (31.78)	—
1	3	5.95 (234.12)	10.18 (0.057)	6.06 (13.34	4.89 (10.78)	10.95 (24.12	24.1
3	4	5.78 (227.454)	11.25 (0.063)	6.50 (14.33)	7.33 (16.17)	13.83 (30.50)	4.0
4	4	5.78 (227.454	9.46 (0.053)	5.47 (12.05)	7.33 (16.17)	12.80 (28.22)	11.2
5	4	5.78 (227.454)	11.96 (0.067)	6.91 (15.24)	7.33 (16.17)	14.24 (31.41)	1.2
6	4	5,78 (227.454)	12.32 (0.069)	7.12 (15.69)	7.33 (16.17)	14.45 (31.86)	-0.1

[a]For the UH-1H tail rotor drive shaft, the total shaft train length = (4 x 57.567) + (1 x 18.651) = 248.919 in. or 6.32 m. Maximum overall shaft segment length to obtain required UH-1 stiffness and strength from the AAMRDL design for each tube type is shown in table 4.
[b]Each bearing assembly (not including end couplings) takes up 5.195 in. (0.132 m) of shaft train length. Each shaft segment contributes 1.47 in. (0.037 m) of shaft train length from the two aluminum end couplings extending beyond the ends of the composite tube.
[c]Each bearing assembly weighs 5.39 lb (2.44 kg).

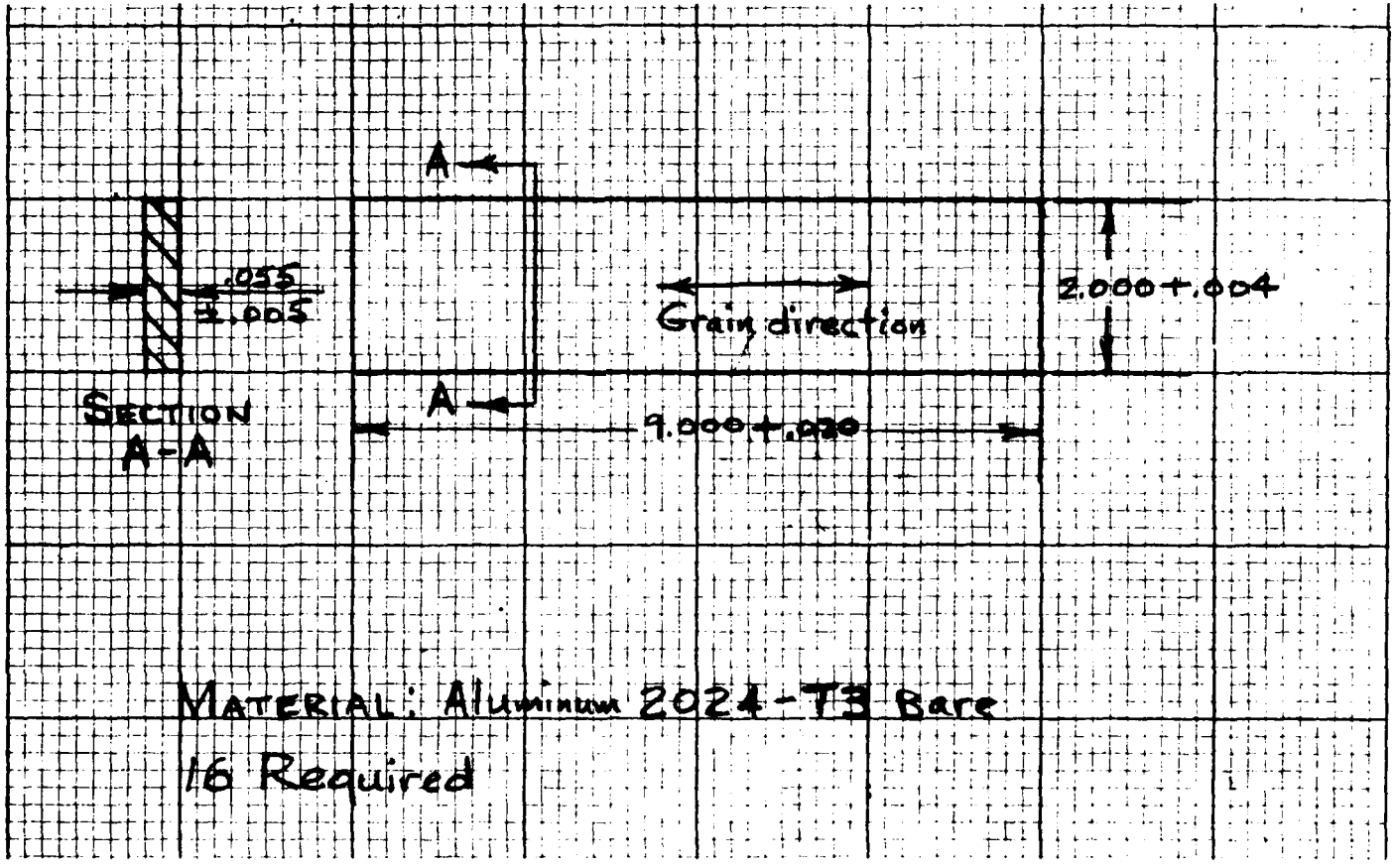


Figure 1. Impact test specimen.

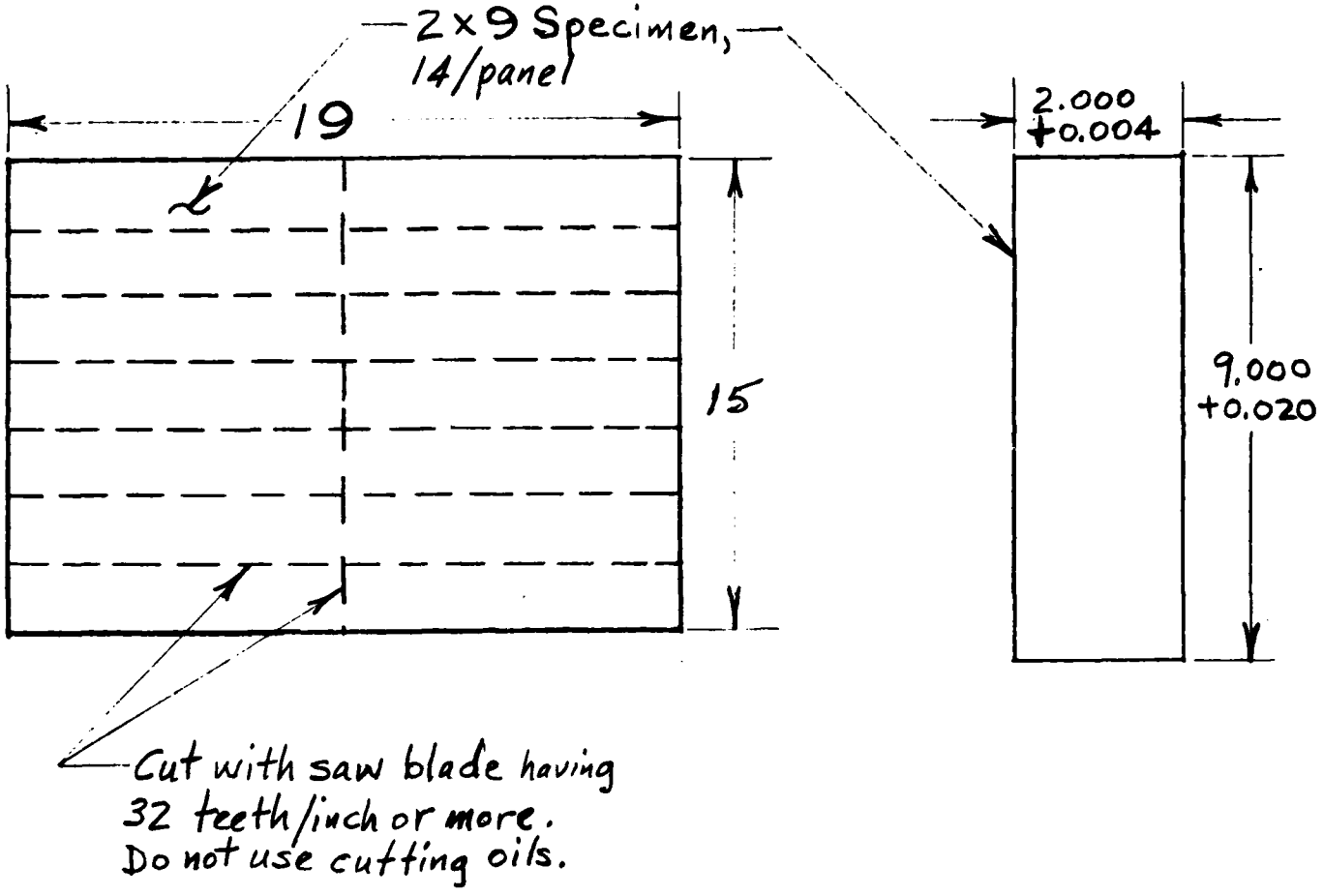


Figure 2. Cutting diagram, composite test specimens.

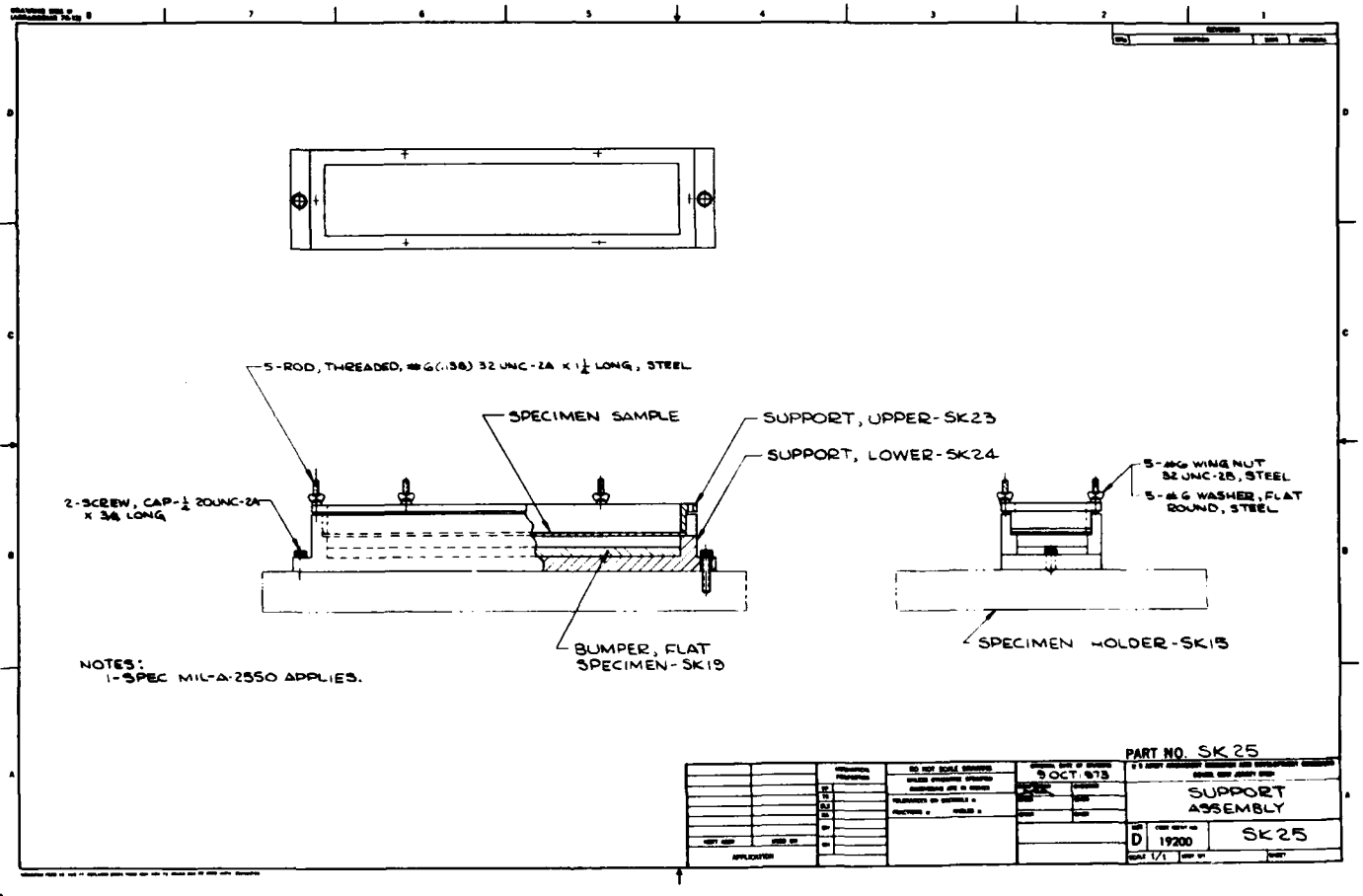


Figure 3. Support fixture for flat specimen impact testing.

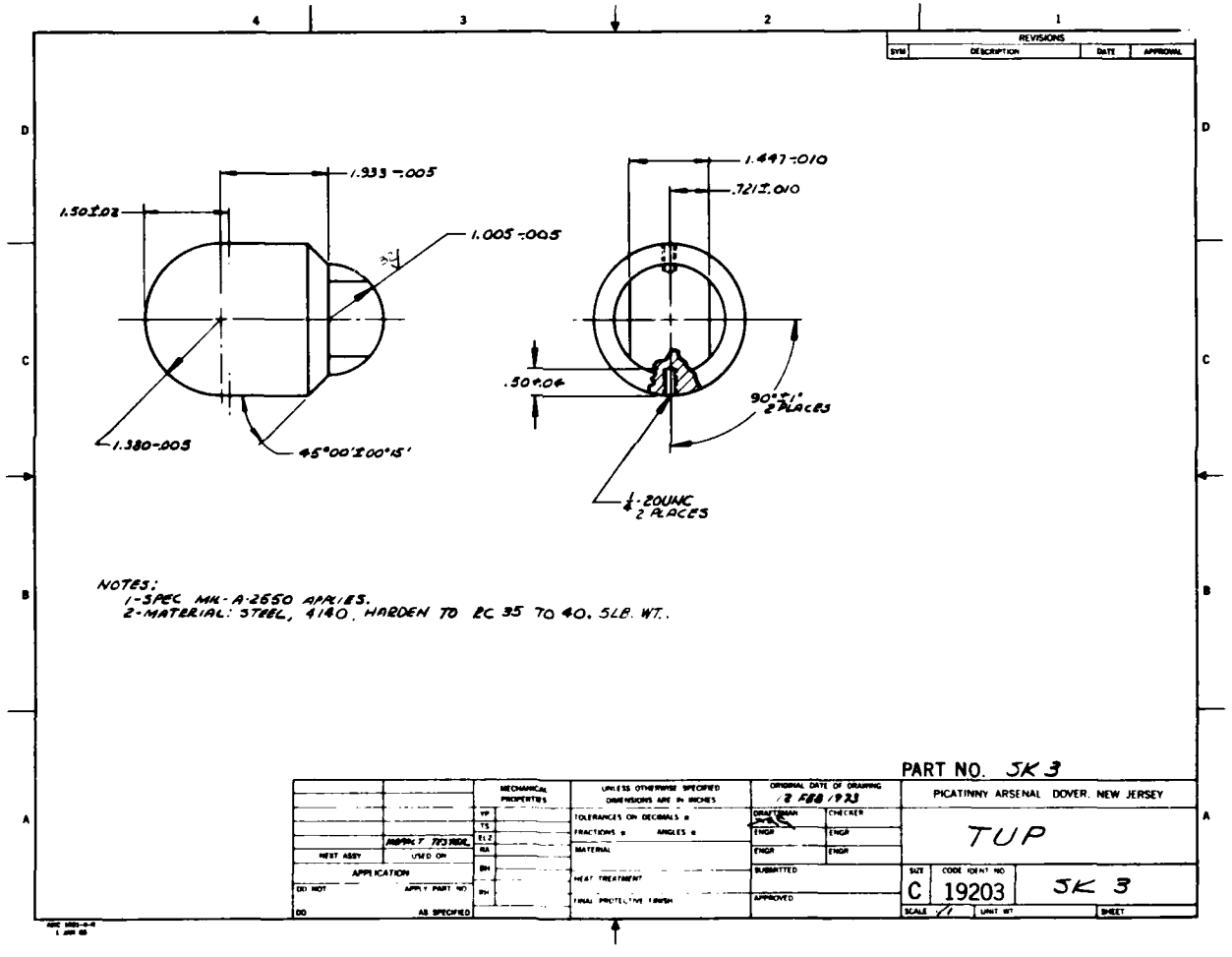


Figure 4. Falling tup for impact testing.

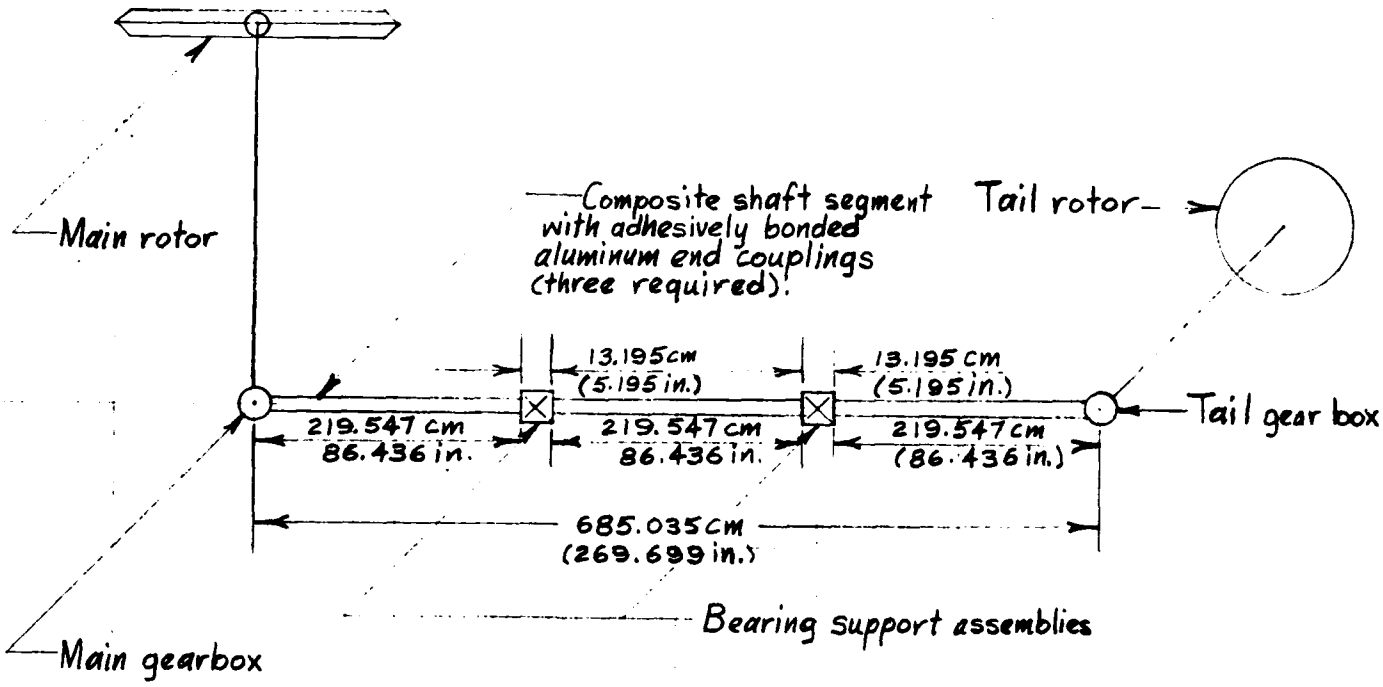


Figure 5. Proposed high modulus composite drive shaft for UH1-H helicopter.

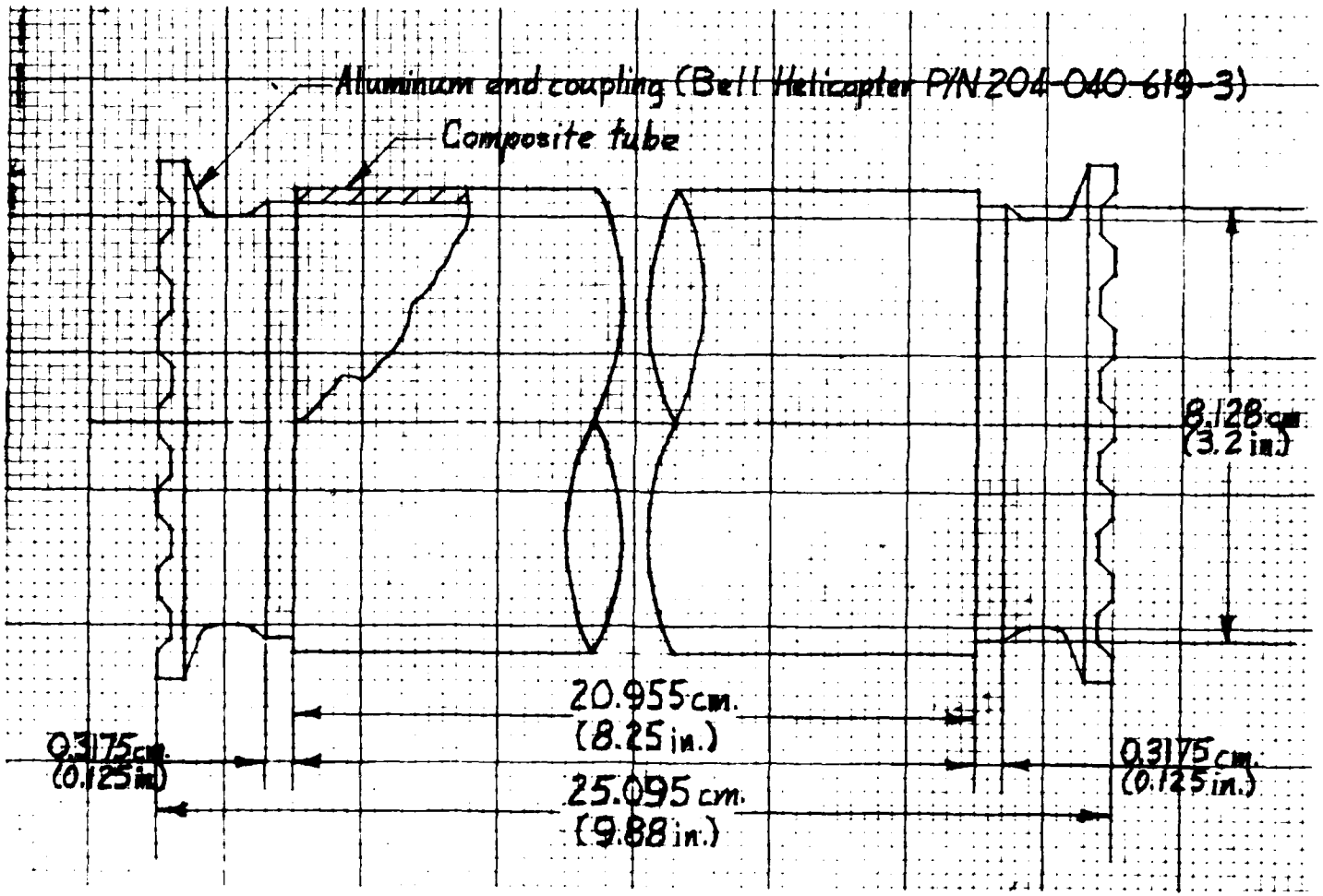


Figure 6. Short shaft test specimen.

