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CARBON FIBERS FOR ELECTRICALLY HEATED SYSTEMS

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Characteristics of fibrous carbon materials and techniques for fabricating them into electrically heated systems have been investigated. The inherent characteristics of carbon fibers, yarns, and fabrics and make of composites of carbon with glass fibers have been evaluated by analytical and experimental means. Materials and techniques for overcoming some of carbon's inherent disadvantages and forming it into usable assemblies have been arrived at by analysis and by fabrication and evaluation of samples.

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It was found necessary to coat carbon materials with a protective layer of elastomer or other substance to overcome carbon's extremely poor abrasion and kink resistance. Coating of the carbon material reduces its flexibility and increases the difficulty of making electrical attachments to it and making electrically continuous seams. Approaches to alleviating the electrical difficulties were developed, but the poor flexibility of coated carbon fabric or composite fabric tends to make it unsuitable for small, complex assemblies such as handwear. Development of more flexible coatings could reverse this conclusion.

Carbon fabrics and/or carbon/glass composite fabrics appear to be ideally suited for relatively large heated assemblies such as vests, casualty bag liners, etc. They can be configured to provide uniform or distributed heating and provide tremendous redundancy of circuits.

FOREWORD

At present, the simplest method of providing uniform overall heat to the hands is by fabricating wired circuits in the appropriate glove configuration. However, a wire breakage means the loss of a complete circuit. Thus, for safety's sake as well as to provide for oveall heat, multiple circuits are required.

The possibility exists that heating for other than the hands may be required. In view of the high cost experience of developing multiple wire heaters for gloves, it behooves the Government investigate all avenues of heater circuitry for application as the need arises.

In view of the limitations of wire heaters, unique materials which can be used as heaters requiring an electrical current are being investigated by Mr. Herman Madnick, Handwear Specialist for the Natick Development Center. Under the auspices of this Center, Synsis, Inc. was contracted to investigate Carbon Fibers for Electrically Heated Systems.

This report examines one of several approaches currently investigated.

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Section I

INTRODUCTION

PROGRAM BACKGROUND

Under certain conditions of exposure to extremely cold environments, heated clothing is an advantageous solution to the problem of avoiding frostbite and maintaining comfort and task proficiency. The use of wire as heater elements is well known and is presently being used for commercial products such as electrically heated gloves, socks, vests, and clothing. Even though this type of heater can be obtained in a wide variety of configurations, the electrical continuity is dependent upon a single or small number of electrical circuits. Since the particular wire materials used are subject to flexural fatigue and subsequent breakage and loss of electrical continuity, clothing fabricated by such techniques is noted for being somewhat fragile and short-lived.

Carbon fibers and other non-metallic materials having electrical resistivity in the appropriate range for being woven directly into flexible electrical heating elements are available. It is possible that these materials may have the other characteristics required for incorporation into personnel clothing as electrical heating elements.

This report describes the results of a program designed to: 1) evaluate current carbon/graphite fiber technology, 2) survey available fibers, yarns, woven and knitted structures using carbon/graphite fibers; 3) test and evaluate existing and readily fabricated structures for application to personnel heating; and 4) establish interim performance and design requirements for carbon/graphite fiber, electrically-heated personnel protective equipment.

Current technology in carbon/graphite fiber production was evaluated through attendance at a three-day seminar on "Science and Technology of Carbon Materials" sponsored by the University of California, review of the literature, and personal contact with individuals involved in the manufacture of carbon products. A survey of available fibers, yarns, woven, and knitted structures was conducted by reviewing brochures, and interviewing personnel in the carbon/graphite fiber industry. Multiple samples of yarns, woven and knitted materials were acquired for tests, and for incorporation into woven composites which were subsequently tested. Test results and published values of mechanical and electrical characteristics of fibers and yarns along with heuristically derived heating requirements were used as the bases for deriving performance and design requirements for electrically heated clothing using carbon/graphite fibers as the current carriers.

Section II

CARBON FIBER TECHNOLOGY

Carbon and graphite materials are typically made by heating carbon-bearing materials in a controlled atmosphere to drive off non-carbon substances and to permit migration and ordering of the carbon atoms. When the heating is carried out at a sufficient temperature and for a sufficiently long period, the result is a highly ordered arrangement of carbon into layers or laminae known as graphite. Within layers, carbon atoms are arranged in a repeated hexagonal array with three bonds acting between each carbon atom and its neighbors. Intermittent and weak bonding occurs between carbon atoms in adjacent layers.

Individual graphite crystals are highly anisotropic: they have excellent electrical conductivity and mechanical strength in the plane of the layers, and relatively poor characteristics in a direction normal to the layers. Volume resistivity, ρ, may be 10^{-1} ohm-cm in the direction normal to the graphite plane compared with 10^{-6} ohm-cm in the direction parallel to the plane. Mechanical properties such as strength, modulus, and elongation vary by approximately the same orders of magnitude.

