

NASA Technical Memorandum 104507

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40367
P19

Effect of Lightning Strike on Bromine Intercalated Graphite Fiber/Epoxy Composites

(NASA-TM-104507) EFFECT OF LIGHTNING STRIKE
ON BROMINE INTERCALATED GRAPHITE FIBER/EPOXY
COMPOSITES (NASA) 19 p CSCL 110

N91-32177

G3/24 Unclass
0040367

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August 1991





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SUMMARY

Laminar composites were fabricated from pristine and bromine intercalated pitch-based graphite fibers. It was found that laminar composites could be fabricated using either pristine or intercalated graphite fibers using standard fabrication techniques. The intercalated graphite fiber composites had electrical properties which were markedly improved over both the corresponding pitch-based and PAN-based composites. Despite composites resistivities more than an order of magnitude lower for the pitch-based fiber composites, the lightning strike resistance was poorer than that of the PAN-based fiber composites. This leads to the conclusion that the mechanical properties of the pitch-fibers are more important than electrical or thermal properties in determining the lightning strike resistance. Based on indicated lightning strike tolerance for high elongation to failure materials, the use of vapor-grown, rather than pitch-based graphite fibers appears promising.

INTRODUCTION

Lightning has a force that can be among the most destructive in nature. Over the past 25 years lightning has, on the average, injured 250 and killed 100 people annually in the United States alone, more people than injured and killed by hurricanes, earthquakes, and tornados combined. The current in a typical lightning stroke may rise to 100 - 200 kA at 200 kV and deposit as much as 40,000 kJ of energy to an area of a few square cm within a few microseconds.

Lightning is of particular concern to the aerospace industry. Aircraft are subjected not only to the cloud-to-ground type lightning which concerns those who must protect buildings from its destructive effects, but also to the more frequent cloud-to-cloud lightning. Despite the efforts of the airline industry to fly around rather than through storm systems, on average each commercial aircraft is struck about once a year by lightning.¹ Military aircraft are struck even more frequently. About one U.S. aircraft per year is lost to lightning strike.

Spacecraft are not immune to the effects of lightning either. Even though they are exposed to the atmosphere for only a short time in flight, several spacecraft, including the manned spacecraft Apollo 12 and Space Transportation System (Shuttle), have been struck during their launch phases. As recently as 1987 Atlas/Centaur-67 was downed by lightning.

Advances in the construction of aerospace structures are increasing the concern for problems associated with lightning strikes. In the drive to lower aircraft and spacecraft weight, low density high strength glass or carbon fiber-epoxy composites are replacing more metallic structures with each new generation. Unfortunately, the electrical and thermal conductivity of these materials are very low compared to the metallic components they are replacing. Thus, the resistive heating of the aircraft skin at the lightning attachment point is very high, and the result is more severe localized damage.

In addition to the use of composite materials for aircraft skins, new generation aircraft tend to have electronic control systems rather than hydraulic or mechanical systems. The latter systems are insensitive to lightning strikes whereas electronic control systems require protection. System protection is necessary because a lightning strike attaches to an aircraft at one point (e.g. at the nose) and detaches or exits at another point (e.g. a wing trailing edge) taking the path of least resistance. The potential drop between the attachment point and the detachment point is dependent on the electrical resistance between those points and the amount of current in the stroke. Given that lightning strokes produce currents on the order of kiloamps, even a low resistance path is likely to have a potential difference orders of magnitude larger than the 5 volt operating range of most microelectronics.

Technological "work-around" solutions to lightning strike susceptibility have been created, but they all suffer drawbacks. Perhaps the most common solution is to provide a conductive veiling material over the outer surface of the composite. Nickel and copper foils and screens have been used most successfully to date, but an effective insulation barrier must be maintained to avoid galvanic corrosion, and an effective moisture barrier is needed to prevent general environmentally driven corrosion. Veil materials are also relatively heavy and provide a larger radar cross-section than composites. If a highly conductive glass or carbon/epoxy composite could be found which would have the required mechanical properties, it could have a major impact on aerospace structure design and development.

There are two approaches to making conductive composites. The first is to improve the conductivity of the matrix material. This is a driving force behind much of the activity directed towards the development of conductive plastics.² The second, which has not been as well explored, is to improve the conductivity of the carbon fibers.

There are three classes of carbon fibers which have application or potential application in the aerospace industry. The first class are made from pyrolysing fibers of polyacrylonitrile (PAN) and are known as PAN-based fibers. These are the fibers which are in most common use by the aerospace industry because of their high strength (3.4 to 5.3 GPa), high modulus (2.2 to 2.7 GPa) and low mass density (about 1.8 g/cm³). The electrical resistivity of these fibers is about 2000 $\mu\Omega$ -cm, a moderate resistivity, but still three orders of magnitude higher than copper. The second class of fibers are spun from mesophase pitch, and are referred to as pitch-based fibers. They differ from the PAN-based fibers in being more crystalline, which results in a slightly more dense fiber (about 2.0 - 2.2 g/cm³) with very high modulus (up to 820 GPa) but somewhat lower strength (about 2.2 GPa). They also have order of magnitude lower electrical resistivities (as low as 220 $\mu\Omega$ -cm).

However, pitch-based fibers are more expensive than PAN-based fibers by about an order of magnitude, and are not produced in large quantity. The third class of fibers is grown by a chemical vapor deposition process from benzene vapor, methane, or other organic gases, and is known as vapor-grown fibers. Although they are still in the experimental stages, they hold enormous promise because they are very crystalline in character and so have low electrical resistivities (50 - 90 $\mu\Omega\text{-cm}$) and very high thermal conductivities (up to 20 W/m-K).

The last two classes of carbon fibers are much more graphitic than the first, and may be referred to as "graphite" fibers. These fibers show promise for having higher lightning strike resistance because of their low electrical resistivity without the drawbacks of required metal foils and screens. In addition, it has been shown that these two classes of fibers can be modified to have even lower resistivities by the process of intercalation.

Intercalation is the insertion of guest atoms or molecules between the carbon sheets (graphene planes) of the graphite lattice. This can be done using either strong oxidizers (Br_2 , ICl , AsF_5 , HNO_3 , etc.) or strong reducers (Li, K, Rb, Cs, etc.). Strong oxidizers pull electrons from the graphite lattice and are called acceptor compounds, and strong reducers give up electrons to the graphite lattice and are called donor compounds. Both supply additional charge carriers to the lattice (holes in the case of acceptor compounds and electrons in the case of donor compounds) without substantially disrupting the lattice, and so lower the electrical resistivity of the graphite. Resistivities in the metallic range have been reported for several different intercalates with several different hosts, including graphite fibers.