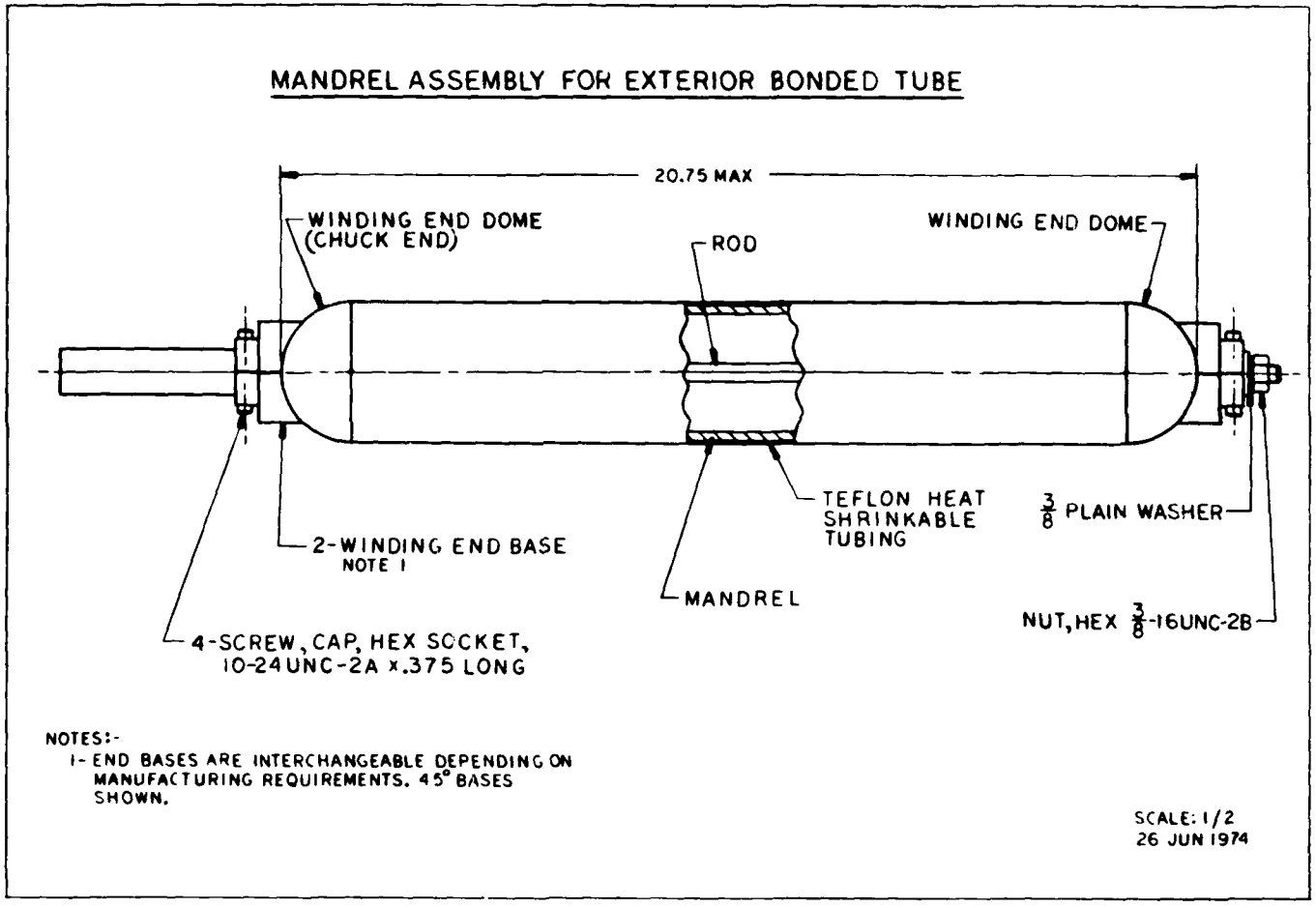
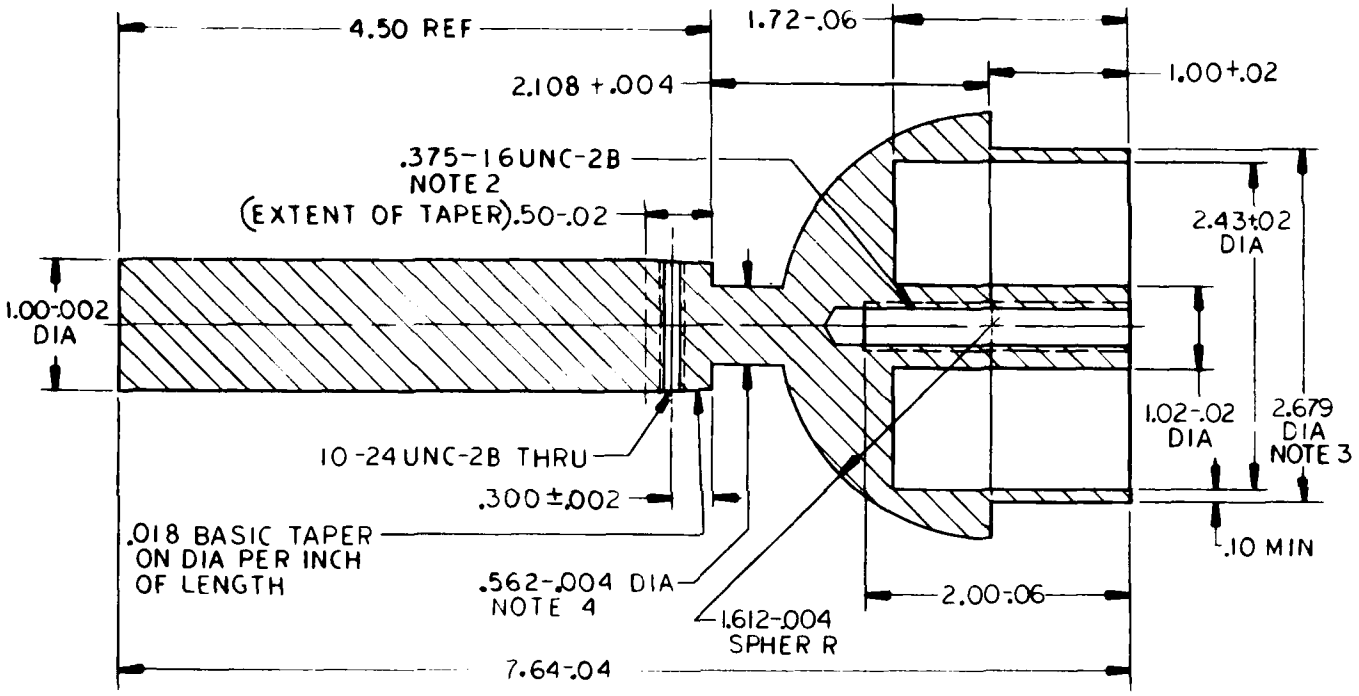


Figure 7. Mandrel assembly for exterior bonded tube

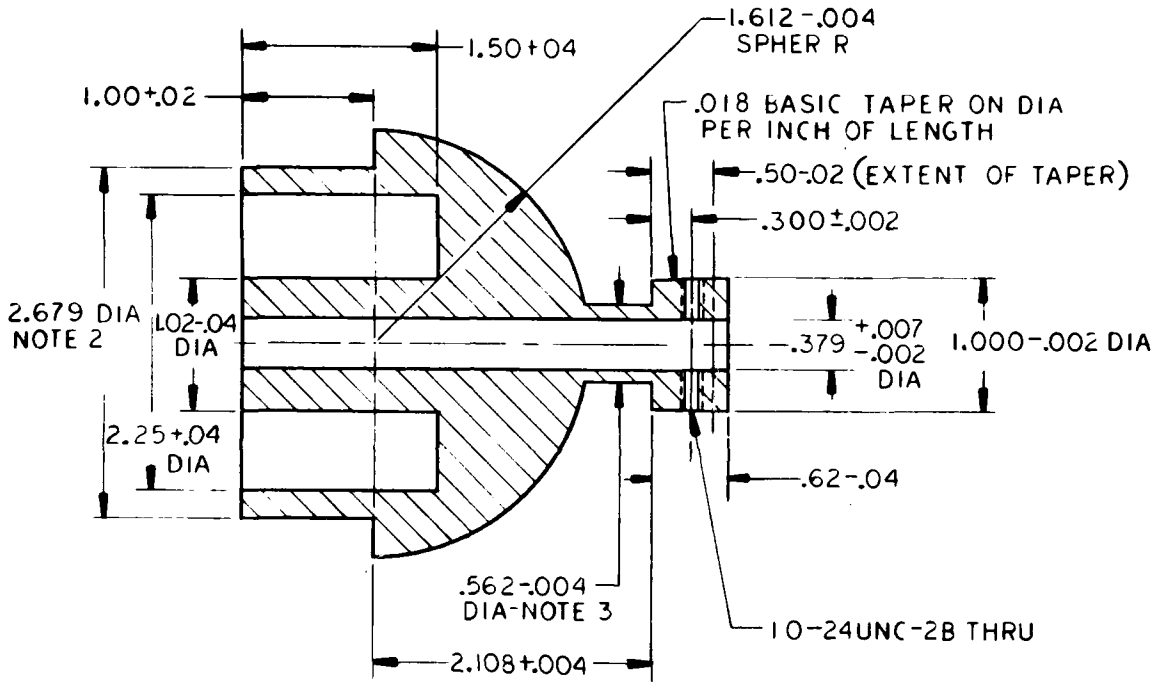


NOTES:

1-MATERIAL:-STEEL, B1112, B1113, LEDALLOY 300, 375, AX.
2-CAUTION: KEEP TAP DRILL DEPTH TO MINIMUM SO AS NOT TO WEAKEN PART AT NECK.
3-SLIDE FIT WITH MANDREL (SH 3 OF 9).
4- THIS NOTE FOR REFERENCE ONLY. THE .562 DIA ALLOWS FOR A 10° WINDING ANGLE.

SCALE: 1/1
SH 1 OF 9

Figure 8. Winding end dome (chuck end).



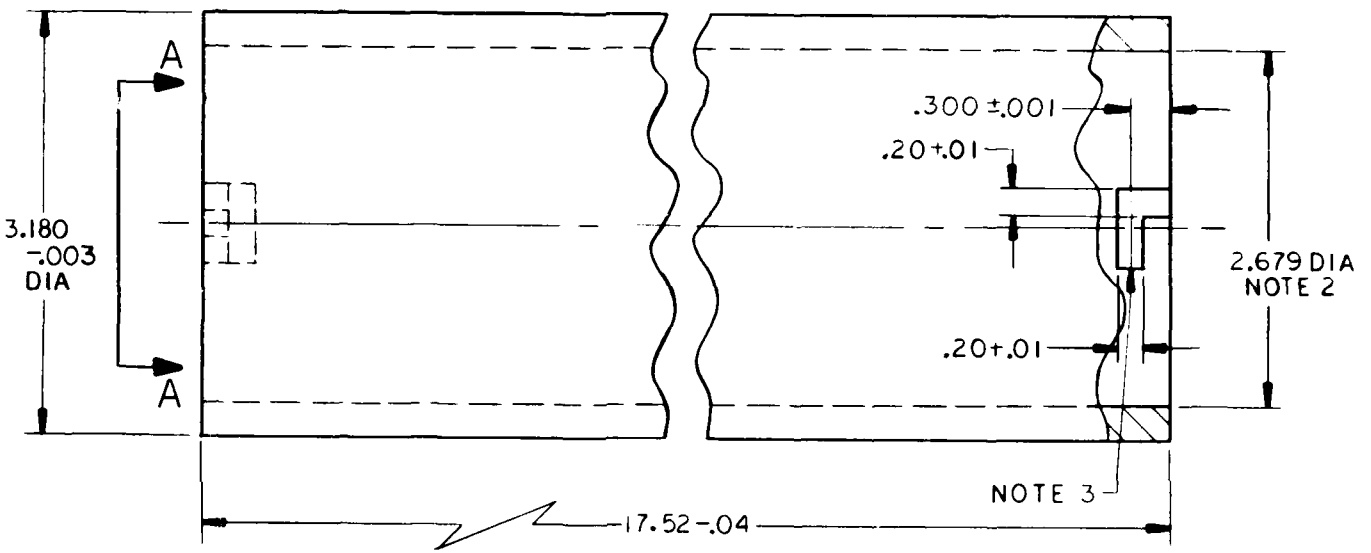
NOTES:

1- MATERIAL: ALUMINUM 2011-T3, 2017-T4, 2024-T4.
2- SLIDE FIT WITH MANDREL (SH3 OF 9).
3- THIS NOTE FOR REFERENCE ONLY. THE .562 DIA ALLOWS FOR A 10° WINDING ANGLE.

SCALE: 1/1

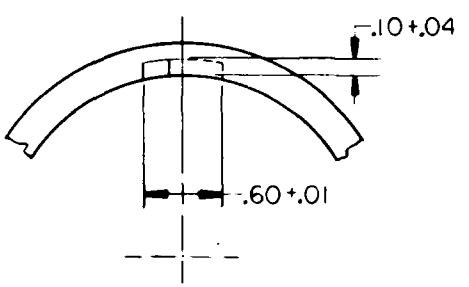
SH 2 OF 9

Figure 9. Winding end dome.



NOTES:

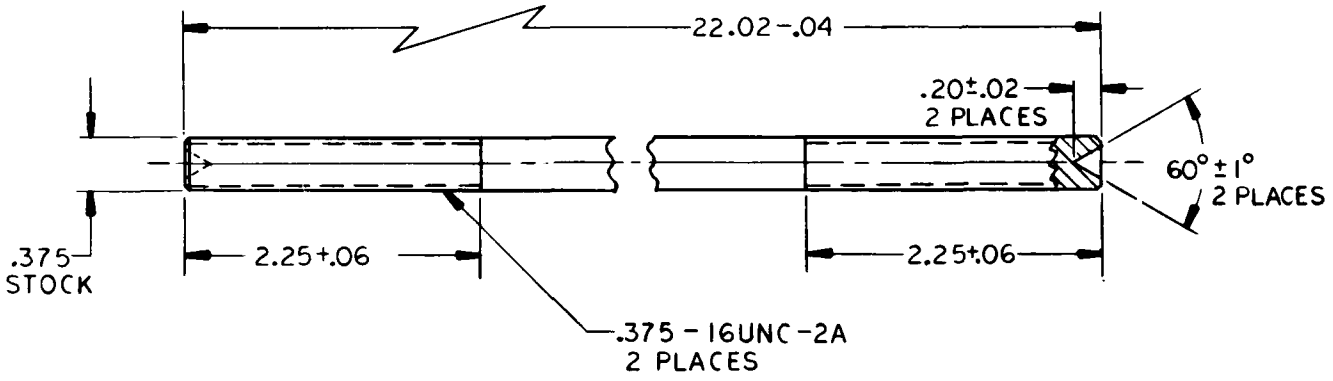
1 - MATERIAL: ALUMINUM, 2011-T3, 2017-T4, 2024-T4.
2 - SLIDE FIT WITH WINDING END DOMES, SH 1 & 2 OF 9 AND CURING END CAPS, SH 6 & 7 OF 9.
3 - TWO RIGHT ANGLE GROOVES 180° APART AT EACH END OF MANDREL. GROOVE OPPOSITE ONE SHOWN TO BE ORIENTATED SO AS TO PROVIDE CIRCULAR LOCKING ACTION WITH PINS IN CURING END CAPS (SH 6 & 7 OF 9).



VIEW A

SCALE: 1/1
SH 3 OF 9

Figure 10. Mandrel.



NOTES:-
1- MATERIAL:- STEEL BAR, COLD FINISHED, C1018, C1117.

SCALE:1/1
SH 5 OF 9

Figure 11. Rod.

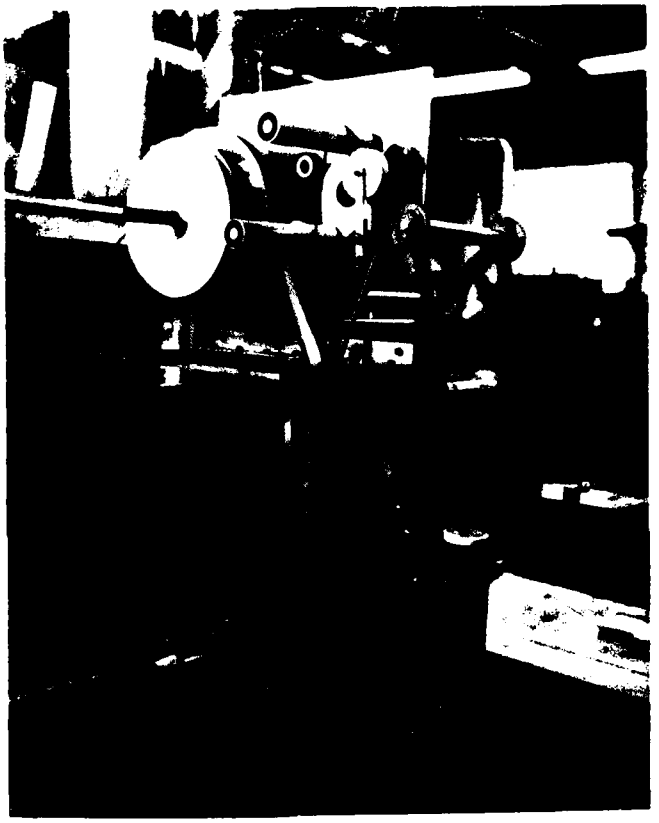


Figure 12. Typical tape winding setup on the W-1 Mc Clean-Anderson winding machine.

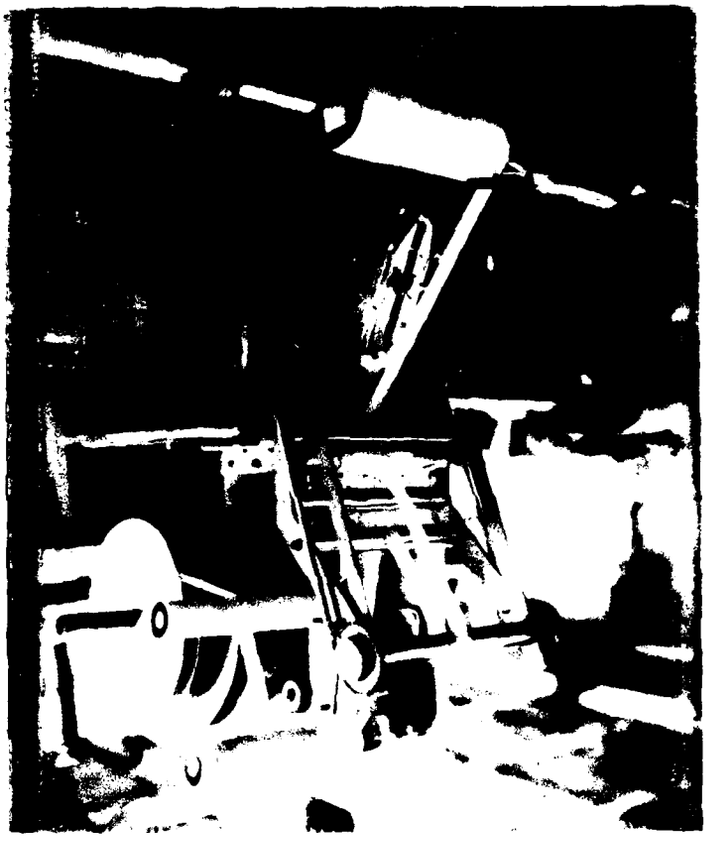
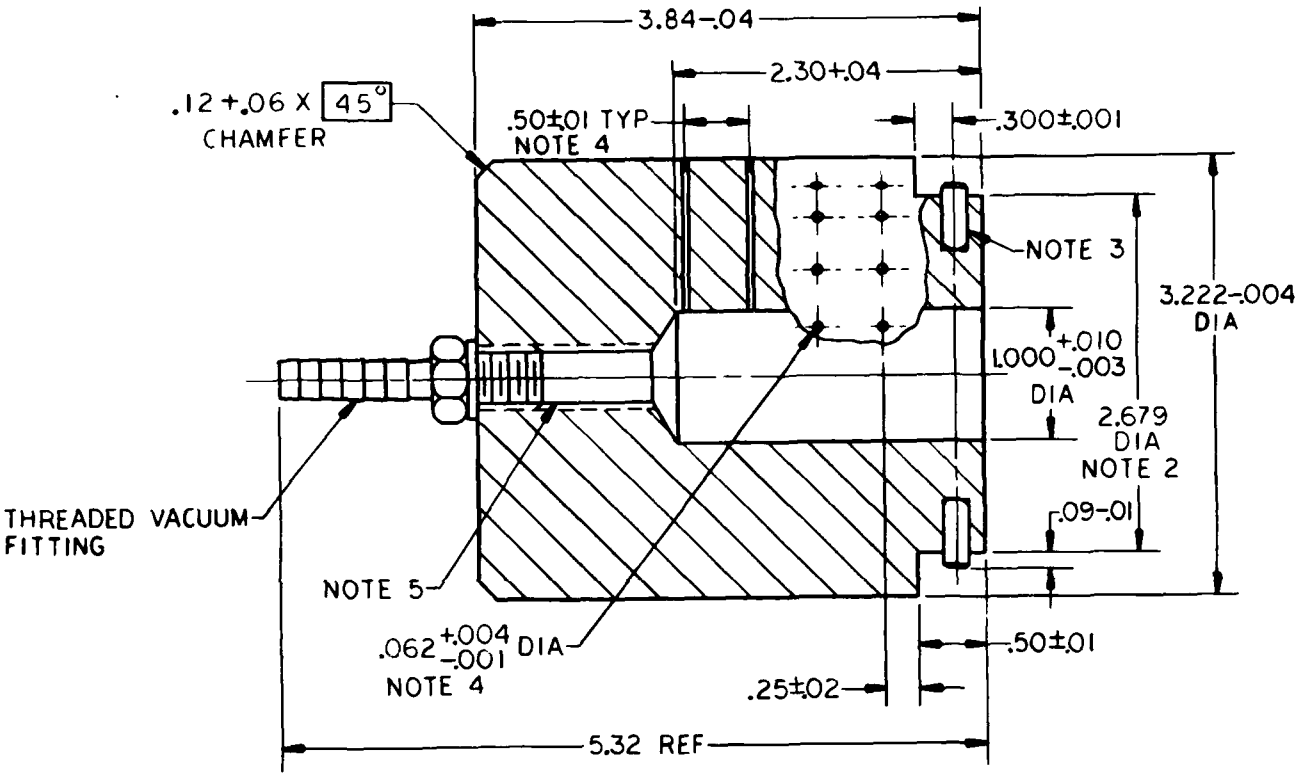


Figure 13. Typical wrapping setup for winding woven nylon tape.

