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OBSERVATION OF ABLATION BEHAVIOR OF
FIBROUS CARBON-CARBON COMPOSITES

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce, Springfield, Virginia 22151
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Document Y-1752

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ABSTRACT

Fibrous carbon-carbon composites which were fabricated by filament winding, felting, and spray lay up, and densified by chemical vapor deposition and liquid resin impregnation were ablation tested using a high-pressure arc jet. Behavior of the composites was examined, and the material characteristics were studied by electron and optical microscopy, radiography, porosimetry, X-ray diffractometry, electrical resistivity, and thermal expansivity. Heat-of-ablation values ranged from 12,000 to 27,500 Btu/lb, and behavior varied from uniform, smooth recession to brittle fracturing of thermal-shock-sensitive composites.

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SUMMARY

Carbon-carbon composites were ablation tested using a high-pressure arc jet. Erosion behaviors were examined by scanning electron and optical microscopy, metallography, radiography, porosimetry, X-ray diffractometry, electrical resistivity, and thermal expansivity. Although these composites were developmental in nature, their performances were ranked for use as guidelines to future studies. Fabrication techniques included filament winding, felting, spray lay up, and filament winding integrated with spraying. Densification was by both the liquid impregnation-carbonization scheme and by the chemical vapor deposition (CVD) technique.

Heat-of-ablation values ranged from 12,000 to 27,500 Btu/lb, and erosions varied from flaw-controlled destruction to uniform and smooth recession. Microscopy revealed that both the carbon and graphite fibers from a rayon precursor were eroded faster than the matrix carbon or graphite. Brittle, thermal-shock-sensitive composites appeared to erode by microfracturing and mechanical particle removal if gross cracking did not destroy the test model.

The common requirements for superior performance in these tests appeared to be: (1) thermal shock resistance attained by the 3,000° C heat treatment; (2) absence of large holes, channels, or delaminations near the ablating surface; (3) isotropic behavior at least in the plane of the lay up; and (4) a fine microstructural element size with a minimum amount of open porosity.

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INTRODUCTION

It is not the intent of this study to relate the ablation of carbon-carbon composites^(a) to a mass-loss model or to a theory of graphite ablation. The intent is to show composite characteristics which are usually related to fabrication techniques, and to relate them qualitatively with the heat of ablation and recession behavior. All of the materials tested were developmental in nature and do not represent the ultimate potentials of the materials.

Unlike most monolithic materials, composites provide designers with the flexibility of specifying unique combinations of material properties which can result in a more effective use of weight and volume. Carbon-carbon composites have the additional potentials of strength retention to very high temperatures,⁽¹⁾ dimensional stability⁽²⁾ (even in rather harsh environments), and resistance to thermally and mechanically induced shock.⁽³⁾ These are attractive, perhaps even essential, characteristics for such applications as heat shields for entry into a planetary atmosphere, spacecraft control thrusters, and disc brake linings for high-speed aircraft.⁽⁴⁾

Interest in the materials examined in this study was primarily for application to heat shields for reentry vehicles. Previous investigators concerned with similar application of graphites and certain carbon-carbon composites have attempted to relate the theory of graphite ablation⁽⁵⁾ with experimentally determined recession rates.⁽⁶⁾ Discrepancies in this type of approach, due to the nonhomogeneous nature of graphite and the lack of consideration for fabrication techniques, have been cited; and, an additional model which considers the graphites as a composite has been proposed.⁽²⁾ This model considers the enhanced removal of the binder material relative to particulates within the microstructure and proposes that particulate ablation is based on the concept of a critical roughness. Previous studies were considered as they relate to the observations made in this study, but no attempt was made to fit the composites examined to a single model. The approach taken was screening in nature, and the composites were ranked according to their relative ablation behavior.

From a population of 61 specimens tested for ablation resistance using a high-pressure arc jet, 24 specimens were subsequently selected for examination. These specimens represent carbon-carbon composites fabricated by

(a) The term "carbon-carbon composite" will be used to include the family of composites which may have a carbon or graphite matrix reinforced with carbon or graphite filaments or fibers.

filament winding, spray lay up, filament winding integrated with a spray lay up, and felting. Densification was by successive liquid impregnation and carbonization and by carbon-vapor infiltration. Ablated specimens were extensively photographed, radiographed, and examined by metallography, scanning electron microscopy, porosimetry, and X-ray diffractometry. Linear thermal expansivity and electrical resistivity were determined on samples taken from specimen areas which were not affected by the ablation test. Results on materials heated to 3,000° C. prior to ablation are compared with the as-processed condition for most of the composites.

OBSERVATIONS OF ABLATION BEHAVIOR

MATERIALS AND FABRICATION

Potential materials for reentry heat shields were subjected to a rapid and inexpensive ablation test using the high-pressure arc-jet facility of the Plasmadyne Division of Geotel, Inc.^(b) The composites which were tested are briefly described in Tables 1 and 2.

Materials

For the fabrication of the composites listed in Tables 1 and 2, different types of carbon and graphite filaments, short lengths of graphite fiber, and carbon felts were employed.

A description of the types of filaments or yarns referred to in Tables 1 and 2 follows.

WYB-85 1/2 - A two-ply graphite yarn produced by the Union Carbide Corporation's Carbon Products Division (UCC-PD). It contains 720 filaments per ply and has a 2.2 twist/inch/yarn. Typically, the strength and elastic modulus are 9×10^4 and 6×10^6 psi, respectively. Density is 1.32 gms/cc.

WYG-130 1/2 (Thornel-50) - A two-ply graphite yarn produced by UCC-PD. It contains 720 filaments per ply and has a 1.5 twist/inch/yarn. Typically, the strength and elastic modulus are 2.85×10^5 and 50×10^6 psi, respectively. Density is 1.63 gms/cc.

CY25 - A five-ply carbon yarn produced by the Graphite Products Division, Carborundum Corporation. It contains 480 filaments per ply and has a 1.1 twist/inch/yarn. Typically, the strength and elastic modulus are 1 to 1.8×10^5 and 3 to 5×10^6 psi, respectively. Density is 1.5 gms/cc.

HMG-50 - A two-ply graphite yarn produced by HITCO. It contains 720 filaments per ply and has a 4.05 twist/inch/yarn. Typically, the strength and elastic modulus are 3×10^5 and 5×10^7 psi, respectively. Density is 1.72 gms/cc.

(b) Ablation tests were conducted by G. F. Wright, Jr, Sandia Laboratories, Albuquerque, New Mexico.

Table 1
DESCRIPTION OF MATERIALS TESTED AS CURVED ABLATION SPECIMENS

Model Number	Density (gms/cc)	Material Description	Carbon Vapor Deposition Temperature (°C)	Heated at 3,000° C?	Source
A-3029-27-1	1.73	Sprayed Chopped Fibers/0-90° Filaments/CVD	1,100		Sandia
27-2(1)	1.67	Sprayed Chopped Fibers/0-90° Filaments/CVD	1,100		Sandia
27-G1(1)	1.70	Sprayed Chopped Fibers/0-90° Filaments/CVD	1,100	Yes	Sandia
27-G2	1.70	Sprayed Chopped Fibers/0-90° Filaments/CVD	1,100	Yes	Sandia
33-1	1.43	45° FW WYB 85 1/2 CVD	1,100		Sandia
33-2(1)	1.36	45° FW WYB 85 1/2 CVD	1,100		Sandia
33-G1(1)	1.40	45° FW WYB 85 1/2 CVD	1,100	Yes	Sandia
33-G2	1.40	45° FW WYB 85 1/2 CVD	1,100	Yes	Sandia
35-1	1.58	45° FW CY2-5/CVD	1,100		Sandia
35-2(1)	1.55	45° FW CY2-5/CVD	1,100		Sandia
35-G1	1.58	45° FW CY2-5/CVD	1,100	Yes	Sandia
35-G2(1)	1.55	45° FW CY2-5/CVD	1,100	Yes	Sandia
39-1	1.53	45° FW T-50/CVD	1,100		Sandia
39-2(1)	1.52	45° FW T-50/CVD	1,100		Sandia
39-G1	1.53	45° FW T-50/CVD	1,100	Yes	Sandia
39-G2(1)	1.53	45° FW T-50/CVD	1,100	Yes	Sandia
43-1	1.39	Sprayed Chopped Fibers/0-90° Filaments/CVD	1,100		Sandia
43-2(1)	1.36	Sprayed Chopped Fibers/0-90° Filaments/CVD	1,100		Sandia
43-G1	1.45	Sprayed Chopped Fibers/0-90° Filaments/CVD	1,100	Yes	Sandia
43-G2(1)	1.39	Sprayed Chopped Fibers/0-90° Filaments/CVD	1,100	Yes	Sandia
47-1	1.42	45° FW T-50/CVD	1,100		Sandia
47-2(1)	1.41	45° FW T-50/CVD	1,100		Sandia
47-G1(1)	1.42	45° FW T-50/CVD	1,100	Yes	Sandia
47-G2	1.42	45° FW T-50/CVD	1,100	Yes	Sandia
53-1(1)	1.65	Sprayed Chopped Fibers/Pitch (submerged)	NA(2)		Y-12
53-2	1.65	Sprayed Chopped Fibers/Pitch (submerged)	NA		Y-12
53-G1(1)	1.65	Sprayed Chopped Fibers/Pitch (submerged)	NA	Yes	Y-12
53-G2	1.64	Sprayed Chopped Fibers/Pitch (submerged)	NA	Yes	Y-12
55-1(1)	1.55	45° FW Hitco HMG-50/CVD	1,100		Sandia
55-2	1.54	45° FW Hitco HMG-50/CVD	1,100		Sandia
55-G1(1)	1.52	45° FW Hitco HMG-50/CVD	1,100	Yes	Sandia
55-G2	1.53	45° FW Hitco HMG-50/CVD	1,100	Yes	Sandia

(1) These specimens were submitted for post-test evaluation.

(2) Material subjected to repeated impregnation and carbonization to 1,000° C.

WYB-115 1/2 (Thornel-25) - A two-ply graphite yarn produced by UCC-PD. It contains 720 filaments per ply and has a 1.6 twist/inch/yarn. Typically, the strength and elastic modulus are 1.8×10^5 and 2.5×10^7 psi, respectively. Density is 1.40 gms/cc.