A substantial drawback of graphite intercalation compounds (GIC's) has been their chemical instability. Many of the compounds which are the most conductive are also the least stable in air. It has been found however, that the stability can be enhanced by the proper selection of fiber and intercalate³. In fact the stability can be controlled to the extent that composites can be fabricated using standard methods and, as would be suspected, composite resistivities can also be lowered substantially.⁴

The purpose of this study was to test pristine and intercalated pitch-base fiber composites under lightning stroke conditions, and to assess the potential of this material as a lightning-strike resistant material for airframe and spaceframe construction.

METHODS AND MATERIALS

Three grades of graphite fibers were used in this study. Thornel P-55, P-75, and P-100 pitch-based graphite fibers, manufactured by Amoco, were chosen because they have reasonably low resistivities, form stable, well characterized residual intercalation compounds with bromine², and are commercially available in spools of indefinite length. The fibers range in resistivity from 950 $\mu\Omega\text{-cm}$, for pristine P-55, to 50 $\mu\Omega\text{-cm}$, for bromine intercalated P-100 and are listed in table I.

The fibers were woven into fabric as the first step in composite fabrication. Six-thousand filament strands of P-55 and P-75 fibers were woven into an 11 by 11 yarns/inch (4.3 by 4.3 yarns/cm) five-harness satin weave by Mutual Industries (Philadelphia, PA). This resulted in an areal weight of about 300 g/m². Because the P-100 fibers are more brittle than the P-55 and P-75, they were handled differently. Two-thousand filament strands were

woven 10 by 10 yarns/inch (4 by 4 yarns/cm) in a plain weave pattern by Fabric Development, Inc. (Quakertown, PA). This resulted in a looser fabric with an areal weight of about 270 g/m², but very little filament breakage.

Four woven fabric samples of each fiber type were then prepared for intercalation. The fabrics were cut into 38 x 38 inch (96 x 96 cm) pieces and rolled to fit inside 10 cm diameter glass tubes. The ends of the tubes were sealed with teflon covered rubber stoppers. Enough bromine was added to each tube to soak the entire fabric with a small amount of excess (about 500 ml). Additionally, the tubes were rolled periodically so that the entire surface of each sample was submerged several times under the excess liquid bromine. Capillary action caused the bromine to soak into the fabric. Thus the conditions were intermediate between a vapor phase and a liquid phase intercalation. Hung and Long have shown that cooling to near 0 °C is necessary for bromine intercalation of P-55 fibers⁵, so in that case the tube was submerged in an ice bath.

After four to seven days, the bromine was cleared out of the tubes into a scrubber using a stream of air. This process required another two to four days, depending upon the amount of excess liquid bromine remaining after the intercalation reaction. The fabric was very stiff and brittle at the end of this process because of residues left by the liquid bromine. To remove the fabrics from the tubes, they were rinsed with bromoform until the residual solvent was nearly colorless. Residual bromine intercalation compounds have been shown to be stable in bromoform for at least several days⁶ thus indicating there was no concern about deintercalation by this process. The bromoform lubricated the graphite filaments, leaving the fabric very pliable. The fabric was then removed from the reaction tube and laid out on a flat surface to dry. Unfortunately, much of the fabric's stiffness returned after the fabric dried. Sample filaments were taken from several locations on each fabric sample, and their resistivity was measured to ensure that the reaction was successful.

At room temperature under bromine atmosphere, there is a bromine mass uptake of about 44 percent of the carbon mass⁷, or about 130 grams of bromine per fabric. The final fiber has about 18 percent bromine by mass, or about 55 grams per fabric. Although the vast majority of the bromine will degas from the fibers within a day⁸, there is noticeable degassing for a week after they are removed from the tubes.

The fabric was shipped to Rohr Industries R&D Laboratory (Riverside, CA) for processing into laminates. The fabric was impregnated by using a film/fabric stacking sequence and then cured. Alternate layers of epoxy film (Hysol-Grafil EA9101-1) and fabric were laid up until four plies of fabric (0°₄) were achieved. The fiber content for all laminates was targeted to be 68 percent fiber by volume. The laminates were all cured at 177 °C (350 °F) at a pressure of 480 KPa (70 psi) for 1.5 to 2 hours. Previous studies have shown that the bromine intercalated fibers are indefinitely stable in air at these temperatures.

The laminate physical properties; resin content, fiber volume, and void content were measured for pristine and intercalated carbon fiber laminates as summarized in Table II. These properties were determined using the acid digestion technique. The resin density was 1.265 g/cm³. The fiber densities were measured using a density gradient technique.⁹ It is interesting to note that the void content is substantially lower in the bromine intercalated samples. This may be due to improved wetting of the fiber by the resin. Portions of the laminates were cut into squares 5.7 cm (2.25 in) on a side. About twenty of these test

coupons were made and characterized for each of the fiber types (120 in all). One large section of the panel, 46 cm (18 in) square was used for the lightning strike tests.

For the purpose of mapping the thickness and resistivity of the 120 coupons, grids were superimposed on them dividing them into eight mm squares. Thickness measurements were made at each of the 49 grid crossings. Resistivity measurements were disregarded for the edge grid lines, so there were 25 resistivity measurements for each coupon.

Thickness measurements were made to nearest 0.005 mm with a digital micrometer. These were used to assess the laminate quality, and to set the thickness indicator on the contact-less conductivity probe.

Resistivity measurements were made using a modified LEI 1010A conductivity probe (Leighton Electronics, Inc., Leighton, PA) in the bulk conductivity mode. The 1010A was modified by Leighton Electronics to operate at 55.55 kHz (as opposed to the standard frequency of 1000 kHz) in order to increase the penetration depth of the probe. Verification of the accuracy of the instrument was provided by standards from both Leighton Electronics and by the National Institute of Standards and Technology.

In addition, a round robin resistivity evaluation of samples, including five samples of each fiber type used in this study, was held with Intercal Co. (Port Huron, MI) and Rohr Industries. They each have R.F. conductivity devices which are comparable, except that the Intercal instrument uses 1 kHz, and the Rohr instrument uses 3000 kHz. Although there were some variations among the three instruments, the values were similar.

It should be noted that the resistivity values obtained using the eddy current technique did not agree with the best measurements using a multi-point technique. The subtleties of this measurement are beyond the scope of this paper but are described in detail elsewhere.⁴ The eddy current resistivity measurement is at the very least indicative of the "true" resistivity of the sample.

Contour plots of the thickness and resistivity of each of the samples were generated using PC-MATLAB (The Math Works, Inc., Sherborn, MA). A linear extrapolation between measured points was used which results in artificially angular results (as in figures 3 and 4). The thickness plots were contoured at 50 μm intervals. The resistivity plots were contoured at a level near 2σ , where σ is the standard deviation of the resistivity values in a single laminate. The values of the grid line intersections were averaged point by point to arrive at the final values. The average values were also contoured to aid the search for systematic measurement errors.