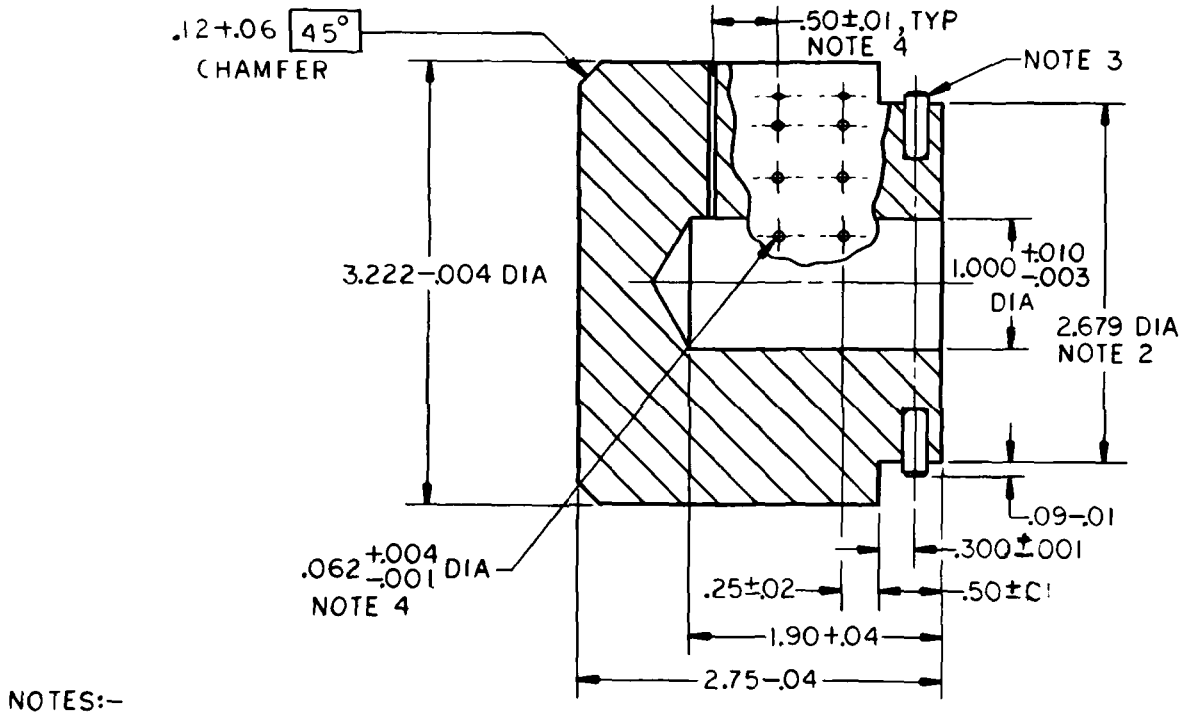


NOTES:-

1-MATERIAL:-ALUMINUM,2011-T3,2017-T4,2024-T4.
2-SLIDE FIT WITH MANDREL (SH 3 OF 9).
3-FORCE FIT .187 DIA X .500 LONG,2 PINS 180° APART TO MATE WITH GROOVES IN MANDREL.
4-DRILL .062 VACUUM HOLES .50 APART AROUND CIRCUMFERENCE, 4 ROWS OF HOLES.
5-DRILL HOLE THRU AND TAP FOR VACUUM FITTING SUPPLIED.

SCALE: 1/1
SH 8 OF 9

Figure 14. Alternate design--curing end cap (vacumm fitting end).



NOTES:-
1-MATERIAL:-ALUMINUM, 2011-T3, 2017-T4, 2024-T4.
2-SLIDE FIT WITH MANDREL (SH 3 OF 9).
3-FORCE FIT .187 DIA X .500 LONG, 2 PINS 180° APART TO MATE WITH GROOVES IN MANDREL.
4-DRILL .062 VACUUM HOLES .50 APART AROUND CIRCUMFERENCE. 3 ROWS OF HOLES.

SCALE: 1/1
SH 9 OF 9

Figure 15. Alternate design--curing end cap.

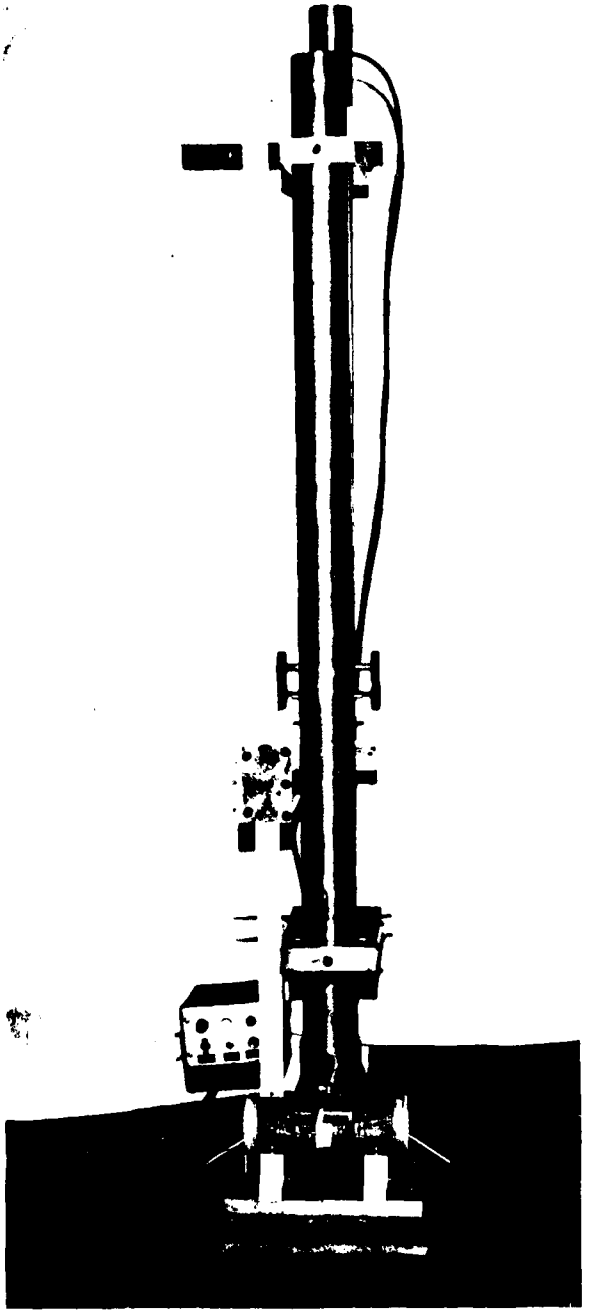


Figure 16. Falling tup impact tester with specimen.

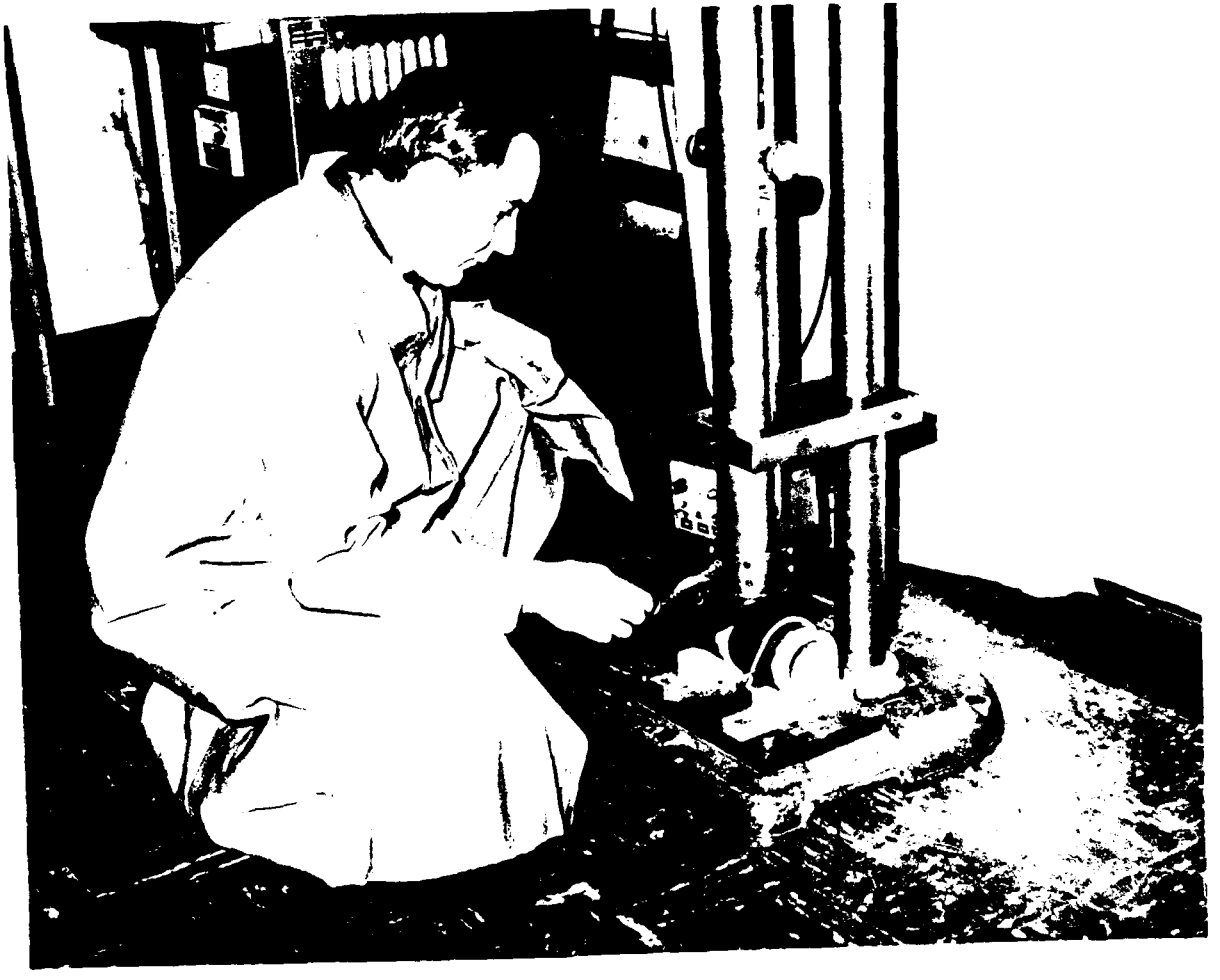


Figure 17. Impact tester showing adjustable electro-magnetic tup support, mounted specimen, and rebound catcher in position.

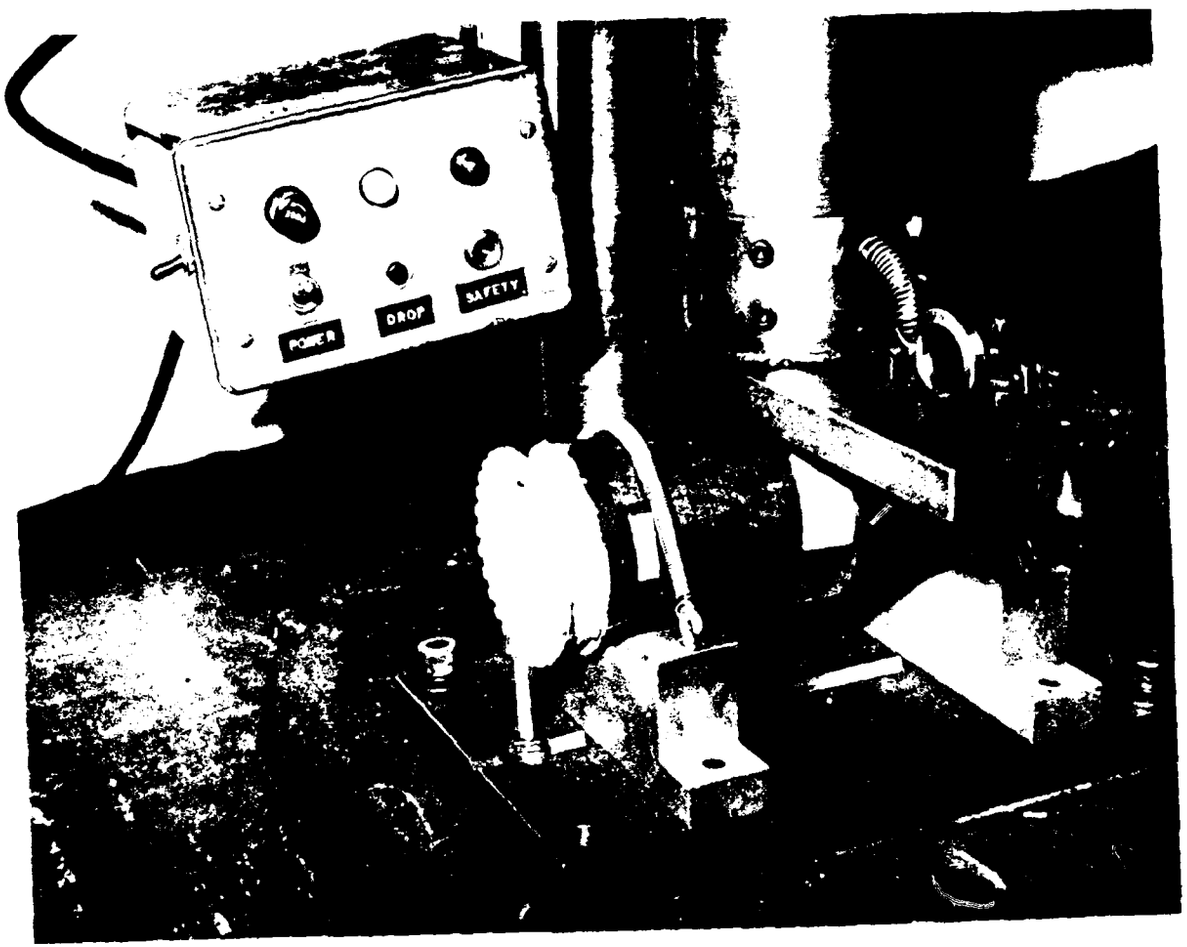


Figure 18. Closeup photo of test specimen in "V" block support showing machine screw with ground head for specimen location.

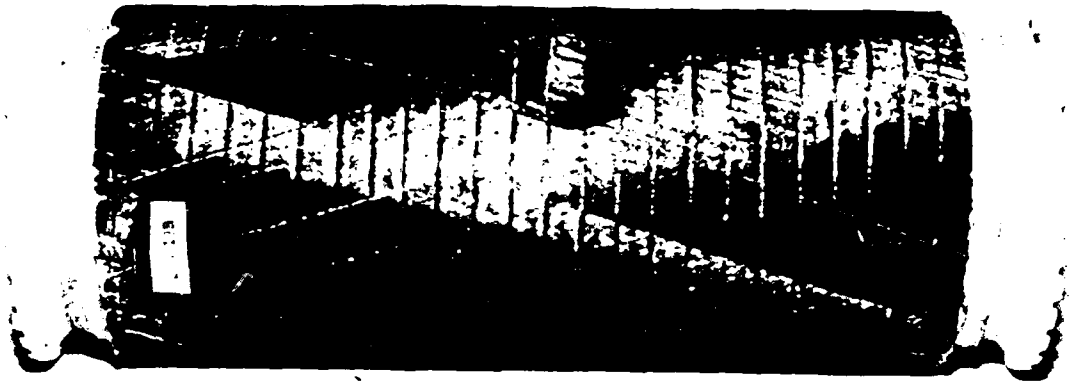


Figure 19. Typical impact damage, type 1 shaft (THORNEL 50-S).

Figure 20. Typical impact result, type 3 shaft (alternating plies of THORNEL 50-S and S-1014 glass).

Figure 21. Typical inner fiber delamination from falling tup, type 3 shaft (alternating plies of THORNEL 50-S and S-1014 glass).

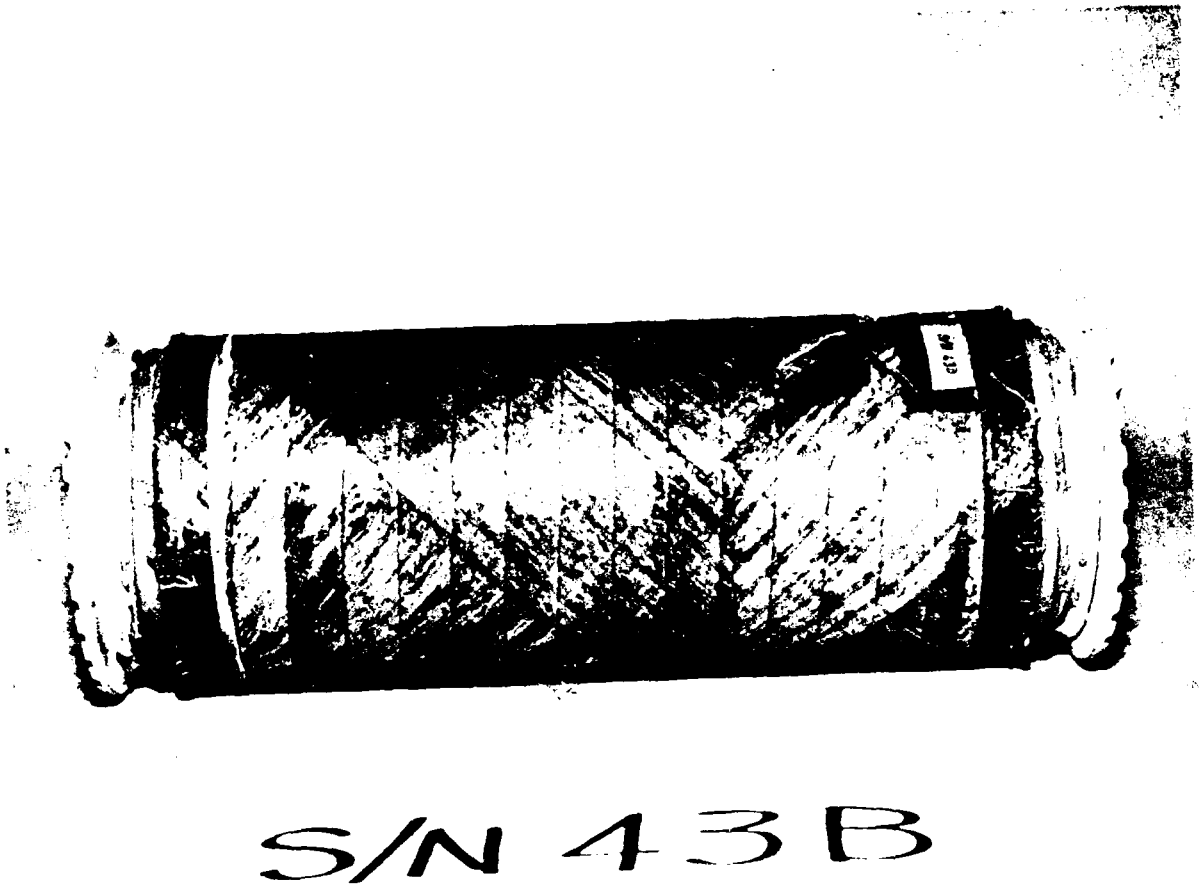


Figure 22. Typical external appearance after impact, type 4 shaft (alternating plies of CELION GY 70-S and KEVLAR 49).

Figure 23. Typical internal appearance after impact, type 4 shaft (alternating plies of CELION GY 70-S and KEVLAR 49).

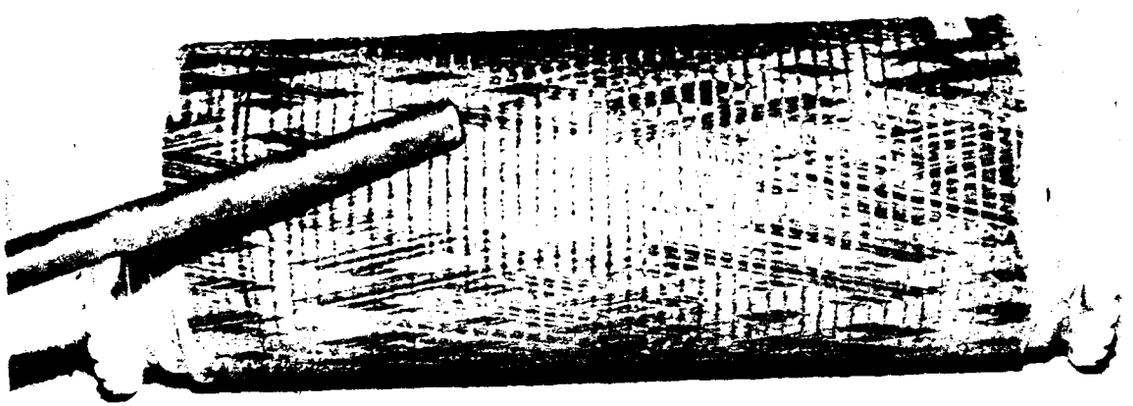


Figure 24. Typical external appearance after impact, type 5 shaft (hybrid tape, THORNEL 50-S and S-1014 glass).