A complete description of each yarn is provided by the manufacturers.(7-10)

The "sprayed chopped fibers" denote a particular type of fiber derived from a Villwyte rayon precursor.(11) After carbonization and heat treatment to 2,000° C, the fibers, chopped as rayon, shrink to a 2-micrometer-diameter

Table 2
DESCRIPTION OF MATERIALS TESTED AS FLAT ABLATION SPECIMENS

Model Number	Density (gms/cc)	Material Description	Carbon Vapor Deposition Temperature (° C)	Heated at 3,000° C ?	Source
A-3039-11-1(1)	1.56	Sprayed Chopped Fibers/CVD	1,150		Y-12
11-2	1.57	Sprayed Chopped Fibers/CVD	1,150		Y-12
13-1	1.59	Sprayed Chopped Fibers/CVD	1,150	Yes	Y-12
13-2(1)	1.59	Sprayed Chopped Fibers/CVD	1,150	Yes	Y-12
37-G1	1.44	Sprayed Chopped Fibers/CVD	1,300	Yes	Sandia
37-G2(1)	1.43	Sprayed Chopped Fibers/CVD	1,300	Yes	Sandia
51-1(1)	1.58	Sprayed Chopped Fibers/0-90° Filaments Pitch	NA(2)		Y-12
51-2	1.62	Sprayed Chopped Fibers/0-90° Filaments Pitch	NA		Y-12
51-G1(1)	1.58	Sprayed Chopped Fibers/0-90° Filaments Pitch	NA	Yes	Y-12
51-G2	1.62	Sprayed Chopped Fibers/0-90° Filaments Pitch	NA	Yes	Y-12
SG-Y-12	1.60	7-Micron-Diameter Short-Chopped Fibers/ Pressed/Pitch	NA	Yes	Y-12
C-1	1.79	Felt Conventional CVD	1,100		Super Temp
C-2	1.79	Felt Conventional CVD	1,100		Super Temp
1(1)	1.60	Felt Inside-Out CVD	1,500		Super Temp
2	1.73	Felt Inside-Out CVD	1,500		Super Temp
3	1.72	Felt Inside-Out CVD	1,500		Super Temp
4	1.75	Felt Inside-Out CVD	1,500	Yes	Super Temp
5(1)	1.72	Felt Inside-Out CVD	1,500	Yes	Super Temp
6	1.56	Felt Inside-Out CVD	1,500	Yes	Super Temp
12	1.45	Felt Inside-Out CVD	1,300		Super Temp
13	1.36	Felt Inside-Out CVD	1,300		Super Temp
15	1.48	Felt Inside-Out CVD	1,300		Super Temp
14	1.44	Felt Inside-Out CVD	1,300	Yes	Super Temp
16	1.34	Felt Inside-Out CVD	1,300	Yes	Super Temp
17	1.40	Felt Inside-Out CVD	1,300	Yes	Super Temp
24	1.72	Felt Inside-Out CVD	1,100	Yes	Super Temp
25	1.74	Felt Inside-Out CVD	1,100	Yes	Super Temp
26	1.74	Felt Inside-Out CVD	1,100	Yes	Super Temp
27	1.74	Felt Inside-Out CVD	1,100		Super Temp

(1) These specimens were submitted for post-test evaluation.

(2) Material subjected to repeated impregnation and carbonization to 1,000° C.

by 250-micrometer-long graphite fiber which can be sprayed through conventional recirculating-type spray guns. Typical strengths are approximately 5×10^5 psi with an estimated elastic modulus of 3 to 6×10^6 psi. For Sample SG-Y-12, listed in Table 2, the short chopped fibers were 7-micrometer-diameter by 250-micrometer-long graphite fibers, and they were also chopped to length as rayon and subsequently carbonized and heated to 2,000° C.

The felt was obtained from the Super-Temp Company, Santa Fe Springs, California, and is designated as RPG.(12) The material is prepared from a rayon precursor and felted as rayon by conventional textile techniques.

An impregnating grade of coal-tar pitch (Allied Chemical Corporation's Grade CP-277-15V) was used for all the liquid impregnations and as the binder for Samples of the 51 and 53 series.

Details of the carbon vapor deposition (CVD) process used to infiltrate these fibrous structures are discussed as part of the fabrication.

Fabrication

For the composites listed in Tables 1 and 2, several fabrication techniques were used independently and in combination. Basically, the fabrication techniques were: (1) filament winding, (2) spray lay up of discontinuous fibers, (3) liquid impregnation, and (4) carbon vapor infiltration. Selected portions from each composite were heated to 3,000° C for comparison purposes.

Filament windings of the two patterns, 45 degrees and 0 - 90 degrees, were made as cylinders and as flat plates, respectively. The 45-degree patterns consisted of a nominal helical wrap angle of 45 degrees with the axis of the cylinder, with a turn-to-circuit ratio of 29/13. They were produced on 4-inch-diameter graphite mandrels.⁽¹³⁾ For the 0 - 90-degree filament patterns; that is, filament axes arranged at 90 degrees to each other, a WYB-115 1/2 type yarn was used. For the 0 - 90-degree patterns, the winding was integrated with alternate layers of short fibers sprayed onto each filament array; ie, a layer of short fibers was applied between each change in the winding direction. No short fibers were included in the 45-degree winding patterns.

Spray lay up of discontinuous fibrous composites has been described elsewhere in detail.⁽¹¹⁾ For these materials, short fibers, a binder, and a solvent were sprayed onto solid mandrels or onto the filament arrays. The solvent was removed by drying subsequent to attaining the desired part thickness, and the composite was heated to approximately 1,000° C to carbonize the binder.

Sample SG-Y-12, which contained short chopped fibers, was fabricated by spray lay up, but the binder was a thermosetting resin (American Reinforced Plastics Company's Type 91-LD). The sprayed structure was compacted and thermoset in a closed die at 150° C prior to carbonization to 1,000° C. The compaction increased the fiber content from 15 to 47 volume percent and the density from 0.25 to 0.8 gm/cc. Further densification was by repeated liquid impregnation with coal-tar pitch and subsequent carbonization to 1,000° C.

Liquid impregnation was the conventional vacuum-pressure procedure described by Lambdin⁽¹¹⁾ except for the 53-1 and 53-2 series of samples. For this material, the final densifications from 0.9 to 1.65 gms/cc were made by

vacuum-pressure impregnations, and the subsequent carbonizations were made with the part submerged in the coal-tar-pitch impregnant. The bath of coal-tar pitch carbonized along with the part and provided some resistance to the pitch being forced from the pores of the material due to gas generation and/or expansion. Also, the bath served as an excellent heat-transfer medium at the low carbonization temperatures.

Carbon-vapor infiltration was by the thermal gradient technique described by Pierson, et al.⁽¹⁴⁾ The mean temperatures of deposition are given in Tables 1 and 2. Decomposition of methane at one atmosphere pressure was the source of the carbon. Samples C-1 and C-2 were infiltrated by the conventional isothermal technique,⁽¹⁵⁾ but they were not post-ablation examined as part of this study.

Graphitization of the selected samples was done in an inert-gas (argon) environment, and the 3,000° C maximum temperature was held for approximately two hours. Parts 53-1 and 53-2 and 51-1 and 51-2 were heated to temperatures of 1,000° C during fabrication. Only Parts 53-G1 and 53-G2 and 51-G1 and 51-G2 were heated to 3,000° C. The 3,000° C temperature was determined by optical pyrometry using suitable sight glass and lens corrections. Temperatures near this level may vary by as much as $\pm 25^\circ$ C.

TEST CONDITIONS

A description of the curved and flat models, tested in the high-pressure arc jet facility of the Plasmadyne Division of Geotel, Inc, and the test environments is presented in Table 3. Details of the testing procedure and the data reduction have been described elsewhere.^(16,17) The tests were conducted in air at a mach number of three. Surface temperatures were monitored on

Table 3
TEST CONDITIONS FOR FLAT AND CURVED MODELS

	Flat Model	Curved Model
Width (in)	2	2
Length (in)	4	4
Thickness (in)	0.5	0.6 - 0.5
Cylindrical Radius (in)	-	2.625
Gas Enthalpy (Btu/lb)	10,000	10,000
Stagnation Pressure (atm)	3	3
Static Pressure (atm)	~ 1.5	-
Heat Flux (Btu/ft ² -sec)	3,000	2,000 ⁽¹⁾
Angle of Attack to Jet (degrees)	45	45

(1) It is believed that the initial heat flux on the curved models quickly increases to the 3,000 Btu/ft²-sec level as soon as erosion starts.

both the curved and flat models and found to be similar during these tests. Heats of ablation (Q^*), erosion rates, ablation depths, and additional test data are given in Table 4 for only those samples selected for the post-test examination. In Table 5, these samples are listed in order of performance with respect to the heat of ablation, and remarks are included on the general behavior of the samples. In the following discussions, most of the data will be arranged in the order presented in Table 5.

POST-TEST OBSERVATIONS AND MATERIAL CHARACTERIZATIONS

From the total list of samples described in Tables 1 and 2, 24 ablation-tested samples were selected for evaluation. As indicated in Tables 1 and 2, samples prepared by the same fabrication technique (in the as-fabricated and as-heat-treated condition) were compared. The two heat-treat conditions were: (1) heat treatment to 3,000° C subsequent to final processing, and (2) no heat treatment above the maximum processing temperature. For the materials densified by CVD and not heat treated, the final processing temperatures were between 1,100 and 1,500° C. Materials densified by liquid infiltration with a coal-tar pitch were heated to a maximum of 1,000° C during processing; ie, without subsequent graphitization. Photographs and data will frequently be compared for the two heat-treat conditions to show the effect of a high-heat-treatment temperature on the ablation performance and thermal shock resistance.

Each of the 24 samples was sectioned for examination (Figure 1). Prior to destructive testing, each sample was photographed, radiographed, and visually inspected. As indicated in Figure 1, sections of each sample were taken for porosity, immersion density, surface area, thermal expansion, electrical resistivity, and X-ray diffraction measurements. Selected areas were examined by optical and electron microscopy and radiography.

Macro Photography

Figures A-1 - A-13 (Appendix) give a comparison of the appearance of the as-processed and graphitized samples after the ablation test. Enlarged views of the ablated zones of these samples are compared in Figures A-14-A-26. These photographs are presented in the order of decreasing heats of ablation, as given in Table 5, and the companion sample prepared by the same fabrication technique except for the final heat treatment is included to show the effect of graphitization prior to testing.