One side of the lightning strike test panels was painted using standard procedures for finishing composite aircraft components. A 5 cm (2 in) margin around the outer edges was left unpainted to facilitate grounding for the lightning test. The lightning tests were conducted to provide a comparative assessment of improvement over standard PAN fiber based composites. The tests were conducted at the Rohr Lightning Test Facility (see fig. 1) using test waveforms as described in MIL-STD 1757A, and SAE Report AE4L¹⁰ for Zone 2A aircraft lightning strike areas. Figure 2 schematically shows the waveform which has three zones. First there is a restrike current (component D) with a peak amplitude of 100 kA (± 10 percent) which lasts no more than 500 μs and provides an action integral ($\int i^2 dt$) of 250 $\text{kA}^2\text{-s}$ (± 20 percent). This is followed by an intermediate current (component B) of 2 kA (± 10 percent) for 5 ms which transfers 10 coulomb of charge. Finally, there is a continuing current (Component C) of about 400 A that lasts for 50 ms and transfers 20 coulomb of charge.

Post-test evaluation included measurement of mass loss, resistivity as a function of distance from strike point, optical microscopy, scanning electron microscopy (SEM), and energy dispersive x-ray spectroscopy (EDS).

RESULTS AND DISCUSSION

Analysis of the coupon thicknesses confirmed the general high quality of the laminates. The standard deviation of the laminate thicknesses among samples ranged from 0.6 to 2.1 percent. There were, however, thickness variations within single samples which were as large as 15 percent from the mean. The variations in sample thickness are summarized in figure 3. In order to try to identify systematic errors in the thickness measurements the average laminate thickness was also calculated by averaging each grid point through all samples of a given type. Contour plots of the average laminate thickness were then drawn. Contours shown in figure 3 were drawn at the 2σ level. Although there appears to be a tendency for the measurements in the middle of the laminate to be somewhat thicker, variations are less than 2σ from the mean in all cases except P-75 + Br. Here the variations are just over 2σ .

The r.f. eddy current resistivities of the samples are summarized in figure 4. The overall trend is for the composite resistivity to be dominated by the fiber type. Thus, the most conductive fibers (bromine intercalated P-100) result in the most conductive composites. Intercalation, which lowers the resistivity of the fibers, lowers the resistivity of the composites a corresponding amount. The average laminate r.f. eddy current resistivity for each laminate type was calculated point by point in a way analogous to that described above for the average composite thickness. The results are shown in Figure 4. Note here that there is a definite trend of higher resistivity at the composite edges. This may be an indication that the edge effects are somewhat larger than anticipated by our measurement technique. The standard deviations are quite small however, ranging from about 1.5 to 3.3 percent. The samples were thus in good qualitative agreement with the rule of mixtures (parallel resistor) model of conduction through a composite. Quantitative agreement, however, was not good.

Further analysis of the coupon resistivity measurements have been reported elsewhere³ and so only the results of that analysis will be summarized. The most important conclusion was that resistivity is a subtle property in composites. The concept of resistivity presumes a homogeneity of material which is not present in a conductive fiber embedded within an insulating matrix. Thus, the "resistivity" of these composites had a directional anisotropy, and a dependence on sample dimensions.¹¹ There are also great difficulties in making contacts to such a sample. In the contactless eddy current technique, results were considerably higher than in conventional four-point measurements in the direction of the weave. Skin-effects that would be present in such a transient event as a lightning strike were not addressed in the analysis. Although it is uncertain exactly what the meaning of the "resistivity" measured was, it is strongly correlated to the transport of current through the sample.

Another important conclusion, which was arrived at by considering the temperature coefficient of the resistance of the composites, was that the process of fabricating the

composites did not significantly change the electrical behavior of the fibers. In addition, the intercalated fibers were also not significantly deintercalated or damaged.

The r.f. eddy current resistivity was also found to be a linear function of laminate thickness. Specific features in the thickness contour plots often have corresponding resistivity features. This can be attributed to local variations in the fiber fill. If the fiber fabric is of uniform thickness, then any thickness variations in the composite will be due to an excess or dearth of resin. An excess of resin will increase percolation lengths and raise the resistivity, and a dearth of resin will have the opposite effect.

Photographs of the front (painted) and back sides of a lightning strike panel made of conventional PAN-based fibers are shown in figure 5. Note in fig. 5a how the lightning bolt had penetrated the top two lamina and blown out a rather large (5 - 6 cm) hole through the paint. In addition, charred material is spread out over an area 12 - 15 cm across, a trail of secondary sparks trailed off towards the edge which was grounded. In fig. 5b, however, it can be seen that there was no penetration through the back of the panel, so this would meet FAA requirement of no laminate penetration. In order for a new material to be accepted as an improvement, the front side must have considerably less damage than is shown in fig. 5, enough that the panel would not have to be repaired after such a strike.

Photographs of both sides of the six pitch-based carbon fiber laminates after subjection to the lightning strike test are shown in figures 6-11. Even a cursory glance at these test panels reveals that the objectives were not met. All six samples exhibited total penetration of the lightning strike with resulting holes 4-5 cm in diameter. Additional tests were performed to determine why the performance of the test panels was so poor.

A comparison of figures 6, 8, and 10 gives an indication of the effect of substituting fiber types. The conductivity, modulus and strength all increase from P-55 to P-75 to P-100. Cracks are observed radially in the 0 and 90 directions from all three laminates, with the P-55 and the P-75 laminate damage being somewhat higher. The sizes of the holes are similar in all three cases. In both the P-55 and the P-75 cases there are free fibers still attached, but in the P-100 case the hole contains almost no free fibers. This probably reflects the greater brittleness of the P-100 fibers.

Comparing figures 6 to 7, 8 to 9, and 10 to 11 reveals the effects of the intercalation. There seems to be little if any affect at all in lightning strike performance. About the only difference is that there appears to be less cracking of the laminate around the hole in P-55 and P-75 laminates.

A conductivity profile across the center of each laminate was measured after the lightning test. If the lightning caused deintercalation this could perhaps be seen as a gradual sloping of the conductivity away from the hole. The data are presented in figure 12 as a function of distance from one side of the hole. The conductivity profile for the intercalated laminates does not look qualitatively different from the pristine, suggesting that if there was any deintercalation it was on a very small scale. These results are consistent with earlier thermal stability tests² which showed that even at relatively high temperatures (400 °C) the kinetics of deintercalation of these fibers is slow (minutes to hours).