Sizeable, single crystals of graphite are a laboratory curiosity; most common graphitized materials are composed of many graphite crystals bound together by disordered carbon or other binders. Because the orientation of individual crystals may not be uniform, electrical resistivity may vary between 10^{-1} and 10^{-6} ohm-cm. with other properties varying in a similar fashion.

The distinction between carbonized material and graphitized material is primarily the extent to which the material contains macroscopic graphite crystals and the associated higher mechanical allowables and electrical conductivity. From the standpoint of producing carbon versus graphite, graphite usually results from exposure of carbon bearing materials to high temperatures (up to 2727° C) for longer periods of time than is the case for carbonized material (1227° C). To some extent, however, time and temperature are interrelated at temperature values exceeding 1227° C so that a material may be highly graphitized either by exposure to extremely high temperatures for short periods or by exposure to more moderate temperatures for long periods. In the case of fibrous materials, application of tension to the fibers during heat treatment appears to promote the orientation of the graphite crystals so that their planes are parallel to the axis of the fiber. The result is better ultimate strength, higher modulus, and somewhat higher conductivity along the fiber axis.

CARBON/GRAPHITE FIBERS

Carbon/graphite fibers can presumably be made from any carbon-bearing natural or artificial fiber. Practically speaking, however, they are typically made from continuous filaments of either rayon or polyacrylonitrile.

These two compounds are characterized by unusually long chain molecules built around a central spine of carbon atoms strung end to end. The process of extruding these filaments tends to lay the molecules out parallel to one another and to the axis of the filament and, thus, to minimize the distances which carbon atoms must migrate to form into ordered arrays.

Polyacrylonitrile has a long chain carbon backbone whose alignment is improved by hot stretching and stabilized by oxidation cross linking at about 200 to 300° C. The orientation is retained during carbonization during which the compound decomposes and loses hydrogen and other impurities leaving behind the condensed carbon. The migration and formation of the carbon atoms into a typical aromatic structure progresses at high temperatures in the range of 2700° to 3000° C. Rayon precursors for carbon fibers are frequently treated with flame retardant type chemicals to increase the carbon yield. The oxidation cross linkages in the chain are largely destroyed and the molecular alignment lost during carbonization, but orientation and therefore modulus, strength and degree of graphitization are sometimes improved by hot stretching the fibers in the plastic range above 2700° C.

Tables 1 and 2, respectively, present material characteristics for some natural and artificial textile fibers and carbon/graphite fibers. The tables are provided as a basis for perceiving the similarities and differences between common fibers and carbon/graphite fibers. Note particularly that, with the exception of glass filaments, all of the standard textile fibers shown have tensile strengths and tensile moduli an order of magnitude lower than is typical for carbon/graphite. Breaking elongation percent, on the other hand, may be as much as an order of magnitude larger for common fibers than for carbon/graphite, glass, and cotton. The implication that carbon/graphite fibers are relatively brittle compared to standard textile fibers is further borne out by comparison of the calculated minimum bend radius; for common fibers this value is a few diameters, while for carbon/graphite it may range to tens or hundreds of diameters.

Despite the relatively high value of the tensile strength of carbon/graphite compared to common textile fibers, there is little actual difference in the "feel" between the two classes of fibers. Individual fibers, or yarns spun of either class of the fibers are not perceptably different from one another in breaking strength or flexibility. The difference occurs between yarns spun from staple-type fibers such as cotton or wool and some carbon/graphite from a polyacrylonitrile precursor and yarn spun from continuous filaments. The staple-based yarns tend to separate rather than to suffer tensile failure of individual filaments.

There is a marked difference in the toughness of carbon/graphite fibers compared to common textile materials. The latter can be kinked or creased to the point of suffering plastic failure and yet recover sufficiently to continue carrying a tensile load. Carbon/graphite fibers, however, exhibit practically no plastic deformation; the fibers tend to fail in tension when kinked or bent into a small radius. It is possible to completely fracture a bundle of fibers or yarn by folding it double and rolling the bend between

Table 1. MATERIAL PROPERTIES OF COMMON FIBERS

Characteristic * \ Fiber	Cotton	Wool	Silk	Nylon	Rayon	Polyacrylonitrile	Nomex	Glass
Length, cm	1.3 - 6.4	3.8 - 38.0	Filament	Filament	Filament	Staple	Filament	Filament
Width, μ	17	28	11	16 - 45	10 - 15	14 - 27	10	10
X-section	Flat tube	Round	Round	Round	Crinulated	Dog bone	Round	Round
Tens. strength, kg/mm^2	31 - 77	14 - 20	32 - 58	60 - 90	45 - 74	22 - 27	67	350 - 450
Tensile modulus, 10^3 kg/mm^2	1.1	0.05	0.20	0.33	0.38	0.10	0.55	11
Breaking strength, gm	10	10	10	50	10	-	10	30
Breaking elongation, %	3 - 7	25 - 35	13 - 31	18 - 28	9 - 22	20 - 28	12	3 - 4
Min. Bend R, widths	13	2	2	3	4	3	7	24
Bend. Failure	Elas. Buck.	Tensile	Tensile	Tensile	Tensile	Tensile	Tensile	Tensile
Volume Resistivity, ohm-cm	10^8	10^8	10^8	10^8	10^8	10^8	10^8	10^8