Table 4
ABLATION DATA AND TEST CONDITIONS FOR CARBON AND GRAPHITE COMPOSITES

Model Number	Model Type ⁽¹⁾	Stagnation Pressure (atm)	Initial Thickness (in)	Final Thickness (in)	Erosion Rate (in/sec)	Heat of Ablation (Btu/lb)	Run Time (sec)
A-3029-27-1	C	2.96	0.630	0.432	0.0198	16,800	10.0
27-2	C	2.96	0.625	0.385	0.0235	14,700	10.2
27-G1	C	3.13	0.631	0.400	0.0226	15,000	10.2
27-G2	C	3.12	0.614	0.400	0.0214	15,900	10.0
33-1	C	3.06	0.621	0.336	0.0279	14,400	10.2
33-2	C	2.98	0.627	0.327	0.0300	14,100	10.0
33-G1	C	3.12	0.618	0.282	0.0336	12,200	10.0
33-G2	C	3.10	0.624	0.308	0.0316	13,000	10.0
35-1	C	3.13	0.621	0.445	0.0220	16,500	8.0
35-2	C	3.00	0.625	0.465	0.0200	18,600	8.0
35-G1	C	3.13	0.606	0.465	0.0168	21,700	8.4
35-G2	C	3.11	0.606	0.445	0.0161	23,000	10.0
39-1	C	3.13	0.506	0.225	0.0281	13,400	10.0
39-2	C	3.13	0.506	0.230	0.0276	13,700	10.0
39-G1	C	3.05	0.498	0.275	0.0223	16,900	10.0
39-G2	C	3.09	0.482	0.250	0.0227	16,600	10.2
43-1	C	2.95	0.552	0.256	0.0290	14,300	10.2
43-2	C	3.00	0.552	0.255	0.0297	14,300	10.0
43-G1	C	3.05	0.569	0.310	0.0259	15,400	10.0
43-G2	C	3.08	0.559	0.325	0.0293	14,100	8.0
47-1	C	3.13	0.501	0.230	0.0339	12,000	8.0
47-2	C	3.13	0.503	0.230	0.0341	12,000	8.0
47-G1	C	3.11	0.476	0.330	0.0183	22,300	8.0
47-G2	C	3.02	0.506	0.316	0.0238	17,100	8.0
53-1	C	3.14	0.607	0.415	0.0192	18,700	10.0
53-2	C	3.01	0.609	0.400	0.0205	17,100	10.2
53-G1	C	3.10	0.594	0.405	0.0187	18,700	10.1
53-G2	C	3.08	0.592	0.468	0.0141	24,800	8.8
55-1	C	3.14	0.501	0.232	0.0264	14,100	10.2
55-2	C	3.14	0.501	0.250	0.0249	15,100	10.1
55-G1	C	3.12	0.515	0.260	0.0255	14,900	10.0
55-G2	C	3.13	0.515	0.241	0.0269	14,000	10.2
11-1	F	3.10	0.502	0.220	0.0282	13,100	
11-2	F	3.00	0.502	0.335	0.0209	17,600	
13-1	F	3.02	0.475	0.468			10.0
13-2	F	3.15	0.502	0.486			2.0
37-G1	F	3.21	0.493	0.215	0.0349	11,500	8.0
37-G2	F	3.00	0.476	0.211	0.0331	12,000	8.0
51-1	F	2.95	0.488	0.345	0.0179	20,300	8.0
51-2	F	2.95	0.498	0.318	0.0219	16,200	8.2
51-G1	F	3.05	0.461	0.328	0.0163	22,400	8.2
51-G2	F	3.09	0.476	0.358	0.0146	24,500	8.1
1	F	2.96	0.508	0.275	0.0233	15,500	10.0
2	F	3.09	0.508	0.316	0.0192	17,400	10.0
3	F	2.94	0.498	0.270	0.0226	14,000	10.0
4	F	3.10	0.524	0.405	0.0119	27,500	10.0
5	F	3.00	0.529	0.385	0.0143	23,400	10.1
6	F	3.05	0.478	0.285	0.0193	19,100	10.0
SG-Y-12(2)	F	6.0	0.500		0.008	21,900	15.0

(1) C - curved model; F - flat model.

(2) Test conditions were different for this sample. Bulk gas enthalpy was 3,000 Btu/lb, heat flux was 1,478 Btu/ft²-sec, and the stagnation pressure was 6 atm.

Table 5
A RANKING ACCORDING TO HEATS OF ABLATION FOR THE
CARBON-CARBON COMPOSITES WHICH WERE EXAMINED
AFTER THE ABLATION TEST

Model Number	Heat of Ablation (Btu/lb)	Specimen Condition After Test
5	23,400	-
35-G2	23,000	Channel Holes
51-G1	22,400	Channel Holes
47-G1	22,300	Delaminated
SG-Y-12	21,900	Uniform Erosion
51-1	20,300	Cracked
53-G1	18,700	-
35-2	18,600	Cracked
53-1	18,200	Cracked
39-G2	16,600	Channel Holes
1	15,500	Cracked
27-G1	15,000	Cracked
55-G1	14,900	-
27-2	14,700	Cracked
43-2	14,300	-
55-1	14,100	-
33-2	14,100	Delaminated
43-G2	14,100	Cracked
39-2	13,700	Channel Holes
11-1	13,100	Cracked
33-G1	13,000	Large Hole
37-G2	12,100	Cracked
47-2	12,000	Delaminated
13-2	-	Cracked

Radiography

Enlarged photographs of the radiographs for three orthogonal views of each sample are presented in Figures A-27 - A-50. These photographs are also presented in the order listed in Table 5. A more quantitative radiographic examination was made on uniformly prepared 0.125-inch-thick slices taken from each sample (Figure 1). Two of these slices were radiographed on the same film with a calibration stepwedge of Type ATJ-S^(c) graphite. A montage of these radiographs and a typical radiograph of the stepwedge are presented in Figure A-51. Typical microdensitometer traces from one of the radiographs are seen in Figure A-52. Using a calibration curve (Figure A-53) obtained from the graphite stepwedge, bulk-density variations were evaluated for each sample by means of the microdensitometer traces taken across the thickness and width dimensions. Maximum and minimum values are compared in Table 6. The bulk density was determined from actual dimensions and weights of the ablation samples prior to testing.

(c) A grade of fine-grain, medium-density (1.82 gms/cc) graphite produced by the Union Carbide Corporation's Carbon Products Division.

Figure 1. SECTIONS TAKEN FROM ABLATION-TESTED SAMPLES.

Table 6
VARIATIONS IN MATERIAL DENSITY DETERMINED FROM
MICRODENSITOMETER TRACES OF RADIOGRAPHS

Sample Number	Bulk Density (gms/cc)	Density Variation Across Width ⁽¹⁾ (gms/cc)		Estimated Density Variations Across Thickness ⁽¹⁾ (gms/cc)					
		Maximum	Minimum	Trace 1		Trace 2		Trace 3	
				Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
5A	1.72	1.82(2)	0.99	3.37(3)	1.19	3.37(3)	1.29	1.91	1.09
35-G2A	1.55	1.73	< 0.5(4)	1.73	< 0.5(4)	4.46(2)	< 0.5(4)	1.66	< 0.5(4)
51-G1A	1.58	1.74	< 0.5(4)	1.74	< 0.5(4)	1.82	1.09	1.66	< 0.5(4)
47-G1A	1.42	1.72	0.79	1.61	1.16	1.52	0.82	1.72	1.21
5G-Y-12	1.60	1.60	1.35	1.60	1.54	1.60	1.50	1.54	1.48
51-1A	1.58	1.84	1.20	1.93	1.25	1.76	1.20	1.76	1.30
53-G1A	1.65	1.75	1.30	1.76	1.25	1.75	1.30	1.68	1.30
35-2A	1.55	1.73	< 0.5(4)	1.73	1.29	1.65	< 0.5(4)	1.65	< 0.5(4)
53-1A	1.65	1.81	1.40	1.81	1.46	2.20	1.28	1.81	1.33
39-G2A	1.53	1.73	< 0.5(4)	2.77(3)	< 0.5(4)	2.47(3)	1.09	1.98	< 0.5(4)
1A	1.60	1.6	1.54	1.6	1.54	1.6	1.31	1.6	1.36
27-G1A	1.70	4.60(3)	1.10	2.48(3)	1.41	2.08(3)	1.24	2.48(3)	1.29
55-G1A	1.52	2.12	0.87	1.72	1.33	1.52	1.05	1.72	1.48
27-2A	1.67	3.60(3)	1.13	1.99(3)	1.19	2.63(3)	1.19	2.63(3)	0.96
43-2A	1.36	2.21(3)	1.72	> 5.0(3)	0.99	2.09	1.10	2.64(3)	0.97
55-1A	1.55	1.66	1.10	1.59	1.46	1.59	< 0.5(4)	1.91	0.94
33-2A	1.36	1.31	< 0.5(4)	1.36	0.93	1.36	< 0.5(4)	1.31	< 0.5(4)
43-G2A	1.39	3.60(3)	< 0.5(4)	2.84(3)	1.10	2.21(3)	0.99	2.84(3)	0.93
39-2A	1.52	2.81(2)	1.05	1.46	< 0.5(4)	1.41	0.82	-	-
11-1A	1.56	1.82	1.41	1.66	1.29	1.66	1.19	1.59	1.24
33-G1A	1.40	1.46	< 0.5(4)	1.46	< 0.5(4)	1.41	< 0.5(4)	1.82	< 0.5(4)
37-G2A	1.43	1.6	1.3	1.76	1.1	1.73	1.15	1.68	1.21
47-2A	1.41	1.68	1.05	1.46	1.05	1.68	1.00	1.60	1.23
13-2A	1.59	1.74	1.47	1.66	1.47	1.66	1.41	1.66	1.28

(1) The slices shown in Figure A-48 were radiographed and the density of the film was related to the bulk density by the use of a calibrated stepwedge, as shown in Figure A-49. Width refers to the two-inch dimension, and a single densitometer trace was made near the center of the part. Thickness refers to the 0.5-inch dimension, and three densitometer traces were made.

(2) High-density coating on one surface.

(3) High-density spots in the material, which could be due to contamination during the ablation test.

(4) Density too low for measurement, apparently caused by holes and delaminations.

Porosity and Density

Porosity, density, surface-area, and pore-size distributions were determined on sections of the unaffected portions of each sample. The pore-size distributions obtained by mercury porosimetry are presented in Figures A-54 - A-66 for the as-processed and heat-treated samples. Porosity data obtained by mercury porosimetry and water immersion are compared with the ablation resistance in Table 7. Also included in Table 7 are the surface areas determined by krypton adsorption using a modification of the BET method.⁽¹⁸⁾ In Table 8, bulk and apparent densities determined by mercury and water intrusion are compared with average bulk densities determined from the sample weight and physical dimensions.

Table 7
POROSITY AND SURFACE AREA OF CARBON-CARBON COMPOSITES

Sample Number	Heat of Ablation (Btu/lb)	Porosity (%)		Porosity < 10 μ (2)	Volume - Average Equivalent Pore Diameter(2) (μ)	Surface Area(3) (m^2/gm)
		To Mercury	To Water(1)			
5A	23,400	21.61	18.9	30.0	19.6	-
35-G2A	23,000	4.0	12.7	64.1	15.5	0.34
51-G1A	22,400	19.7	16	71.4	8.9	0.39
47-G1A	22,300	11.7	16.6	66.0	15.8	0.55
5G-Y-12A	21,900	16.6	11	98.3	2.4	0.59
51-1A	20,300	10.0	15.9	22.8	25.4	0.26
53-G1A	18,700	21.9	13.0	56.2	13.1	0.35
35-2A	18,600	3.0	7.6	65.1	17.2	0.12
53-1A	18,200	10.1	11.0	28.2	16.6	0.19
39-G2A	16,600	8.2	10.4	78.0	11.7	0.48
1A	15,500	10.4	8.6	42.4	16.1	0.24
27-G1A	15,000	9.1	9.9	52.2	12.1	0.26
55-G1A	14,900	7.9	11.5	82.0	8.8	0.57
27-2A	14,700	6.0	5.0	51.9	13.1	0.17
43-2A	14,300	21.6	17.6	61.9	12.8	0.40
55-1A	14,100	6.5	8.9	69.9	13.1	0.34
33-2A	14,100	5.4	13.1	54.7	18.1	0.39
43-G2A	14,100	20.2	18.8	79.8	6.3	0.46
39-2A	13,700	6.7	9.4	75.9	9.9	0.43
11-1A	13,100	5.2	4.2	93.1	5.1	0.33
33-G1A	13,000	7.0	14.4	59.6	17.2	0.37
37-G2A	12,100	13.6	14.8	93.6	4.8	0.54
47-2A	12,000	9.7	13.2	58.9	20.1	0.38
13-2A	-	6.6	8.2	80.5	7.8	0.23

(1) Determined by the water immersion method.

(2) Determined by the mercury porosimetry method.

(3) Determined by the BET method.

