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CARBON-FIBER THERMAL INSULATION

Z. L. Ardary
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OAK RIDGE Y-12 PLANT

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Oak Ridge Y-12 Plant

P.O. Box Y, Oak Ridge, Tennessee 37830

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ABSTRACT

A low-density, discontinuous carbon fiber composite material has been developed primarily for use in advanced aerospace systems. The material is ideally suited for high-temperature applications (to 4,500° F) which require excellent thermal insulation in combination with needed cushioning and load support. The composite consists of short carbon fibers (10 - 30 mils long) bonded together with a small amount of pyrolyzed starch (carbon) binder.

A vacuum filtration process, utilizing a dilute water slurry containing carbon fibers and starch particles, is used in fabricating the composite material. Flat slabs, hollow cylinders, and hollow conical frusta are some of the more conventional shapes which have been formed with this process. Curing, drying, and furnacing operations are employed to effect a semirigid, carbon-bonded fibrous structure.

Bulk densities between 0.11 and 0.26 gm/cc were obtained by adjusting the material parameter and processing techniques. Compressive strengths generally increased with density and were in the range from 15 to 150 psi at a 10 percent deflection. Typical values of thermal conductivity, in an argon atmosphere, were between 0.46 and 0.77 Btu-in/hr-°F-ft² at a 1,000° F mean temperature. The thermal conductivity increased with temperature to 4.0 - 5.5 Btu-in/hr-° F-ft² at 4,000° F.

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SUMMARY

A low-density, discontinuous carbon fiber composite was developed primarily for use in advanced aerospace systems. The material is ideally suited for high-temperature applications (to 4,500° F) which require excellent thermal insulation in combination with needed cushioning and load support. The composite consists of short carbon fibers (10 - 30 mils long) bonded together with a small amount, by weight, of carbon binder. Rayon fibers and various starches, both of which have coking yields in the order of 20 - 25 weight percent, serve as the precursors for the carbon fibers and binder.

A vacuum-filtration process is used in fabricating the composite material. From a dilute water slurry containing carbon fibers and insoluble starch particles, a part is vacuum molded on a perforated metal mandrel of the desired shape. A wide variety of shapes can be molded, depending on the particular mandrel design employed. Flat slabs, hollow cylinders, and hollow conical frusta are some of the more conventional shapes which have been formed with this process. After forming, the molding, which consists of starch particles dispersed in a fibrous mat with residual water, is processed through curing (90° C), drying (90° C), and furnacing (1,000° C) operations to effect a semirigid, carbon-bonded fibrous structure. Machining to reasonably close tolerances can be readily performed with single-point tooling.

Material parameters and processing techniques were varied in a study designed to generate a wide range in property values for the fibrous composite. Bulk densities between 7 and 16 pcf (0.11 to 0.26 gm/cc) were obtained. The compressive strengths, evaluated at room temperature, were in the range from 15 to 150 psi at a 10 percent deflection. At a 1,000° F mean temperature in an argon environment, coefficients of thermal conductivity between 0.46 and 0.77 Btu-in/hr-°F-ft² were observed. The thermal conductivity increased with temperature to 4.0 - 5.5 Btu-in/hr-°F-ft² at 4,000° F.

The effects of varying the binder concentration, fiber length and diameter, and fiber concentration on the physical and thermal properties of the material can be summarized as follows:

1. Increasing the binder (as carbon) content from approximately 5 to 30 weight percent resulted in: (a) an increase in density from 7.0 to 11.5 pcf, (b) an increase in the compressive strength at a 10 percent deflection from 10 to 35 psi, and (c) an increase in the coefficient of thermal conductivity from 0.46 to 0.76 Btu-in/hr-°F-ft² at a 1,000° F mean temperature.
2. Material prepared from 10-mil-long carbon fibers had a higher density, strength, and thermal conductivity than material made with either 30, 50, or 100-mil-long fibers. The 10-mil-long fiber material had a density of 11.3 pcf, a compressive strength of 100 psi at a 10 percent deflection, and a thermal conductivity of 0.68 Btu-in/hr-°F-ft² at 1,000° F.
3. Use of larger-diameter fibers, for a given length, gave the composite a higher density, strength, and thermal conductivity. Compressive strengths at a 10 percent deflection of the materials prepared from 7 and 2-micron-diameter fibers were 36 and 13 psi, respectively. At 1,000° F, thermal conductivities of the composites containing 7 and 2-micron-diameter fibers were 0.58 and 0.51 Btu-in/hr-°F-ft², respectively.

4. Significant strength improvement was obtained by increasing the fiber concentration with mechanical compaction during curing of the material. Increasing the density from 8 to 15 pcf resulted in an increase in compressive strength, at a 10 percent deflection, from about 15 to 165 psi. The thermal conductivity at 1,000° F increased from 0.51 to 0.71 Btu-in/hr-°F-ft² with an increase in density from 7.1 to 16.2 pcf.
5. The most effective method of improving the strength of the carbon fiber composite was by increasing the fiber concentration through compaction. This technique gave the greatest strength improvement per unit increase in density and thermal conductivity.

INTRODUCTION

In August 1967, the Oak Ridge Y-12 Plant^(a) became interested in low-density fibrous composites when a need arose for a thermal insulating material for reentry vehicle applications. As a result of the Y-12 effort, Palarite,⁽¹⁾ a carbon-bonded silica fiber insulation with a temperature capability of 2,000° F in vacuum or inert atmospheres, was developed. Palarite was an especially attractive material for aerospace applications because, in addition to a very low coefficient of thermal conductivity, it had a low density and a resilient nature which enabled it to withstand severe forces of vibration, shock, and acceleration.

In early 1968, advanced test programs imposed more severe reentry conditions, necessitating the development of a similar material with a temperature capability up to 5,000° F. The natural successor to Palarite was a fibrous carbon composite which was fabricated in the same manner as Palarite but with the substitution of carbon fibers for silica fibers. Like Palarite, the carbon-fiber composite is a low-density, low-thermal-conductivity material in which load-supporting and cushioning characteristics can be varied over a wide range to suit a variety of design considerations.