Figure 25. Slight inner fiber delamination after impact, type 5 shaft (hybrid tape, THORNEL 50-S and S-1014 glass).

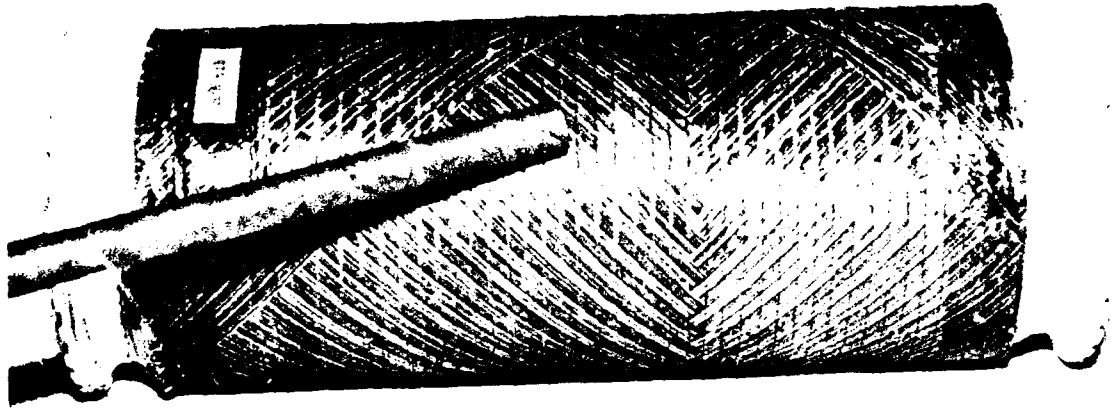


Figure 26. Typical external appearance after impact, type 6 shaft (hybrid tape, THORNEL 50-S and Kevlar 49).

Figure 27. Typical inner appearance after impact, type 6 shaft (hybrid tape, THORNEL 50-S and Kevlar 49).

APPENDIX A

HIGH PERFORMANCE REINFORCED PLASTIC COMPOSITE LAMINATES FOR IMPACT SCREENING

Test Panel Requirements

All panels that were procured were made with continuous fibers and met the dimensional requirement illustrated in figure A-1. Panels procured from General Structures Corporation tended to be thicker than other panels tested; this was due to their method of fabrication (three dimensional weave). Generally, all panels were to meet the following requirements:

1. Each laminate shall have an even number of plies. The total number shall be determined by the cured ply thickness of the fiber being laminated, e.g., if the cured ply thickness is 0.0203 cm (0.008 in.), six plies would produce a total laminate thickness of 0.122 cm (0.048 in.) or the even number of plies closest to 0.127 cm (0.050 in.).

2. The ply layup shall be an alternating plus and minus 45 degrees (+ and -45°).

3. The fiber content of the cured laminate shall be 55 $\pm$ 5% by volume and shall be reported to the closest percentile.

4. Each laminate shall be identified as to supplier's name, material, and laminate construction description.

Whittaker and Fiber Science Panels

Additional requirements were levied on the Whittaker and Fiber Science panels. Table A-1 lists the many requirements and panel configurations procured from the Whittaker and Fiber Science Corporations.

Cure Schedules

Methods used to cure the various matrix resins are presented below:

1. ERX 67 Matrix Resin[1] --Apply a partial vacuum of 127 to 178 mm (5 to 7 in.) of mercury to the bag layup and place the layup in a preheated press or autoclave and heat as rapidly as possible to 121°C (250°F). When the laminate temperature reaches 71°C (160°F), apply full vacuum and 207 kPa (30 psi) of external pressure. When the laminate temperature reaches 116°C (240°F), maintain this temperature for 30 minutes. Increase the laminate temperature to 160°C (320°F) and maintain this temperature for two hours. After this two hour period, lower the laminate temperature to 48.9°C (120°F) under pressure. Release the pressure and strip the laminate from the vacuum bag after it has reached room temperature.

2. ERLB 4617[2] Matrix Resin (cured with 45 g of MDA per 100 g of epoxy resin)--To a vacuum bag layup, apply a full vacuum of 736 mm (29 in.) of mercury and during a 30 minute period, heat until the laminate temperature reaches 93.3°C (200°F). Maintain this temperature for two hours. Then increase the laminate temperature to 166°C (330°F) during the next 30 minutes and maintain the higher temperature for three hours. Following this, lower the laminate temperature under vacuum to room temperature over the course of the next half hour, release the vacuum, and strip the laminate from the bag.

3. RD2257-14A and B[3] Matrix Resin (60:40 ratio by weight of parts A and B)--To a vacuum bag layup, apply full vacuum of 736 mm (29 in.) of mercury at room temperature and heat the vacuum bag layup until the laminate temperature reaches 121°C (250°F) during a 15 minute period and maintain this laminate temperature for

---

[1]Standard matrix resin used; a brominated bisphenol-A epoxy resin cured with methylene dianiline (MDA) (20 parts per hundred parts of resin) Shell Chemical Company, One Shell Plaza, Houston, Texas 77002.

[2]Union Carbide Corporation, 270 Park Avenue, New York, New York 10017.

[3]A polyurethane from Hughson Chemicals Division of the Lord Corporation, 2000 West Grandview Blvd., Erie, Pennsylvania 16512.

30 minutes. Following this, lower the laminate temperature to room temperature, release the vacuum, and strip the laminate from the bag.

4. APOGEN 101/230 Matrix Resin--Apply full vacuum to the bag layup and allow to cure at 23.9°C (75°F) for at least one hour, release the vacuum, and strip the laminate from the bag. The ratio of the 101 resin to the 230 curing agent shall be 35:6.

5. NR-150A Matrix Resin--The actual procedure for preparing the laminate having the NR-150A matrix resin was not reported by the Whittaker Corporation, however, they did state that they followed the recommendations in the supplier's literature. The information published by the Plastics Department of E.I. duPont de Nemours and Company, Inc. is presented in part below:

"NR-150 binder solutions are polyimide precursors dissolved in dimethylformamide (DMF) solution. These experimental products are intended for use as composite binders and adhesives in high temperature applications. Applying the solution to a substrate and curing at high temperature will produce an amorphous aromatic thermoplastic polyimide which can be molded above its glass transition temperature at modest pressures to eliminate voids produced during initial cure."

A suggested procedure for making vacuum bag-autoclave molded laminates using polyimide NR-150A is re-presented from the duPont brochure below:

"a. Stack plies in vacuum bag and apply full vacuum to consolidate the prepreg. Use glass cloth coated with TEFLON on top and bottom to allow volatiles to escape. Follow this with several layers of glass fabric to soak up any excess binder which may be squeezed out. At least one layer of glass cloth on the top and bottom should be free of resin at the end of the run so that an open porous surface can be maintained in the curing laminate at all times. This facilitates the release of volatiles.

b. Release vacuum and put into autoclave at room temperature.

c. Apply 1-5 psi vacuum. Heat up the autoclave (5°F/minute) according to the following schedule:

(1) Heat successively to 347, 392, and 482°F (175, 200, and 250°C, respectively) and hold for 1 hour at each temperature.

(2) Pull full vacuum, apply 200 psi, and heat to 482°F (250°C) for 1 hour and to 600°F (316°C) for 3 hours.

(3) Cool under prerssure and discharge part having less than 2% voids and a Tg approximating 536°F (280°C).

The above procedure has been used to prepare laminates 100-125 mils thick. Preparation of thicker laminates may require longer times to obtain optimum properties. The above procedure has not been optimized. Abbreviated cycles might work as well."

6. E-702 Matrix Resin--The actual procedure for preparing the laminates containing the E-702 matrix resin was not reported by the Whittaker Corporation; however, they did state that they followed the supplier's recommendations.[4]

EXXON Panels

A description of the panels supplied by EXXON Enterprises Incorporated is supplied in table A-2. The 55% fiber content requirement was waived in EXXON's case in all but one panel since the fiber contents shown in table A-2 were as high as they could make them.

---

[4]U.S. Polymeric, Inc., Dyer Road, Santa Ana, California.

Table A-1

MATERIAL CONFIGURATIONS PROCURED FROM WHITTAKER CORPORATION

Code number	Fiber	Matrix resin	Laminate construction, ply oreintation (degrees)[d]	No. of laminates
A1	GY70-S[a,b]	ERLB 4617/MDA[c]	$(+ \text{ and } -45)_6$	1
A2	GY70-S	ERX 67/MDA[e]	$(+ \text{ and } -45)_6$	1
A3	GY70-U[b]	ERX 67/MDA	$(+ \text{ and } -45)_6$	1
A4	GY70-S	RD2257-14A+14B[f]	$(+ \text{ and } -45)_6$	1
A5	GY70-S	ERX 67/MDA	(80,45,0,0,45,80)	1
A6	GY70-S	ERX 67/MDA	(90,0,0,0,0,90)	1
A7	GY70-S	APOGEN 101/230[g]	$(+ \text{ and } -45)_6$	1
B1	GY70-S	NR150A[h]	$(+ \text{ and } -45)_6$	1
B2	MODMOR I-S[i]	ERX 67/MDA	$(+ \text{ and } -45)_6$	1
B3	MODMOR I-U	ERX 67/MDA	$(+ \text{ and } -45)_6$	1
B4	MAGNAMITE A-S[j]	ERX 67/MDA	$(+ \text{ and } -45)_6$	1
B5	MAGNAMITE A-U	ERX 67/MDA	$(+ \text{ and } -45)_6$	1
B6	THORNEL 75-S[k]	ERX 67/MDA	$(+ \text{ and } -45)_6$	1
C1	MODMOR I-U and 104 Glass Fabric[l]	ERX 67/MDA	$(+45M,0G1,-45M,+45M,0G1,-45M,+45M,0G1,-45M)_9$	1
C2	MODMOR I-U and Pellon Veil[m] Type 8650(V)	ERX 67/MDA	$(+45M,0V,-45M,+45M,0V,-45M,+45M,0V,-45M)_9$	1
C3	GY70-S and S-2 Glass[n]	ERX 67/MDA	$(+45GY,-45GY,+45GY,-45G1,+45G1,-45G1)_6$	2
C4	GY70-S and PRD 49-III[o]	ERX 67/MDA w/GY E702[u] w/PRD	$(+45GY,-45GY,+45GY,-45PRD,+45PRD,-45PRD)_6$	2
D1	GY70-S and NOMEX Honeycomb[p,q]	ERX 67/MDA	$(+45GY,-45GY,+45GY,$[q] NH$,+45GY,-45GY,+45GY)_7$	1
D2	S-2 Glass, NOMEX Honeycomb, and GY70-S	ERX 67/MDA	$+45G1,-45G1,+45G1,$[r] NH$,+45GY,-45GY,+45GY)_7$	1
D3	PRD 49-III, NOMEX Honeycomb, and GY70-S	E702 w/PRD and ERX 67/MDA w/GY70-S	$+45PRD,-45PRD,+45PRD,$[s] NH$,+45GY,-45GY,+45GY)_7$	1

Table A-1 (Continued)

Code number	Fiber	Matrix resin	Laminate construction, ply orientation (degrees)	No. of laminates
D4	GY70-S and NOMEX Honeycomb	ERX 67/MDA	$((\pm 45GY)_6, NH, (\pm 45GY)_6)_{13}^{t}$	1
D5	PRD 49-III	ERX 67/MDA	$(+ \text{ and } -45)_6$	1
D6	PRD 49-III	E702[u]	$(+ \text{ and } -45)_6$	1

[a]CELION GY70-S is high modulus continuous filament graphite fiber manufactured by the Celanese Corporation, Morris Court, Summit, New Jersey 07901.
[b]The letter S following a fiber designation refers to a fiber treatment to enhance interlaminar shear strength; the letter U following a fiber designation indicates the fiber has had no treatment.
[c]ERLB 4617 was a cyclo aliphatic epoxy resin (no longer commercially available) manufactured by the Union Carbide Corporation, 270 Park Avenue, New York, New York 10017. MDA is an acronym for methylene dianiline, a curing agent for epoxy resins.
[d]The system for describing the laminate construction was to denote the fiber ply orientations from top to bottom (left to right) after the convention described in volume 1, paragraph 1.0.3 of reference 3.
[e]ERX 67 is a brominated bisphenol-A epoxy resin manufactured by the Shell Chemical Co., One Shell Plaza, Houston, Texas 77002.
[f]RD2257-14A+14B is a polyester type polyurethane resin and curing agent system manufactured by the Hughson Chemicals Division of the Lord Corporation, 2000 W. Grandview Blvd., Erie, Pennsylvania 16512.
[g]APOGEN 101/230 is a room temperature curing epoxy resin and curing agent manufactured by the Apogee Products Group of M&T Chemicals, Inc., Woodbridge Road and Randolph Avenue, Rahway, New Jersey 07065 and De Carlo Avenue, Richmond, California 94804.
[h]NR 150A is an amorphous aromatic thermoplastic polyimide dissolved in dimethylformamide (DMF). The DMF evaporates during cure. The system was manufactured by the Plastics Department of E.I. duPont de Nemours and Company, Inc., Wilmington, Delaware 19898.
[i]MODMOR I is a bundle of continuous graphite fibers manufactured by Morganite Research and Development Limited, London, England.
[j]MAGNAMITE A is a bundle of continuous graphite fibers (low modulus) manufactured by Hercules, Inc., Wilmington, Delaware 19898.
[k]THORNEL 75 is a continuous graphite fiber yarn manufactured by the Union Carbide Corporation, 270 Park Avenue, New York, New York 10017.
[l]104 Glass Fabric is a woven fabric manufactured by J.P. Stevens and Company, Inc., 1185 Avenue of the Americas, New York, New York 10036.

Table A-1 (Continued)

[m]Pellon Veil (Type 8650) is a polyester type non-woven textile product manufactured by the Pellon Corporation, 221 Jackson Street, Lowell, Massachusetts, 01852.

[n]S-2 Glass is a bundle of unidirectional, high modulus, continuous glass fibers manufactured by the Owens-Corning Fiberglas Corporation, Fibergas Tower, Toledo, Ohio 43659.

[o]PRD 49-III (now known as KEVLAR 49) is a bundle of continuous filament, high modulus organic (polyaramid) fibers manufactured by the Textile Fibers Department of E.I. duPont de Nemours and Co., Inc., Wilmington, Delaware 19898.

[p]NOMEX Honeycomb is a cellular structure made from a polyamide type paper and a thermosetting resin. The polyamide paper was made by E.I. duPont de Nemours and Co., Inc. and the cellular structure was made by the Hexcel Corporation, 11711 Doublin Boulevard, Dublin, California 94566.

[q]Three plies of GY70-S approximately 0.063 cm (0.025 in.) thick were laminated to each face of the NOMEX Honeycomb which was 0.254 cm (0.100 in.) thick. The honeycomb used was Hexcel Corporation's hexagonal AFC_3 series with 0.476 cm (3/16 in.) cell size and in a density of 7.2 kg/m^3 (4.5 lb/ft^3).

[r]This is the same construction as was described in footnote q except that S-2 Glass was substituted for the GY70-S on one side of the honeycomb.

[s]This is the same construction as was described in footnote q except that PRD49-III was substituted for the CY70-S on one side of the honeycomb.

[t]Six plies of GY70-S approximately 0.127 cm (0.050 in.) thick were laminated to each face of the NOMEX Honeycomb which was 0.254 cm (0.100 in.) thick. The honeycomb used was that described in footnote q.

[u]E702 is a proprietary epoxy resin system manufactured by U.S. Polymeric, Inc., Dyer Road, Santa Ana, California.

Table A-2

MATERIAL CONFIGURATIONS PROCURED FROM OTHER SOURCES[a]

Code number	Fiber	Matrix resin	Fiber content vol. %	No. of laminates
A'[b]	PRD 49-III, Style 181[c]	ELVAMIDE 8061 Nylon[d]	40	1
B'[b]	PRD 49-III, Style 181	EXXON Polypropylene A11506[e]	40	1
C'[b]	PRD 49-III, Style 181	MERLON M40F Polycarbonate[f]	40	1
D'[g]	CELION GY70-S	Proprietary FSI Resin	55	1
E'[b]	CELION GY70-S	ELVAMIDE 8061 Nylon	40	1
F'[b]	CELION GY70-S	ELVAMIDE 8061 Nylon	55	1
G'[b]	CELION GY70-S	MERLON M40F Polycarbonate	40	1
H'[b]	CELION GY70-S	EXXON Polypropylene A11506	40	1
J'[h]	PRD 49-III/E-Glass	ERX 67/MDA	55	1
K'[h]	E-Glass	ERX 67/MDA	63	1
L'[i]	2024-T3 (Bare) Aluminum		--	1

[a]All laminates were 38.1 x 48.26 cm (15 x 19 in.) by a nominal 0.127 cm (0.050 in.) thick, except where noted, each laminate having an even number of fiber plies oriented + and -45°.

[b]Supplied by EXXON Enterprises, Inc.

[c]Square weave fabric plied up on the bias.

[d]A nylon resin manufactured by E.I. duPont de Nemours and Company, Inc., Wilmington, Delaware 19898.

[e]A polypropylene resin manufactured by EXXON Chemical Co., P.O. Box 3272, Houston, Texas 77001.

[f]A polycarbonate resin manufactured by the Mobay Chemical Corporation, Pittsburgh, Pennsylvania 15205.

[g]Supplied by Fiber Science, Inc., 245 E. 157th Street, Gardena, California 90248. The laminate was coded as G-P-001 by Fiber Science and the matrix resin was identified as a special FSI resin system proprietary to Fiber Science.

[h]Supplied by the General Structures Corporation, 2141 Miramar Drive, Balboa, California 92661. Their identification of J' was GS 3002, an integrally woven hybrid truss-core panel having PRD 49-III faces with an E-Glass core. The faces were approximately 0.0635 cm (0.025 in.) thick and the core was approximately 0.028 cm (0.011 in.) thick. Their identification of K' was GS 1002, also an integrally woven truss-core panel with a 0.028 cm (0.011 in.) thick core with two faces. Each face was a two-ply construction approximately 0.0432 cm (0.017 in.) thick.

[i]These specimens were prepared in the shops of Picatinny Arsenal.

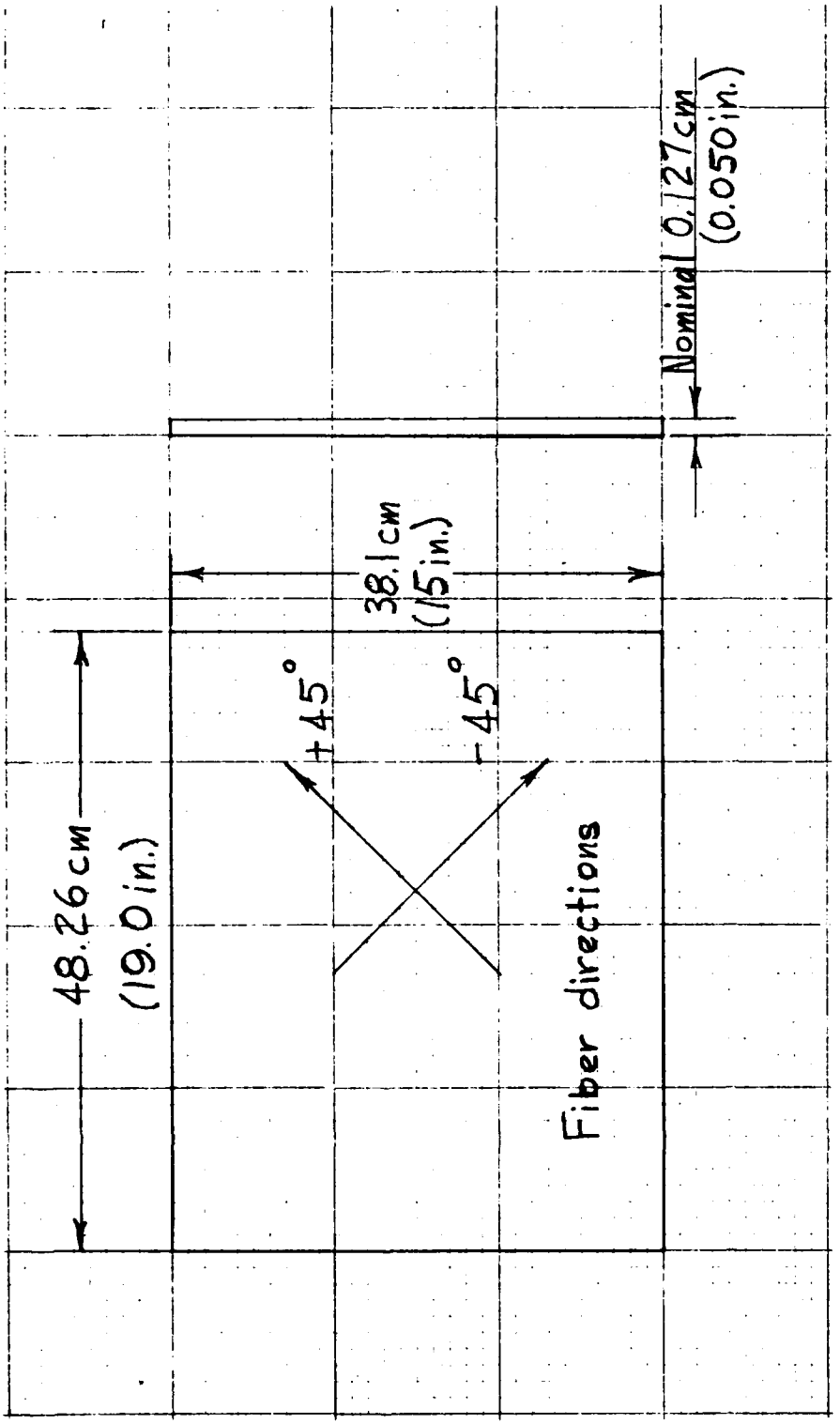


Figure A-1. Impact test panels.

APPENDIX B

PAMED SPECIFICATION 102

CONTINUOUS COLLIMATED FIBER TAPE, EPOXY RESIN IMPREGNATED

1. Acknowledgement: Vendor shall mention this specification number and its revision letters, if any, 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: For winding tubes and other surfaces of revolution which when cured are designed to function continuously at temperatures up to 200°F.