* Taken from "Materials Engineering", Mid October, 1969

Table 2. MATERIAL PROPERTIES OF CARBON/GRAPHITE FIBERS

Fiber / Characteristics *	Carborundum	Union Carbide				Stackpole			Hitco	
	C/G	300G	400G	VYBC	WYBG	30A	30C	30Y	C	G
Equivalent Diameter	9.4	6.9	6.3	9.5	8.9	7.5	7.5	7.5	7.5	7.5
Tensile Strength, kg/mm^2	340-610	253	298	410	310	1400-1600	950-1300	770-1000	40	12
Tensile Modulus, 10^3 kg/mm^2	10-20	24	23	20	20	100	100	100	-	-
Breaking Strength, gm	20-40	10	10	30	20	60-70	40-60	30-40	1.8	0.5
Breaking Elongation, %	3	1.1	1.3	2.0	1.5	1.5	1.3	1	-	-
Min. Bend R, diameters	30	90	80	50	70	100	100	100	-	-
Carbon Assay, %	99.7	92	93	90	78.8	-	-	-	94	99
Volume Resistivity, 10^{-4} ohm-cm	20	16	18	60	35	24	24	24	-	-
Surface Area/Cylindrical Area	3.5	3	2.8	470	12	-	-	-	-	-
Density, gm/cc	1.5	1.76	1.78	1.53	1.32	1.78	1.78	1.78	1.8-1.9	1.4-1.6
Precursor	Rayon	-	-	-	-	PAN	PAN	PAN	-	-
Form,	C/G	G	G	G	G	C	C	C	C	G
Fiber Length, cm	Cont.	Cont.	Cont.	Cont.	Cont.	Cont.	Cont.	1.3-13	Cont.	Cont.

* Source; Manufacturers' published data sheets

the thumb and forefinger. Despite the extremely high tensile ultimate strength of the fibers, they are very easily fractured due to their extremely small size. An inherent lack of toughness is a considerable liability for materials being considered for incorporation into personal clothing.

A specific comparison between the minimum bend radius of common textile fibers and that for carbon/graphite shows that only cotton and glass fibers have a "brittleness" (as indicated by minimum bend radius in fiber diameters) of the same order of magnitude as carbon/graphite. The number for cotton, incidentally, is misleading since it is based on the assumption that cotton fibers are round and solid with the diameter equal to a typical fiber width, rather than flat and hollow with an aspect ratio of 3 or more to 1. It is more likely that, unless restrained, cotton fibers typically bend around the small dimension and fail by elastic or plastic buckling of the tube on the compression side. Under these conditions they will probably withstand multiple cycles of being bent to a very small radius without failure.

Glass fiber, which has a minimum bend radius approximately equivalent to that of the most flexible of the carbon/graphite fibers, is well known for its brittleness. Fabric woven or knitted from glass fibers and yarns is notable for its poor wearing qualities and its tendency to shed large numbers of small, needle-like fragments producing a respiratory, ocular, and cutaneous irritant. Brief exposure of a small number of individuals to carbon/graphite yarn fibers and fabrics revealed several who suffered cutaneous irritation from exposure to the fiber fragments.

YARNS AND FABRICS

Table 3 indicates several yarn and fabric configurations which are currently available. Note that the limited availability of various configurations is dictated not by what is possible but by what current applications call for. The current applications fall under two broad categories: 1) reinforcements for high-stiffness, high-strength composites, and 2) fixed, relatively high-temperature electrical heater applications. It is worth noting that, historically, several producers of carbon/graphite fibers have had an interest in the low temperature (less than 37.8°C), flexible heater market and, have in the past, produced fabrics of mixed carbon/graphite and glass yarns. According to sources within the industry, applications for these flexible heaters did not become commercially feasible, with the result that production was stopped and the mixed-fiber fabrics were withdrawn from the market.

A telephone survey of carbon yarn availability conducted in December of 1974 yielded the information that current stocks were largely depleted and would not be replenished until late 1975 unless a specific, large-volume demand appeared. Overall demand for yarn for all applications may well be at a very low level.