The density, strength, and coefficient of thermal conductivity of carbon-fiber composites are primarily dependent upon the relative concentrations, or overall volume fractions, of carbon fibers and binder. A study was conducted in which a wide range of values for these properties was induced through the alteration of process and material parameters. Variables which were investigated included: binder concentration, fiber length and diameter, and concentration of fibers (controlled by mechanical compaction). The principal objectives of the program were to: (1) determine methods of optimizing the properties with respect to maximum strength and minimum thermal conductivity for a particular density, (2) extend the range of properties available in the material, thereby providing greater flexibility in the design of thermal protection systems, and (3) investigate the feasibility of certain processes and develop the fabrication technology that is required for generating the desired material properties.

(a) Operated for the U S Atomic Energy Commission by the Union Carbide Corporation's Nuclear Division.

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DISCONTINUOUS CARBON-FIBER COMPOSITES

FABRICATION PROCESS

Introduction

The process for composite fabrication can, in a broad sense, be considered in three phases: (1) batch preparation, (2) forming, and (3) heat treatment. Preparation of the batch includes: (a) carbonizing and chopping the fibers, and (b) blending the fibers and starch particles into a very dilute, homogeneous dispersion of solids in a water slurry. Vacuum filtration is used to form, or mold, the solids onto a mandrel of the desired configuration. Finally, heat-treatment operations, consisting of a low-temperature (gelation and drying) and high-temperature (furnacing) phase, are performed to effect a carbon-bonded fibrous structure which can then be machined to the required dimensions. A flow diagram of the entire process is presented in Figure 1.

Materials

Starch - Type S-516 starch has been most often employed as the binder precursor. The material is a reagent-grade potato starch with an average particle size of approximately 25 - 30 microns. It is largely insoluble in water of neutral pH and, upon heating above 60° C in the presence of water, is readily gelatinized. The viscosity at 25° C of a 15 weight percent solution of this starch, obtained by initially heating the water-starch mixture to 100° C and then cooling to 25° C, is in the range of 220 - 300 centipoise.

The theoretical carbon, hydrogen, and oxygen contents of the starch (whose empirical formula is $C_6H_{10}O_5$) are 44.2, 6.2, and 49.4 weight percent, respectively. A spectrochemical analysis of Type S-516 starch is reported in Table 1. Pyrolysis of the starch during the fabrication process generally yields 20 to 25 weight percent carbon.

Carbon Fibers - The carbon fibers are prepared by heat treating Villwyte^(b) rayon fibers to 1,350° C in an inert atmosphere. An approximate 20 - 25 weight percent yield is obtained from the pyrolysis operation. Average diameter of the rayon fibers is near 3.7 microns. During carbonization, the rayon fibers undergo a linear shrinkage of nearly 40 percent and the resultant fiber diameter is about 2 microns. In this report, the lengths of carbon fibers are referred to as 10, 30, 50, and 100 mils, although these lengths are actually the lengths of the rayon precursor fibers.

Figure 1. PROCESS FLOW CHART FOR PRODUCING LOW-DENSITY CARBON-FIBER COMPOSITES.

(b) Villwyte rayon fibers are a product of Midland Ross, Inc, Cleveland, Ohio. Precision chopping of the rayon fibers to lengths of either 10, 30, 50, or 100 mils was performed by Micro-Fibers, Inc, Pawtucket, Rhode Island.

Table 1
SPECTROCHEMICAL ANALYSIS OF
TYPE S-516 STARCH

Element	Concentration (ppm)	Element	Concentration (ppm)
Ag	< 0.2	Li	3
Al	4	Mg	36
As	< 2	Mn	2
Au	< 0.2	Mo	< 0.2
B	0.2	Na	144
Ba	< 0.2	Nb	< 0.2
Be	< 0.2	Ni	< 0.7
Bi	< 2	P	>180
Ca	180	Pb	< 0.2
Cd	< 0.2	Rh	< 4
Co	< 4	Sb	< 0.2
Cr	< 0.2	Si	20
Cs	< 11	Sn	0.7
Cu	4	Th	< 0.7
Fe	4	Ti	< 1
Ga	< 0.2	U	< 18
Ge	< 0.2	V	< 0.2
Hf	2	W	< 2
In	< 0.2	Zn	< 11
K	117	Zr	< 0.4

After pyrolysis, the fibers are vacuum drawn through a Wiley mill. Purpose of the milling is to separate those fibers which are either naturally clumped or slightly bonded together due to the pyrolysis operation. The mill design is such that different sizing plates can be inserted to effect varying degrees of size or length reduction. A sizing plate with 2-mm-diameter (~ 0.079 inch) holes is generally used in milling the carbon fibers. The length of the fibers after milling is not seriously altered, although it is likely that some reduction in length does occur.

Slurry Preparation

A water slurry containing carbon fibers and insoluble starch is prepared and subjected to mechanical agitation for approximately 30 minutes. This operation provides additional separation of fiber aggregates and gives a homogeneous dispersion of solids within the liquid. Recycling of the slurry during

mixing is conducted by means of a centrifugal pump which draws the liquid from the bottom of the slurry tank and returns it to the top of the tank. This action assists in minimizing the settling of solids to the bottom of the tank while mixing.

The water slurries are prepared with a low concentration of solids in order to enhance the fiber separation and enable a homogeneous dispersion of solids to be achieved during the mixing operation. Generally, the total solids content (fibers and starch) of the slurry does not exceed one weight percent. A typical formulation might consist of 0.35 weight percent fibers, 0.35 weight percent starch, and 99.3 weight percent filtered process water.

Vacuum-Molding Operation

The molding procedure consists of the following operations: (1) fill the molding container with water; (2) start pumping the slurry into the molding vessel, simultaneously applying a slight vacuum (~ 26 inches Hg) inside the perforated mandrel; (3) continue feeding the slurry into the molding vessel until the slurry tank is depleted, maintaining a head of slurry above the top of the perforated mandrel at all times; (4) continue the vacuum, after all of the solids are deposited on the mandrel, until the desired residual water content within the molding is reached. A schematic diagram of the process equipment is given in Figure 2.