3. Applicable Documents: The following publications form a part of this specification to the extent specified herein. The latest issue of each specification shall apply unless otherwise noted.

3.1. SAE Publications: Available from Society of Automotive Engineers, Inc., Two Pennsylvania Plaza, New York, N.Y. 10001.

3.1.1. Aerospace Material Specifications: AMS3894A - Tensile Strength, Modulus, and Short Beam Shear Strength

3.2. ASTM Publications: Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pa. 19103 ASTM D792 - Specific Gravity and Density of Plastics by Displacement. ASTM D3171-73 - Fiber Content of Reinforced Resin Composites. ASTM D638-71a - Test for Tensile Properties of Plastics.

4. Technical Requirements:

4.1. Detail Specifications: The requirements for a specific material shall consist of all the requirements herein in addition to the requirements specified in the applicable detail specification. In the case of any conflict between the requirements of this basic specification and an applicable detail specification, the requirements of the detail specification shall govern.

4.2. Material:

4.2.1. Construction: The product shall consist of parallel, unidirectional fibers arranged in a single, plane layer, both fiber and resin meeting the requirements of the applicable detail specifications hereunder.

4.2.2. Ends: Unless otherwise specified, the product shall contain no unspliced yarn or tow ends.

4.2.3. Storage Life: The product shall meet the requirements of this specification when tested at any time up to six months from the date of receipt by the purchaser provided it has been stored at a maximum temperature of 0°F (-18°C) in the original containers.

4.2.4. Working Life: The product shall meet the requirements of this specification when tested after exposure at a relative humidity not higher than 70% and at room temperature for a continuous period of up to 10 days.

4.2.5. Bending: The product shall withstand bending through an angle of 180 degrees around a 1.0 in. diameter mandrel with the fiber direction perpendicular to the axis of bend without visible material damage; magnification of 10X shall be used in examination for damage.

4.2.6. Fiber: Fiber used in making the product shall be as described in Table 1. It may be in either tow or yarn form but it must have properties sufficient to meet the requirements for both the prepreg and cured stages as applicable.

4.2.7. Resin: Resin used in making the product shall have properties sufficient to meet the requirements for both the prepreg and cured stages as applicable. Further, the vendor shall certify in the Report of Qualification Tests that:

(1) All tape types contain the same resin and curing system.

(2) All tape types received the matrix resin by the same process.

Table B-1

CONTINUOUS COLLIMATED FIBER PREPREG TAPE CLASSIFICATION

PAMED Tape Designation	Fiber Component	Description and Mechanical Properties of Cured Composite
Type 1	Graphite Fiber No. 1	Table 2
Type 2	Graphite Fiber No. 2	Table 3
Type 3	S-Glass	Table 4
Type 4	KEVLAR 49	Table 5
Type 5	Graphite Fiber No. 1 and S-Glass	Table 6
Type 6	Graphite Fiber No. 1 and KEVLAR 49	Table 7
Type 7	Graphite Fiber No. 2 and S-Glass	Table 8
Type 8	Graphite Fiber No. 2 and KEVLAR 49	Table 9

4.3. Properties of Uncured Impregnated Material: The product as received shall conform to the requirements of this specification. Responsibility for inspection, sampling procedure, and testing frequency are described under 5., Quality Assurance Provisions. Properties of the uncured product shall be as specified below.

4.3.1. Width, inches - 0.25, ± 0.010

4.3.2. Thickness, inches - As required to yield a cured ply thickness of 0.0075, ± 0.001.

4.3.3. Minimum continuous length - 300 ft. ± 1.

4.3.4. Volatile Content, % by weight - To be reported.

4.3.5. Resin Content, % by weight - To be reported

4.3.6. Gel Time, minutes - To be reported

4.3.7. Tack - Room temperature adhesion to Teflon film.

4.3.8. Tensile Strength, lbs. - 20, minimum

4.4. Properties of Cured Laminate: The properties of cured product shall be determined from specimens cut from a test panel prepared from the product supplied. Requirements of test panel preparation are described under 4.4.1. Required properties, number of specimens per test, and test methods to be used are shown in Tables 2 through 9.

4.4.1. Preparation of Test Laminate: Test laminates of suitable thickness and area shall be prepared from sufficient plies of impregnated material oriented unidirectionally and cured via the "Vacuum Bag" technique at a temperature appropriate to provide optimum properties. The resultant laminate shall be uniform in thickness within ±0.003 in. and shall have a fiber content of 60 volume % ± 3. Description of the curing procedure is to be reported.

Table B-2

DESCRIPTION AND REQUIRED PROPERTIES OF UNIDIRECTIONAL CURED COMPOSITE, TYPE 1

Description/ Required Property	VALUE (1) $70^{\circ}F \pm 2$	$200^{\circ}F \pm 2$	Test Method
Ply thickness, inches	0.0075 ± 0.001	-	5.5.2.1.
Fiber Content, Vol. %	60 ± 3	-	5.5.2.3.
Density, lbs./in.^{3}	TBR (2)	-	D792
Tensile Strength, min.			
Longitudinal, psi	110,000	100,000	Procedure 4.5.6. of AMS 3894A
Transverse, psi	TBR	TBR	
Tensile Modulus, min.			
Longitudinal, psi	27×10^6	26×10^6	Procedure 4.5.6. of AMS 3894A
Transverse, psi	TBR	TBR	
Elongation at Break, %	TBR	TBR	4.5.6. of AMS 3894A and 10.2 of ASTM D638
Short Beam Shear Strength, min., psi	8500	6900	Procedure 4.5.9. of AMS 3894A

Notes: (1) An average of four determinations per property test is required. No individual value shall be less than 90% of the specified average value.

(2) TBR - To be reported.

Table B-3

DESCRIPTION AND REQUIRED PROPERTIES OF UNIDIRECTIONAL CURED COMPOSITE, TYPE 2

Description/ Required Property	VALUE (1) 70°F ± 2	200°F ± 2	Test Method
Ply thickness, inches	0.0075 ± 0.001	-	5.5.2.1.
Fiber Content	60 ± 3	-	5.5.2.3.
Density, lbs./in.^{3}	TBR (2)	-	ASTM D792
Tensile Strength, min.			
Longitudinal, psi	95,000	90,000	Procedure 4.5.6. of
Transverse, psi	TBR	TBR	AMS 3894A
Tensile Modulus, min.			
Longitudinal, psi	42 x 10^6	40 x 10^6	Procedure 4.5.6. of
Transverse, psi	TBR	TBR	AMS 3894A
Elongation at break, %	TBR	TBR	4.5.6. of AMS 3894A and 10.2 of ASTM D638
Short Beam Shear Strength, min., psi	8500	6900	Procedure 4.5.9. of AMS 3894A

Notes: (1) An average of four determinations per property test is required. No individual value shall be less than 90% of the specified average value.

(2) TBR - To be reported.

Table B-4

DESCRIPTION AND REQUIRED PROPERTIES OF UNIDIRECTIONAL CURED COMPOSITE, TYPE 3

Description/ Required Property	VALUE (1) $70^{\circ}F \pm 2$	VALUE (1) $200^{\circ}F \pm 2$	Test Method
Ply thickness, inches	0.0075 ± 0.001	-	5.5.2.1.
Fiber Content, Vol. %	60 ± 3	-	5.5.2.3.
Density, lbs./in.^{3}	TBR (2)	-	ASTM D792
Tensile Strength, min.			
Longitudinal, psi	200,000	180,000	Procedure 4.5.6. of AMS 3894A
Transverse, psi	TBR	TBR	
Tensile Modulus, min.			
Longitudinal, psi	$6.0 \cdot x\ 10^6$	5.7×10^6	Procedure 4.5.6. of AMS 3894A
Transverse, psi	TBR	TBR	
Elongation at break, %	TBR	TBR	4.5.6. of AMS 3894A and 10.2 of ASTM D638
Short Beam Shear Strength, min., psi	9,900	8,200	Procedure 4.5.9. of AMS 3894A

Notes: (1) An average of four determinations per property test is required. No individual value shall be less than 90% of the specified average value.

(2) TBR - To be reported.

Table B-5

DESCRIPTION AND REQUIRED PROPERTIES OF UNIDIRECTIONAL CURED COMPOSITE, TYPE 4

Description/ Required Property	VALUE (1) $70^{\circ}F \pm 2$	VALUE (1) $200^{\circ}F \pm 2$	Test Method
Ply thickness, inches	0.0075 ± 0.001	-	5.5.2.1.
Fiber Content, Vol. %	60 ± 3	-	5.5.2.3.
Density, lbs./in.^{3}	TBR (2)	-	ASTM D792
Tensile Strength, min.			
Longitudinal, psi	175,000	157,000	Procedure 4.5.6. of AMS 3894A
Transverse, psi	TBR	TBR	
Tensile Modulus, min.			
Longitudinal, psi	11 x 10^6	10 x 10^6	Procedure 4.5.6. of AMS 3894A
Transverse, psi	TBR	TBR	
Elongation at break, %	TBR	TBR	4.5.6. of AMS 3894A and 10.2 of ASTM D638
Short Beam Shear Strength, min., psi	8,500	6,900	Procedure 4.5.9. of AMS 3894A

Notes: (1) An average of four determinations per property test is required. No individual value shall be less than 90% of the specified average value.

(2) TBR - To be reported.

Table B-6

DESCRIPTION AND REQUIRED PROPERTIES OF UNIDIRECTIONAL CURED COMPOSITE, TYPE 5

Description/ Required Property	VALUE (1) 70°F ± 2	200°F ± 2	Test Method
Ratio, Type 1 Fiber: Type 3 Fiber	1:1 (by volume)	-	Calculate
Ply thickness, inches	0.0075 ± 0.001	-	5.5.2.1.
Fiber Content, Vol. %	60 ± 3	-	5.5.2.3.
Density, lbs./in.^{3}	TBR (2)	-	ASTM D792
Tensile Strength, min.			
Longitudinal, psi	100,000	90,000	Procedure 4.5.6. of AMS 3894A
Transverse, psi	TBR	TBR	
Tensile Modulus, min.			
Longitudinal, psi	13.5 x 10^6	13 x 10^6	Procedure 4.5.6. of AMS 3894A
Transverse, psi			
Elongation at Break, %	TBR	TBR	4.5.6. of AMS 3894A and 10.2 of ASTM D638
Short Beam Shear Strength, min., psi	8,500	6,900	Procedure 4.5.9. of AMS 3894A

Notes: (1) An average of four determinations per property test is required. No individual value shall be less than 90% of the specified average value.

(2) TBR - To be reported.

Table B-7

DESCRIPTION AND REQUIRED PROPERTIES OF UNIDIRECTIONAL CURED COMPOSITE, TYPE 6

Description/ Required Property	VALUE (1) $70^{\circ}F \pm 2$	VALUE (1) $200^{\circ}F \pm 2$	Test Method
Ratio, Type 1 Fiber: Type 4 fiber	1:1 (by volume)	-	Calculate
Ply thickness, inches	0.0075 ± 0.001	-	5.5.2.1.
Fiber Content, Vol. %	60 ± 3	-	5.5.2.3.
Density, lbs./in.^{3}	TBR (2)	-	ASTM D792
Tensile Strength, min.			
Longitudinal, psi	87,000	78,000	Procedure 4.5.6. of AMS 3894A
Transverse, psi	TBR	TBR	
Tensile Modulus, min.			
Longitudinal, psi	13.5×10^6	13×10^6	Procedure 4.5.6. of AMS 3894A
Transverse, psi	TBR	TBR	
Elongation at Break, %	TBR	TBR	4.5.6. of AMS 3894A and 10.2 of ASTM D638
Short Beam Shear Strength, min., psi	8,500	6,900	Procedure 4.5.9. of AMS 3894A

Notes: (1) An average of four determinations per property test is required. No individual value shall be less than 90% of the specified average value.

(2) TBR - To be reported.

Table B-8

DESCRIPTION AND REQUIRED PROPERTIES OF UNIDIRECTIONAL CURED COMPOSITE, TYPE 7

DESCRIPTION/ REQUIRED PROPERTY	VALUE (1) $70^{\circ}F \pm 2$	VALUE (1) $200^{\circ}F \pm 2$	TEST METHOD
Ratio, Type 2 Fiber: Type 3 Fiber	1:1 (by volume)	-	Calculate
Ply thickness, inches	0.0075 ± 0.001	-	5.5.2.1.
Fiber Content, Vol. %	60 ± 3	-	5.5.2.3.
Density, lbs./in.^{3}	TBR (2)	-	ASTM D792
Tensile Strength, min.			
Longitudinal, psi	100,000	90,000	Procedure 4.5.6. of AMS 3894A
Transverse, psi	TBR	TBR	
Tensile Modulus, min.			
Longitudinal, psi	21×10^6	20×10^6	Procedure 4.5.6. of AMS 3894A
Elongation at Break, %	TBR	TBR	4.5.6. of AMS 3894A and sec. 10.2 of ASTM D638
Short Beam Shear Strength, min., psi	8,500	6,900	Procedure 4.5.9. of AMS 3894A

Notes: (1) An average of four determinations per property test is required. No individual value shall be less than 90% of the specified average value.

(2) TBR - To be reported.

Table B-9

DESCRIPTION AND REQUIRED PROPERTIES OF UNIDIRECTIONAL CURED COMPOSITE, TYPE 8

DESCRIPTION/ REQUIRED PROPERTY	VALUE (1) $70^{\circ}F \pm 2$	VALUE (1) $200^{\circ}F \pm 2$	TEST METHOD
Ratio, Type Z Fiber, Type 4 Fiber	1:1 (by volume)		Calculate
Ply thickness, inches	0.0075 ± 0.001	-	5.5.2.1.
Fiber Content, Vol. %	60 ± 3	-	5.5.2.3.
Density, lbs./in.^{3}	TBR (2)	-	ASTM D792
Tensile Strength, min.			
Longitudinal, psi	87,000	78,000	Procedure 4.5.6.
Transverse, psi	TBR	TBR	of AMS 3894A
Tensile Modulus, min.			
Longitudinal, psi	21×10^6	20×10^6	Procedure 4.5.6. of
Transverse, psi	TBR	TBR	AMS 3894A
Elongation at Break, %	TBR	TBR	Procedure 4.5.6. AMS 3894A and 10.2 of ASTM D638
Short Beam Shear Strength, min., psi	8,500	6,900	Procedure 4.5.9. of AMS 3894A

Notes: (1) An average of four determinations per property test is required. No individual value shall be less than 90% of the specified average value.

(2) TBR - To be reported.

4.5. Quality: The product shall be uniform in quality and condition, clean, and free from foreign materials and from internal and external imperfections detrimental to fabrication, appearance, or performance of parts.

5. Quality Assurance Provisions:

5.1. Responsibility for Inspection: The product vendor shall supply all samples and shall be responsible for performing all required tests. Results of such tests shall be reported to the purchaser as required by 5.6.. Purchaser reserves the right to perform such confirmatory testing as he deems necessary to assure that the product conforms to the requirements of this specification.

5.2. Classification of Tests:

5.2.1. Qualification Tests: These are tests to establish an approvable sample or to determine conformance of the product to all technical requirements of this specification. Test reports of all properties/requirements itemized under 4.3 and 4.4 require approval as described in 5.4.

5.2.2. Acceptance Tests: These are tests to assure unfiromity of quality within the total purchased quantity and to assure agreement of approved sample quality with production quality. Test reports of all properties/requirements itemized under 4.3 require approval as described in 5.4.

5.3. Sampling:

5.3.1. Definitions:

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

5.3.1.2. Lot - For the purpose of this specification, a lot shall consist of one tape type produced in one manufacturing cycle, under substantially constant conditions, and offered for acceptance at one time. Lot numbers shall be designated by the vendor.

5.3.2. 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 4.3 shall be made in accordance with Table 10 below:

Table 10

Lot Size (No. of Rolls)	No. of Rolls to be Tested
1-5	3
6-25	7
26-50	11
51-100	23

5.3.3. Sampling Procedure:

5.3.3.1. Remove roll from cold storage, keep in moisture-proof bag, and allow to warm to room temperature.

5.3.3.2. Remove roll from moisture-proof bag.

5.3.3.3. Remove enough material from this roll to conduct tests.

5.3.3.4. Replace balance of roll in moisture-proof bag and reseal. Replace sealed roll in cold storage.

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

5.4. Approval:

5.4.1. The vendor shall submit three copies of a report showing results of Qualification Tests to the purchaser and receive written approval from the purchaser before any material is shipped to the purchaser unless such approval be waived.

5.4.2. The vendor shall submit three copies of a report showing results of Acceptance Tests with each shipment to the purchaser and shall certify in writing that he has used ingredients, manufacturing procedures, processes, and methods of inspection on production material which are essentially the same as those used on the approved sample material. If any change is necessary in ingredients, in type of equipment for processing, or in manufacturing procedures which could affect quality or properties of the material, the vendor shall submit a detailed statement describing materials and processes used on the original approved material as compared with the proposed revised materials and/or processes. No production material made by the revised procedure shall be shipped prior to receipt of the purchaser's approval of such procedure.

5.5. Test Methods and Procedures:

5.5.1. Preimpregnated "B" Stage Tape:

5.5.1.1. Width - This measurement shall be determined in the way it would be done during tape winding; i.e., under tension while being wrapped around a mandrel. Accuracy shall be consistent with the specified tolerance.

5.5.1.2. Thickness and Length - Thickness shall be governed by the cured composite ply thickness requirement as described in 4.3.2., 4.4.1., and Tables 2 through 9. Accuracy of measurement for both thickness and length shall be consistent with the specified tolerance.

5.5.1.3. Volatile Content:

5.5.1.3. (1) Construct a two inch diameter by six inch long tube by rolling a six by 36 inch piece of Mylar film (E.I. duPont 200A or equivalent) and stapling the ends. Precondition the tube in a forced air oven maintained at 163 ± 3°F for 20 minutes. Cool the tube to ambient temperature in a desiccator, and weigh to the nearest milligram (W_1).

(2) Wind a minimum length of one yard of tape on the tube. Tape ends are secured by tucking them under adjacent windings. Do not overlap tape otherwise, and maintain a minimum gap of $\frac{1}{4}$" between adjacent turns. Weigh specimen and tube to the nearest milligram (W_2).

(3) Suspend the tube and specimen in a forced air oven maintained at 163 ± 3°F for 20 ± 0.5 minutes.

(4) Cool to ambient temperature in a desiccator, and weigh to the nearest milligram (W_3).

(5) Calculate volatile content as follows:

$$\text{Volatile Content, percent} = \frac{W_2 - W_3}{W_2 - W_1} \times 100, \text{ where}$$

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

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

5.5.1.4. Resin Content:

(1) Make a volatile content determination on a sample cut adjacent to the sample to be used for resin content determination. The procedure shall be as specified in 5.5.1.3.

(2) Cut a sample of material approximately three grams in any convenient size.

(3) Weigh the sample to the nearest 0.0001 gram. Record this as W_1.

(4) Place the sample in a 400 millilter beaker. Add 200ml of DMF (Dimethyl Formamide). Boil for five minutes. (Time starts when the DMF starts to boil.)

(5) Cool the sample. Pour off the DMF. Wash the sample twice with acetone.

(6) Place the washed sample in a tared aluminum pan. Dry the sample for 30 minutes in an oven maintained at 163 ± 3°F.

(7) Cool the sample to ambient temperature in a desiccator.

(8) Re-weigh the sample to the nearest 0.0001 gram. Record the weight as W_2. Calculate the resin content by weight as follows:

Resin Content (% by weight) = $\frac{W_1 - (W_1 V) - W_2}{W_1 - (W_1 V)}$ 100, where:

W_1 = original sample weight. W_2 = weight of sample after resin extraction. V = % Volatile Content (per 5.5.1.3.).

(9) Calculate the arithmetic mean of three determinations as resin content of the sample. Report both individual results and the arithmetic mean.

5.5.1.5. Gel Time:

(1) Place a sample (approximately $\frac{1}{4}$" x $\frac{1}{4}$") between two cover slips on a Fisher Johns melt point meter preset at 170°C.

(2) Start timer and probe the specimen with a wooden pick. When resin gels, stop time; and report time to gel.

(3) Report the average of three determinations.

5.5.1.6. Tack:

(1) Cut a one inch length of prepreg tape from its roll, and press it against a piece of 0.020" thick Teflon film using moderate finger pressure.

(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 a new 30-minute period upon repressing the same specimen with finger pressure. (Only one repress test is 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.

5.5.1.7. Tensile Strength:

5.5.1.7.1. Apparatus:

(1) A testing machine (Instron model TCC or equivalent) capable of measuring strength up to 200# 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 $1\frac{1}{4}$ inch wide steel jig. (One-half of an NOL ring testing fixture can be used).

5.5.1.7.2. 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.

5.5.2. Cured Laminate:

5.5.2.1. Ply Thickness - This value shall be calculated from the expression, ply thickness = $\frac{A}{B}$, where A is the laminate thickness and B is the number of plies in the laminate.

5.5.2.2. Density - ASTM D792-66 and 70.

5.5.2.3. Fiber Content:

5.5.2.3.1. Fiber Types 1 through 8 - Composites containing these fibers shall have fiber contents determined by means of the acid digestion method (Procedure A) described in ASTM D3171-73.

5.5.3. 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 purchaser.

5.6. Reports:

5.6.1. The vendor shall submit reports as described under 5.4 approval. These reports shall include the purchase order number, material specification number and revision letters, if any, vendor's material designation, lot number, roll numbers, date of manufacture, quantity (tape length), and location of test samples within the lot and reel.

5.6.2. The vendor's Qualification Test report shall include identification of the fiber and resin system used, the cure cycle of the test laminate, and a statement that the product conforms to all other technical requirements of this specification.

6. Preparation for Delivery:

6.1. Identification - The tape sealed carton for each roll of tape shall be identified with the following information:

(1) Fiber tape, type _____, epoxy resin impregnated.

(2) Specification number

(3) Vendor's name

(4) Vendor's code number and name of the fiber and resin impregnating system.

(5) Date of impregnation

(6) Vendor's lot number and vendor's roll number.

In addition, each roll shall be identified with the same information on the inside of the core such that even if the original waterproof 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 on the inside of the core) shall be thin enough to avoid an interference problem when mounting the roll on the spindle of an unwinding device.

6.2. Packaging:

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

6.2.2. 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 inch thick low density polyethylene sheeting. Roll cartons shall be marked as in 6.1 (above).