Table 3. AVAILABLE CARBON/GRAPHITE YARNS AND FABRICS

Characteristics / Yarn	Plies Yarn	Filaments Ply	Yarn Denier gm/9000 m	Avg Break. Strength N	Elect. Res Ohms/cm	Avg Yield m/Kg	Tenacity gm/denier
Carborundum							
C GSCY 2-5	5	480	1750	36	2.95	5140	2.13
G GSGY 2-5							
C GSCY 2-10	10	720	5250	89	1.02	1714	1.75
G GSGY 2-10							
C GSCY 2-20	20	720	10,500	178	0.54	857	1.75
G GSCY 2-20							
Union Carbide							
G WYP 30 1/0	1	3000	1717	60	1.65	5242	3.6
G WYM 30 1/0	1	3000	1488	52	1.86	6048	3.5
G WYM 60 1/0	1	1500	698	23	4.00	12,894	3.3
C VYB 105-1/5	5	480	2250	85	3.61	4000	3.8
C VYB 70-1/2	2	720	1400	53	5.74	6428	3.8
G WYB 125-1/5	5	480	1760	44	2.30	5114	2.4
G WYB 85-1/2	2	720	1100	27	3.94	8182	2.3
Stackpole							
C 30/Y	-	-	450 & up 800 std	-	-	20,000 11,250	- -
Hitco							
C CY-2	2	720	1165	22	-	7725	-
C CC-7	7	720	4382	102	-	2054	-
G GC-7	7	720	3738	31	-	2408	-
G GC-10	10	720	5332	43	-	1688	-
G GC-20	20	720	10,600	50	-	849	-

Table 3. AVAILABLE CARBON/GRAPHITE YARNS AND FABRICS (concluded)

Characteristic / Fabric	TYPE	YARN COUNT WARP	YARN COUNT FILL	WEIGHT OZ/YD^2	MATERIAL	ELEC RES ohms/sq	ELONGATION %
Carborundum							
GSCC - 2	Plain	64	64	7.5	Carbon	0.54	5
GSGC - 2	Plain	50	40	7.5	Graphite	0.55	5
GSCC - 8	8 - H.S.	64	64	7.9	Carbon	0.51	5
GSGC - 8	8 - H.S.	50	40	7.5	Graphite	0.54	5
Union Carbide							
VCK	5 - H.S.	40	38	8.2	Carbon	W0.4, F0.46	-
WCA	Plain	27	21	7.2	Graphite	W0.39, F0.53	-
WCG	Plain	33	30	3.0	Graphite	W0.95, F1,01	-
WCL	8 - H.S.	51	49	7.2	Graphite	W0.43, F0.45	-
Stackpole							
SW - 8	8 - H.S.	37-40	37-40	8.2-8.9	Carbon	.30	-
PW - 3	Plain	46-48	42-44	3.2-3.5	Carbon	.74	-
PW - 6	Plain	21-23	28-30	6.0-6.3	Carbon	.40	-
HITCO							
CCA - 2	8 - H.S.	50	50	8	Carbon	-	-
G1965	Plain	26	25	8	Graphite	-	-
G1966	8 - H.S.	54	50	7.5	Graphite	-	-

Section III

TESTING AND EVALUATION

A number of simple tests were conducted with carbon/graphite materials in order to evaluate their suitability for fabrication into electrically heated personnel clothing. The tests were very simple and were oriented toward evaluating suitability of the materials for: 1) fabrication by weaving and/or knitting, 2) use as an electrically conductive structure, and 3) general suitability for use as an item of clothing. It was assumed throughout the testing that the eventual use of the structures to be produced would put them in a position in which they would be largely protected against many of the stressors which items of clothing typically are subject to. It was assumed, for example, that a heating element for the hands would exist as a liner for an abrasion and moisture resistant glove rather than serving as the wearing surface itself. This assumption was felt to be immediately called for by the previously observed fragile nature of the carbon/graphite materials. Modifications of the material characteristics by coating or other treatments were, however, studied in an attempt to improve the durability of the fabrics and yarns.

HANDLING PROPERTY

In order to facilitate the handling of yarns and fabrics made of carbon/graphite fibers, they are frequently provided by the supplier with a PVA sizing which helps to bond together and protect the individual fibers. The sizing is usually a very thin coating and is insufficient to provide complete electrical insulation of the fibers, but is sufficient to interfere with adequate electrical bonding to the fiber bundles. The material can be removed by a hot water rinse or by simply baking at 149°C - 204.5°C but this is an additional operation preparatory to making an electrical connection to the material.

The basic handling properties of the yarn and fabric composed of carbon/graphite fibers was simply evaluated by several techniques. Samples of the yarn and fabric were enclosed in clean polyethylene bags which were subsequently heat-sealed and tumbled in a home clothes dryer without heat. The results of this test on PVA-sized polyacrylonitrile and rayon precursor yarn and PAN and rayon based fabrics revealed the efficacy of PVA sizing applied to the yarns and fabrics for partial protection of the filaments against rough handling. The yarns and fabrics which were treated with PVA showed little or no accumulation of carbon/graphite dust within the sealed bag after an hour of tumbling. Fabrics and yarns from a rayon precursor also showed little tendency to "dust" after an hour of tumbling though they did appear to break down perceptably more than the PVA-treated materials. Unsized PAN fabrics and yarns showed the greatest tendency to break down under rough handling; there was extensive dusting on the inside of the bag containing this material.