Generally, a perforated mandrel, with hole diameters of either $1/16$ or $1/8$ inch, is used as the substrate for depositing the solids during filtration. A conical frustum made of perforated metal can be seen in Figures 3 and 4. Mandrels for relatively simple shapes such as flats, cylinders, cones, and conical frusta can be readily fabricated from the perforated metal. To prevent fibers and starch from being drawn through the mandrel during filtration,

the mandrel must be covered with a porous cloth or a felt material. Various weaves of cotton cloth, and rayon or carbon felts in thicknesses up to 1/4 inch, can be used for this purpose.

Figure 2. VACUUM-MOLDING PROCESS EQUIPMENT.

Use of a separate container for the forming operation is desirable for at least two reasons: (1) settling of solids in the molding vessel can be minimized by making the vessel as small as possible in relation to the size of the perforated mandrel, and (2) agitation and recycling of the slurry can continue in the tank, thereby maintaining a homogeneous material feed to the molding container. The bottom half of a molding container, used in conjunction with a perforated conical mandrel, is shown in Figure 5.

The residual water content in the molded material, controlled by the dewatering time, is an important variable. An excessive water content will increase the tendency for delaminations (interlaminar separations) to occur during later curing and drying operations due to shrinkage effects and additional migration of the binder to part surfaces. If the water concentration is too low, gelation of the starch is only partially achieved and the result, after pyrolysis, is a weak carbon bond between the fibers. For these reasons, dewatering of moldings is controlled to give a water-to-solids weight ratio of approximately 1 to 1.

Total time required for the molding operation is generally in the range from 5 - 15 minutes and is primarily dependent on the vacuum capacity (gallons/minute) of the system, thickness of the molding, and the type and proportion of the solids in the formulation. Filtration time is decreased with increasing vacuum capacity and decreasing molding thickness. Dependence of filtration time on the batch formulation is not well defined, although fiber length, fiber diameter, and the starch/fiber proportions are known to be important variables.

Curing, Drying, and Furnacing

Process operations following vacuum molding are performed to effect a semirigid carbon-bonded fibrous structure. Operations include: curing (gelation) of the starch binder, drying, and furnacing (pyrolysis of the starch).

Figure 3. PERFORATED FORMING MANDREL.

131918

Figure 4. A MANDREL AND ITS VACUUM-MOLDING PROCESS EQUIPMENT.

131920

Figure 5. BOTTOM SECTION OF A MOLDING CONTAINER.

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Gelation occurs when the amylopectin membrane surrounding the starch granule ruptures, releasing the amylose core which forms a colloidal dispersion in water. Disruption of the membrane begins in most starches between 64 and 71° C.

In order to achieve complete starch gelation, the fibrous molding is heated to 90° C for at least six hours in an air atmosphere saturated with water vapor. This high-humidity environment is generated by sealing the part in a plastic bag; subsequent heating at 90° C fills the bag with water vapor. By allowing the moisture to diffuse out of the bag over a period of 7 - 10 days, a slow rate of drying is insured. With the recirculating air dryers currently in use, this technique promotes a uniform drying rate within the molding and reduces differential shrinkages which can lead to the formation of structural defects.

The molded parts are generally left on the perforated mandrel during the curing and drying operations in order to prevent distortions in shape which may occur after the starch is gelatinized. Distortion of the molding, especially in large parts, can arise due to slumping of the viscous, gelatinized mass under its own weight. After complete drying, the fibers are well bonded and the moldings can be removed from the forming mandrel.

Pyrolysis of the starch to effect a carbon bond is conducted by heating the molding to 1,000° C in an inert atmosphere. Since the carbon fibers have been previously heat treated to 1,350° C, shrinkage during pyrolysis is low, generally in the order of 1 - 2 percent.

Because of the low shrinkage and high porosity of the material, a fast rate of heating to 1,000° C is not detrimental to the integrity of the molding. Induction furnaces have been used to heat parts to 1,000° C in times as short as three hours. It is important that minimal temperature gradients exist within the furnace in order to heat the molding uniformly. If the molding is nonuniformly heated, distortion and delamination may occur due to differential shrinkages.

Mention should be made of the microstructure induced by the vacuum-forming process. The tendency is for the individual fibers to align themselves with their lengths parallel to the mandrel surface (or perpendicular to the force generated by the vacuum). As a result, the structure is layered, or laminated, as seen in Figure 6.

The carbon (pyrolyzed starch) bond between fibers is in the form of thin laminar sheets and webs. Bonding occurs at fiber junctures, between fiber edges, and through complete encapsulation of the fibers. The thin carbon bond can be seen in the transmission electron micrographs presented in Figure 7. Several broken pieces of the pyrolyzed starch laminae are seen in View (c). The carbon-webbing effect can be easily seen in the scanning electron micrograph of Figure 8.

Machining

The composite material can be machined to reasonably close tolerances (± 5 mils) with single-point tooling or diamond grinding wheels. Surface quality and edge definition are good. Very thin slitting wheels can be used for the cutting operations.

Figure 6. MICROSTRUCTURE OF A CARBON-FIBER COMPOSITE.

(a) Transmission Micrograph; 9,000X; Area I

(b) Transmission Micrograph; 9,000X; Area II

(c) Transmission Micrograph; 21,000X (pyrolyzed starch laminae)

Figure 7. CARBON FIBERS BONDED WITH PYROLYZED STARCH (CARBON).

Figure 8. CARBON WEB BOND. (Scanning Electron Micrograph; 2,140X)

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Figures 9 through 12 are photographs of several machined parts, fabricated for use as thermal insulators in aerospace applications.

129608

Figure 9. THERMAL INSULATION OF THE APOLLO 11 SEISMIC EXPERIMENT.