6.2.3. Packaging for Environmental Control - Material shall be so packaged with refrigerent (dry ice) in insulated cartons such that temperature of the product will not exceed 40°F during transit from vendor to purchaser. Responsibility for assuring this condition rests with the vendor until shipment is signed for by the purchaser on an appropriate bill of lading.

APPENDIX C

PREPREG TAPE PROPERTIES

Exceptions to PAMED Specification 102 Agreed to by Picatinny Arsenal and the Composites Division, Ferro Corporation

5 May 1975 Memorandum to Procurement Directorate[1]

1. Para 4.2.3 - The storage period at -17.8°C (0°F) or lower shall be changed to three months instead of six months.

2. Para 4.3.2 - The thickness of the tape shall be 0.019 ± 0.0038 cm (0.0075 ± 0.0015 in.) instead of 0.019 ± 0.0025 cm (0.0075 ± 0.001 in.).

3. Table 5 - The longitudinal tensile modulus values shall read, "65,500 MPa (9.5×10^6 psi) at 21.1°C (70°F) and 62,053 MPa (9.0×10^6 psi) at 93.3°C (200°F) instead of 75,842 MPa (11.0×10^6 psi) and 68,948 MPa (10^7 psi).

4. Tables 6, 7, 8, and 9 - Values attainable with the product Ferro supplies under "tensile strength", "tensile modulus", and "short beam shear" shall be as close to those in the tables as their "Best Effort" will provide and are "To be reported" (TBR).

14 July 1975 Memorandum to Procurement Directorate[2]

Table 2, type 1 tape - Tensile strength and short beam shear strength shall be the highest Ferro's "Best Effort" will provide when using the vacuum bag cure technique. These strengths are "TBR" instead of 758 MPa (110,000 psi) (min) at 21.1°C (70°F) and 689 MPa (100,000 psi) at 93.3°C (200°F) for tensile strength and 58.6 MPa (8500 psi) (min) at 21.1°C (70°F) and 47.6 MPa (6900 psi) (min) at 93.3°C (200°F) for the short beam shear strength.

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[1] Reference 5, p 37

[2] Reference 5, p 43

Further, Ferro was requested to report inspection of the broken short beam shear test specimens to determine whether they got tensile or shear breaks and to report which type they found.

6 August 1975 Memorandum to Procurement Directorate[3]

Table 5, type 4 tape - Tensile strength and short beam shear strength shall be the highest Ferro's "Best Effort" will provide when using the vacuum bag cure technique. These strengths are "TBR" instead of 1206.6 MPa (175,000 psi) (min) at 21.1°C (70°F) and 1082.5 MPa (157,000 psi) (min) at 93.3°C (200°F) for the tensile strength and 58.6 MPa (8500 psi) (min) at 21.1°C (70°F) and 47.6 MPa (6900 psi) (min) at 93.3°C (200°F) for the short beam shear strength.

22 Dec 1975 Comment 2 to Procurement Directorate Memorandum of 17 Dec 1975[4]

1. Para 4.3.1 - Ferro requested that type 2 tape be supplied 0.236 ± 0.038 cm (0.093 ± 0.015 in.) wide instead of 0.635 ± 0.0254 cm (0.250 ± 0.010 in.).

2. Table 3, type 2 tape - Ferro requested that the tensile strength, tensile modulus, and short beam shear strength be revised as shown below:

Parameter	PAMED 102*	Ferro Request*
Tensile strength, MPa (psi)		
Longitudinal @ 21.1°C (70°F)	655 (95,000)	517 (75,000)
@ 93.3°C (200°F)	620.5 (90,000)	448.2 (65,000)

[3]Reference 5, p 44

[4]Reference 5, pp 69-71

*Ferro reported that the PAMED 102 values are attainable under optimum conditions with an autoclave cure. The requested values are the best they were able to attain using vacuum bag cures.

Tenside modulus, GPa (psi x 10^6)		
Longitudinal @ 21.1°C (70°F)	289.6 (42.0)	268.9 (39.0)
@ 93.3°C (200°F)	275.8 (40.0)	248.2 (36.0)
Short Beam Shear, MPa (psi)		
@ 21.1°C (70°F)	58.6 (8500)	37.9 (5500)
@ 93.3°C (200°F)	44.8 (6500)	34.4 (5000)

5 Jan 1976 Comment 2 to Procurement Directorate Memorandum of 29 Dec 1975[5]

Table 7, type 6 tape - Ferro requested that they be excused from reporting transverse tensile properties at 93.3°C (200°F). Their 15 Dec 1975 letter is excerpted below, "--We have made several attempts to run transverse tensile properties on the type 6 material (a 50/50 blend of THORNEL 50-S and KEVLAR 49-380 denier). The panels cured to make the test specimens are so fragile they are nearly impossible to machine to test coupon size. We managed to complete the testing at room temperature but do not feel it will be possible to obtain meaningful data at 93.3°C (200°F). We, therefore, request this requirement be deleted.

[5]Reference 5, pp 75,76

Prepreg and Cured Test Panel Data Reported by Ferro Corporation

TYPE 1 TAPE[6]

Description: THORNEL 50-S collimated tape impregnated with Ferro epoxy resin system CE9015[7]

Date of manufacture: 4 to 8 September 1975.

Prepreg Property Test Results

Roll No.	Length, Meters (Ft.)	Resin Content, %	% Volatiles at 68.9 kPa (10 psi) and 162.3°C (325°F)	Gel Time, Minutes, at 162.3°C (325°F)
1	365.8 (1200)	33.0	0.6	9
2	304.8 (1000)	37.1	1.1	9
3	182.9 (600)	36.3	0.6	9
4	304.8 (1000)	37.0	0.5	9
5	182.9 (600)	36.8	0.5	9
6	234.7 (770)	37.0	0.4	9
Total	1575.8 (5170)	36.2 (Av.)	0.62 (Av.)	

Tack test - All rolls passed. Tensile strength, N (lb) = 1574.7 (354).

Layup and Curing Procedure for Cured Properties Test Panels

The following description of the fabrication of the Longitudinal Tensile and the Transverse Tensile and Short Beam Shear test panels from Type 1 prepreg tape is typical of the fabrication of the rest of the tape types. Only the number of plies of tape and bleeder and/or breather material vary to suit the tape thickness and resin content. The objective was to obtain a cured panel having a fiber content of 60±3 vol. %.

1. Longitudinal Tensile Panel - Apply FREKOTE 33[8] release agent to the inside surface of the top and bottom aluminum caul plates. Lay up six plies of CE9015/THORNEL 50-S unitape, one ply of porous trifluoroethylene (TFE) release bleeder, one ply of 1581 style glass cloth top bleed, one ply of CELGARD[9] top release which extends 0.635 cm (0.25 in.) over the entire layup, and 1.27 cm (0.5 in.) wide coroprene side dams (to prevent wash out). Apply a 0.16 cm (0.063 in.) thick aluminum top plate, two plies of 1581 breather, and a nylon film vacuum bag over the layup. To cure, apply 34.5 kPa (5 psi) of vacuum and heat from room temperature to 148.9°C (300°F) at 1.67 to 3.33°C (3 to 6°F) per minute. At 148.9°C(300°F), apply full vacuum and continue heating to 176.7°C (350°F). Maintain the full vacuum and 176.7°C (350°F) temperature for four hours.

(6) Reference 5, pp 48, 57, and 58
(7) Description of this system was not disclosed to Picatinny Arsenal since it was regarded as proprietary to the Ferro Corporation.
(8) Ex: Frekote, Inc., Boca Raton, Florida 33432
(9) Ex: Celanese, Inc.
* Plus one ply of 120 style glass top bleed.

2. Transverse Tensile and Short Beam Shear Panels - Use the same procedure as in (1), except layup 12 plies of CE9015/THORNEL 50-S unitape and use two plies of 1581 bleeder cloth on top of the ply of porous TFE release bleeder.

Tabulated below are the number of plies of prepreg tape, bleeder, and breather materials used in the fabrication of the test panels.

Tape Type	Plies of Prepreg in Long. Panel	Plies of 1581 Bleed, Long. Panel	Plies of 1581 Breather, Long. Panel	Plies of Prepreg in Trans. Panel	Plies of 1581 Bleed, Trans. Panel
1	6	1	2	12	2
2	5	1	2	10	2
3	6	1	2	10	2
4	7	2	2	14	4
5	5	1	2	10	2*

6 Test panel fabrication descriptions not reported by Ferro.

Mechanical Properties of Cured Test Panels, Type 1 Tape

Property	Value 21.1°C(70°F)	93.3°C(200°F)
Tensile Strength, MPa(psi)		
Longitudinal	585.4(84,900)	590.9(85,700)
Transverse	13.0(1,880)	12.2(1,770)
Tensile Modulus, GPa(psi X 10^6)		
Longitudinal	188.2(27.3)	180.0(26.1)
Transverse	4.5(0.65)	4.2(0.61)
Elongation, % at break		
Longitudinal	0.32	0.35
Transverse	0.30	0.34
Tensile Laminate		
Thickness per ply, cm(in.)	0.0223(0.0088)	-
Fiber content, vol. %	59.2	-
Density, gm/cm^3 (lb/$in.^3$)	1.459(0.0527)	-
Shear laminate		
Fiber content, (calculated), vol. %	59.6	-
Density, gm/cm^3 (lb/$in.^3$)	1.456(0.0526)	-
Short beam shear strength, MPa(psi)	25.8(3,740)	26.6(3,860)

TYPE 2 TAPE [10]

Description: CELION GY70-S collimated tape impregnated with Ferro epoxy resin system CE9015.

Date of manufacture: Not reported (assumed to be during January 1976). 1.45 kg (3.2 lb) shipped, length of tape not reported.

Prepreg Property Test Results

	Resin content, %	Resin flow, % at 103.4 kPa (15 psi) and 162.3°C (325°F)	% Volatiles at 68.9 kPa (10 psi) and 162.3°C (325°F)	Gel time, minutes, at 162.3°C (325°F)
Lot average	39.8	16.4	1.0	9.83

Tensile strength - Not reported
Tack test - All eight rolls passed

Mechanical properties of cured test panels, type 2 tape

Property	Value			
	21.1°C (70°F)		93.3°C (200°F)	
Tensile strength, MPa (psi)				
Longitudinal	519.9	(75,400)	391.5	(56,781)
Transverse	11.6	(1,682)	9.7	(1,408)
Tensile modulus, GPa (psi x 10^6)				
Longitudinal	271	(39.30)	268.9	(39.0)
Transverse	5.0	(0.73)	4.6	(0.66)
Elongation, % at break				
Longitudinal	0.21		0.21	
Transverse	0.23		0.27	
Short beam shear strength, MPa (psi)	39.0	(5,659)	35.3	(5,120)
Thickness per ply, cm (in.)	0.0203	(0.008)		
Fiber volume, %	58.9			
Density, gm/cm^3 (lb/$in.^3$)	1.605	(0.058)		

[10] Reference 5, pp 82-84

TYPE 3 TAPE[1]

Description: Ferro S-1014 collimated glass fiber tape impregnated with Ferro epoxy resin system CE9015.

Date of manufacture: 2 September 1975.

Prepreg property test results

Roll no.	Length m (ft)	Resin content %	Resin flow, % at 103.4 kPa (15 psi) and 162.3°C (325°F)	% Volatiles at 68.9 kPa (10 psi) and 162.3°C (325°F)	Gell time, minutes, at 162.3°C (325°F)
1	243.8 (800)	32.6	16.2	0.6	9
2	304.8 (1,000)	33.0		0.5	9
3	304.8 (1,000)	30.5	15.8	0.5	9
Total	853.4 (2,800)	32.03 (Av)	16.0 (Av)	0.53 (Av)	

Tack test - All rolls passed.Tensile stength, N(lb) = 1,490.2 (335)

Mechanical properties of cured panels, type 3 tape

Property	Value 21.1°C) (70°F)	93.3°C (200°F)
Tensile strength, MPa (psi)		
Longitudinal	1616.8 (234,500)	1276.2 (185,100)
Transverse	20.8 (3,010)	18.8 (2,730
Tensile modulus, GPa (psi x 10^6)		
Longitudinal	58.6 (8.5)	50.3 (7.3)
Transverse	11.7 (1.7)	11.7 (1.7)
Elongation, % at break		
Longitudinal	1.8	2.5
Transverse	0.2	0.2
Short beam shear, MPa (psi)	68.3 (9,900)	56.5 (8,200)
Thickness per ply cm (in.)	0.0173 (0.0068)	
Fiber volume, %	62.9	
Density, gm/cm^3 ($lb/in.^3$)	1.993 (0.072)	

[1] Reference 5, pp 55, 56

TYPE 4 TAPE[12]

Description: KEVLAR 49 collimated tape impregnated with Ferro epoxy resin system CE9015.

Date of manufacture: 30 August 1975.

Prepreg property test results

Roll no.	Length m	Length (ft)	Resin content %	Resin flow, % at 103.4 kPa (15 psi) and 162.3°C (325°F)	% Volatiles at 68.9 kPa (10 psi) and 162.3°C (325°F)	Gel time, minutes, at 162.3°C (325°F)
1	304.8	(1,000)	34.3	12.4	1.4	2.58
2	304.8	(1,000)	36.2		1.5	
3	396.2	(1,300)	36.6		1.9	
Total	1005.8	(3,300)	35.7 (Av)		1.6 (Av)	

Tack test - All rolls passed. Tensile strength, N (lb) = 1534.6 (345)

Mechanical properties of cured test panels, type 4 tape

Property	21.1°C (70°F)	93.3°C (200°F)
Tensile strength, MPa (psi)		
Longitudinal	1016.3 (147,400)	977.7 (141,800)
Transverse	1.3 (192)	1.3 (184)
Tensile modulus, GPa (psi x 10^6)		
Longitudinal	78.6 (11.4)	71.0 (10.3)
Transverse	0.21(0.03)	0.24 (0.035)
Elongation, % at break		
Longitudinal	0.9	0.9
Transverse	1.4	1.7
Short beam shear, MPa (psi)	19.6 (2,850)	17.7 (2,570)
Thickness per ply, cm (in.)	0.015 (0.006)	
Fiber volume, %	Test per ASTM D3171-73 dissolves fiber	
Density, gm/cm^3 (lb/$in.^3$)	1.279 (0.0462)	

[12] Reference 5, pp 59, 60

TYPE 5 TAPE[13]

Description: THORNEL 50-S graphite and S-1014 glass fibers collimated into one 50/50 by volume tape and impregnated with Ferro epoxy resin system CE9015.
Date of manufacture: 18 October 1975.

Prepreg property test results

Roll no.	Length m	Length (ft)	Resin content %	Resin flow, % at 103.4 kPa (15 psi) and 162.3°C (325°F)	% Volatiles at 68.9 kPa (10 psi) and 162.3°C (325°F)	Gel time, minutes, 162.3°C 325°F)
1	192	(630)	40.7	22.0	0.7	9.5
2	192	(630	38.4	22.0	0.7	9.5
3	189	(620)	39.7	22.0	0.7	9.5
4	192	(630)	38.6	22.0	0.7	9.5
5	116	(380)	39.5	22.0	0.7	9.5
Total	881	(2,890)	39.38 (Av)			

Tack test - All rolls passed. Tensile strength, N(lb) = 965.3 (217).

Mechanical properties of cured test panels, type 5 tape

Property	Value 21.1°C (70°F)	Value 93.3°C (200°F)
Tensile strength, MPa (psi)		
Longitudinal	496.4 (71,990)	542.9 (78,744)
Transverse	16.4 (2,375)	13.2 (1,908)
Tensile modulus, GPa (psi x 10^6)		
Longitudinal	122.7 (17.8)	126.2 (18.3)
Transverse	7.2 (1.04)	5.8 (0.84)
Elongation, % at break		
Longitudinal	0.45	0.55
Transverse	0.20	0.25
Short beam shear, MPa (psi)	41.7 (6,045)	38.7 (5,609)
Thickness per ply, cm (in.)	0.0216 (0.0085)	
Fiber volume, %	57.5	
Density, gm/cm^3 (lb/$in.^3$)	1.639 (0.0592)	

[13] Reference 5, pp 61,62

TYPE 6 TAPE[14]

Description: THORNEL 50-S graphite and KEVLAR 49 fibers collimated into one 50/50 by volume tape and impregnated with Ferro epoxy resin system CE9015.
Date of manufacture: Not reported (assumed to be during January 1976).

Prepreg property test results

Roll no.	Length m	Length (ft)	Resin content %	Resin flow, % at 103.4 kPa (15 psi) and 162.3°C (325°F)	% Volatiles at 68.9 kPa (10 psi) and 162.3°C (325°F)	Gel time, minutes, at 162.3°C (325°F)
1	Not reported		44.3	29.0	1.1	13.5
2	Not reported		45.0	29.0	0.8	13.5
3	Not reported		43.2	29.0	1.2	13.5
4	Not reported		45.1	29.0	1.1	13.5
5	Not reported		46.0	29.0	1.1	13.5
6	Not reported		47.1	29.0	1.1	13.5
7	Not reported		47.8	29.0	1.5	13.5
8	Not reported		48.0	29.0	1.2	13.5
9	Not reported		49.0	29.0	1.3	13.5
10	Not reported		49.0	29.0	1.3	13.5
Average			46.45		1.17	

Tack test - All rolls passed. Tensile strength - not reported.

Mechanical properties of cured test panels, type 6 tape

Property	Value 21.1°C (70°F)	93.°C) (200°F)
Tensile strength, MPa (psi)		
Longitudinal	614.3 (89,100)	624.0 (90,500)
Transverse	1.7 (244)	1.7 (250)
Tensile modulus, GPa (psi x 10^6)		
Longitudinal	146.9 (21.3)	128.2 (18.6)
Transverse	5.8 (0.84)	5.2 (0.76)

[14] Reference 5, pp 78-81

Elongation, % at break		
Longitudinal	0.43	0.46
Transverse	0.36	0.40
Short beam shear, MPa (psi)	32.30 (4,682)	29.30 (4,250)
Thickness per ply, cm (in.)	Not reported	
Fiber volume, %	61.40	
Density, gm/cm^3 (lb/in.^{3})	1.3094 (0.0473	

Ferro Corporation's Data Acquisition Notes

In a Ferro Corporation letter to Picatinny Arsenal dated 3 February 1976,[15] Ferro described the methods used to calculate fiber volumes and reported the values they used for fiber and resin densities. The information presented below is a digest of that letter.

Fiber contents of all tape types were obtained by acid digestion (presumably ANSI/ASTM method D3171, Procedure A) except the type 3 (S-1014 glss), which was obtained by burnoff (presumably by ASTM D2587). Since KEVLAR 49 will digest in acid along with the epoxy resin, the digestion time for the type 4 tape was kept short to minimize this digestion of the KEVLAR 49. No attempt was made to correct for any weight loss which may have been suffered by the S-1014 glass in the THORNEL 50-S/S-1014 hybrid (type 5) tape digestion. Type 6 tape (THORNEL 50-S/KEVLAR 49 hybrid) was acid digested for a longer time span in order to assume that all of the KEVLAR 49 was digested. The remaining fiber was assumed to be only THORNEL 50-S fiber and its weight was doubled to obtain the total fiber weight in the type 6 test sample. Ferro reported the densities of the materials used to make the tapes as shown in the table below.

Tape type no.	Material	Density gm/cm^3
	CE9015 resin system	1.038
1	THORNEL 50-S graphite fiber	1.67
2	CELION GY 70-S graphite fiber	1.96
3	Ferro S-1014 glass fiber	2.49
4	KEVLAR 49 aramid fiber	1.45
5	1:1 volume ratio mixture of THORNEL 50-S and S-1014 fiber, $\frac{1.67 + 2.49}{2}$	2.08

[15]Reference 5, pp 85,86

6	1:1 volume ratio mixture of THORNEL 50-S and KEVLAR 49 fibers, $\frac{1.67+1.45}{2}$ =	1.56

APPENDIX D

CALCULATION OF RESIN BLEEDOUT TO OBTAIN A CURED COMPOSITE TUBE WITH 60 VOLUME PERCENT FIBER

Due to fund limitations, no experimental data were gathered to determine as accurately as possible the amount of nylon bleeder tape required to provide 60 volume percent fiber in each tube type. Shown below are calculations which provide a theoretical prediction of the amount of shrink tape which should be applied to each tube type.

Fiber content calculations

Fiber volume fraction

$$= \frac{\text{cm}^3 \text{ fiber}}{\text{cm}^3 \text{ composite}} = \frac{\left(\frac{\text{g fiber}}{\text{g fiber/cm}^3 \text{ fiber}}\right)}{\left(\frac{\text{g composite}}{\text{g composite/cm}^3 \text{ composite}}\right)}$$

Using one gram of prepreg as a basis, and Ferro data[1], the fiber volume fraction may be calculated as shown below for the type 1 (THORNEL 50-S/CE9015 tape:

1 gram of prepreg = 0.362 g resin + 0.00617 g volatiles. Neglecting void content, the fiber content = 1 - (0.362 + 0.00617) = 0.6318 g

Neglecting void content, the volume of the resin + volatiles =

$$\frac{\text{g resin + volatiles}}{\text{resin density}} = \frac{0.36817}{1.038} = 0.355 \text{ cm}^3$$

$$\text{fiber volume} = \frac{0.6318}{1.67 \text{ g fiber/cm}^3 \text{ fiber}} = 0.378 \text{ cm}^3$$

total volume, fiber, resin, volatiles = 0.355 + 0.378 = 0.733 cm^3

[1] From appendix C.

Therefore, the density of type 1 tape = $\frac{1}{0.733}$ = 1.364 g/cm^3 and the fiber volume fraction = $\frac{0.6318/1.67}{1/1.364} = \frac{0.378}{0.733} = \underline{0.5157}$

Using the same methodology, the fiber volume fractions for the other tape types were calculated. The results are summarized in table D-1 along with the results of calculations of the bleedout required to obtain a 60 volume percent fiber content in each cured tube type.

Calculations to obtain required bleedout for 60 volume percent fiber.