In another simple but relatively uncontrolled test, unsized yarns were pulled between the thumb and forefinger to determine their tendency to fuzz.

The yarns of a PAN precursor showed a significantly greater tendency to loose material in this test - probably because of being composed of short-staple rather than continuous fiber.

In a previously mentioned test of kinking resistance, carbon/graphite yarns were compared with more common textile yarns. The test consisted of folding a piece of yarn back on itself and rolling the bend between the thumb and forefinger. In this test, all of the common textile materials passed without observable fiber breakage, while all of the carbon/graphite yarns and several samples of glass fiber roving showed considerable or complete fiber fracture. Though they did fail, the carbon/graphite yarn produced by the Carborundum Co. and the glass fiber roving performed appreciably better than the typical carbon/graphite material; it consistently required more cycles of rolling the folded yarn back and forth and greater pressure to create the same degree of fracturing than with the other carbon/graphite yarns. In another test, one-inch wide samples of fabric were drawn under tension over the edge of a .030-inch-thick piece of metal with a polished full radius. The edge was set on a horizontal with the plane of the material at 45° to the vertical and the fabric was caused to execute a 90° bend while passing over the edge. Tension was provided by suspending a 1-kg weight from the free end of the strip hanging downward and motion was provided by pulling the other end of the strip back and forth in a horizontal direction by hand. The free edges of the fabric strip were sealed with a polyvinylchloride flexible adhesive.

All of the uncoated fabric samples tested in this manner showed extensive fuzzing and loss of material within 10 to 20 cycles of abrasion. Only slight differences were noted between the sized and unsized fabric. The fuzzing and yarn breakage was completely eliminated up to perhaps 100 cycles by precoating the strips with low durometer polyurethane elastomers and polyvinylchloride. The coatings were extremely thin due to an unsuccessful attempt to dilute the polymer sufficiently with solvents to produce a brushed-on coating which would not seal the pores of the fabric. In addition to being largely impermeable to water or water vapor, the fabrics were considerably stiffened by the coatings even though the polyurethane and polyvinylchloride were of a 50 and 30 durometer composition, respectively.

ELECTRICAL PROPERTIES

Two strips of carbon fabric (Stackpole PW-6) were prepared for electrical tests. Both strips were approximately 1 inch wide by 24 inches long. One strip was composed of fabric cut lengthwise out of the basic material avoiding defects and the selvage edge, while the second was made up of several bias cut strips sewn end to end. Resistances of the two strips were measured to determine the relationship of the resistance in a bias direction to the resistance along the direction of the main fibers. The bias cut strip was found to have the resistance approximately 20% higher than that of the strip cut in the fiber direction when allowances were made for differences in dimensions. Theoretically, the difference should approach 40% if the fibers were extremely small and widely spaced or perhaps higher still if the contact resistance at the yarn crossings were appreciable.

The resistance of the two strips was compared again following treatment by saturating them in vinyl plastisol and baking to cure the coating. Surprisingly, even though the coating should have infiltrated the fiber crossing points and increased the contact resistance by a large degree, the bias cut strip still only had a resistance approximately 30% higher than that of the strip cut parallel to the warp direction.

The results of these tests indicate that carbon fabrics or carbon/glass composites can be treated almost as uniform sheets of conductive material with little if any variation in properties with orientation (unless the variation is designed into the composite).

The electrical properties of several existing carbon/graphite fabrics are given in table 3. It is seen from the table that the properties are very similar from one fabric to another and even between manufacturers. It is also seen that the resistances are rather low so that, for example, 12 volts impressed across a square of fabric having a resistance of .54 ohms/sq. would produce a power dissipation of 267 watts with a current of some 22 amperes.

Note that the above result is true regardless of the dimensions of the square; it is equally true for a one-inch square or a one-yard square. If the designer is constrained to use carbon fabric, he must arrange the fabric and the electrical connections so as to produce the equivalent of a very long slender strip of fabric. Thus, for example, if the arrangement produces the equivalent of a strip ten units long and one unit wide with electrical connections at either end, the equivalent resistance will then be 5.4 ohms. Again, this result is obtained regardless of the magnitude of the units.