CHARACTERIZATION OF THE COMPOSITE MATERIAL

Introduction

A program was conducted to characterize the properties of the carbon-fiber composite materials. Material parameters and process techniques were adjusted to effect a reasonably wide range in strength. Related variations in density and thermal conductivity were evaluated in order to determine the best methods of improving strength in terms of minimal increases in density or thermal conductivity. Variables employed included binder concentration, fiber length and diameter, and fiber concentration (controlled by mechanical compaction during curing).

It should be emphasized that the parametric studies were conducted on specimens taken from easily fabricated disc billets. The feasibility of process scale up for fabricating specific part geometries (ie, hollow cylinders and frusta) has not been investigated for all of the material parameters and process techniques considered in the characterization program.

However, some of these formulations and process techniques have been employed in the course of special production activities.

Figure 10. A FLAT INSULATOR.

127709

Sample Preparation

Type S-516 starch and pyrolyzed rayon (carbon) fibers were two materials that were used in preparing fibrous composites for property evaluation. The vacuum-filtration process, described earlier in this report, was used to fabricate large disc billets (about 12 inches in diameter by 1 1/2 inches thick) of the composite materials.

The binder (as carbon) concentration was varied between 5 and 35 weight percent by adjusting the relative proportions of starch and fiber in the slurry formulations. Six different formulations were used, with starch/fiber weight ratios between 0.25/1.00 and 2.00/1.00, as indicated in Table 2. Four large discs of each composition were fabricated using 30-mil-long by 2-micron-diameter fibers and machined into test specimens for evaluation of their physical, mechanical, and thermal properties.

Figure 11. HOLLOW INSULATOR FRUSTUM.

134393

Figure 12. HOLLOW INSULATOR CONE AND FRUSTA.

126898

Table 2

COMPRESSIVE STRENGTHS OF CARBON-FIBER COMPOSITES WITH VARIOUS BINDER CONCENTRATIONS
(Fibers were 30 Mils Long and 2 Microns in Diameter)

Sample	Slurry Composition (Starch-to-Fiber Weight Ratio)	Bulk Density (pcf)	Binder (carbon) Content (wt %)	Compressive Strength (psi) (at percent deflection)						
				2	4	6	8	10	14	20
A-1-3	0.25:1.00	7.3	5.2	1.0	1.3	5.4	8.4	11.0	15.1	19.1
A-1-4	0.25:1.00	7.4	5.2	1.6	3.8	8.1	10.2	12.9	16.7	20.6
A-1-5	0.25:1.00	7.3	5.2	0.6	1.7	3.2	5.2	7.4	12.2	17.4
A-1-6	0.25:1.00	7.3	5.2	0.7	1.7	3.1	5.2	7.9	12.9	18.0
Average		7.3	5.2					9.8		18.8
B-1-1	0.50:1.00	7.6	9.3	0.8	2.4	4.8	8.2	12.0	19.4	
B-1-2	0.50:1.00	7.6	9.3	1.3	2.8	5.4	8.9	12.9	20.2	28.2
B-1-4	0.50:1.00	7.5	9.3	1.6	4.7	9.0	13.3	17.3	23.8	
B-1-7	0.50:1.00	7.7	9.3	1.4	3.2	6.2	10.0	14.2	21.9	29.7
Average		7.6	9.3					14.1		28.9
C-2-1	0.75:1.00	7.9	8.9	1.3	3.1	6.1	9.5	14.0	22.4	31.4
C-2-2	0.75:1.00	7.9	8.9	1.4	4.0	7.8	11.9	16.6	25.0	33.1
C-2-4	0.75:1.00	7.9	8.9	1.1	2.8	4.5	7.8	12.0	20.5	29.7
C-2-5	0.75:1.00	7.7	8.9	2.4	5.7	9.9	14.1	18.4	25.5	32.3
C-2-7	0.75:1.00	7.9	8.9	2.4	7.1	12.0	17.0	21.5	28.7	34.9
Average		7.9	8.9					16.5		32.3
D-2-1	1.00:1.00	7.3	13.9	1.1	3.1	5.9	9.2	12.3	17.8	24.1
D-2-4	1.00:1.00	7.2	13.9	1.4	3.8	7.1	10.6	13.3	18.4	24.5
D-2-5	1.00:1.00	7.2	13.9	1.0	3.0	6.1	9.5	12.7	18.4	24.8
D-2-6	1.00:1.00	7.2	13.9	1.0	3.3	6.4	9.9	13.4	21.6	25.5
D-2-7	1.00:1.00	7.3	13.9	1.3	3.7	6.9	10.2	13.7	19.4	25.3
Average		7.2	13.9					13.1		24.8
E-2-1	1.50:1.00	11.3	26.6	1.4	3.3	6.4	10.5	15.6	29.0	
E-2-2	1.50:1.00	11.6	26.6	1.8	5.0	9.3	15.8	24.1	46.0	
E-2-5	1.50:1.00	11.5	26.6	2.5	5.1	9.9	16.4	25.5	52.3	77.2
E-2-7	1.50:1.00	11.5	26.6	2.0	4.5	9.1	14.1	21.2	42.2	67.9
Average		11.5	26.6					21.6		72.5
F-3-2	2.00:1.00	12.2	33.4	3.4	12.7	16.8	38.5	51.5	70.7	84.7
F-3-4	2.00:1.00	12.1	33.4	3.0	9.9	18.4	28.3	40.3	62.0	78.9
F-3-5	2.00:1.00	12.1	33.4	3.8	11.3	20.1	31.1	42.4	63.0	80.4
F-3-6	2.00:1.00	12.0	33.4	2.5	7.1	14.3	24.1	33.8	55.6	75.7
F-3-7	2.00:1.00	12.2	33.4	1.4	5.7	13.4	22.6	33.8	55.5	76.3
Average		12.1	33.4					40.4		79.2

Composite materials were prepared with carbon fibers having lengths of 10, 30, 50, and 100 mils (2 microns in diameter). Four discs were fabricated with fibers of each length. In order to maintain a similar binder content in the materials and establish fiber length as the only significant variable, an identical starch/fiber weight ratio was used in the slurry formulations.