Thermal Expansion

Thermal-expansion specimens were cut from the ablation samples (Figure 1), and the expansion for the three orthogonal directions was measured using an automatic recording quartz dilatometer(19) for the temperature range from room temperature to 1,000° C. Cumulative expansions ($\Delta L/L_0$) as a function of temperature for the three directions of each sample are shown by the graphs of Figures A-67 - A-90. Using the method of least squares, these data were fitted to a second or third-order polynomial. The constants of these equations are presented in Table 9. The average coefficients of thermal expansion for the four temperature intervals and the three specimen orientations are presented in Table 10. From the coefficients in Table 10, three ratios for the orthogonal directions were calculated and are tabulated in Table 11. In Table 12, the expansion rates are compared for the two heat treatments. Most of the materials exhibited a lower expansion rate subsequent to the 3,000° C heat treatment.

Table 8
BULK AND APPARENT DENSITIES OF CARBON-CARBON COMPOSITES

Sample Number	Heat of Ablation (Btu/lb)	Average Bulk Density(1) (gms/cc)	Bulk Density (gms/cc)		Apparent Density (gms/cc)	
			From Mercury(2)	From Water(3)	From Mercury(2)	From Water(3)
5A	23,400	1.72	1.64	1.65	2.09	2.03
35-G2A	23,000	1.55	1.61	1.44	1.68	1.66
51-G1A	22,400	1.58	1.71	1.61	2.13	1.93
47-G1A	22,300	1.42	1.53	1.35	1.73	1.62
SG-Y-12	21,900	1.60	1.60	1.60	1.92	1.82
51-1A	20,300	1.58	1.67	1.57	1.85	1.87
53-G1A	18,700	1.65	1.66	1.68	2.13	1.93
35-2A	18,600	1.55	1.60	1.50	1.65	1.62
53-1A	18,200	1.65	1.66	1.62	1.84	1.82
39-G2A	16,600	1.53	1.65	1.50	1.80	1.68
1A	15,500	1.60	1.61	1.52	1.80	1.66
27-G1A	15,000	1.70	1.66	1.70	1.82	1.88
55-G1A	14,900	1.52	1.62	1.50	1.76	1.69
27-2A	14,700	1.67	1.72	1.63	1.73	1.71
43-2A	14,300	1.36	1.51	1.42	1.62	1.72
55-1A	14,100	1.55	1.56	1.45	1.67	1.59
33-2A	14,100	1.36	1.41	1.29	1.49	1.49
43-G2A	14,100	1.39	1.37	1.43	1.72	1.76
39-2A	13,700	1.52	1.61	1.46	1.72	1.61
11-1A	13,100	1.56	1.60	1.62	1.69	1.69
33-G1A	13,000	1.40	1.46	1.34	1.57	1.57
37-G2A	12,100	1.43	1.65	1.66	1.91	1.95
47-2A	12,000	1.41	1.46	1.35	1.62	1.55
13-2A	-	1.59	1.62	1.57	1.74	1.70

(1) Determined from weight and dimensions prior to the ablation test.

(2) Bulk density determined by mercury porosimetry using the sample volume measured at a pressure of 1.8 psia. This pressure will fill all holes larger than 100 micrometers. The apparent density determined from the volume of samples at 15,000 psia.

(3) Bulk density determined by water immersion and the apparent density determined after evacuation of the sample immersed in water.

Electrical Resistivity

Electrical resistivities were determined on specimens taken from the A-B plane of the ablation samples (Figure 1). From these data (Table 13), the electrical resistivities appear to be approximately equal for the two orthogonal directions within the plane. However, several of the ablation samples delaminated badly on sectioning and were eliminated from this evaluation. The effects of the 3,000° C heat treatment are apparent from this measurement.

X-Ray Diffraction

The specimens used for radiographic examination were also used as X-ray diffraction specimens. Accurate determination of the crystallite size, L_c , and the interlayer spacing, C_o , is complicated due to the very low absorption

Table 9
EQUATION CONSTANTS OF THE CUMULATIVE EXPANSION
AS A FUNCTION OF THE TEMPERATURE FOR
CARBON-CARBON COMPOSITES

Sample Number	Equation Constants(1)			
	A x 10 ⁻⁴	B x 10 ⁻⁶	C x 10 ⁻⁹	D x 10 ⁻¹²
5A	0.17	2.05	0.95	
5B	- 1.29	2.71	1.16	
5C	- 2.48	4.52	1.11	
35-G2A	- 1.39	3.18	0.94	
35-G2B	- 1.56	2.90	0.87	
51-G1A	- 0.65	1.30	1.20	
51-G1B	- 0.20	0.81	1.39	
51-G1C	- 2.16	5.22	1.10	
47-G1A	- 0.60	1.08	1.10	
47-G1B	- 0.13	- 0.40	1.30	
5G-Y-12A	- 0.80	1.14	1.18	
5G-Y-12B	- 0.62	0.34	1.22	
5G-Y-12C	- 0.28	1.00	0.04	
51-1A	- 1.64	3.32	0.20	
51-1B	- 1.52	2.64	0.93	
51-1C	- 4.29	7.45	0.08	
53-G1A	- 0.85	1.80	1.12	
53-G1B	- 1.72	2.26	0.91	
53-G1C	- 3.63	6.17	0.83	
35-2A	- 1.39	2.54	1.57	
35-2B	- 1.16	2.32	1.63	
35-2C	- 2.20	2.87	2.56	
53-1A	- 1.07	2.17	1.65	
53-1B	- 1.72	1.43	1.67	
53-1C	- 2.95	5.28	1.28	
39-G2A	0.23	- 0.69	1.68	
39-G2B	0.18	- 1.34	1.80	
39-G2C	- 3.28	6.19	1.03	
1A	- 3.13	5.11	0.64	
1B	2.59	3.85	0.86	
1C	- 2.38	4.41	1.26	
27-G1A	- 1.16	2.32	1.42	
27-G1B	- 0.74	1.81	1.20	
27-G1C	1.12	1.43	1.43	
55-G1A	0.10	- 0.07	1.27	
55-G1B	0.24	0.62	1.29	
55-G1C	- 2.58	3.88	1.20	
27-2A	1.09	2.63	3.17	- 1.31
27-2B	- 1.02	2.38	2.77	- 0.97
27-2C	- 2.78	5.60	1.06	
43-2A	- 0.59	1.56	1.22	
43-2B	- 0.75	0.88	1.24	
43-2C	- 5.19	9.35	- 1.30	
55-1A	0.36	- 0.57	3.07	- 1.10
55-1B	0.12	- 0.34	1.72	
55-1C	- 4.32	7.55	- 0.80	
33-2A	- 2.28	2.27	1.80	
33-2B	- 1.92	3.41	0.77	
33-2C	- 2.36	4.72	0.59	

(1) The form of the equation is:

$$\text{Expansion (in/in)} = A + B\Delta T + C(\Delta T)^2 + D(\Delta T)^3,$$

where ΔT represents the temperature above the datum level, usually room temperature.

Table 9 (Continued)

Sample Number	Equation Constants(1)			
	A x 10 ⁻⁴	B x 10 ⁻⁶	C x 10 ⁻⁹	D x 10 ⁻¹²
43-G2A	- 0.18	0.32	1.26	
43-G2B	0.02	0.18	1.13	
43-G2C	- 2.05	4.82	0.88	
39-2B	0.39	- 0.68	1.83	
39-2C	- 3.25	6.84	1.38	
11-1A	- 3.27	4.65	0.76	
11-1C	3.85	3.40	1.78	
33-G1A	- 1.37	2.28	1.18	
33-G1B	2.09	1.54	1.58	
33-G1C	- 2.51	3.71	1.03	
37-G2A	- 1.77	3.09	1.09	
37-G2B	- 1.94	3.60	0.91	
37-G2C	- 3.47	7.23	- 0.71	
47-2A	0.21	- 0.98	2.03	
47-2B	0.31	- 0.16	0.76	
13-2A	- 1.10	2.66	0.64	
13-2B	- 2.14	4.19	0.68	
13-2C	- 3.39	5.05	0.68	

coefficient of carbon, strain in the lattice, sample misalignment, and variation within the materials. Therefore, each specimen was examined using identical preparation, specimen alignment, and scanning procedures to provide the best possible relative correlation between the materials. Specimens were examined on a horizontal diffractometer, and the alignment was accomplished using a preadjusted knife edge. The values of C_0 were determined from the (00.2) peak position, and the apparent crystallite size was calculated using the relation $L_c = 0.89 \lambda / (\beta \cos \theta)$, where λ represents the wave length of the incident X rays, β the width at half height of the (00.2) reflection, and θ the Bragg angle. The crystallite size is referred to as "apparent" since several factors, including lattice strain, instrumental size broadening, and polarization also lead to line broadening.

The data are presented in Tables 14 and 15. Effects of heat treatment to 3,000° C are apparent from the comparison in Table 15.

Microstructural Examination

Several of the materials listed in Tables 1 and 2 were examined in detail using metallography, scanning electron microscopy, and selected area photography. Photographs from these examinations are presented in Figures A-91 - A-130 and include views of fractured, machined, and ablated areas. Photographs from the three techniques are presented together for each material, and the presentation follows the order of ablation performance listed in Table 5. Selected features are noted in the photographs and will be referred to in the discussion of the results.

Table 10
COEFFICIENTS OF THERMAL EXPANSION FOR
SEVERAL CARBON-CARBON COMPOSITES

Sample Number ⁽¹⁾	Heat of Ablation (Btu/lb)	Coefficients of Thermal Expansion ($^{\circ}\text{C}^{-1} \times 10^{-6}$)			
		RT-400 ⁽²⁾	RT-600	RT-800	RT-1000
5A	23,400	2.3	2.7	2.9	3.1
5B	23,400	3.0	3.4	3.6	3.7
5C	23,400	4.7	5.1	5.2	5.4
35-G2A	23,000	3.4	3.7	3.9	4.0
35-G2B	23,000	3.1	3.4	3.6	3.7
35-G2C	23,000	5.4	5.8	6.2	6.2
51-G1A	22,400	1.7	2.1	2.3	2.5
51-G1B	22,400	1.5	1.8	2.1	2.3
51-G1C	22,400	5.4	5.9	6.1	6.2
47-G1A	22,300	0.7	1.1	1.3	1.5
47-G1B	22,300	0.1	0.4	0.7	0.9
47-G1C	22,300	(3)	(3)	(3)	(3)
SG-Y-12A	21,900	1.5	1.9	2.1	2.3
SG-Y-12B	21,900	1.4	1.7	2.0	2.1
SG-Y-12C	21,900	1.0	1.0	1.0	1.1
51-1A	20,300	3.4	3.3	3.4	3.4
51-1B	20,300	3.0	3.2	3.4	3.5
51-1C	20,300	7.0	7.3	7.4	7.2
53-G1A	18,700	2.2	2.5	2.7	2.9
53-G1B	18,700	2.2	2.8	3.0	3.1
53-G1C	18,700	1.0	6.5	6.7	6.7
35-2A	18,600	3.1	3.6	3.9	4.1
35-2B	18,600	3.0	3.5	3.8	4.0
35-2C	18,600	3.7	4.4	4.8	5.4
53-1A	18,200	2.9	3.3	3.6	3.8
53-1B	18,200	1.8	2.4	2.8	3.0
53-1C	18,200	5.5	6.0	6.2	6.4
39-G2A	16,600	0.1	0.5	0.8	1.1
39-G2B	16,600	-0.6	-0.1	0.3	0.5
39-G2C	16,600	6.2	6.7	6.8	7.0
1A	15,500	5.0	5.3	5.4	5.5
1B	15,500	4.8	5.1	5.2	5.3
1C	15,500	6.0	6.3	6.4	6.4
27-G1A	15,000	3.0	3.3	3.6	3.8
27-G1B	15,000	2.3	2.6	2.8	3.0
27-G1C	15,000	2.6	2.7	2.9	3.1
55-G1A	14,900	0.5	0.8	1.0	1.2
55-G1B	14,900	-0.1	0.2	0.4	0.7
55-G1C	14,900	4.2	5.0	5.4	5.7
27-2A	14,700	3.7	4.1	4.3	4.4
27-2B	14,700	3.6	3.9	4.2	4.4
27-2C	14,700	5.7	6.1	6.4	6.6
43-2A	14,300	2.0	2.3	2.6	2.8
43-2B	14,300	1.2	1.6	1.9	2.1
43-2C	14,300	7.8	8.0	7.9	7.7
55-1A	14,100	0.6	1.0	1.3	1.5
55-1B	14,100	0.3	0.8	1.1	1.4
55-1C	14,100	6.4	6.9	7.2	7.4
33-2A	14,100	2.5	3.3	3.7	3.6
33-2B	14,100	3.4	3.8	4.0	4.1
33-2C	14,100	4.8	5.0	5.2	5.2

(1) The specimen orientations referred to as A, B, and C are described in Figure 1; the material descriptions are given in Table 1.