Let X = grams of resin the prepreg must lose to yield 60 volume percent fiber in the cured composite.

$$\text{volume fraction} = 0.60 = \frac{\left(\frac{\text{g fiber}}{\text{g fiber/cm}^3\ \text{fiber}}\right)}{\left(\frac{\text{g fiber}}{\text{g fiber/cm}^3} + \frac{\text{g resin} - X}{\text{g resin/cm}^3\ \text{resin}}\right)}$$

Calculation for the amount of resin required to be bled from each type of prepreg is illustrated by the calculation shown below for the type 1 prepreg:

Make the basis for solving for X be one gram of type I prepreg tape.

Therefore, 0.60 =

$$\frac{(0.63183/1.67)}{\left(\frac{0.63183}{1.67} + \frac{(0.36817 - X)}{1.038}\right)} = \frac{(0.378)}{\left(0.378 + \frac{(0.36817 - X)}{1.038}\right)}$$

$X = \underline{0.1066\ \text{g resin/g prepreg}}$.

Thus, the volume of resin to be bled out per unit volume of prepreg (type 1) is:

$$\frac{\text{cm}^3\ \text{resin (to be lost)}}{\text{cm}^3\ \text{prepreg}} = \left(\frac{\text{g resin}}{\text{g prepreg}}\right) \times \left(\frac{\text{g prepreg}}{\text{cm}^3\ \text{prepreg}}\right) \times \left(\frac{\text{cm}^3\ \text{resin}}{\text{g resin}}\right)$$

$$= \left(\frac{0.1066}{1}\right) \times (1.364) \times \left(\frac{1}{1.038}\right) = \underline{0.14}$$

Using the same procedure, the resin bleedout for the other tape types were calculated and the results summarized in table D-1.

Nylon tape required for bleedout

From previous tube fabrication experience and assessment of the prepreg fiber content (volume percent) data, it was concluded that the minimum amount of nylon tape required for any of the prepreg tape types should be a 100% overwrap. See figure D-1 for a graphic presentation of the various possibilities, 100% through 500%.

From the bleedout required data of table D-1, it can be seen that the type 4 tape requires the least amount of bleedout, type 1 requires 0.14/0.09 or 1.555 times as much, type 2 requires 2.888 times as much, type 3 requires 2.555 times as much, type 5 requires 3.222 times as much, and type 6 requires 3.333 times as much bleedout as type 4 tape. If it is assumed that type 4 tape should receive a 100% overwrap, the other wraps may be calculated from the factors listed above.

From the layout of figure D-1 it can be seen that a 50% increase in overwrap over type 4 yields three layers instead of two (200% instead of 100% overwrap) and the lead, L = 0.847 cm (0.333 in.). From calculations developed in reference 5 pp 92-99, the outside diameter of the wound tube after the last double ply was wound was 8.664 cm (3.411 in.). Thus, from the relationship,

$L = \frac{\text{tube O.D.}}{\tan \alpha}$, for a type 1 tape tube, α is 84.416° when L = 0.847 cm (0.333 in.).

The distance L, for the other tape types was calculated using the type 4 tape bleedout data from table D-1 as a base. Given the starting point of 100% overwrap for type 4 tape, a lead of 1.27 cm (0.50 in.) from figure D-1, and knowing that the lead, L, varies inversely with the number of wrap thicknesses, and that the number of wrap thicknesses varies directly with the bleedout required, L may be calculated by the expression

$$L = 1.27 \times \frac{1}{\left(\frac{\text{bleedout of type X tape}}{\text{bleedout of type 4 tape}}\right)}.$$

For type 1 tape, the bleedout ratio, type 1/type 4 is approximately 1.5, hence L for type 1 = 1.27 x 1/1.5 = 0.847 cm (0.333 in.) L for the other tape types was calculated in a similar fashion. Using the calculated L and O.D. value, the winding angle, α, was calculated for each of the tape types. Summarized below are the calculations for the nylon tape windings for all tape types.

Tape[a] type	Lead, L,[b] calculation, cm (in.)	Last ply O.D. cm (in.)	Winding angle, α degrees
1	$L = \frac{1.27}{1.5} = 0.847$ (0.333)	8.664 (3.411)	84.42
3	$L = \frac{1.27}{2.3} = 0.552$ (0.217)	8.603 (3.387)	86.33
4	L = 1.27 (0.50)	8.55 (3.368)	81.56
5	$L = \frac{1.27}{3.0} = 0.423$ (0.167)	8.816 (3.471)	87.25
6	$L = \frac{1.27}{3.0} = 0.423$ (0.167)	8.649 (3.405)	87.20

[a] A nylon tape wrap for type 2 tape was not required since type 2 tape was never a final double ply winding.
[b] 1.27 cm corresponds to the lead for type 4 tape (100% overwrap).

Table D-1. Data summary for composites curing to 60 volume % fiber[a]

Prepreg tape type	Fiber density g/cm^3	Average[b] resin content, wt. %	Average[b] volatile content, wt. %	Prepreg[c] fiber content, wt. %	Prepreg[c] fiber content, vol. %	Pregpreg[c] density, g/cm^3	Bleedout required for 60 vol. % fiber composite[c]	
							g resin/ g prepreg	cm^3 resin/ cm^3 prepreg
1	1.67	36.20	0.62	63.18	51.57	1.364	0.1066	0.14
2	1.96	39.80	1.00	60.10	44.43	1.447	0.1866	0.26
3	2.49	32.03	0.53	67.43	46.33	1.711	0.1383	0.23
4	1.45	35.70	1.60	62.70	54.60	1.264	0.0741	0.09
5	2.08	39.38	0.70	59.92	42.73	1.484	0.2015	0.29
6	1.56	46.45	1.17	52.38	42.26	1.258	0.2438	0.30

[a]Resin density = 1.038 g/cm^3 (Ferro Corp. data).
[b]Ferro Corp. data.
[c]Calculated.

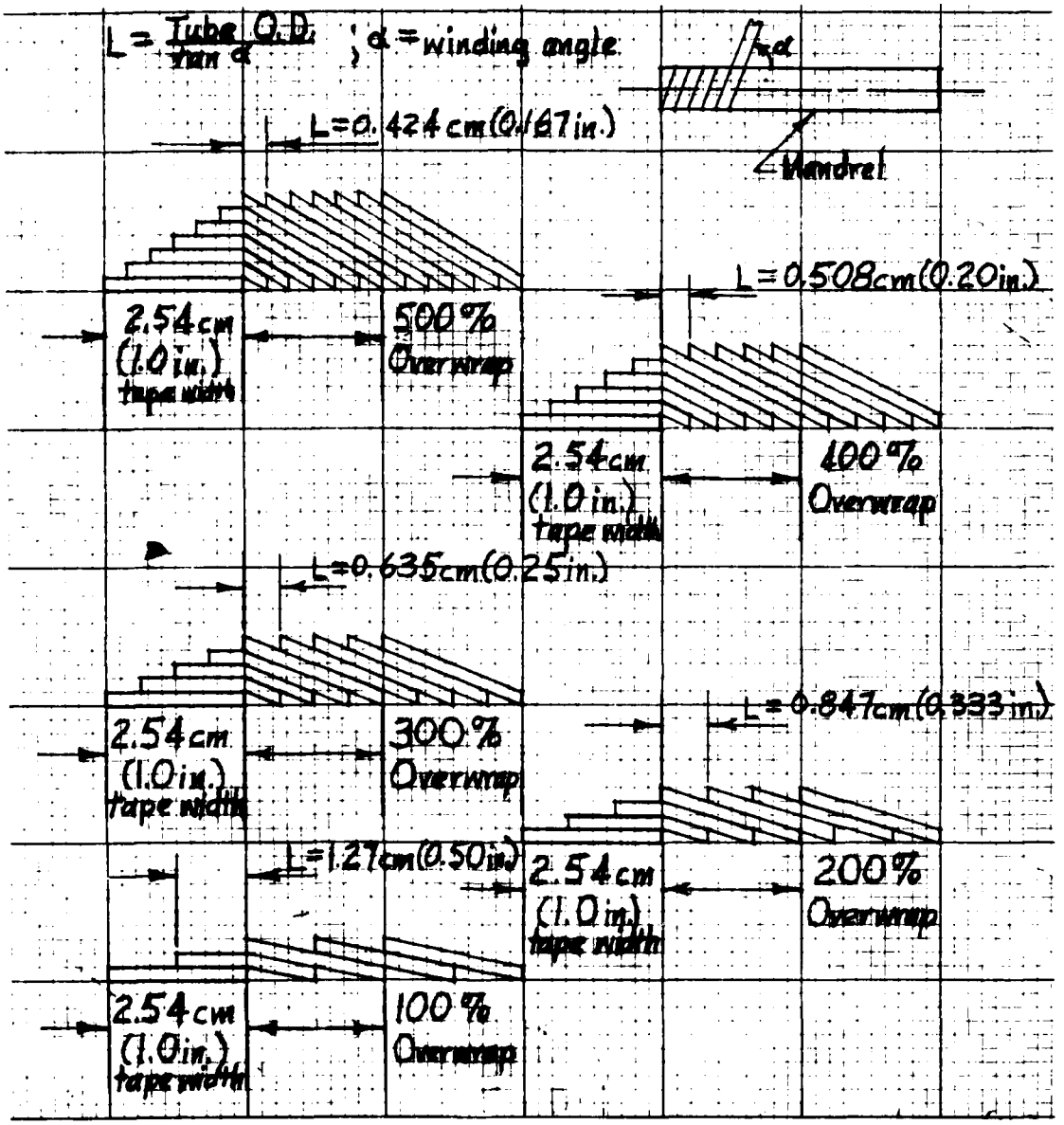

Figure D-1. Cross sectional layout of various woven nylon tape windings for prepreg resin bleedout control.

APPENDIX E

ADHESIVE BONDING OF ALUMINUM END COUPLINGS

Bonding Fixture

The fixture used to hold the composite tube in its proper position relative to the end couplings during adhesive injection and subsequent heat cure was designed and fabricated at Picatinny Arsenal. Details of construction are shown in figures E-1 through E-9.

Bonding Procedure

The end couplings used to prepare the shaft specimens described in this report were salvaged from decommissioned UH-1 helicopters, consequently they were received with several types of organic coating in addition to the anodize coating they received at the time of manufacture. Some couplings were gray, some were green, and some had a shiny off-white appearance. After some preliminary trials, it was found that all coatings were removable with epoxy stripper, MS-111.[1] Some of the off-white coating, although softened by the stripper, had to be wire brushed to be removed.

Once the coating was removed, the next step was to remove the original anodize coating in order to provide the desired aluminum oxide coating for maximum adhesive-to-aluminum bond strength. The anodize coating removal was accomplished by immersing the couplings in a 93°C (200°F) Oakite 33[2] solution for 5 to 15 minutes. This was followed by a tap water rinse and subsequent immersion of the couplings in a room temperature Amchem[3] No. 7 solution for 5 to 10 minutes. This last treatment was used to remove the black smut (thought to be a deposition of finely divided metal from the aluminum alloy which was insoluble in the Oakite 33 solution) left after the Oakite 33 immersion. The loose anodize film was then

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[1]MS-111, a stripping agent for cured epoxy resins, Miller-Stephenson Chemical Co., Inc., P.O. Box 628, Danbury, Connecticut 06810.

[2]Oakite Products, Inc., 50 Valley Road, Berkeley Heights, New Jersey 07922.

[3]Amchem Products, Inc., Ambler, Pennsylvania 19002.

scrubbed off under warm tap water and the couplings were dried under heat lamps.

The Amchem No. 7 solution was made up as follows:

100 mL nitric acid
22.6 gm of No. 7 Amchem powder
Tap water to make a total of 0.0011 m^3 (1 qt) of solution.

In accordance with the instructions of note 2 of figure E-3, twelve of the sixteen rivet holes were filled with epoxy resin[4]. Every other hole in the row of holes closest to the retaining ring of figure E-4 was left open for use as adhesive injection ports. The hole filling was accomplished by placing a 1.27 cm (0.5 in.) square piece of pressure sensitive tape over the outside of the hole and filling it from the inside using a small pallet knife. After a room temperature cure of approximately twelve hours, the squares of tape were removed and inspected for voids. Where necessary, these voids were filled with fresh adhesive and allowed to cure. Following this cure, excess adhesive around holes was cleaned off (where necessary) using a fine file or abrasive cloth.

All rubber "O" rings (fig. E-3) and retaining rings (fig. E-4) were cleaned in a dilute solution of Oakite 33 to remove soil, grease, or oil. They were then rinsed in warm tap water and allowed to drain-dry. Following drying, a rubber "O" ring was assembled onto each retaining ring as shown in figure E-3 and stored preparatory to assembly to the aluminum end coupling.

The outside bonding area of each end coupling was wiped with an acetone wetted tissue to remove finger oils and residual adhesive from the squares of masking tape. Each coupling was then immersed in a hot acid solution (65°C/149°F) for 10 minutes to provide the desired aluminum oxide coating previously mentioned. This treatment is referred to as the FPL etch[5] and is the same acid solution referred to on page 17 of reference 2. For reader convenience, the recipe is as follows:

---

[4]Scotch Weld structural adhesive no. 2216, 3M Company, St. Paul, Minnesota.

[5]An aluminum surface treatment developed by the Forest Products Laboratories, Madison, Wisconsin for maximum adhesive-to-aluminum bond strength.

1 pbw sodium dichromate
10 pbw sulfuric acid (98% reagent grade)
30 pbw deionized water.

The couplings were then rinsed in tap water, first a quick dip in a water filled beaker, then a rinse under warm tap water from a faucet. This was followed by a deionized water rinse from a dispensing bottle. The water was in turn rinsed off with isopropyl alcohol from a dispensing bottle and the isopropyl alcohol was blown off with a stream of filtered dry air. The retaining rings were assembled to the couplings with ungloved hands, but extra care was exercised to avoid finger contact with the intended bonding area. Vinyl examination gloves were purposely not used because of the risk of contaminating the bonding area with plasticizer from the gloves. The assemblies were then individually wrapped in paper tissue and stored in individual metal cans until time to bond them to the composite tubes.

The composite tubes were prepared for bonding by first tying down ravelled fibers at the tube ends (where necessary--this was typically the need in the case of those tubes having KEVLAR 49 in the outer ply). The loose fiber treatment was accomplished by applying a 1.2 cm (0.5 in.) wide strip of epoxy adhesive[6] around each end of the tube. The "tie-down" adhesive was allowed to cure at room temperature for approximately 12 hours. The bonding area on the inside of each end of the tube was further prepared by abrading it with 80J grit aluminum oxide abrasive cloth. These areas were then wiped clean with a paper tissue wetted with acetone and allowed to dry.

At this point, the tubes and couplings were ready for bonding. Two end couplings and one composite tube were assembled into the bonding fixture according to the instructions of figure E-1. Except for injecting the adhesive from inside the end coupling, the rest of the bonding procedure was as described in reference 2, page 19.

In order for the adhesive to be injected from the inside of the end coupling, it was necessary to fashion an injection tube with a 90 degree curve in it. This was accomplished by means of some copper tubing and a copper fitting whose threads were compatible with the threads on the polyethylene adhesive cartridge.

---

[6]A 1:1 volume ratio of either EPON 828 or EPON 815 and VERSAMID 140, either Shell Chemical Co., Houston, Texas or the Miller-Stephenson Chemical Co., Danbury, Connecticut.

The tip end of the copper tubing was turned slightly to allow it to be inserted into the coupling holes and also to provide a seat for a small O-ring which provided a sealing function during adhesive injection.

The bonding fixture with the assembled parts were warmed for approximately one-half hour by placing it in a preheated, air-circulating, 66°C (150°F) oven. The one-part epoxy adhesive,[7] packed in polyethylene cartridges compatible with the SEMCO Model 250-6 pneumatically activated adhesive-injection gun, was prepared for injection into the bond line space as follows:

1. An adhesive cartridge was removed from the freezer and placed in a 66°C (150°F) oven for 20 minutes.

2. After 20 minutes of oven-warming, the cartridge was removed from the oven, the tip plug was removed, a short nozzle was inserted, and the metal gun retainer was placed around the tube. A thermocouple was then inserted into the adhesive through the nozzle, and the cartridge was returned to the oven.

3. When the adhesive reached a temperature of 66°C (150°F), both the assembly and the cartridge were removed from the oven.

The fixture/shaft assembly was rechecked to be sure that the couplings were still in their proper positions and the wing nuts tight. The tip of the injection fitting was inserted into one of the coupling holes and adhesive was injected at approximately 276 kPa (40 psi) air pressure. The instructions of notes 4 and 5 in figure E-10 were followed in completing the injection phase. Filling holes were covered with aluminum tape and excess adhesive was wiped off. The assembly was placed in a preheated 121°C (250°F) oven and allowed to cure for one hour. Upon removal from the oven, the shaft was disassembled from the fixture, excess resin was trimmed off, and the aluminum tape was removed from the couplings.

---

[7]Scotch Weld structural adhesive no. 2214 hi-density, 3M Company, St. Paul, Minnesota.

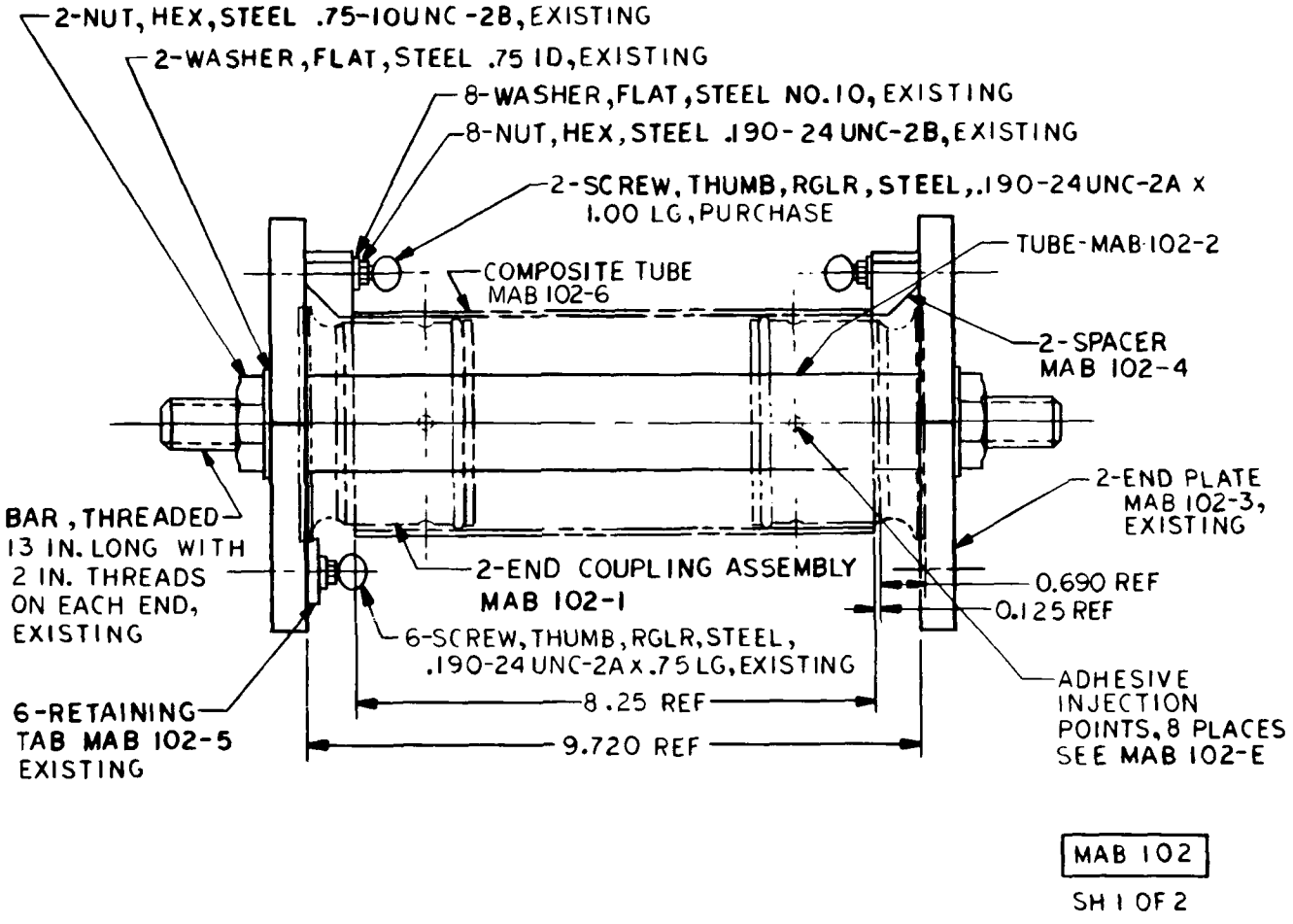


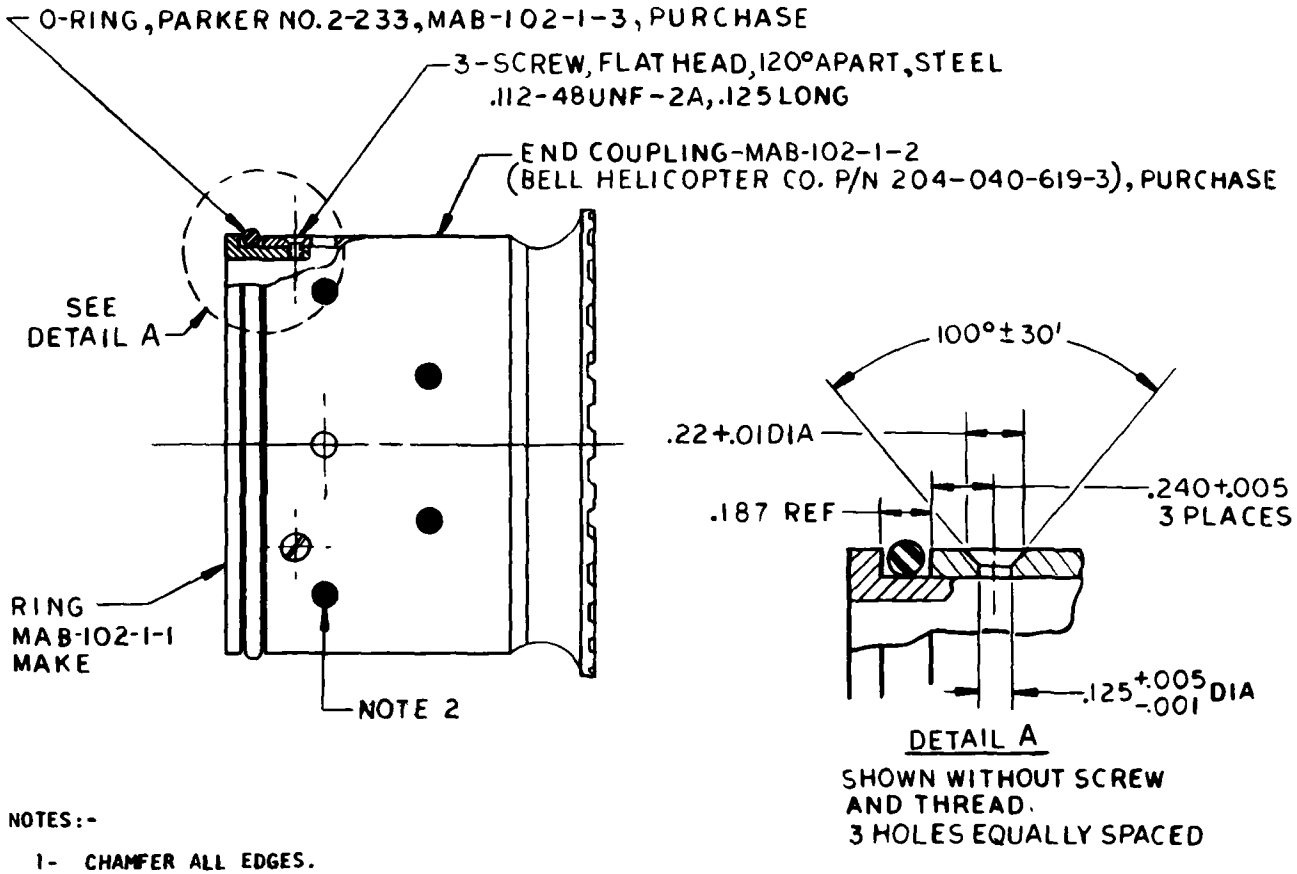
Figure E-1. Graphite/epoxy tube bonding fixture.