In order to study the region near the hole, EDS bromine dot maps were generated of the regions up to the hole. They confirm that there is no bromine depletion up to the edge of the broken fibers.

A comparison of the extremes in resistivity, pristine P-55 (fig. 6) and intercalated P-100 (fig. 11) indicates that there is very little difference in the lightning damage even though

the resistivity varies by nearly an order of magnitude. Thus, composite resistivity is not as important as other factors in determining lightning strike resistance. This is also bolstered by the comparison to the PAN fiber composite damage to those of the pitch.

This perhaps leads us towards either fiber strength or elongation-to-break as critical parameters. If one considers aluminum skins, which show little if any damage in such a strike, one begins to question the role of strength. All of the fiber composites show strength superior to that of aluminum. Although there can be little doubt that the extremely low resistivity of aluminum is a factor in its excellent resistance to lightning strike, its flexibility, no doubt, also plays an important role.

It seems that the extremely low elongation to break (less than 0.5 percent) may be the critical factor here. As the lightning imparts its energy pulse to the surface much of it is converted to heat through ohmic heating. This vaporizes much of the resin in the immediate area and causes the fibers to expand. The thermal shock is what shatters the fibers and causes the hole.

Given this scenario, how might composite surfaces be protected from lightning strike? One method is to provide a low resistance surface to minimize the ohmic heating. Perhaps part of the difficulty with the approach taken in this study is that the fibers were embedded through the laminate thickness contributing more to the bulk conductivity than to the surface conductivity. Another tact would be to have a surface layer which was not structural. If a veil of short conductive fibers were on the surface, as they expanded they would not shatter as easily, and even if they did there would be few consequences for the structure. Based on the strong indication of the importance of elongation properties a promising tactic would be to use a fiber which is less brittle, and has a high elongation to break tolerance such as vapor grown graphite fibers, which undergo a "sword in the sheath" failure mode instead of brittle fracture.¹²

CONCLUSIONS

It was found that laminar composites of intercalated graphite fibers could be made using standard fabrication techniques. The resulting composites had electrical properties which were markedly improved over PAN based composites. But even though composite resistivities were more than an order of magnitude lower for the pitch-based fiber composites, the lightning strike resistance was poorer. This leads us to the conclusion that the mechanical properties of the pitch-fibers are more important than electrical or thermal properties in determining the lightning strike resistance. One might still expect to see a marked improvement in the lightning strike resistance of composites if a system is developed which can utilize the electrical properties of the intercalated graphite composites, but can avoid the mechanical properties short-comings. One possibility may be the use of a thin layer of intercalated vapor-grown graphite fibers as a veiling material.

ACKNOWLEDGEMENTS

The authors would like to acknowledge F. Lincoln Vogel, of Intercal Company, for his assistance with the composite resistivity measurements and many helpful discussions. The authors would also like to acknowledge the contribution of these Rohr engineers for their contribution to the technical work: Tracie Nguyen established the laminate fabrication procedure; John Pins conducted resistivity measurements and lightning strike tests.

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**TABLE I. - CARBON/GRAPHITE FIBER
RESISTIVITIES**

	PAN, $\mu\text{m-cm}$	P-55, $\mu\text{m-cm}$	P-75, $\mu\text{m-cm}$	P-100, $\mu\text{m-cm}$
Pristine	2000	950	760	320
Bromine intercalated	----	370	280	67

TABLE II. - LAMINATE PHYSICAL PROPERTIES

	P-55		P-75		P-100	
	pris	Br ₂	pris	Br ₂	pris	Br ₂
Fiber volume percent	56.2	54.0	58.7	58.5	64.0	48.0
Resin weight percent	28.0	31.0	27.6	30.6	24.3	38.7
Void volume percent	6.5	3.8	5.0	0.0	2.9	0.0
Fiber density, g/cm ³	2.182	2.214	2.056	2.141	2.039	2.293
Resin density, g/cm ³	1.265	1.265	1.265	1.265	1.265	1.265