(2) These are the temperature ranges; eg, room temperature - 400 $^{\circ}$ C.

(3) Not tested because the specimens were too badly damaged.

Table 10 (Continued)

Sample Number(1)	Heat of Ablation (Btu/lb)	Coefficients of Thermal Expansion ($^{\circ}\text{C}^{-1} \times 10^{-6}$)			
		RT-400(2)	RT-600	RT-800	RT-1000
43-G2A	14,100	0.8	1.1	1.4	1.6
43-G2B	14,100	0.6	0.9	1.2	1.4
43-G2C	14,100	5.0	5.3	5.5	5.6
39-2A	13,700	(3)	(3)	(3)	(3)
39-2B	13,700	0.3	0.6	1.0	1.3
39-2C	13,700	7.0	7.5	7.8	8.1
11-1A	13,100	4.2	5.0	5.2	5.1
11-1B	13,100	4.4	4.6	4.8	4.9
11-1C	13,100	4.9	5.4	5.6	5.7
33-G1A	13,000	2.6	2.9	3.2	3.4
33-G1B	13,000	2.6	3.0	3.2	3.4
33-G1C	13,000	3.7	4.2	4.4	4.5
37-G2A	12,100	3.3	3.7	4.0	4.1
37-G2B	12,100	3.8	4.2	4.4	4.5
37-G2C	12,100	6.6	6.7	6.4	6.4
47-2A	12,000	-0.04	0.4	0.8	1.1
47-2B	12,000	0.2	0.4	0.5	0.7
47-2C	12,000	(3)	(3)	(3)	(3)
13-2A	(4)	2.9	3.0	3.2	3.2
13-2B	(4)	4.2	4.5	4.6	4.8
13-2C	(4)	4.8	5.3	5.5	5.5

(4) Specimen cracked at the start of the ablation test.

DISCUSSION OF THE OBSERVATIONS

Carbon-carbon composites can be fabricated by numerous techniques. The components of a composite can be varied, and subsequent processing conditions, such as heat treatment, can be adjusted. Exercising these options results in a wide range of composite properties which influence the performance and ultimate utilization of these materials. The samples listed in Tables 1 and 2 represent a few of the possible carbon-carbon composite combinations which were selected for screening as to ablation behavior.

Within the list of Tables 1 and 2, the following groups and subgroups of materials exist:

1. a 45-degree filament-wound pattern, with a CVD matrix and with the following yarn types:
 - a. Thornel-50 (WYG-130 1/2),
 - b. HMG-50,
 - c. WYB-85 1/2, and
 - d. CY2-5;

2. a 0 - 90-degree filament-wound pattern of WYB-115 1/2 yarn integrated with sprayed short fibers of carbon and with the following type matrices:
 - a. CVD, and
 - b. carbon or graphite derived from coal-tar pitch;
3. a sprayed structure of short carbon fibers with the following matrices:
 - a. CVD, and
 - b. carbon or graphite derived from coal-tar pitch; and
4. a felted fibrous structure with a CVD matrix.

Also, each of the different types of composites were ablation tested in both the as-processed condition and after a heat treatment to 3,000° C. The samples which were heat treated are indicated in Tables 1 and 2.

Table 11
RATIOS OF THE COEFFICIENTS OF THERMAL EXPANSION
FOR THREE ORTHOGONAL DIRECTIONS OF
CARBON-CARBON COMPOSITES

Sample Number	Heat of Ablation (Btu/lb)	CTE Ratios ⁽¹⁾		
		C/A	C/B	A/B
5	23,400	1.74	1.46	0.84
35-G2	23,000	1.55	1.67	1.08
51-G1	22,400	2.48	2.70	1.08
47-G1	22,300	(2)	(2)	1.67
5G-Y-12	21,900	0.48	0.52	1.09
51-1	20,300	2.12	2.06	0.97
53-G1	18,700	2.31	2.16	0.93
35-2	18,600	1.32	1.35	1.02
53-1	18,200	1.68	2.14	1.27
39-G2	16,600	6.36	14.0	2.2
1	15,500	1.16	1.21	1.04
27-G1	15,000	0.82	1.03	1.27
55-G1	14,900	4.75	8.15	1.71
27-2	14,700	1.50	1.50	1.00
43-2	14,300	2.75	3.67	1.33
55-1	14,100	4.93	5.28	1.07
33-2	14,100	1.37	1.27	0.93
43-G2	14,100	3.50	4.0	1.14
39-2	13,700	(2)	6.23	(2)
11-1	13,100	1.12	1.16	1.04
33-G1	13,000	1.32	1.32	1.00
37-G2	12,100	1.56	1.42	0.91
47-2	12,000	(2)	(2)	1.57
13-2	-	1.72	1.15	0.67

(1) The ratios were calculated using the coefficients of expansion for the temperature range from room temperature to 1,000° C. A, B, and C refer to the direction of orientations shown in Figure 1.

(2) Specimens too badly damaged to test in certain orientations.

Table 12
EFFECT OF HEAT TREATMENT ON THE THERMAL EXPANSION
OF CARBON-CARBON COMPOSITES

Sample Identification		Coefficients of Thermal Expansion ⁽³⁾ (°C ⁻¹ × 10 ⁻⁶)					
		A Direction		B Direction		C Direction	
		HT	NHT	HT	NHT	HT	NHT
5	1	3.1	5.5	3.7	5.3	5.4	6.4
35-G2	35-2	4.0	4.1	3.7	4.0	6.2	5.4
51-G1	51-1	2.5	3.4	2.3	3.5	6.2	7.2
47-G1	47-2	1.5	1.1	0.9	0.7	(4)	(4)
SG-Y-12	(5)	2.3	(5)	2.1	(5)	1.1	(5)
53-G1	53-1	2.9	3.8	3.1	3.0	6.7	6.4
39-G2	39-2	1.1	(4)	0.5	1.3	7.0	8.1
27-G1	27-2	3.8	4.4	3.0	4.4	3.1	6.6
55-G1	55-1	1.2	1.5	0.7	1.4	5.7	7.4
43-G2	43-2	1.6	2.8	1.4	2.1	5.6	7.7
33-G1	33-2	3.4	3.8	3.4	4.1	4.5	5.2
37-G2	(5)	4.1	-	4.5	-	6.4	-
13-2	11-1	3.2	5.1	4.8	4.9	5.5	5.7

(1) These samples, identified as HT, were annealed at 3,000° C subsequent to fabrication and infiltration.

(2) These samples, identified as NHT, were tested without being heated above the final processing temperatures shown in Tables 1 and 2.

(3) Temperature range from room temperature to 1,000° C.

(4) Specimen too badly damaged to test.

(5) A sample of this type was not ablation tested.

From the ablation test on these composites and the relative ranking according to ablation behavior and composite characteristics, information was obtained on the following:

1. the effect of heat treatment on ablation resistance;
2. the relative behavior of fiber and matrix;
3. the relative behavior of different type yarns and fibers;
4. the relative behavior of different type matrices; and
5. the effect of fabrication on performance.

From an initial examination of the materials listed in Table 5, it is apparent that flaws and defects within the materials must also be included as a part of any rating of performance. Again, it is emphasized that these composites are developmental in nature and do not represent ultimate composite fabrication procedures. However, the flaws have influenced the ablation results and this should be emphasized.

Examination of the heat-of-ablation data listed in Table 5 for the materials fabricated as indicated in Tables 1 and 2 reveals that the five best materials, which yielded heats of ablation from 21,900 to 23,400 Btu/lb, were heat treated to 3,000° C. If the average heats of ablation for each type of composite listed in Table 4 are considered, a slightly different ranking from Table 5 results. This ranking and the ranges of the data are presented in Table 16 for the ten best performers. Although the ranking is different, the same materials compose the top-ten performer list. Also, the three materials with the highest heats of ablation are the same for both Tables 5 and 16. Table 16 also shows that within the scatter of the data obtained from the ablation test the six best materials have about equal ablation resistance. Again, these six materials were all heat treated to 3,000° C. Figures A-1 - A-6 and Figures A-14 - A-19 show the erosion patterns of these materials along with the unheat-treated specimens for comparison. The unheat-treated composites in Figures A-14 - A-16 and A-19 show obvious cracks which indicate the brittle nature and

Table 13
ELECTRICAL RESISTIVITY OF SEVERAL
CARBON-CARBON COMPOSITES

Sample Number(1)	Average Resistivity(2) (ohm - cm x 10 ⁻³)	Range of Resistivity Values (ohm - cm x 10 ⁻³)	
		Maximum	Minimum
5A	0.50	0.51	0.48
5B	0.41	0.41	0.41
35-G2A	2.14	2.18	2.07
51-G1A	0.56	0.57	0.56
51-G1B	0.51	0.51	0.51
SG-Y-12A	0.81	0.83	0.78
SG-Y-12B	0.85	0.86	0.84
51-1A	4.51	4.64	4.35
53-G1B	0.51	0.51	0.51
35-2A	7.4	7.9	7.0
35-2B	7.4	7.8	6.9
53-1A	4.10	4.21	4.13
53-1B	4.37	4.38	4.35
39-G2A	2.82	3.18	2.22
39-G2B	2.79	2.95	2.60
1-A	5.16	5.18	5.14
27-G1A	1.05	1.08	0.93
55-G1A	3.78	5.05	2.38
27-2B	4.34	5.11	4.13
43-2B	6.54	6.67	6.35
55-1A	3.40	4.06	2.0
33-2A	6.57	6.67	6.35
43-G2B	5.32	5.43	5.24
39-2A	5.2	5.57	5.0
33-G1	4.52	4.89	4.11
37-G2A	2.54	2.72	2.30
13-2B	5.8	5.9	5.7

(1) Samples 11-1, 47-2, and 47-G1 were too badly damaged to obtain an adequate sample.

(2) Values represent the average of eight measurements.