DWG NO.	MAKE/PURCHASE	QUANTITY
MAB102 1	MAKE	2/SHAFT
MAB102-1-1	MAKE	2/SHAFT
MAB102-1-2	PURCHASE	2/SHAFT
MAB102-1-3	PURCHASE	2/SHAFT
MAB102-2	MAKE	1
MAB102-3	EXISTING	2
MAB102-4	MAKE	9
MAB102-5	EXISTING	8
MAB 102-6	MAKE	1

MAB 102

SH 2 OF 2

Figure E-2. Make/purchase parts.



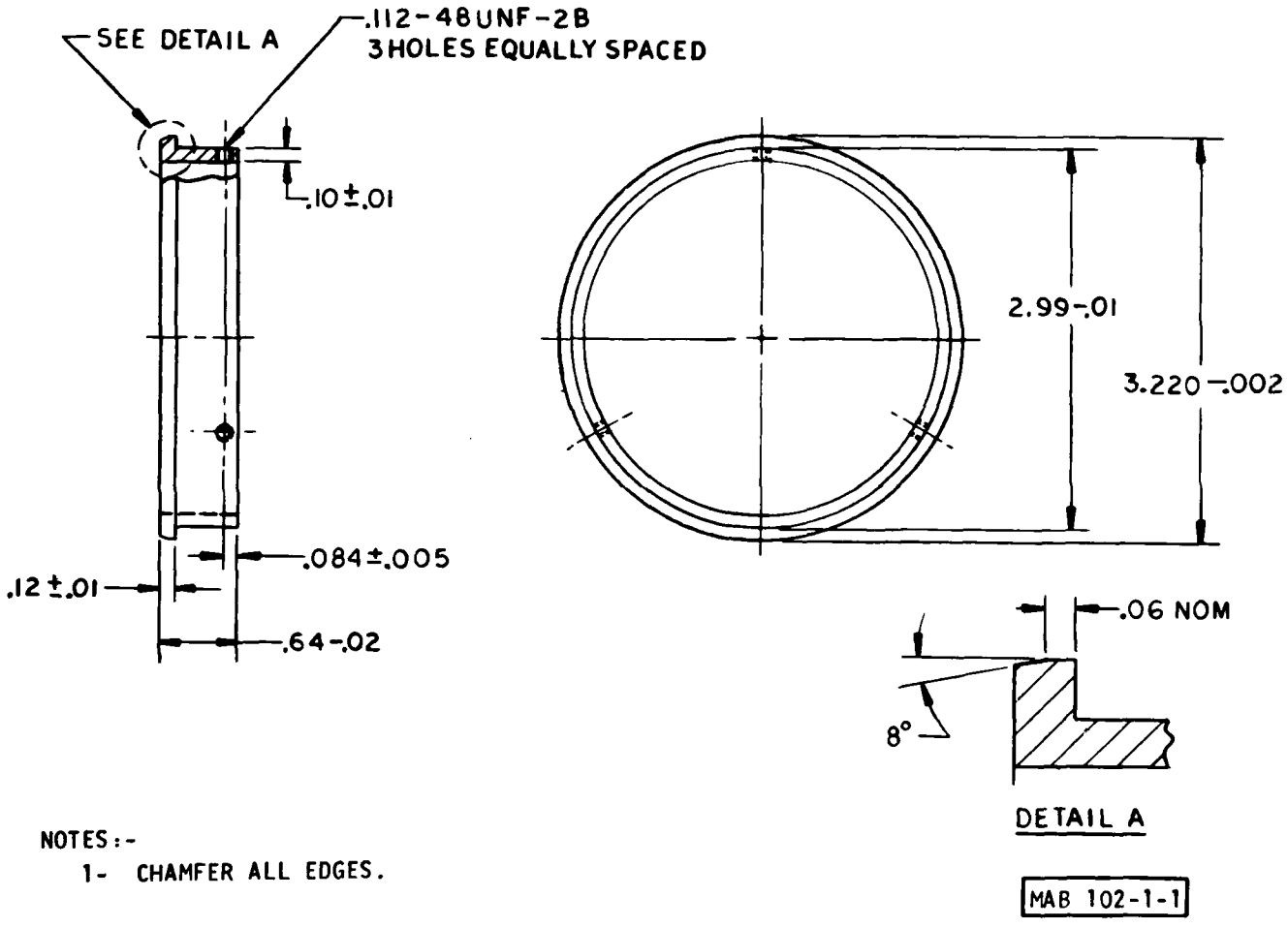
NOTES:-

1- CHAMFER ALL EDGES.

2- TWELVE EXISTING HOLES TO BE FILLED WITH EPOXY; FILL EVERY OTHER HOLE IN NOTED ROW OF HOLES. UNFILLED FOUR HOLES TO BE USED FOR INJECTING BONDING ADHESIVE.

MAB 102-1

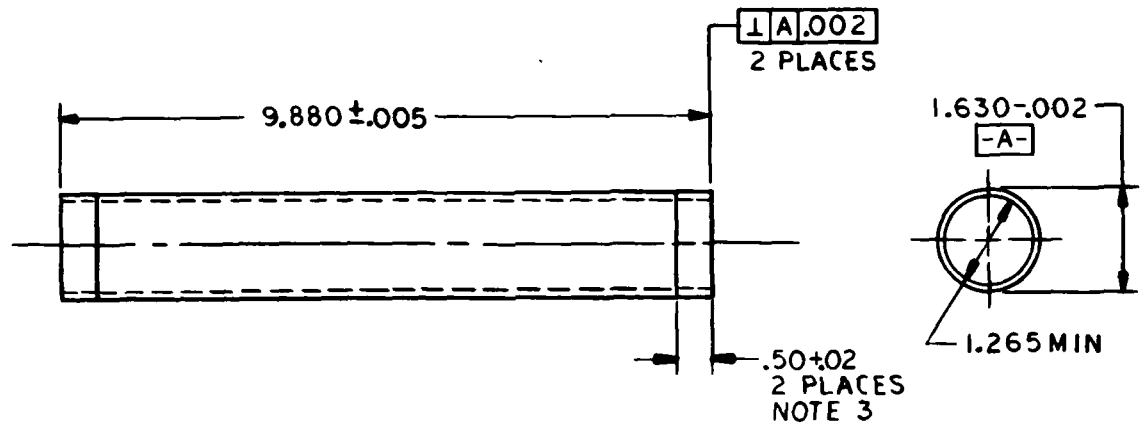
Figure E-3. End coupling assembly.



NOTES:-

1- CHAMFER ALL EDGES.

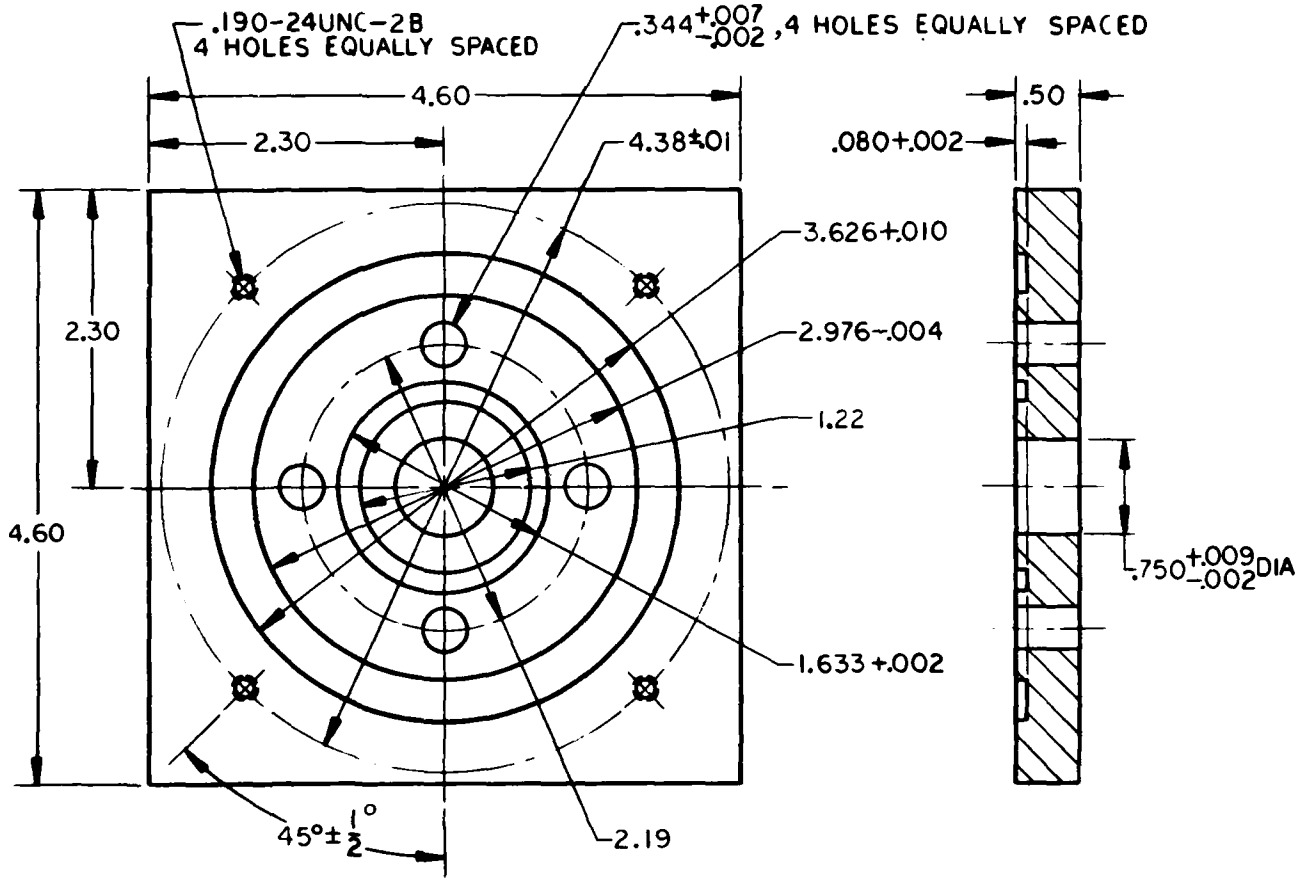
Figure E-4. Ring (aluminum).



NOTES:-
1- CHAMFER ALL EDGES.
2- UNLESS SHOWN OTHERWISE TOLERANCES ARE ±.02.
3- 1.630-.002 DIA TO BE MAINTAINED FOR THIS DISTANCE AT EACH END.

MAB 102-2

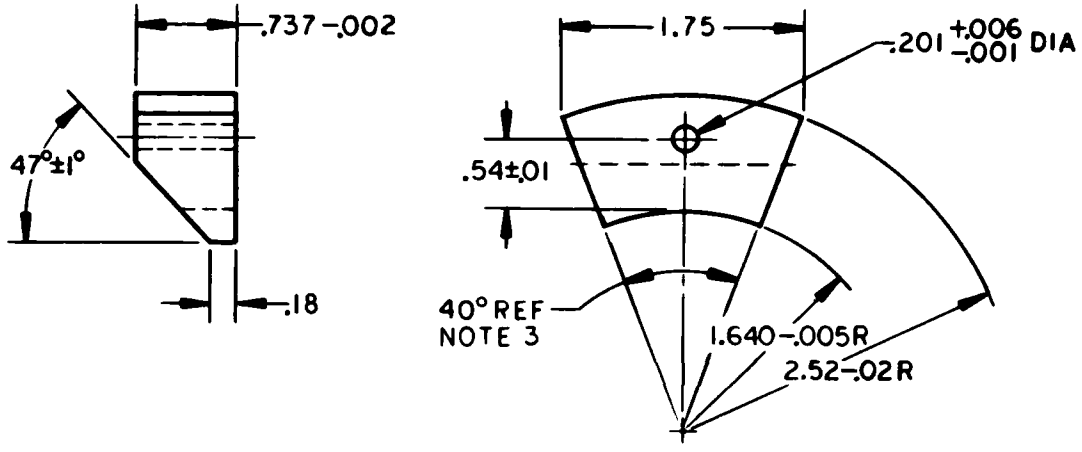
Figure E-5. Tube (aluminum).



NOTES:-
1- CHAMFER ALL EDGES.
2- UNLESS SHOWN OTHERWISE TOLERANCES ARE ±.02.

MAB 102-3

Figure E-6. End plate (aluminum), existing.



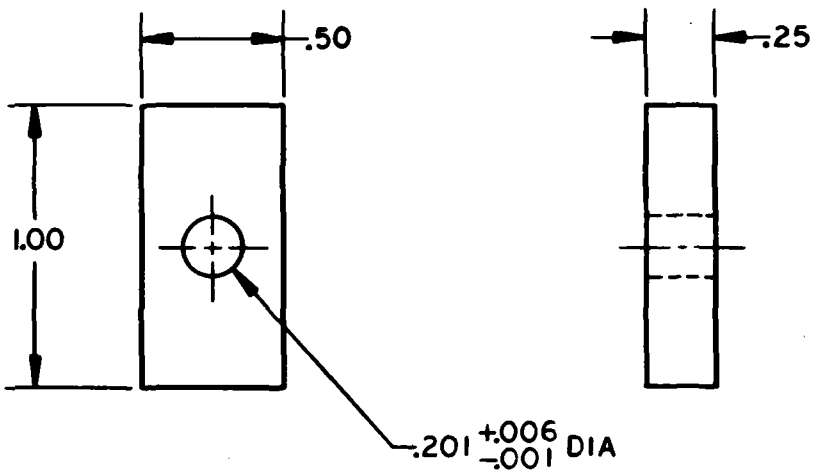
SPACER (TEFLON)

NOTES:-

1- CHAMFER ALL EDGES.
2- UNLESS SHOWN OTHERWISE TOLERANCES ARE ±.02.
3- CUT FROM TURNED PIECE. YIELD 9 SPACERS.

MAB 102-4

Figure E-7. Spacer (teflon).



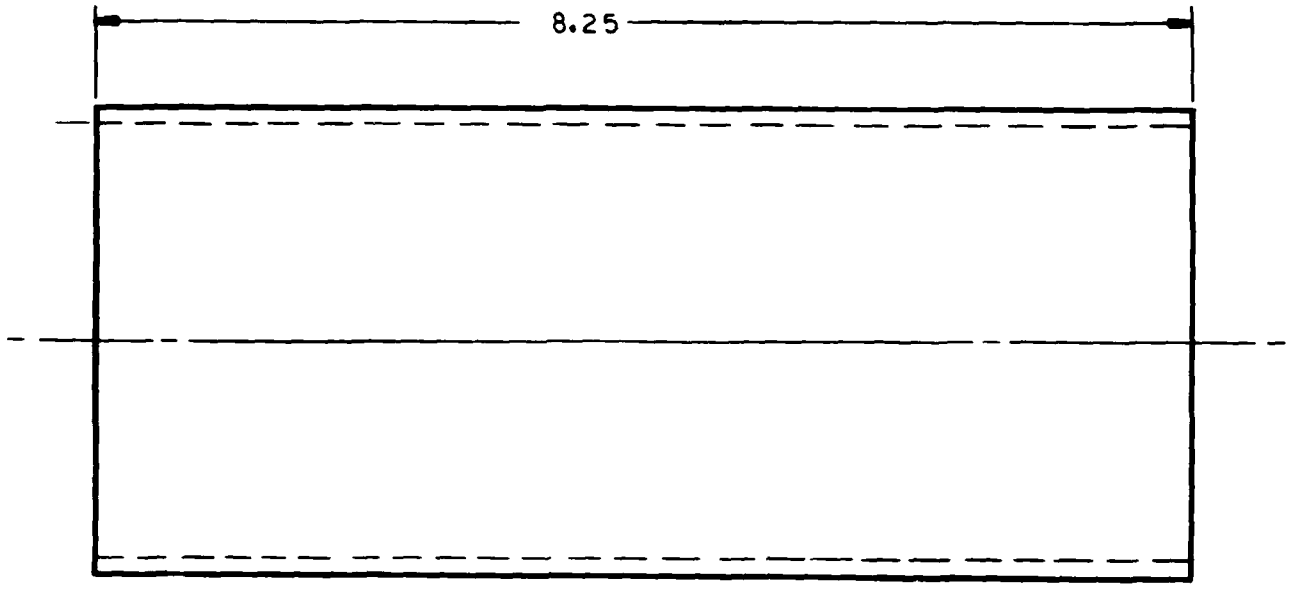
NOTES:-

1- CHAMFER ALL EDGES.

2- UNLESS SHOWN OTHERWISE TOLERANCES ARE ± .02.

MAB 102-5

Figure E-8. Retaining tab (steel), existing.



NOTES:-
1-UNLESS SHOWN OTHERWISE TOLERANCES ARE ±.02.

MAB 102-6

Figure E-9. Composite tube (test specimen).

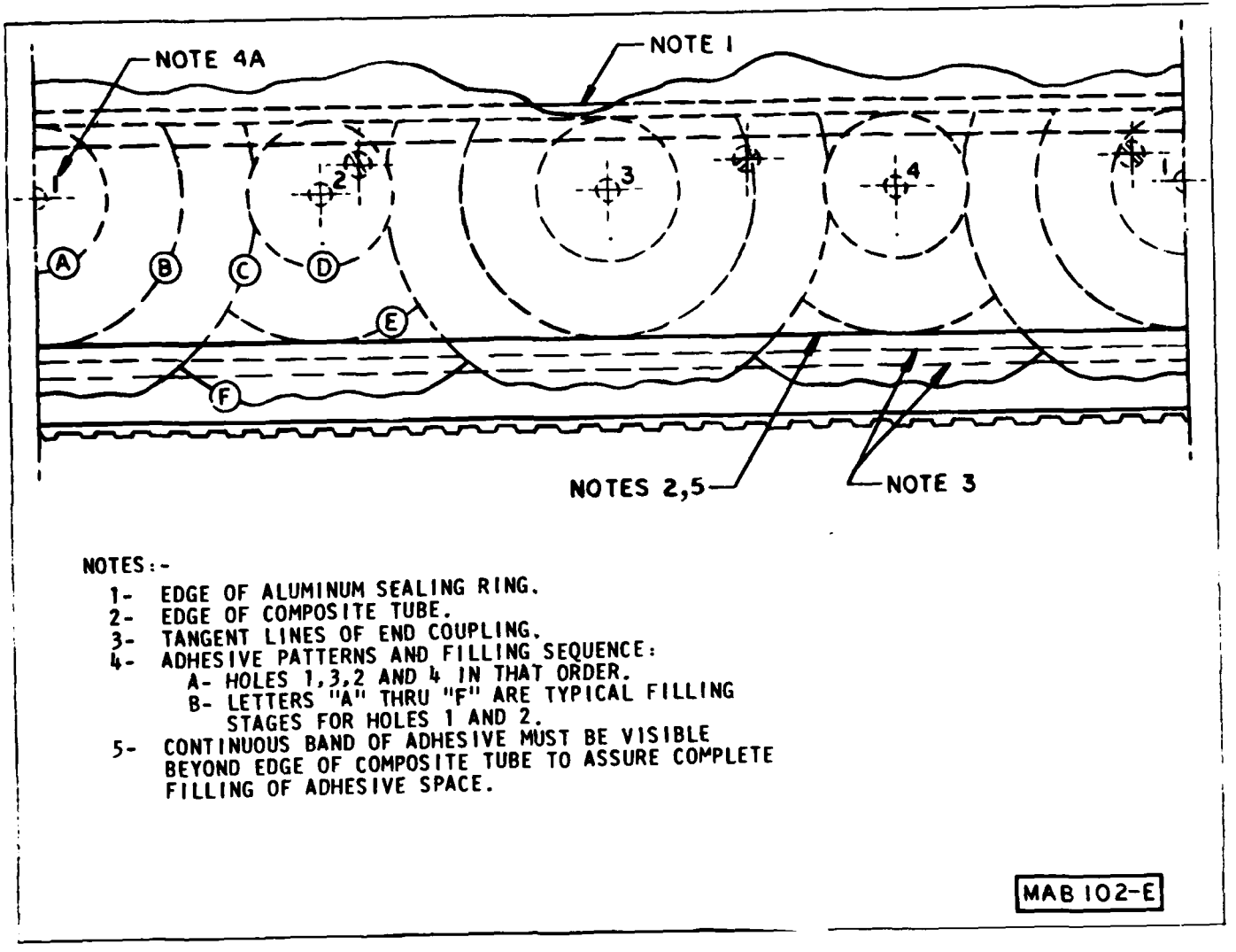


Figure E-10. Expanded layout of aluminum end coupling and composite tube.

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