Fibrous composites were made using fibers with 30-mil lengths and diameters of 2 and 7 microns. Four discs with fibers of each diameter were fabricated. A starch/fiber weight ratio of 1.00/1.00 was used in each case.

Mechanical compaction was employed to make composites with densities between 10 and 17 pcf. Vacuum-molded discs of material were pressed between metal plates at pressures ranging from 100 to 300 psi. The compacted material was held at the pressed thickness during subsequent gelation and drying operations. The metal plates were removed prior to pyrolysis of the starch binder. Eight discs were fabricated with this technique using 30-mil-long, 2-micron-diameter carbon fibers; in each case, the slurry formulation consisted of starch and fibers in a 1.00/1.00 weight ratio.

Dimensions and geometries of the test specimens machined from the disc billets were as follows: (1) for compressive strength, a 3-inch-diameter by 1-inch-thick disc; (2) for ultimate flexural strength, a 3-inch by 1/2-inch by 1/4-inch bar; (3) for tensile strength, a 1-inch-diameter by 1-inch-thick disc; (4) for shear strength, a 1 1/2-inch-OD by 7/16-inch-ID by 3/4-inch-long cylinder; and (5) for thermal conductivity, a 7-inch-diameter by 5/8-inch-thick disc. Orientation of the test specimens with respect to the disc billet from which they were obtained is shown in Figure 13. Here, the flat surfaces of the 12-inch-diameter disc are parallel to the X-Y plane. The carbon fibers have a preferred

Figure 13. TEST SPECIMEN ORIENTATION WITH RESPECT TO THE DISC BILLET.

orientation with their axes lying parallel to, but random in, the X-Y plane (ie, the fiber longitudinal axes were perpendicular to the force generated by vacuum during fabrication).

Property Measurements

Compressive testing was performed at room temperature using an Instron Universal testing machine at a crosshead speed of 0.05/in/min. Load-strain curves were obtained up to a 20 percent deflection. Ultimate flexural strengths were determined using a thirds-point loading scheme on an Instron testing machine at a crosshead speed of 0.05 in/min. Specimen strain in both cases was measured with a Tinius-Olsen deflectometer.

Room-temperature tensile testing was performed on the Instron testing machine after the specimens had been glue bonded with epoxy adhesive to "T" caps. Shear specimens were also tested on the Instron at a crosshead speed of 0.05 in/min, using the ASTM standard method for rigid plastics (hollow cylinder sample geometry).

Thermal conductivity measurements between a 200 and 1,200° F mean temperature were taken in an argon atmosphere using a Northrup comparative apparatus. The apparatus utilizes a disc sample and standard in a steady-state heat flow condition. Thermal conductivity of the unknown is calculated from the temperature drops across the unknown and standard, the thicknesses of the unknown and standard, and the thermal conductivity of the standard material. Min-K 1301,^(c) was used as the standard in all measurements.

Thermal conductivities between 1,500 and 4,000° F for several composite materials were determined at the Southern Research Institute, Birmingham, Alabama. Measurements were taken in argon and vacuum using a radial inflow apparatus.⁽²⁾

Binder Concentration

An improvement in the compressive strength of the composite was observed as the binder content was increased. The compressive test data are presented in Table 2; the relation between the average compressive strength (at 10 and 20% deflection) and binder concentration is illustrated in Figure 14. Actual stress-strain curves for the materials in Series A - F are reproduced in the Appendix.

The average compressive strength at a 10 percent deflection increased from 10 to 40 psi with an increase in binder content from 5 to 35 weight percent; the associated increase in density was from 7.3 to about 12.1 pcf. At a 20 percent deflection, the increase in compressive strength was from 20 to 90 psi. The variation in strength with binder content appeared to be nearly linear.

The ultimate flexural strength of the composite also increased with increasing binder content. Data from flexural testing are presented in Table 3; the relation between flexural strength and binder concentration is shown in Figure 15. Increasing the binder content from 5 to 30 weight percent resulted in an increase in the ultimate flexural strength from 100 to

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Figure 14. EFFECT OF BINDER (AS CARBON) CONTENT ON THE COMPRESSIVE STRENGTH OF CARBON-FIBER COMPOSITES. (30-Mil-Long by 2-Micron-Diameter Fibers)

nearly 300 psi. Although a linear relationship between flexural strength and binder content was indicated in Figure 15, the real variation was difficult to predict due to the relatively large scatter in the data.

The tensile strength of the composite material increased with increasing binder content; however, there did not appear to be a correlation between binder concentration and shear strength. Tensile and shear test data are given in Table 4. For composites containing 4.9, 8.1, and 20.8 weight percent binder, tensile strengths were 49.3, 124.5, and 173.3 psi, respectively. Shear strengths of 42.2, 28.5, and 44.6 psi were found for materials which contained 4.8, 8.9, and 14.0 weight percent binder, respectively.

The low-temperature (200 - 1,200° F) thermal conductivity increased as the binder concentration was increased. The thermal conductivities (K) of materials containing 4.9, 15.5, 20.8, and 33.6 weight percent binder were determined. The results of these tests are displayed in Figure 16. A linear increase in thermal conductivity from 0.26 Btu-in/hr-°F-ft² at 200° F to 0.46 Btu-in/hr-°F-ft² at 1,000° F was observed for the composite containing 4.9 weight percent binder. For the material containing 33.6 weight percent binder, K increased from 0.46 Btu-in/hr-°F-ft² at 200° F to 0.76 Btu-in/hr-°F-ft² at 1,000° F. Thermal conductivities of materials with intermediate binder contents were between these extremes. It might have been expected that the total heat transfer at a higher temperature (> 1,000° F) would be reduced as the carbon binder content was increased, due to increased attenuation of thermal radiation by carbon. However, as indicated by the relative slopes of the K-versus-temperature curves in Figure 16, this reduction does not occur in the temperature range below 1,200° F. The increased solid conduction due to the additional carbon binder apparently offsets any reduction in radiant transfer.