Table 14
LATTICE SPACINGS AND APPARENT CRYSTALLITE SIZE FOR
SEVERAL CARBON-CARBON COMPOSITES

Sample Number	Interplanar Spacings, $d(002)^{(1)}$ (A)		Apparent Crystallite Size, $L_c^{(2)}$ (A)	
	Uncorrected	Corrected	bg	g
5	3.379	3.370	257	237
35-G2	3.405	3.397	75	78
51-G1	3.384	3.375	242	189
47-G1	3.425	3.417	73	73
SG-Y-12	3.385	3.377	212	191
51-1	3.503	3.499	19	20
53-G1	3.387	3.379	280	229
35-2	3.483	3.475	36	36
53-1	3.508	3.504	-	20
39-G2	3.428	3.420	77	77
1	3.451	3.443	-	67
27-G1	3.407	3.399	86	90
55-G1	3.439	3.431	69	67
27-2	3.471	3.463	42	38
43-2	3.471	3.463	-	49
55-1	3.443	3.435	44	54
33-2	3.476	3.469	37	43
43-G2	3.415	3.407	73	79
39-2	3.465	3.457	40	46
11-1	3.503	3.495	78	41
33-G1	3.453	3.444	72	67
37-G2	3.386	3.377	174	162
47-2	3.455	3.447	-	48
13-2	3.445	3.438	79	66

(1) Uncorrected $d(002)$ values obtained from powdered samples were corrected for Lorentz polarization, low specimen absorption, Compton and atomic scattering, and reflection by the monochromator.

(2) Crystallite size was determined on machined samples (bg) and on a selected screen fraction (-100, +200 mesh) after grinding (g).

lack of thermal shock resistance of these materials. Radiography (Figures A-32, A-34, A-35, and A-37) reveals the extent of the cracking around the ablated areas. In general, most of the materials which were not heat treated to the higher temperature cracked during the ablation test. Two specimens (43-G2 and 27-G1) craze cracked during the 3,000° C heat treatment. This action is shown in Figures A-21, A-23, A-38, and A-44. There was an exception to this general behavior in that specimens of the 39, 47, and 55 series did not exhibit gross cracks across planes parallel with the surface of the specimens. However, these specimens were badly delaminated after testing, as shown in Figures A-42, A-45, A-49, and A-51. All of these composites contained high-modulus ($\sim 50 \times 10^6$ psi) graphite yarns and were densified by CVD, as indicated in Table 1.

Table 15
EFFECT OF HEAT TREATMENT ON THE LATTICE INTERLAYER
SPACING AND APPARENT CRYSTALLITE SIZE FOR
SEVERAL CARBON-CARBON COMPOSITES

Sample Identification		Interplanar Spacings ⁽¹⁾ (A)		Apparent Crystallite Size ⁽¹⁾ (A)	
Heat Treated	Not Heat Treated	HT	NHT	HT	NHT
5	1	3.370	3.443	237	67
35-G2	35-2	3.397	3.475	78	36
51-G1	51-1	3.375	3.499	189	20
47-G1	47-2	3.417	3.447	73	48
SG-Y-12	(2)	3.377	-	191	-
53-G1	53-1	3.379	3.504	229	20
39-G2	39-2	3.420	3.457	77	46
27-G1	27-2	3.399	3.463	90	38
55-G1	55-1	3.431	3.435	67	54
43-G2	43-2	3.407	3.463	79	49
33-G1	33-2	3.444	3.469	67	43
37-G2	(2)	3.377	-	162	-
13-2	11-1	3.438	3.495	66	41

(1) See footnotes for Table 14.

(2) Specimens were not available for examination.

Table 16
RANKING ACCORDING TO THE HEAT OF ABLATION FOR THE
TEN BEST CARBON-CARBON COMPOSITES EVALUATED

Model Number	Heat of Ablation (Btu/lb)		
	Minimum	Maximum	Average ⁽¹⁾
A-3029-51-G	22,400	24,500	23,450
-5-	19,100	27,500	23,300
A-3029-35-G	21,700	23,000	22,350
SG-Y-12	21,900	21,900	21,900
A-3029-53-G	18,700	24,800	21,750
A-3029-47-G	17,100	22,300	19,700
A-3029-51-	16,200	20,300	18,250
A-3029-53-	17,100	18,200	17,650
A-3029-35-	16,500	18,600	17,550
A-3029-39-G	16,600	16,900	16,750

(1) Average values are based on the two or three specimens of each type tested (see Table 4).

The thermal expansion data (Tables 10 and 11) for the three composites containing the high-modulus yarns (47-2, 39-2, and 55-1) show the effect of the anisotropic filaments on the composite expansion. The expansions are very small for the directions within the plane of filaments, and this low expansion probably accounts for the absence of cracks which cross these planes. The expansion values for directions normal to the surface of the part (interlaminar direction) are large, and this anisotropy in the expansion of the composite probably caused the delaminations observed. Microstructural examination of

these composites reveals a brittle behavior during fracture of Specimen 47-2 (Figure A-108) and during the ablation of Specimen 55-1 (Figure A-121). Even the heat-treated specimens of these composites showed a brittle tendency (Figures A-107 and A-117). In particular, ablation of this type of material appears to include a large amount of material loss by microfracture and mechanical removal.

Returning to the superior behavior of the materials which were heat treated, it appears from the erosion patterns that gross fabrication flaws influenced the results more than the microporosity. In Table 7, the total porosity less than 100 micrometers (determined from the mercury intrusion of accessible pores with diameters less than 100 μ) varied randomly from 3 to 22 percent for the top ten materials. The percentage of the total porosity with openings less than 10 micrometers ranged from 23 to 98 percent. These results do not indicate that fine porosity is unimportant, but do show that gross flaws must be eliminated before the fine-porosity spectrum will be of real significance. In fact, examination of the pore-size distributions in Figures A-54 - A-66 reveals that, for most of the materials, more than 90 percent of the porosity is actually available in pores with openings smaller than 50 micrometers. One additional observation on the porosity is that the total porosity and the fraction of porosity with a pore size less than ten micrometers increased when the composites were heat treated to 3,000° C. This result is probably due to the additional shrinkage which causes fine cracks in the matrix. Figures A-104, A-114, and A-115 show such cracks for a matrix derived from coal-tar pitch.

For the ten best materials listed in Table 8, the bulk densities range from 80 to 94 percent of the apparent density except for two specimens (51-G1 and 53-G1). For these specimens the bulk densities are only about 75 percent of the apparent density. A relationship between density or the fraction of the apparent density and ablation behavior was not established. This problem is not unexpected since most of the composites were densified to above 80 percent of the maximum possible density. The high heats of ablation and the relatively low fraction of the apparent density of Specimens 51-G1 and 53-G1 suggest that an additional potential is possible for higher density material of this type.

Scanning electron microscopy (Figure A-92) of the ablation area of Specimen 5 revealed that the carbon fibers derived from a rayon precursor were lost preferentially from the CVD matrix. Metallography (Figures A-93 and A-94) showed that the fibers were present in the CVD matrix prior to ablation and were removed by preferential oxidation or vaporization once the CVD coating was penetrated. Other specimens also exhibited this behavior. Figure A-95 shows the same results for the felt sample (Sample 1) which was not heat

treated after infiltration. Figures A-100, A-102, A-119, A-128, and A-129 show similar behavior for filaments and short-chopped fibers in a CVD matrix, and Figures A-104 - A-106, A-114, and A-116 show this preferential loss relative to matrices derived from coal-tar pitch. The loss of fibers, derived from rayon, has been observed previously by Stover.⁽³⁾ He further noted that only the graphite fibers derived from polyacrylonitrile (PAN) were able to survive an ablation test without being etched away.

To summarize these microstructural observations, it appears that rayon produces poor-quality graphite which does not resist thermochemical erosion as well as either certain types of pyrocarbon or graphite and carbons derived from coal-tar pitch. Both the carbon (CY2-5) and graphite (HMG-50, Thorne1-50, etc) fibers exhibited this behavior.

In terms of uniformity of erosion, Specimens SG-Y-12, 53-G1, and 5 exhibited the best performances. These composites have common structural features in that all contain short-length fibers arranged in a nearly two-dimensional isotropic configuration. Thermal expansion, being a reasonable indicator of isotropy, shows, in Tables 10 and 11, that the A and B directions (Figure 1) for these three composites expand at about equal rates. The actual values of the coefficients of linear thermal expansion are comparable and relatively low for the A and B directions of these specimens. In particular, Table 12 shows that the 3,000° C heat treatment lowered the coefficients appreciably for these two directions relative to the interlaminar or C direction. This lowering of the coefficient of thermal expansion is characteristic of the behavior of carbon as it graphitizes. Further evidence that these three composites have graphitized to a certain degree is the lower electrical resistivities (listed in Table 13) and the smaller lattice spacings, d_{00} (given in Table 15), compared to the unheat-treated material.

Several other types of composites appeared to graphitize, as shown in Tables 12, 13, and 15, but a few material combinations which obviously did not graphitize as a result of the 3,000° C heat treatment are Samples 13-2, 33-G1, 55-G1, and 47-G1. The ablation behavior of these materials reflect the brittle, near-glass-like nature of such composites. The effects of this brittleness on the erosion is seen in Figures A-101, A-107, and A-119; Figures A-12, A-13, A-25, and A-26 show the gross cracking which is a result of the poor thermal shock resistance. This cracking, as indicated previously, was observed for most of the unheat-treated composites, and was the most common source of failure for all the materials tested.

CONCLUSIONS

From the observations and data presented, it appears that superior performance, but perhaps not the ultimate, can be attained for a variety of carbon-carbon composites. If adequate thermal shock resistance can be attained by graphitizing the carbon matrix, either CVD, graphite, or graphite derived from coal-tar pitch appears to be a suitable matrix. Heats of ablation between 20,000 and 24,000 Btu/lb are possible for materials prepared by filament winding, felting, and spray lay up; and, as long as the fibers are derived from a rayon precursor, it does not apparently affect the ablation rate if they are carbon or graphite. A major problem area associated with these materials is the prevention of flaws and defects which cause nonuniform erosion such as that shown in Figures A-15 - A-17, and A-24.

To realize heat-of-ablation values above 20,000 Btu/lb, it appears from this study that the following composite characteristics are important:

1. thermal shock resistance, which is obtained by the combination of high strain to failure, high thermal conductivity, low and near isotropic thermal expansion, and reasonable strength (a high heat-treatment temperature appears to help certain composites attain such shock resistance);
2. fine, uniform, microstructural elements with the elimination of gross defects such as holes, layering, and filament buckling or misplacement;
3. isotropic behavior for at least the plane of the lay up and not too large a mismatch with the interlaminar direction; and
4. low total porosity with a large percentage less than some critical size and/or a high percentage of the theoretical density.

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ACKNOWLEDGEMENTS

We acknowledge the help on this work by numerous individuals at the Sandia Laboratories and the Oak Ridge Y-12 Plant. In particular, we appreciate the help and contributions of M. D. Nelson, A. J. Taylor, R. K. Bennett, Jr, and D. A. Carpenter of the Y-12 Plant; and C. F. Wright, Jr and E. R. Frye of Sandia Laboratories.