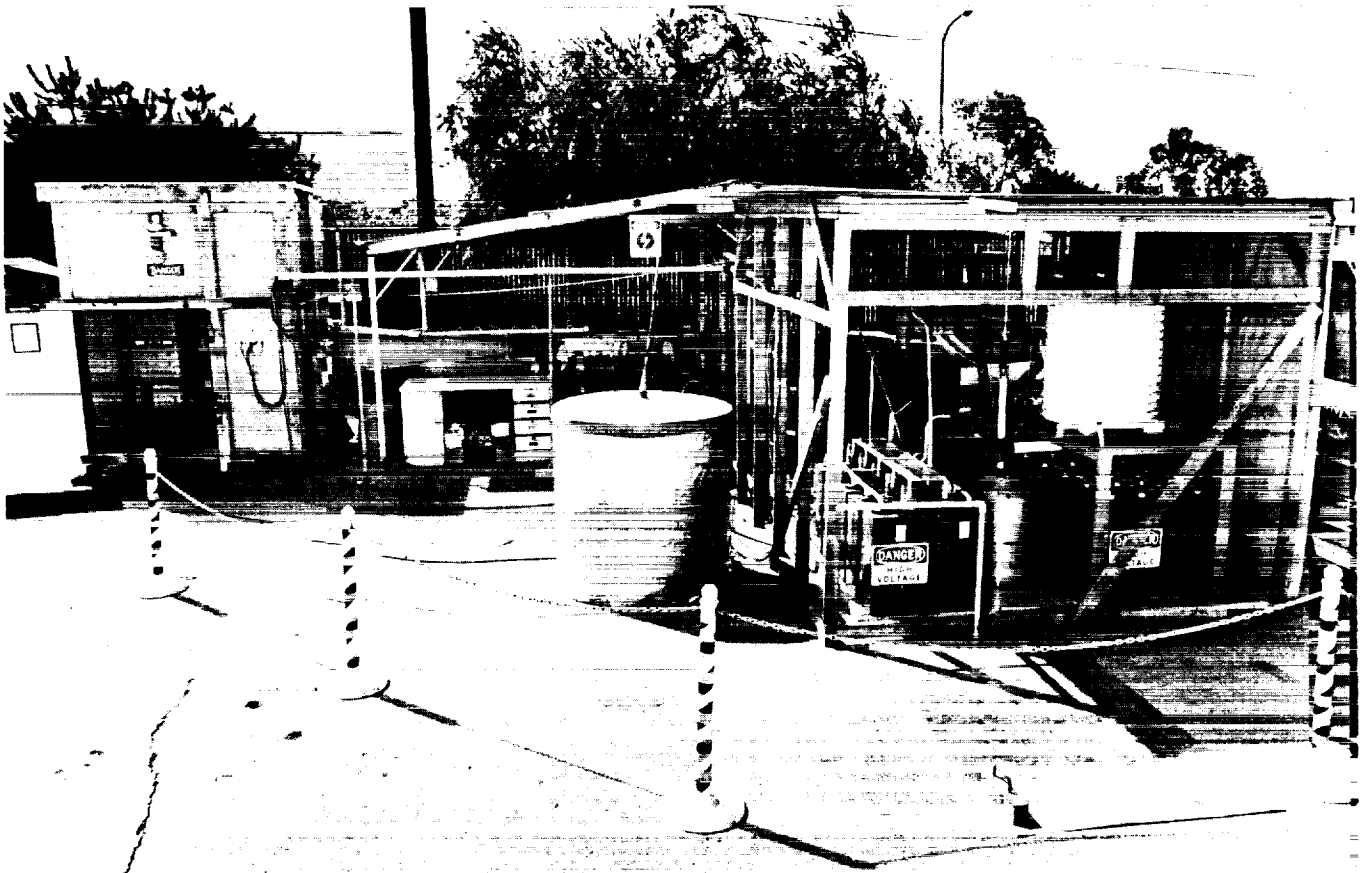


Figure 1.—The Rohr Industries Lightning Test Facility where the lightning strike tests were carried out.

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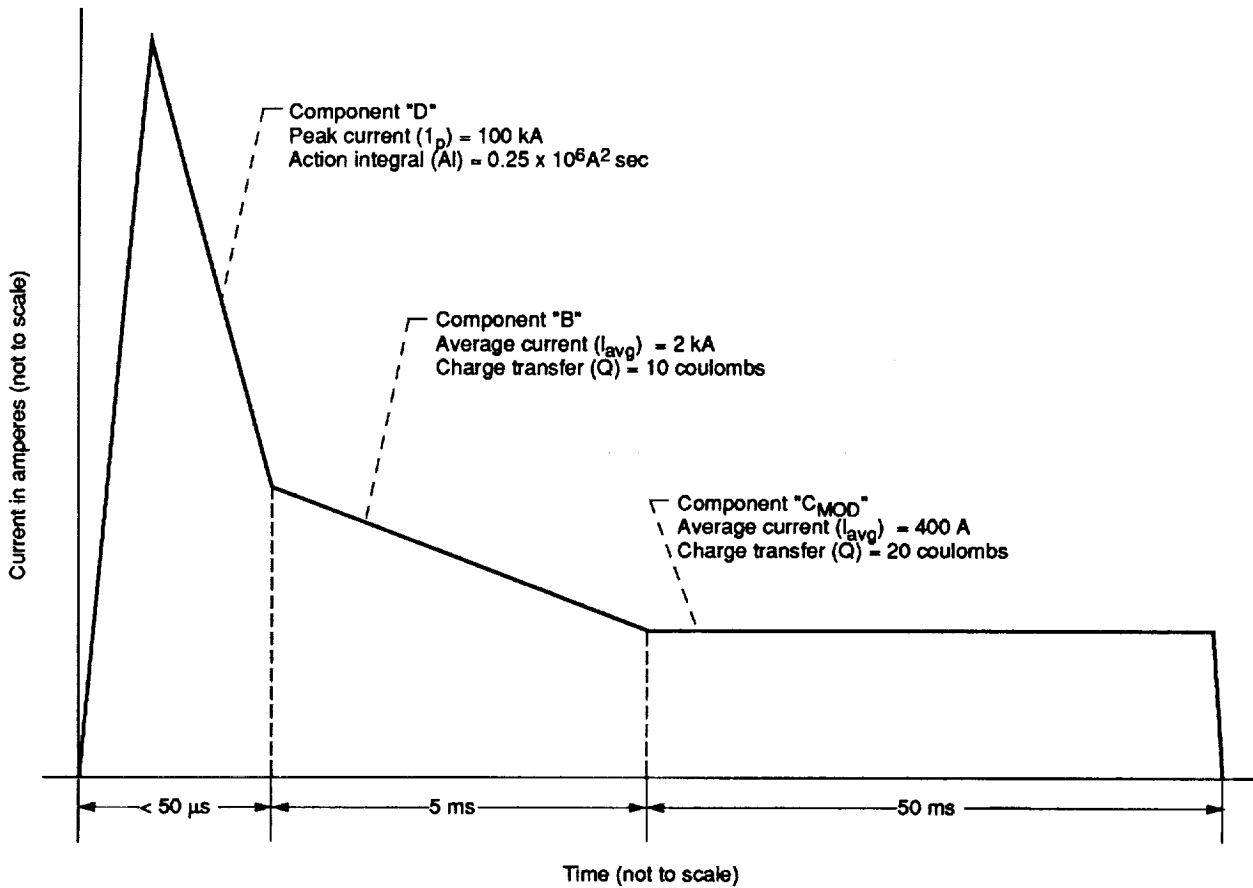


Figure 2.—Zone 2A simultaneous "D-B-C_{MOD}" current waveform.

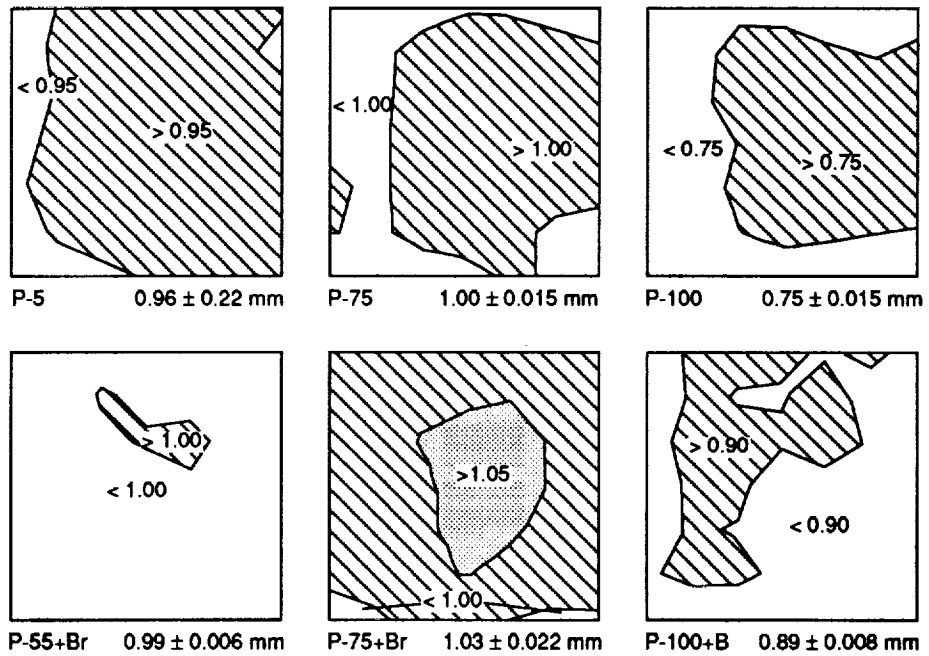


Figure 3.—Average laminate thickness.