The equations relating overall resistance, current flow, and power dissipation are as follows:

$$R_T = \alpha \frac{l}{w}$$

$$I = \frac{V \cdot w}{\alpha \cdot l}$$

$$P_T = \frac{V^2}{\alpha} \cdot \frac{w}{l}$$

where R_T = total resistance, ohms,
α = area resistance, ohms/sq,
l & w = length and width of rectangular fabric segment,
V = voltage, volts
I = current, amperes
and P_T = power, watts

Table 4 presents sample currents and power dissipations for square segments of a material having a basic resistance of .054 ohms per square as a function of voltage across the square. The last two columns to the right of the table show power dissipations for segments of the fabric that have an aspect

Table 4. EFFECTS OF INPUT VOLTAGE ON PERFORMANCE OF CARBON CLOTH HEATERS

(Square segment with resistance =0.54 ohms/sq)

V (volts)	I (amperes)	W (watts)	$\frac{5W}{18}$ (watts)	$\frac{5W}{9}$ (watts)
1.5	2.8	4.2	1.2	2.3
2.85	5.3	15.1	4.2	8.4
3.0	5.6	16.8	4.7	9.3
4.5	8.3	37.4	10.4	20.8
5.7	10.6	60.4	16.8	33.6
6.0	11.0	66.0	18.3	36.7
8.6	15.8	135.0	37.5	75.0
9.0	16.7	150.0	41.7	83.3
11.4	21.1	241.0	66.9	133.9
12.0	22.2	266.0	73.9	147.8

ratio of 5/18 and 5/9, respectively (these correspond approximately to the aspect ratios of a glove measured from cuff to finger tips to the cuff on the opposite surface (18) and across its width (5) and to a glove measured from cuff to fingertips).

The table shows that a glove fabricated with the front and rear portions electrically isolated from one another along the side seams and connected at the tips of the digits would dissipate approximately 10 watts if powered by a 4.5-volt supply connected across the palm-side cuff and the cuff at the back of the hand. A glove fabricated to be electrically contiguous at all seams and powered by a 2.85-volt source (lithium organic primary cells) connected to the cuff and to the tips of the digits would dissipate 8.4 watts per side face or a total of approximately 17 watts.

Other items of personal equipment can be similarly designed to dissipate the required amount of power by appropriate selection of input voltage, and by selective isolation and interconnections of various segments of the heating areas. Any heating device fabricated of this material has the advantage of tremendous redundancy in circuitry; each of the carbon fibers essentially serves as a separate circuit element. A one-inch wide segment of fabric may have on the order of 100,000 to 150,000 separate fibers connected in parallel.

ELECTRICAL INSULATION

Electrical insulation of carbon yarns or fabrics serves two purposes; it provides for electrical isolation of adjacent circuit elements, and provides a protective covering which reduces the susceptibility of the material to abrasion and kinking. The possibility of providing electrical insulation at several stages was investigated.

Several firms were contacted regarding to possibility of coextruding carbon yarn with a urethane or PVC coating. It seemed likely from conversations with these individuals that continuous lengths of insulated yarn could be produced with very thin(0.010) consistent coatings. Such insulated yarn was considered as a direct replacement for current wire-wound heating assemblies with the advantage being that, since the carbon yarn has a somewhat higher resistance than the typical wire heaters, it would be possible to use a greater number of parallel paths for the same voltage input and thus increase the redundancy of the heater system.

Two approaches were considered for the application of insulative and protective coatings to carbon fabric and/or to carbon/glass composite fabrics. These included a process in which the fabric was to be saturated with a material such as PVC or polyurethane and subsequently cured and an alternative in which the fabric might be sandwiched between calendered layers of partially cured elastomer or other material. In this latter process, the protective coating would be permanently bonded to the carbon or composite fabric by hot curing between pressure rollers. The simple saturating and coating process has the advantage of simplicity and ease while the laminating process had the potential advantage of avoiding infiltration of insulating material into the yarn crossing points with the resulting increases in material resistance in directions other than the warp or fill directions.

Laboratory samples of coated and insulated material were prepared by brush coating carbon fabric with vinyl platisols and polyurethane elastomer and baking to cure. No samples of laminated material were prepared though conversations with specialists in this field indicated that no particular problems should be anticipated.

ELECTRICAL BONDING

Bonding to carbon fiber, carbon yarns and fabric was investigated from two standpoints; methods were investigated for electrical bonding to the uncoated material, and for forming electrical connections to materials which had previously been coated. Fabric manufacturers suggested a method involving folding a fine mesh metallic screen over the edge of the fabric and applying solder to the screen to bond the two sides of the screen together through the carbon fabric. This was attempted but no reliable results were ever attained.

An alternative approach was also suggested by carbon fabric manufacturers which was dependent upon electroplating those portions of a piece of fabric where electrical connections were to be made. Plated connections using copper were accomplished and the electrical continuity between the carbon fabric and the copper plate were found to be good. It was also possible to solder connections to the plated region.

The utility of the plated connection is somewhat questionable from a reliability standpoint, however; the plated region represents a hard spot in the fabric which increases the likelihood of kinking or bending at the periphery of the plating with consequent tensile failure of the fiber. There is also a question as to whether the differential rates of thermal expansion of the plating material and the carbon (carbon has an extremely low coefficient of thermal expansion) might not intermittently create gaps between the plating and the carbon yarn. The presence of an electrical current across this interface and possible existence of contaminants would create a high likelihood of corrosion which might eventually affect circuit continuity.