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APPENDIX

(a) Sample 5, Graphitized, $Q^* = 23,400$

130127

(b) Sample 1, As Processed, $Q^* = 15,500$

Figure A-1. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (2X)

(a) Sample 35-G2, Graphitized, $Q^* = 23,000$

130125

(b) Sample 35-2, As Processed, $Q^* = 18,600$

Figure A-2. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (2X)

(a) Sample 51-G1, Graphitized, $Q^* = 22,400$

(b) Sample 51-1, As Processed, $Q^* = 22,300$

130130

Figure A-3. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (2X)

(c) Sample 47-G1, Graphitized, $Q^* = 22,300$

130114

(b) Sample 47-2, As Processed, $Q^* = 12,000$

Figure A-4. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (2X)

130120

Figure A-5. PHOTOGRAPH OF A CARBON-CARBON COMPOSITE AFTER ABLATION TESTING.
(2X; Sample SG-Y-12, Graphitized, $Q^* = 21,900$)

(a) Sample 53-1, As Processed, $Q^* = 18,200$

130124

(b) Sample 53-G1, Graphitized, $Q^* = 18,700$

Figure A-6. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (2X)

(a) Sample 39-2, As Processed, $Q^* = 13,700$

130126

(b) Sample 39-G2, Graphitized, $Q^* = 16,600$

Figure A-7. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (2X)

(a) Sample 27-G1, Graphitized, $Q^* = 15,000$

(b) Sample 27-2, As Processed, $Q^* = 14,700$

130123

Figure A-8. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (2X)

(a) Sample 55-1, As Processed, $Q^* = 14,100$

(b) Sample 55-G1, Graphitized, $Q^* = 14,900$

Figure A-9. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (2X)

130115

(a) Sample 43-2, As Processed, $Q^* = 14,300$

(b) Sample 43-G2, Graphitized, $Q^* = 14,100$

130122

Figure A-0. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (2X)

(a) Sample 33-G1, Graphitized, $Q^* = 13,000$

(b) Sample 33-2, As Processed, $Q^* = 14,000$

130121

Figure A-11. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (2X)

(a) Sample 11-1, As Processed, $Q^* = 13,100$

(b) Sample 13-2, Graphitized, $Q^* = --$

130129

Figure A-12. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (2X)

Figure A-13. PHOTOGRAPH OF A CARBON-CARBON COMPOSITE AFTER ABLATION TESTING. (2X; Sample 37-G2, Graphitized, $Q^* = 12,100$)

(a) Sample 5, Graphitized, $Q^* = 23,400$

130141

(b) Sample 1, As Processed, $Q^* = 15,500$

130140

Figure A-14. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. ($\sim 5\times$)

(a) Sample 35-G2, Graphitized, $Q^* = 23,000$

130109

(b) Sample 35-2, As Processed, $Q^* = 18,600$

130110

Figure A-15. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~5X)

(a) Sample 51-G1, Graphitized, $Q^* = 22,400$

130116

(b) Sample 51-1, As Processed, $Q^* = 20,300$

130139

Figure A-16. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~5X)

(a) Sample 47-G1, Graphitized, $Q^* = 22,300$

130138

(b) Sample 47-2, As Processed, $Q^* = 12,000$

130108

Figure A-17. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. ($\sim 5X$)

130137

Figure A-18. PHOTOGRAPH OF A CARBON-CARBON COMPOSITE AFTER ABLATION TESTING. (~5X; Sample SG-Y-12, Graphitized, $Q^* = 21,900$)

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(a) Sample 53-G1, Graphitized, $Q^* = 18,700$

130132

(b) Sample 53-1, As Processed, $Q^* = 18,200$

130144

Figure A-19. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~5X)

(a) Sample 39-G2, Graphitized, $Q^* = 16,600$

(b) Sample 39-2, As Processed, $Q^* = 13,700$

130145
Figure A-20. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~5X)

(a) Sample 27-G1, Graphitized, $Q^* = 15,000$

130134

(b) Sample 27-2, As Processed, $Q^* = 14,700$

130133

Figure A-21. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. ($\sim 5\times$)

(a) Sample 55-G1, Graphitized, $Q^* = 14,900$

130117

(b) Sample 55-1, As Processed, $Q^* = 14,100$

130113

Figure A-22. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~5X)

(a) Sample 43-G2, Graphitized, $Q^* = 14,100$

130112

(b) Sample 43-2, As Processed, $Q^* = 14,300$

130131

Figure A-23. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. ($\sim 5X$)

(a) Sample 33-G1, Graphitized, $Q^* = 13,000$

(b) Sample 33-2, As Processed, $Q^* = 14,100$

130136
Figure A-24. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~5X)

(a) Sample 13-2, Graphitized, $Q^* = \infty$

130118

(b) Sample 11-1, As Processed, $Q^* = 13,100$

130138

Figure A-25. PHOTOGRAPHS OF CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~5X)

130119

Figure A-26. PHOTOGRAPH OF A CARBON-CARBON COMPOSITE AFTER ABLATION TESTING. (~5X; Sample 37-G2, Graphitized, $Q^* = 12,100$)

Figure A-27. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 5)

Figure A-28. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 35-G2)

Figure A-29. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~ 2X; Sample 51-G1)

Figure A-30. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 47-G1)

Figure A-31. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample SG-Y-12)

Figure A-32. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 51-1)

Figure A-33. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 53-G1)

Figure A-34. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~ 2X; Sample 35-2)

Figure A-35. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~ 2X; Sample 53-1)

Figure A-36. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 39-G2)

Figure A-37. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 1)

Figure A-38. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. ($\sim 2X$; Sample 27-G1)

Figure A-39. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 55-G1)

Figure A-40. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 27-2)

Figure A-41. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 43-2)

Figure A-42. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 55-1)

Figure A-43. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~ 2X; Sample 33-2)

Figure A-44. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. ($\sim 2X$; Sample 43-G2)

Figure A-45. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~ 2X; Sample 39-2)

Figure A-46. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. ($\sim 2\times$; Sample 11-1)

Figure A-47. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~ 2X, Sample 33-C1)

Figure A-48. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. ($\sim 2X$; Sample 37-G2)

Figure A-49. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. ($\sim 2\times$; Sample 47-2)

Figure A-50. RADIOGRAPHS FOR THREE ORTHOGONAL VIEWS OF THE CARBON-CARBON COMPOSITES AFTER ABLATION TESTING. (~2X; Sample 13-2)

Figure A-51. RADIOGRAPHS OF 0.125-INCH-THICK PLATES FROM ABLATION SPECIMENS THAT ARE ARRANGED IN ORDER OF THEIR DECREASING HEATS OF ABLATION.

Figure A-52. TYPICAL MICRODENSITOMETER TRACES FOR A CARBON-CARBON COMPOSITE. (Sample 35-2)

Figure A-53. RADIOGRAPH FILM DENSITY AS A FUNCTION OF THE MATERIAL BULK DENSITY-THICKNESS PRODUCT AS DETERMINED FROM THE TYPE ATJ-5 GRAPHITE STEPWEDGE.

(a) Sample 5, Graphitized

(b) Sample 1, As Processed

Figure A-54. PORE-SIZE DISTRIBUTIONS DETERMINED BY MERCURY POROSIMETRY.

(a) Sample 35-G2, Graphitized

(b) Sample 35-2, As Processed

Figure A-55. PORE-SIZE DISTRIBUTIONS DETERMINED BY MERCURY POROSIMETRY.

Figure A-56. PORE-SIZE DISTRIBUTIONS DETERMINED BY MERCURY POROSIMETRY.

(a) Sample 47-G1, Graphitized

(b) Sample 47-2, As Processed

Figure A-57. PORE-SIZE DISTRIBUTIONS DETERMINED BY MERCURY POROSIMETRY.

Figure A-58. PORE-SIZE DISTRIBUTION DETERMINED BY MERCURY POROSIMETRY. (Sample SG-Y-12 Graphitized)

(a) Sample 53-G1, Graphitized

(b) Sample 53-1, As Processed

Figure A-59. PORE-SIZE DISTRIBUTION DETERMINED BY MERCURY POROSIMETRY.

(a) Sample 39-G2, Graphitized

(b) Sample 39-2, As Processed

Figure A-60. PORE-SIZE DISTRIBUTION DETERMINED BY MERCURY POROSIMETRY.

(a) Sample 27-G1, Graphitized

(b) Sample 27-2, As Processed

Figure A-61. PORE-SIZE DISTRIBUTION DETERMINED BY MERCURY POROSIMETRY.

(a) Sample 55-G1, Graphitized

(b) Sample 55-1, As Processed

Figure A-62. PORE-SIZE DISTRIBUTION DETERMINED BY MERCURY POROSIMETRY.

(a) Sample 43-G2, Graphitized

(b) Sample 43-2, As Processed

Figure A-63. PORE-SIZE DISTRIBUTION DETERMINED BY MERCURY POROSIMETRY.

(a) Sample 33-G1, Graphitized

(b) Sample 33-2, As Processed

Figure A-64. PORE-SIZE DISTRIBUTION DETERMINED BY MERCURY POROSIMETRY.

(a) Sample 13-2, Graphitized

(b) Sample 11-1, As Processed

Figure A-65. PORE-SIZE DISTRIBUTION DETERMINED BY MERCURY POROSIMETRY.

Figure A-66. PORE-SIZE DISTRIBUTION DETERMINED BY MERCURY POROSIMETRY (Sample 37-G2, Graphitized)

Figure A-67. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 5; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-68. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 1; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-69. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 35-G2; Designations A and B Refer to the Sample Orientations Shown in Figure 1)

Figure A-70. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 35-2; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-71. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 51-G1; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-72. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 51-1; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-73. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 47-2; Designations A and B Refer to the Sample Orientations Shown in Figure 1)

Figure A-74. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 47-G1; Designations A and B Refer to the Sample Orientations Shown in Figure 1)

Figure A-75. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen SG-Y-12; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-76. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 53-G1; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-77. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 53-1; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-78. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 39-1; Designations B and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-79. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 39-G2; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-80. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 27-G1; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-81. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 27-2; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-82. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 55-G1; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-83. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 55-1; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-84. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 43-G1; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-85. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 43-2; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-86. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 33-G1; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-87. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 33-2; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-88. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 11-1; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-89. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 13-2; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

Figure A-90. CUMULATIVE EXPANSION AS A FUNCTION OF TEMPERATURE FOR A CARBON-CARBON COMPOSITE. (Specimen 37-G2; Designations A, B, and C Refer to the Sample Orientations Shown in Figure 1)

131080

Figure A-91. A MACHINED SURFACE IN THE UNDAMAGED AREA OF THE CARBON VAPOR DEPOSITION FELT SAMPLE. (Sample 5; Note that the Fibers Appear to be Absent from the Channels of the Pyrocarbon; 50X)

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13887

100X

7517

300X

13886

300X

13885

1,000X

Figure A-92. SCANNING ELECTRON MICROGRAPHS OF THE ABLATION ZONE OF SAMPLE 5. (Again, the Fibers Appear to have been Removed from Most of the Pyrocarbon Tubes)

F-581-1a

100X; Bright Field Illumination

F-581-1d

250X; Bright Field Illumination

F-581-1b

100X; Polarized Light

F-581-1e

500X; Bright Field Illumination

Figure A-93. PHOTOMICROGRAPHS OF THE EDGE OF THE ABLATION ZONE OF SAMPLE 5. (Layers of the CVD Contain Material that Ranges from Highly Anisotropic to Near Isotropic; Note Coating Failures Near the Ablating Surface)