Table 3

FLEXURAL STRENGTHS OF CARBON-FIBER COMPOSITES WITH VARIOUS BINDER CONCENTRATIONS
(Fibers were 30 Mils Long and 2 Microns in Diameter)

Sample Series	Slurry Composition (Starch-to-Fiber Weight Ratio)	Number of Specimens	Average Bulk Density (pcf)	Average Binder Content (wt %)	Average Ultimate Strength (psi)	Average Modulus of Elasticity ($\times 10^4$ psi)
A	0.25 : 1.00	18	7.4	5.1	105	0.4
B	0.50 : 1.00	16	7.7	9.3	147	1.1
C	0.75 : 1.00	16	7.5	14.1	141	1.1
D	1.00 : 1.00	18	8.6	15.7	204	1.5
E	1.50 : 1.00	16	11.1	25.6	319	2.7
F	2.00 : 1.00	12	11.7	34.5	285	2.8

Table 4

TENSILE AND SHEAR STRENGTHS OF CARBON-FIBER COMPOSITES WITH VARIOUS BINDER CONCENTRATIONS
(Fibers were 30 Mils Long and 2 Microns in Diameter)

Sample Series	Slurry Composition (Starch-to-Fiber Weight Ratio)	Number of Specimens	Average Bulk Density (pcf)	Average Binder Content (wt %)	Average Tensile Strength (psi)	Average Shear Strength (psi)
A	0.25 : 1.00	3	7.0	4.9	49.3	-
C	0.75 : 1.00	4	7.9	8.1	124.5	-
E	1.50 : 1.00	3	11.0	20.8	173.3	-
A	0.25 : 1.00	4	7.6	4.8	-	42.2
B	0.50 : 1.00	6	7.5	8.9	-	28.5
D	1.00 : 1.00	7	9.2	14.0	-	44.6

Figure 15. EFFECT OF BINDER (AS CARBON) CONTENT ON THE FLEXURAL STRENGTH OF CARBON-FIBER COMPOSITES. (30-Mil-Long by 2-Micron-Diameter Fibers)

Figure 16. THERMAL CONDUCTIVITY OF FIBROUS CARBON COMPOSITES. (30-Mil-Long by 2-Micron-Diameter Fibers)

Fiber Length

The compressive strengths of composites prepared from 10-mil-long carbon fibers was substantially higher than those made from 30 or 100-mil-long fibers. Test data are presented in Table 5; the stress-strain curves are given in the Appendix. At a 10 percent deflection, the compressive strengths of materials containing 10, 30, and 100-mil-long fibers were 100, 13, and 17 psi, respectively. The higher strength observed for the 10-mil-long fiber

Table 5

EFFECT OF FIBER LENGTH ON THE COMPRESSIVE STRENGTH OF CARBON-FIBER COMPOSITES

Sample	Fiber Length ⁽¹⁾ (mils)	Bulk Density (pcf)	Binder Content (wt %)	Compressive Strength (psi) (at percent deflection)						
				2	4	6	8	10	14	20
K-5-2	10	11.3	14.0	28.3	84.6	98.9	103.7	107.4	113.9	123.9
K-5-3	10	11.3	14.0	36.8	85.7	99.0	103.0	106.0	110.6	119.5
K-5-5	10	11.3	14.0	36.9	89.1	101.9	105.4	108.2	112.9	121.4
K-5-6	10	11.2	14.0	43.9	95.1	104.7	107.5	109.9	114.6	122.8
K-5-7	10	11.3	14.0	31.1	86.3	100.4	103.3	106.1	111.5	120.3
Average		11.3						107.4		121.4
D-2-1	30	7.3	13.9	1.1	3.1	5.9	9.2	12.3	17.8	24.1
D-2-4	30	7.2	13.9	1.4	3.8	7.1	10.6	13.3	18.4	24.5
D-2-5	30	7.2	13.9	1.0	3.0	6.1	9.5	12.7	18.4	24.8
D-2-6	30	7.2	13.9	1.0	3.3	6.4	9.9	13.4	19.2	25.5
D-2-7	30	7.3	13.9	1.3	3.7	6.9	10.2	13.7	19.4	25.3
Average		7.2						13.0		24.6
I-1-1	100	7.4	16.2	2.8	5.9	10.2	14.1	18.1	23.5	28.3
I-1-3	100	7.3	16.2	2.8	5.8	10.0	14.3	18.4	24.3	29.7
I-1-4	100	7.3	16.2	1.8	5.1	9.9	14.3	18.4	24.1	29.0
I-1-6	100	7.5	16.2	1.8	4.2	6.6	10.2	14.1	21.2	29.0
I-1-7	100	7.5	16.2	2.7	5.0	8.8	13.4	17.7	24.4	31.1
Average		7.4						17.2		29.4

(1) Two-micron-diameter fibers.

material can most likely be attributed to its greater density. Densities of the composites prepared with 10, 30, and 100-mil-long fibers were 11.3, 7.2, and 7.4 pcf, respectively.

The flexural strength was also highest for the composite made with 10-mil-long fibers. Flexural, tensile, and shear test data are reported in Table 6. The ultimate flexural strengths of materials made with 10, 30, and 100-mil-long fibers were 498, 204, and 137 psi, respectively.

Table 6
RELATION BETWEEN FIBER LENGTH AND THE FLEXURAL, SHEAR,
AND TENSILE STRENGTH OF CARBON-FIBER COMPOSITES

Fiber Length ⁽¹⁾ (mils)	Number of Specimens	Average Bulk Density (pcf)	Average Binder Content (wt %)	Average Ultimate Flexural Strength (psi)	Average Shear Strength (psi)	Average Tensile Strength (psi)
10	16	12.0	14.1	498	-	-
30	18	7.7	13.4	204	-	-
100	16	6.3	15.1	137	-	-
10	7	11.5	14.3	-	62	-
30	7	9.2	11.4	-	45	-
50	7	9.7	16.1	-	50	-
10	4	11.3	14.3	-	-	116
30	4	7.9	11.4	-	-	124
100	4	7.4	16.1	-	-	81

(1) Two-micron-diameter fibers.