Specially designed mechanical connectors with points which would pass through carbon fabric and crimp over the opposite side were considered but rejected (plain staples were tried) due, again, to the fact that they would create hard spots which would be likely to promote kinking and failure of individual fibers and yarns. The common crimped tube connector used for splicing wires or attaching terminals was rejected for use on individual carbon yarns for similar reasons.

An approach using a cording foot on a sewing machine and a small flexible metallic braid appeared to yield excellent results for attachments to fabric samples. In effect, the metallic braid was laid down on the surface of the carbon fabric and stitched in place with a narrow zigzag using high tension for the upper and lower threads to force the braid into intimate contact with the carbon. Obviously, this joint suffers the same deficiencies as the plated joint in that the contact resistance might be expected to be increased as the metallic material oxidizes It is quite possible, however, that if this joint were coated with an impermeable protective coating, electrical degradation of the joint might be forestalled or completely eliminated. An additional alternative would be to coat the joint with any one of several conductive elastomers which would not only protect the braid against corrosion but also reduce the contact resistance between the braid and the fabric to an extremely low value.

Joints between adjacent pieces of carbon or composite fabric as between elements of a fabricated assembly can be handled rather simply in the uncoated state. For plain carbor fabrics, it appears quite sufficient to form a lap seam using non-conductive thread. Some care is required in selecting the seam design to avoid those which would impose sharp kinks or bends on the carbon yarns but good electrical continuity is obtained with even the simplest seams.

Since the carbon yarn is unusually inert, chemically, the usual concern for progressive degradation of the electrical continuity across a simple mechanical attachment such as a sewn seam does not apply. Application of a protective and electrically isolating coating across the joint would also protect against the infiltration of foreign material which might affect joint continuity.

Joints and seams of composite glass/carbon fabrics are somewhat complicated by the relatively wide spacing of the carbon yarns. It would be extremely difficult to attempt to match and connect individually the respective conductive fibers in two pieces of composite which were to be joined. Alternatives include: 1) applying a metallic bus of flexible braid to the edges of the panels to be connected and subsequently mechanically bonding the braided buses together (solder or crimped connectors), 2) sandwiching a strip of plain carbon cloth into the seam in such a way as to provide a bus along the length of the seam, and 3) cementing the panels together along the seam line with a conductive elastomer prior to stitching. Of the three approaches the use of conductive elastomers appears to be the most promising; it is not possible to guarantee that each of the conductive yarns in a composite fabric will have an adequate mechanical contact with either a metallic or a carbon busing strip to ensure continuity across the seam.

Several materials are available for accomplishing the third approach to attaching an electrical conductor to carbon/graphite heater elements. These materials range from a precious metal-loaded RTV silicone elastomer to carbon granule-loaded flouroelastomer. The silver loaded RTV has a volume resistivity of about 0.01 ohm/cm while carbon loaded materials have resistivities in the range 1 to 100 ohm/cm. The silicone elastomer system (0.01 ohm-cm for the silver loaded material and 100 ohm/cm for the carbon loaded material) have desirable mechanical properties: they are extremely flexible, show good adhesion to the carbon fabrics and fibers, and exhibit reasonably low durometers. The flouroelastomer (1.0 ohm/cm) has good strength but relatively low elongation, and is relatively stiff. Table 5 summarizes some of the mechanical and electrical properties of these materials.

Table 5. PROPERTIES OF CONDUCTIVE ELASTOMERS AND COATINGS

	Type	Hardness Durometer A	Vol. Res. Ohm/cm	Density gm/cc	Solids %	Consistency
DuPont LR3-372	1-part or 2-part	80% elong.	0.15-20	-	14-18 carbon	creamy or paste
Technical Wire Prod. Inc.						
72-00034	1-part	stiff	<0.002Ω/sq @ 3-4 mil	2.69	47 silver	thin paint
72-00039	2-part	70	0.01	2.28	85 silver	thin paste
72-00002	1-part	60	0.01	3.06	- silver	thick paste
72-00040	1-part	70	100	1 15	72 carbon	creamy paste
CON/RTV-Ni	1-part	70	0.1	3.65	73 nickel	liquid
Emerson & Cumming						
Eccobond 59-C	1-part	low	0.001	-	high silver	smooth paste
Eccocoat CC-4	1-part spray	low	0.001 /sq sprayed coating	-	high silver	liquid

Of the methods available for attaching electrical conductors to carbon/graphite heater assemblies, the use of conductive cements appears the most promising. The cements are sufficiently flexible to avoid the formation of hard spots in the heater assembly, and to avoid the progressive separation from the graphite materials due to differential rates of thermal expansion. They offer a considerable advantage in ease of application over electrically plating of connection points and have a much higher reliability than mechanically bonded connectors. For several applications the use of the relatively highly conductive silver-loaded material is desirable, but, in most cases, their high conductivity can probably be replaced by a metallic braid bonded in place through use of the relatively less expensive carbon-loaded elastomers.