✓
4

F-581-1c 100X; Edge of A-B Plane of Felt

F-581-2a 100X; View Normal to A-B Plane of Felt

F-581-2c 500X

F-581-2b 250X

Figure A-94. PHOTOMICROGRAPHS OF THE UNAFFECTED AREA OF SAMPLE 5. (Note that the Layers of the CVD on the Fibers are More Obvious and that the Fibers are Present with the Structure; Sensitive Tint Illumination)

13891

100X

13890

300X

13889

1,000X

13888

3,000X

Figure A-95. SCANNING ELECTRON MICROGRAPHS OF THE ABLATION ZONE OF THE CARBON VAPOR DEPOSITION FELT.
(Sample 1 which was Fabricated Exactly as Sample 5, but was not Heat Treated to 3,000° C)

Figure A-96. PHOTOMICROGRAPH OF A MACHINED SURFACE OF SAMPLE 35-G2 WHICH WAS MADE OF FILAMENT-WOUND CY2-5 YARN INFILTRATED BY CARBON VAPOR DEPOSITION. (The Topography of the Pyrocarbon in the Voids Near the Filament Crossovers Appears to be More Massive than Within the Filament Bundles; 50X)

Figure A-97. THIS MONTAGE OF PHOTOMICROGRAPHS SHOWS THE DIFFERENCE IN THE PYROCARBON STRUCTURE THROUGHOUT THE THICKNESS OF SAMPLE 35-G2. (15X)

F-580-2a

50X

F-580-2b

250X

Figure A-98. PHOTOMICROGRAPHS OF THE UNAFFECTED MATERIAL IN SAMPLE 35-G2. (Large Voids between Yarn Bundles, Fine Porosity with the Bundles, and Cracks are Obvious Flaws; Sensitive Tint Illumination)

F-580-1a

50X

F-580-1b

250X

Figure A-99. THESE PHOTOMICROGRAPHS OF SAMPLE 35-G2 SHOW THE EFFECT OF THE FLAWS AND VARIATIONS IN THE STRUCTURE OF THE CARBON VAPOR DEPOSITION ON ABLATION. (Sensitive Tint Illumination)

13879

100X

13878

300X

7173

1,000X

7171

1,000X

Figure A-100. THESE SCANNING ELECTRON MICROGRAPHS SHOW THE ABLATION ZONE OF SAMPLE 35-G2. (Apparently, the Carbon Vapor Deposition is More Resistant to Erosion than the Fibers which Appear to be Eroded Away)

13883

100X

13882

300X

13881

1,000X

13880

3,000X

Figure A-101. THESE SCANNING ELECTRON MICROGRAPHS OF SAMPLE 35-2 SHOW EVIDENCE OF MORE BRITTLINESS THAN IN SAMPLE 35-G2 WHICH WAS HEATED TO 3,000° C. (Views are of the Ablation Zone)

As Deposited

8341

100X

8340

1,000X

8343

1,000X

After Ablation

8342

3,000X

Figure A-102. SCANNING ELECTRON MICROGRAPHS OF THE MASSIVE PYROCARBON ON THE FILAMENTS IN SAMPLE 35-2.

8323

1,000X

8322

3,000X

Figure A-103. SCANNING ELECTRON MICROGRAPHS OF A FRACTURED SURFACE OF SAMPLE 35-2. (Shows the Nature of the Fiber-to-Pyrocarbon Bond and the Brittle Nature of this Composite)

13908

100X

13906

1,000X

13907

300X

13905

3,000X

Figure A-104. SCANNING ELECTRON MICROGRAPHS OF THE ABLATION ZONE OF SAMPLE 51-G1. (Shows that the Graphite Derived from Coal-Tar Pitch Survived the Ablation Longer than the Carbon Fibers Derived from Rayon; Note that the Erosion Seems to be Enlarging the Surface-Connected Pores)

131074

Figure A-105. AN ERODED HOLE IN SAMPLE 51-G1 WHERE A FILAMENT BUNDLE WAS ONCE CONTAINED. (50X; Note that the Fibers have been Eroded Away)

13895

100X

13893

1,000X

13894

300X

13892

3,000X

Figure A-106. SCANNING ELECTRON MICROGRAPHS OF SAMPLE 51-1. (This Sample was Fabricated Identical to Sample 51-G1 Except that it was Not Heated to 3,000° C)

13924

100X

13922

1,000X

13923

300X

13921

3,000X

Figure A-107. SCANNING ELECTRON MICROGRAPHS OF THE ABLATION ZONE OF SAMPLE 47-G1. (Note that only a few of the Thornel-50 Fibers appear to be present near the ablating surface, but the carbon vapor deposition matrix remains)

8327

3,000X

8325

1,000X

Figure A-108. SCANNING ELECTRON MICROGRAPHS OF A FRACTURED SURFACE OF THE UNAFFECTED MATERIAL OF SAMPLE 47-2.

131077

Figure A-109. PHOTOMICROGRAPH OF THE MACHINED SURFACE OF SAMPLE 47-2. (Shows the Poorly Bonded Fiber Bundles and the Absence of Massive Pyrocarbon within the Voids; 50X)

131072

Figure A-110. PHOTOMICROGRAPH OF THE SURFACE OF THE ABLATION ZONE OF SAMPLE SG-Y-12. (Shows the Small, Uniform Porosity which has been Enlarged Somewhat by the Ablation; 50X)

F-582-2a

100X

F-582-2b

250X

Figure A-111. PHOTOMICROGRAPHS OF SAMPLE SG-Y-12 SHOWING THE FIBER STRUCTURE AND THE POROSITY FOR AN UNAFFECTED AREA. (This is a Discontinuous Fiber Composite with a Graphite Matrix Derived from Coal-Tar Pitch; Sensitive Tint Illumination)

F-582-1a

100X

F-582-1b

250X

F-582-1c

1,000X

Figure A-112. PHOTOMICROGRAPHS OF AN EDGE OF THE ABLATION ZONE OF SAMPLE SG-Y-12 SHOWING THE EFFECT OF THE POROSITY ON THE EROSION. (Sensitive Tint Illumination)

7720

300X

7717

600X

7719

1,000X

Figure A-113. SCANNING ELECTRON MICROGRAPHS OF THE ABLATION ZONE OF SAMPLE SG-Y-12.

8328

500X

8336

300X

Figure A-114. SCANNING ELECTRON MICROGRAPHS OF THE ABLATION ZONE COMPARED WITH A FRACTURED SURFACE FROM AN UNDAMAGED AREA OF SAMPLE 53-G1. (The Erosion is Similar to that Seen in Figure A-104)

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8339

3,000X

8338

3,000X

8334

600X

Figure A-115. SCANNING ELECTRON MICROGRAPHS OF SAMPLE 53-G1 SHOWING DETAILS OF THE CRACKS WITHIN THE GRAPHITE MATRIX DERIVED FROM COAL-TAR PITCH. (Note the Apparent Bond to the Fiber)

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13928

100X

13927

300X

8330

1,000X

13925

3,000X

Figure A-116. SCANNING ELECTRON MICROGRAPHS OF THE ABLATION ZONE OF SAMPLE 53-1. (Compare this Erosion with the Graphitized Material Shown in Figure A-114)

13916

100X

13914

1,000X

13915

300X

13913

3,000X

Figure A-117. SCANNING ELECTRON MICROGRAPHS OF THE ABLATION ZONE OF SAMPLE 39-G2 SHOWING THE EXTREMELY BRITTLE NATURE OF THIS MATERIAL EVEN AFTER HEAT TREATMENT TO 3,000° C.

✓
6

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Figure A-118. PHOTOMICROGRAPH OF THE EDGE OF THE ABLATION ZONE OF SAMPLE 55-1. (Note that the Erosion is More Severe Near the Open Holes in the Winding Pattern; 50X)

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7714

200X

7713

3,000X

7715

10,000X

Figure A-119. SCANNING ELECTRON MICROGRAPHS OF THE ABLATION ZONE OF SAMPLE 55-1 SHOWING THE RESULTS OF EROSION ON THIS FILAMENT-WOUND HGM-50 INFILTRATED WITH PYROCARBON.

F-583-1a

50X

F-583-1c

250X

Figure A-120. PHOTOMICROGRAPHS OF MATERIAL AT THE EDGE OF THE ERODING SURFACE OF SAMPLE 55-1. (Notice that Large Chunks of Material were Removed; Sensitive Illumination)

F-583-2a

250X; Sensitive Tint

F-583-2b

250X; Polarized Light

F-583-3

250X; Sensitive Tint

Figure A-121. PHOTOMICROGRAPHS SHOWING THE GENERAL FEATURES OF THE MICROSTRUCTURE FOR SAMPLE 55-1.
(Taken from an Area which was not Exposed During Testing)

131081

Figure A-122. PHOTOMICROGRAPH OF A MACHINED SURFACE OF SAMPLE 27-2 SHOWING THE PATH OF A CRACK THROUGH THE MATERIAL. (Refer to Figure A-21 for the Extent of the Cracking in this Material; 50X)

7514

300X

7512

300X

7513

200X

Figure A-123. SCANNING ELECTRON MICROGRAPHS OF A FRACTURED SURFACE OF SAMPLE 27-2. (Note the Brittle Nature of the Sprayed Chopped Fiber that is Infiltrated with Pyrocarbon Relative to the Continuous Filament)

F-584-1a

35X

F-584-1b

250X

F-584-2

100X

Figure A-124. PHOTOMICROGRAPHS OF SAMPLE 27-2 NEAR THE ERODING SURFACE. (Sensitive Tint Illumination)

131076

131075

Figure A-125. PHOTOMICROGRAPHS OF SAMPLES 43-2 and 43-G2. (These Samples Exhibit the Erosion Pattern for This Type of Material in the Two Heat-Treated Conditions; 50X)

F-579-1a

35X; Sensitive Tint

F-579-1b

100X; Bright Field Illumination

F-579-1e

1,000X; Bright Field Illumination

Figure A-126. PHOTOMICROGRAPHS OF SAMPLE 43-2 NEAR THE EDGE OF THE ERODING SURFACE. (Nonuniform Porosity and Cracking are Obvious)

F-579-2a

50X

F-579-2c

250X

Figure A-127. PHOTOMICROGRAPHS OF AN AREA OF SAMPLE 43-2 WHICH WAS NOT ERODED. (Details of Cracks as they Intersect Filament Bundles are Shown)

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13912

100X

13911

300X

13910

1,000X

13909

3,000X

Figure A-128. SCANNING ELECTRON MICROGRAPHS OF THE ABLATION ZONE OF SAMPLE 11-1 SHOWING THAT THE FIBERS HAVE BEEN ERODED FROM THE CARBON VAPOR DEPOSITION MATRIX.

13920

100X

13919

300X

13918

1,000X

13917

3,000X

Figure A-129. SCANNING ELECTRON MICROGRAPHS OF THE ABLATION ZONE OF SAMPLE 37-G2. (Fiber Loss from the Carbon Vapor Deposition Coatings is Apparent)

Ablation Zone

131082

Machined Surface

131069

Figure A-130. PHOTOGRAPH OF THE EDGE OF THE ABLATION ZONE OF SAMPLE 33-G1 SHOWING THE EFFECT OF A WINDING FLAW ON THE EROSION PATTERN. (A View of a Machined Surface of the Winding Pattern is Included for Reference)