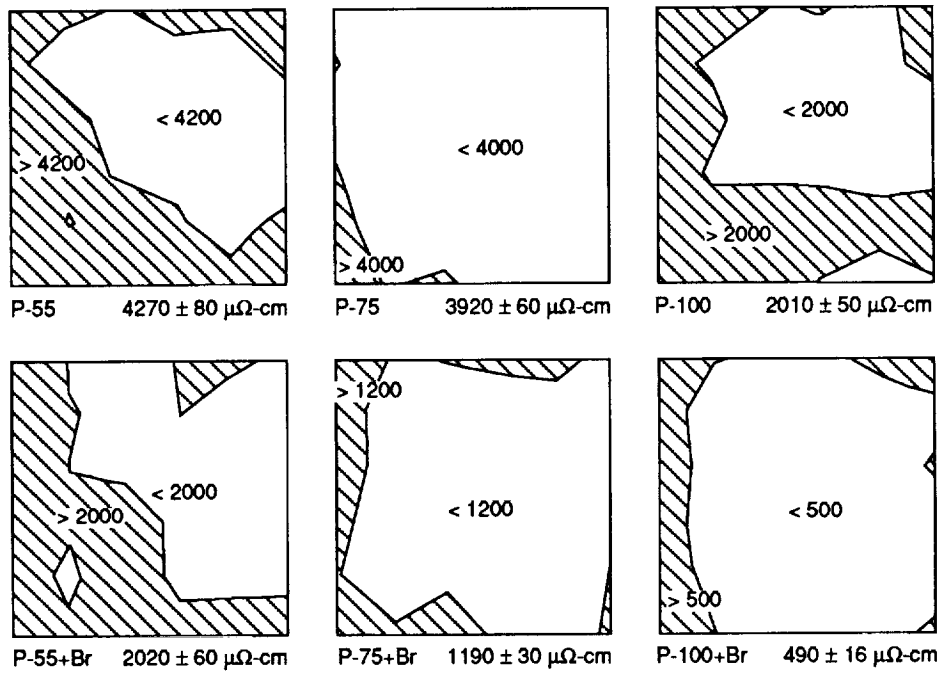


Figure 4.—Average laminate R.F. eddy current resistivity.

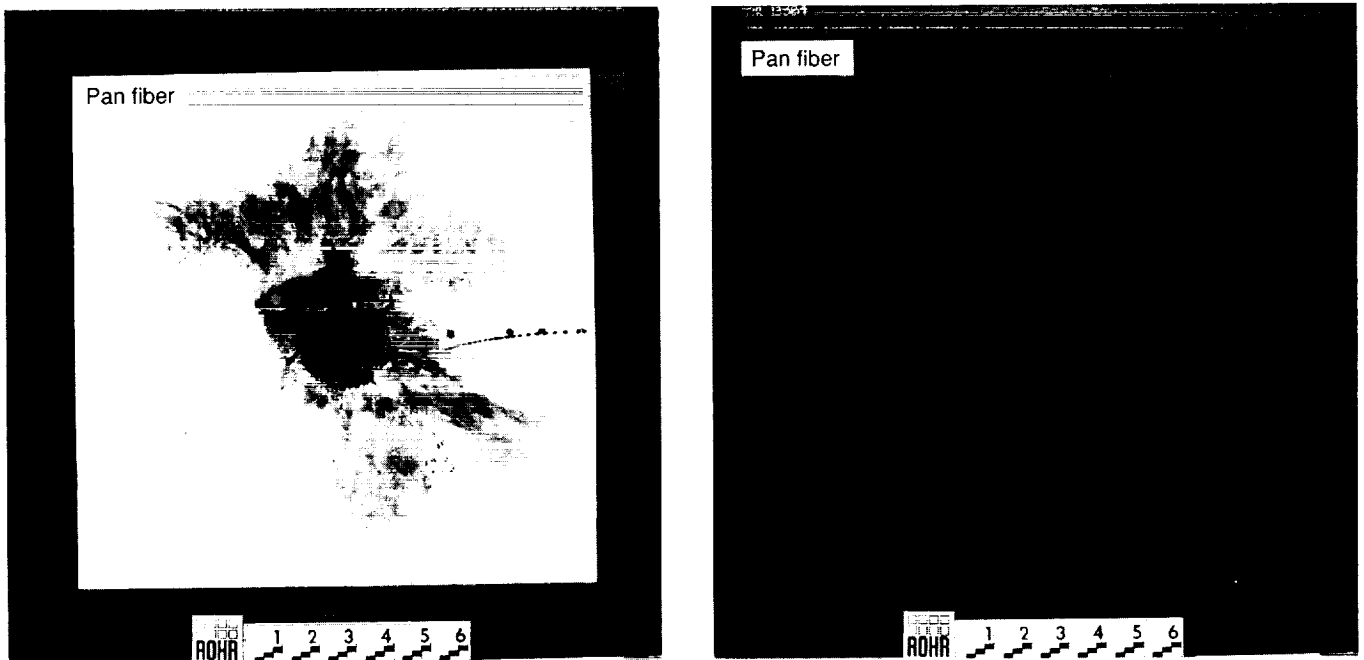


Figure 5.—Lightning strike damage on a painted PAN-based carbon fiber/epoxy composite.

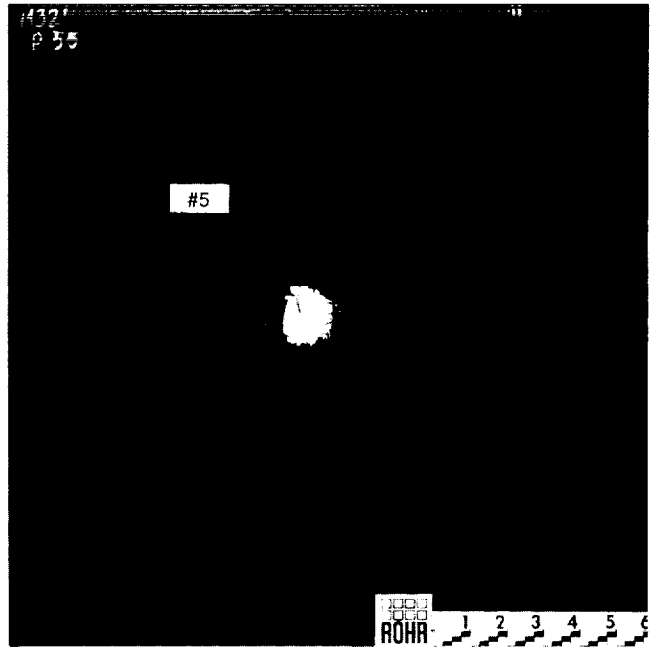


Figure 6.—Lightning strike damage on a painted P-55 pitch-based carbon fiber/epoxy composite.