There were no obvious correlations between fiber length and the resulting tensile or shear strength. Shear strengths of composites containing 10, 30, and 50-mil-long fibers were 61, 45, and 50 psi, respectively; tensile strengths of materials made with 10, 30, and 100-mil-long fibers were 116, 124, and 81 psi, respectively.

The thermal conductivity(K) of the higher-density, 10-mil-long fiber composite was greater than that observed for the materials prepared with longer fibers. Thermal conductivity data are presented in Table 7. The thermal conductivities of composites containing

Table 7
EFFECT OF FIBER LENGTH ON THE THERMAL CONDUCTIVITY
OF FIBROUS CARBON COMPOSITES

Fiber Length ⁽¹⁾ (mils)	Bulk Density (pcf)	Binder Content (wt %)	Thermal Conductivity in Argon (Btu-in/hr-° F-ft ²)		
			400° F	800° F	1,000° F
10	10.50	14.1	0.49	0.61	0.68
30	7.10	15.5	0.34	0.44	0.50
50	8.45	16.1	0.34	0.45	0.51
100	8.60	17.3	0.35	0.47	0.54

(1) Two-micron-diameter fibers.

30, 50, and 100-mil-long fibers were quite similar ($0.50 - 0.54 \text{ Btu-in/hr-}^{\circ}\text{F-ft}^2$) at $1,000^{\circ}\text{F}$. A K value of $0.68 \text{ Btu-in/hr-}^{\circ}\text{F-ft}^2$ was determined for the 10-mil-long fiber material.

Thermal conductivity of the composite material prepared with 10-mil-long, 2-micron-diameter fibers was determined in the temperature range from $1,500$ to $4,000^{\circ}\text{F}$. Measurements were performed at Southern Research Institute in both an argon and vacuum environment. The data are presented in Figure 17.

Figure 17. THERMAL CONDUCTIVITY OF COMPOSITES CONTAINING TEN-MIL-LONG, TWO-MICRON-DIAMETER CARBON FIBERS (Density $\approx 0.2 \text{ gm/cc}$)

In argon, the thermal conductivity increased from approximately $1.5 \text{ Btu-in/hr-}^{\circ}\text{F-ft}^2$ at $1,700^{\circ}\text{F}$ to $4.0 - 5.5 \text{ Btu-in/hr-}^{\circ}\text{F-ft}^2$ at $4,000^{\circ}\text{F}$. Variability in the data can be partially attributed to differences in specimen densities. In vacuum, the thermal conductivity was $0.8 \text{ Btu-in/hr-}^{\circ}\text{F-ft}^2$ at $1,700^{\circ}\text{F}$ and increased to $3.1 \text{ Btu-in/hr-}^{\circ}\text{F-ft}^2$ at $4,000^{\circ}\text{F}$. As would be expected, the effect of the environment (argon vs vacuum) on the thermal conductivity is more pronounced at low temperatures where gaseous conduction provides a higher proportion of the total heat transfer. At elevated temperatures, where radiation becomes the predominate mode of heat transfer, the effect of atmosphere on the thermal conductivity is less significant.

Fiber Diameter

Composite material prepared with 7-micron-diameter fibers had a higher density and compressive strength than material made with 2-micron-diameter fibers (Table 8). The

Table 8
EFFECT OF FIBER DIAMETER
ON THE COMPRESSIVE STRENGTH
OF FIBROUS CARBON COMPOSITES

Sample	Fiber Diameter (1) (μ)	Bulk Density (pcf)	Compressive Strength (psi) (at percent deflection)					
			2	4	6	8	10	20
X-1	7	10.9	8	14	22	27	30	46
X-2	7	12.1	8	21	28	34	38	56
X-3	7	11.6	9	21	28	33	37	52
X-4	7	11.7	9	20	27	32	35	49
X-5	7	11.2	10	19	24	29	33	47
X-6	7	12.9	15	28	37	43	48	72
X-7	7	11.9	9	17	23	28	32	51
X-8	7	11.9	6	15	22	29	31	48
Average		11.8	9	19	26	32	36	53
D-1	2	7.4	1	3	6	9	12	24
D-4	2	7.2	1	4	7	11	13	24
D-5	2	7.3	1	3	6	10	13	25
D-6	2	7.3	1	3	6	10	13	26
D-7	2	7.4	1	4	7	10	14	25
Average		7.3	1	3	6	10	13	25

(1) Fibers were 30 mills long.

that of the 7-micron-diameter fiber material (13.0 pcf). Thermal conductivity data between 200 and 1,100° F are given in Figure 18. At a 1,000° F mean temperature, coefficients of thermal conductivity for composites containing 2 and 7-micron-diameter fibers were 0.51 and 0.58 Btu-in/hr-° F-ft², respectively.

Compacted Composite Materials

Increasing the volume fraction of fibers by mechanical compaction resulted in significant improvements in the compressive and flexural strengths of the composite. The results of testing are presented in Tables 10 and 11. Bulk density was used as an indicator of the degree of compaction.

Compressive stress-strain curves for the specimens in Table 10 are reproduced in the Appendix.

The compressive strength at a 10 percent deflection increased from 94 to 165 psi with an increase in density from 10.8 to 15.0 pcf. Data presented earlier indicated that the compressive strength of noncompacted composites (density ~ 8 pcf) with a similar binder content and prepared with the same type of fibers was in the order of 15 - 20 psi. The ultimate flexural strength increased from 440 to 970 psi with a density increase from 12.3

7-micron-diameter fiber material had a density of 11.8 pcf and a compressive strength of 36 psi at a 10 percent deflection and 53 psi at a 20 percent deflection. The composite containing 2-micron-diameter fibers had a density of 7.3 pcf and a compressive strength of 13 psi at a 10 percent deflection, and 25 psi at a 20 percent deflection.

The larger-diameter fibers also imparted a higher flexural strength to the composite (Table 9). Flexural strengths of the 7 and 2-micron-diameter fiber materials were 320 and 200 psi, respectively.