From a fabrication standpoint, there are significant advantages to dealing with a previously coated material when assembling a heater device. The primary advantage is that the coated material is considerably more durable and does not require the extreme care in handling that the uncoated material does. With the advantage of ease of handling, however, comes an added difficulty in forming interconnections between adjacent panels and power connections to the assembly. There appear, however, to be means of circumventing these difficulties.

For plain carbon or graphite fabric, adequate electrical continuity across seam lines may be accomplished by incorporating one or more rows of stitching with bare metal wire into the seam in such a way that it passes through both layers of fabric. Power connections can similarly be applied by cording a length of flexible metallic braid to the fabric with metallic stitching at the appropriate locations.

For composite fabrics it is necessary to prepare the fabric prior to coating by laying down a bead of conductive elastomer along the edge to be seamed or at the location where the power connection is to be made. Following coating of the fabric, metallic stitching at the seam or at the power attachment is located so as to run through the bead of conductive elastomer.

Section IV

CONCLUSIONS AND RECOMMENDATIONS

Carbon fibers and fabrics appear to have some application to the problem of providing electrically heated personnel clothing and equipment. The characteristics of the material may, however, create some difficulties in achieving a suitable design. A primary difficulty is the extremely fragile nature of the material which virtually requires the application of protective coatings, consequently increasing bulk and stiffness and eliminating permeability. The fragile nature of the material contributes, as well, to some difficulties in electrical design; the necessity to use an extremely large number of fibers to gain strength results in electrical resistances in ohms/square which are somewhat inconveniently low for fabrics composed totally of carbon/graphite.

Two methods are apparent for achieving adequate strength with a more conveniently low electrical resistance. Both of these involve producing composites of carbon/graphite fibers with glass fibers. In the first approach, the composite is produced in the yarn stage by spinning plies of carbon/graphite fibers with glass fiber plies. For some combinations of glass plies and carbon/graphite plies (e.g. Carborundum) it would be satisfactory to spin a yarn with equal amounts of twist in the two components. These materials have tensile moduli and breaking elongation which are sufficiently similar so that tensile loads on the yarn will be carried approximately equally by the two components. For carbon/graphite plies having tensile moduli appreciably higher than those of glass roving, it would be desirable to design the yarn with more twist to the carbon than for the glass.

A potential difficulty with the design of composite yarn has to do with the fact that carbon/graphite yarns are typically spun before the final heat treatment. Since the heat treatment takes place at temperatures at which the carbon material is somewhat plastic, each ply takes a permanent set in its twisted configuration. Thus, if it were desired to produce a composite yarn with a resistance in ohms/cm higher than what is currently available (e.g. a composite with one ply having 480 filaments/ply which would produce a composite yarn with an approximate resistance of 18 ohms/cm) it would be necessary to acquire some specially fabricated carbon/graphite plies. A low filament count ply, incidentally, might be sufficiently fragile to create some difficulty in spinning.

Either the pure carbon/graphite or composite yarn can be used by individually insulating yarns which can be installed in heater elements in much the same way that metallic conductors are currently used. The resistance of these fiber bundles would typically be higher than that of the metallic conductors and, thus, would permit greater redundancy to be achieved by using a multiplicity of parallel-connected bundles. Termination and interconnection of these fiber bundles however, would continue to be a problem; the only practical approach at present appears to be the use of electrically conductive adhesives to electrically bond exposed fibers and mechanically bond to the insulating covering. It is difficult to imagine how this could be accomplished by any means other than manually, and this leaves heater fabrication as labor-intensive as with metallic conductors.

Composite fabrics can be produced either by weaving with the composite yarn or by weaving a combination of carbon and glass yarns into a single fabric. The second approach has the advantage of being realizable with existing materials. The approach of using composite yarns, however, may have the advantage in the long run since achieving electrical continuity across a seam between two panels of material woven of composite yarn might be more straight forward than the same process where individual carbon yarns are separated by several intermediate yarns of non-conductive glass.

Carbon and graphite fabrics and composite fabrics require protective coatings to give them acceptable abrasion resistance and some degree of protection against kinking or creasing with the resulting fracture of individual carbon fibers. In addition, with pure carbon or graphite fabric, because of the unusually low resistance of the material in ohms/square, it is also necessary to use low voltage power supplies, dropping resistors in series, or a design which produces the effect of long, narrow strips of the fabric between the power terminals. Again, the most appropriate means for bonding to the carbon/graphite fabrics appears to be through the use of conductive cements or elastomers. For applications such as a heated casuality bag liner, the material would be unparalleled in its ability to provide uniformly distributed power dissipation and enormous redundancy.