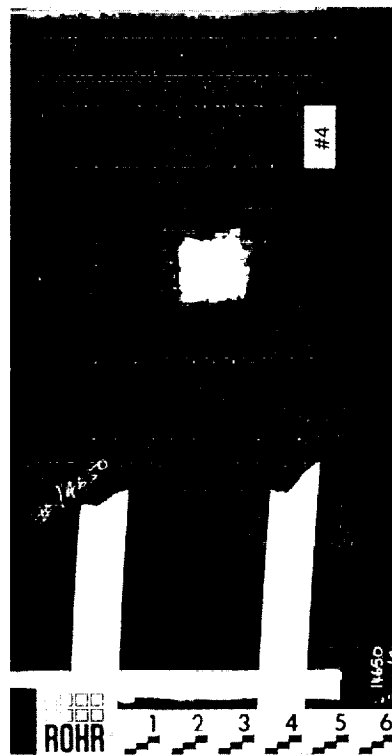
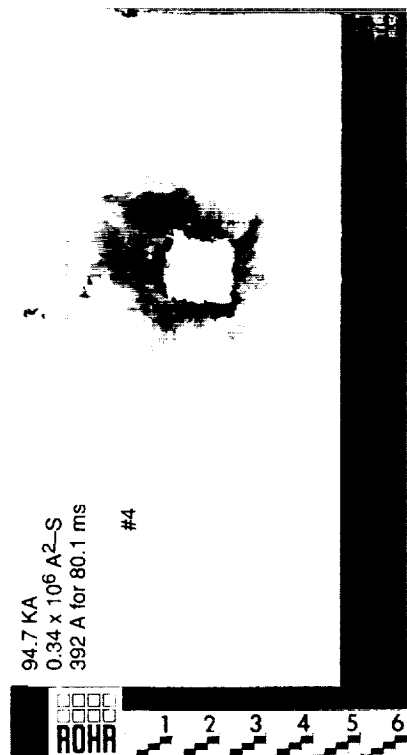


Figure 7.—Lightning strike damage on a painted bromine intercalated P-55 pitch-based carbon fiber/epoxy composite.

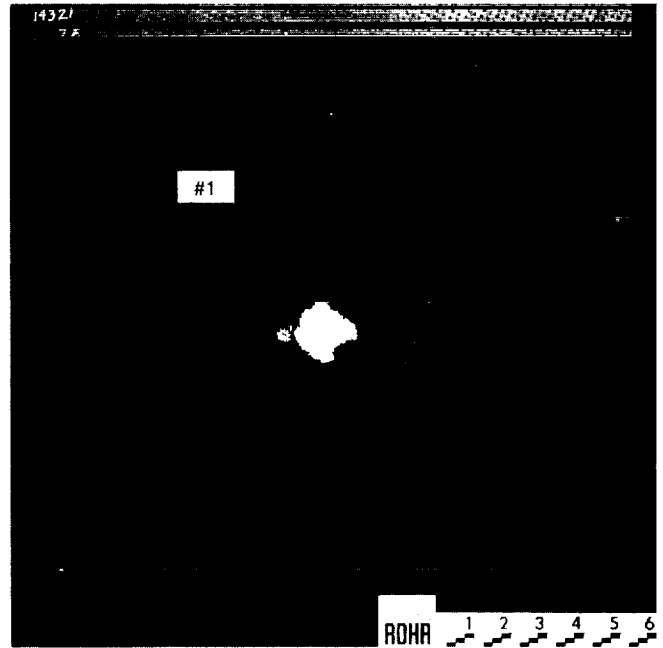
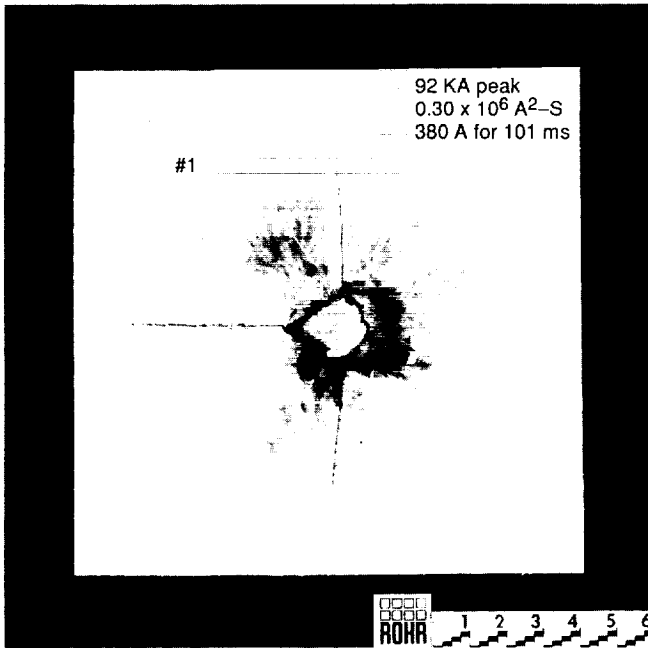


Figure 8.—Lightning strike damage on a painted P-75 pitch-based carbon fiber/epoxy composite.