Thermal conductivity of the 2-micron-diameter fiber composite (7.1 pcf) was slightly less than

Table 9
EFFECT OF FIBER DIAMETER ON THE
FLEXURAL STRENGTH OF
FIBROUS CARBON COMPOSITES

Fiber Diameter (1) (μ)	Number of Specimens	Average Density (pcf)	Average Flexural Strength (psi)
2	18	7.7	200
7	14	13.8	320

(1) Fibers were 30 mills long.

Figure 18. THERMAL CONDUCTIVITY OF CARBON-FIBER COMPOSITES CONTAINING TWO AND SEVEN-MICRON-DIAMETER FIBERS. (Fibers are 30 Mils Long)

to 17.4 pcf. Noncompacted material (density ~ 8 pcf) had flexural strengths in the range of 150 - 200 psi.

Thermal conductivity of the compacted composites increased with increasing density or degree of compaction. Thermal conductivity data are presented in Figure 19. Included for comparative purposes is the thermal conductivity of a noncompacted composite. In going from a 7.1-pcf noncompacted material to a 16.2-pcf compacted composite, the thermal conductivity at a 1,000° F mean temperature increased from 0.51 to 0.71 Btu-in/hr-° F-ft².

Table 10

COMPRESSIVE STRENGTHS OF COMPACTED CARBON-FIBER COMPOSITES
(Fibers were 30 Mils Long and 2 Microns in Diameter)

Sample	Bulk Density (pcf)	Compressive Strength (psi) (at percent deflection)						
		2	4	6	8	10	14	20
SC-2-4	10.8	12.0	42.4	67.2	82.1	94.1	117.4	142.9
SC-2-3	11.2	20.5	72.2	105.4	121.4	130.2	145.7	164.1
SC-2-1	11.5	17.3	66.5	106.1	124.5	134.4	151.4	172.6
SC-2-2	12.0	25.5	90.5	128.7	142.9	152.1	167.6	-
SC-20-3	14.0	32.6	76.4	105.4	122.4	135.8	161.3	189.6
SC-20-4	14.3	39.6	92.7	118.8	136.5	150.7	176.8	207.2
SC-11-7	14.3	35.1	79.2	104.7	122.4	138.0	165.5	202.3
SC-20-2	14.5	26.9	90.5	120.3	138.6	154.2	181.8	215.0
SC-20-1	14.8	17.7	59.4	106.8	135.9	154.2	182.5	215.0
SC-11-10	14.8	34.7	105.8	131.3	151.4	169.1	199.5	241.9
SC-11-6	14.9	30.0	84.9	116.3	140.1	161.0	194.7	237.7
SC-11-8	15.0	43.9	96.2	125.2	147.1	165.5	193.8	234.8

Table 11

**FLEXURAL STRENGTH OF COMPACTED
CARBON-FIBER COMPOSITES**
(Fibers were 30 Mils Long and
2 Microns in Diameter)

Sample Series	Number of Specimens	Average Bulk Density (pcf)	Average Ultimate Flexural Strength (psi)
SC-30	14	12.3	442
SC-11	10	13.4	614
SC-21	18	14.5	759
SC-40	12	17.4	966

Conclusions

Increasing the density of the carbon-fiber composite by mechanical compaction gave the largest increase in strength per unit increase in density. Compressive strength-density trade offs for the material and process parameters investigated are indicated in Figure 20. A probable explanation for the substantial strength improvement resulting from compaction is that it simultaneously increases the volume fraction of both fibers and binder.

The use of shorter, 10-mil-long carbon fibers also gave a significant increase in strength. The effect of shorter fibers on strength can also be viewed in terms of an increase in the volume fraction of fibers and binder due to a higher packing density.

Pressing the material to higher densities was the best method of enhancing strength with regard to a minimal increase in the coefficient of thermal conductivity. Compressive strength-thermal conductivity trade offs observed in the parametric studies are shown in Figure 21.

Figure 19. EFFECT OF COMPACTION ON THE THERMAL CONDUCTIVITY OF FIBROUS-CARBON COMPOSITES. (30-Mil-Long by 2-Micron-Diameter Fibers)

Figure 20. COMPRESSIVE STRENGTH-DENSITY TRADE OFFS OBSERVED IN CARBON-FIBER COMPOSITES.

Figure 21. COMPRESSIVE STRENGTH-THERMAL CONDUCTIVITY TRADE OFFS OBSERVED IN CARBON-FIBER COMPOSITES.

REFERENCES

- (1) Reynolds, C. D. and Ardary, Z. L.; *Polarite Thermal Insulation*, Y-1716; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; April 28, 1970.
- (2) Smyly, E. D.; *The Thermal Conductivity of a Carbon Fiber Composite*; Southern Research Institute, Birmingham, Alabama; April 10, 1970.

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APPENDIX

COMPRESSIVE STRESS-STRAIN CURVES OF FIBROUS COMPOSITES

In Figures A-1 through A-11, compressive stress-strain curves are reproduced for Sample Series A - F (Table 2, Page 23), I and K (Table 5, Page 29), and SC-2, SC-11, and SC-20 (Table 10, Page 33). The densities and binder concentrations of the test specimens are reported in these tables.

Figure A-1. STRESS-STRAIN CURVES FOR SAMPLE SERIES A.

Figure A-2. STRESS-STRAIN CURVES FOR SAMPLE SERIES B.

Figure A-3. STRESS-STRAIN CURVES FOR SAMPLE SERIES C.

Figure A-4. STRESS-STRAIN CURVES FOR SAMPLE SERIES D.

Figure A-5. STRESS-STRAIN CURVES FOR SAMPLE SERIES E.

Figure A-6. STRESS-STRAIN CURVES FOR SAMPLE SERIES F.

Figure A-7. STRESS-STRAIN CURVES FOR SAMPLE SERIES I.

Figure A-8. STRESS-STRAIN CURVES FOR SAMPLE SERIES K.

Figure A-9. STRESS-STRAIN CURVES FOR SAMPLE SERIES SC-2.

Figure A-10. STRESS-STRAIN CURVES FOR SAMPLE SERIES SC-11.

Figure A-11. STRESS-STRAIN CURVES FOR SAMPLE SERIES SC-20.