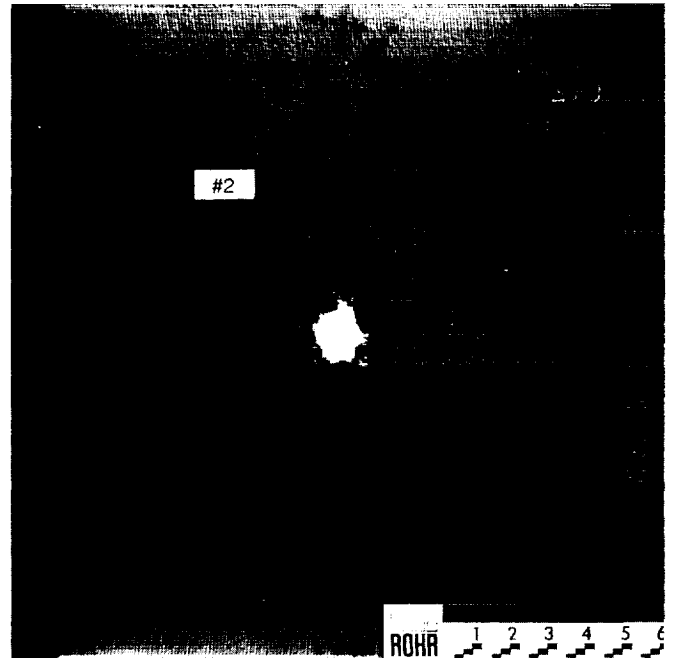
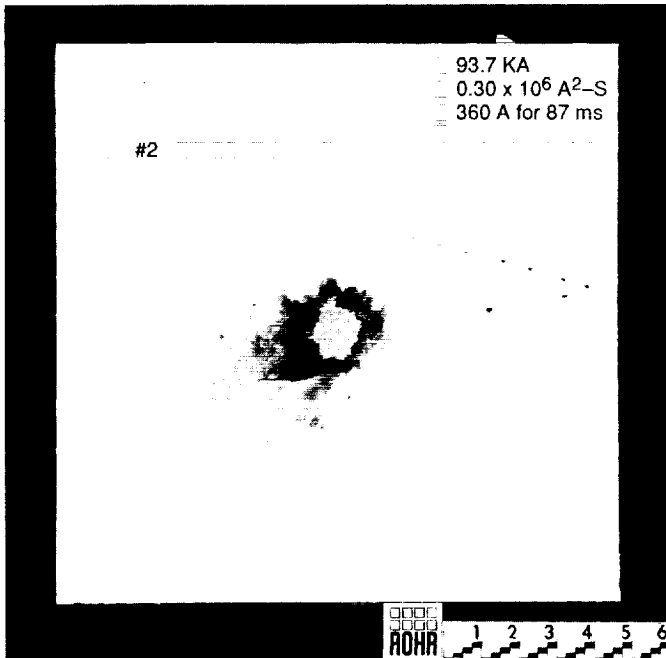


Figure 9.—Lightning strike damage on a painted bromine intercalated P-75 pitch-based carbon fiber/epoxy composite.

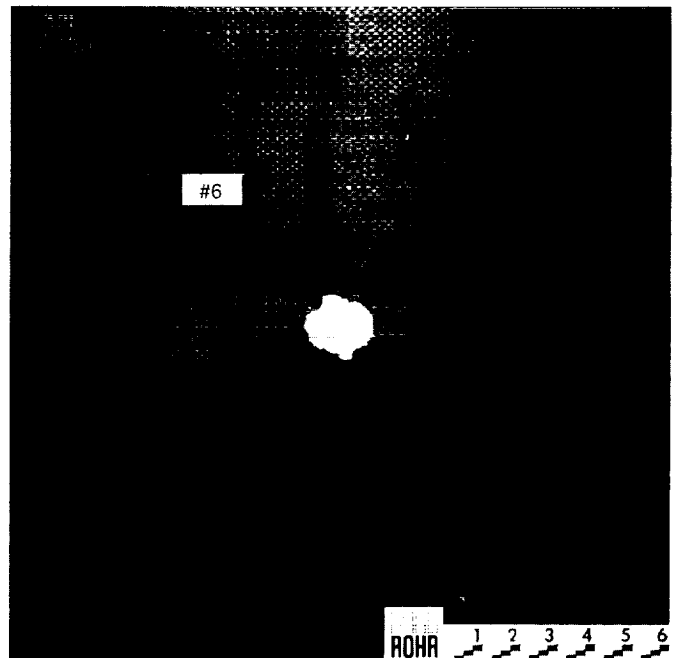
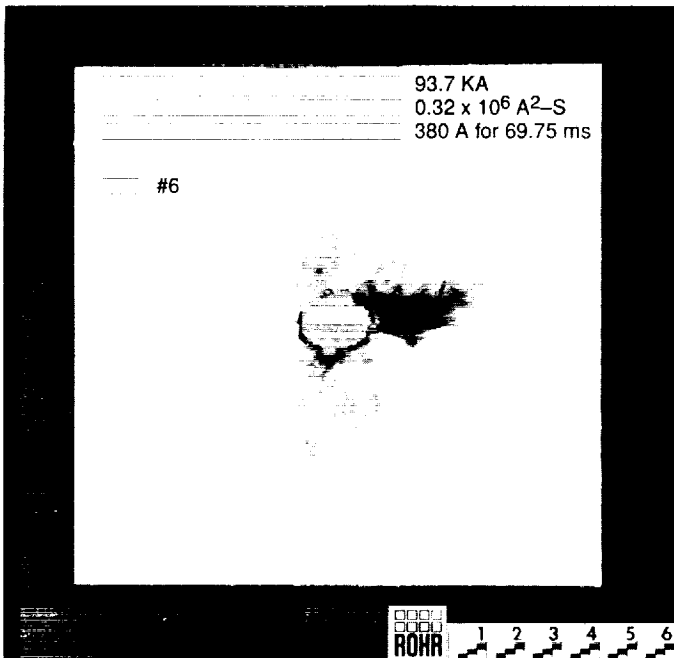


Figure 10.—Lightning strike damage on a painted P-100 pitch-based carbon fiber/epoxy composite.

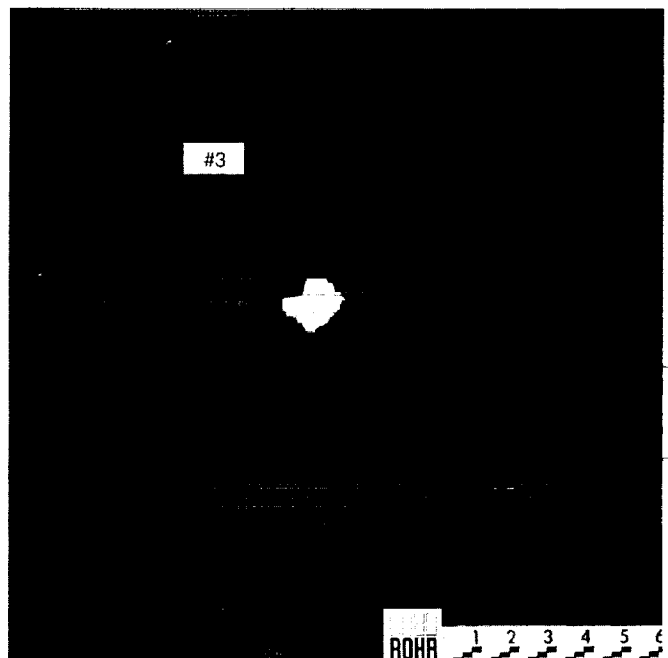


Figure 11.—Lightning strike damage on a painted bromine intercalated P-100 pitch-based carbon fiber/epoxy composite.

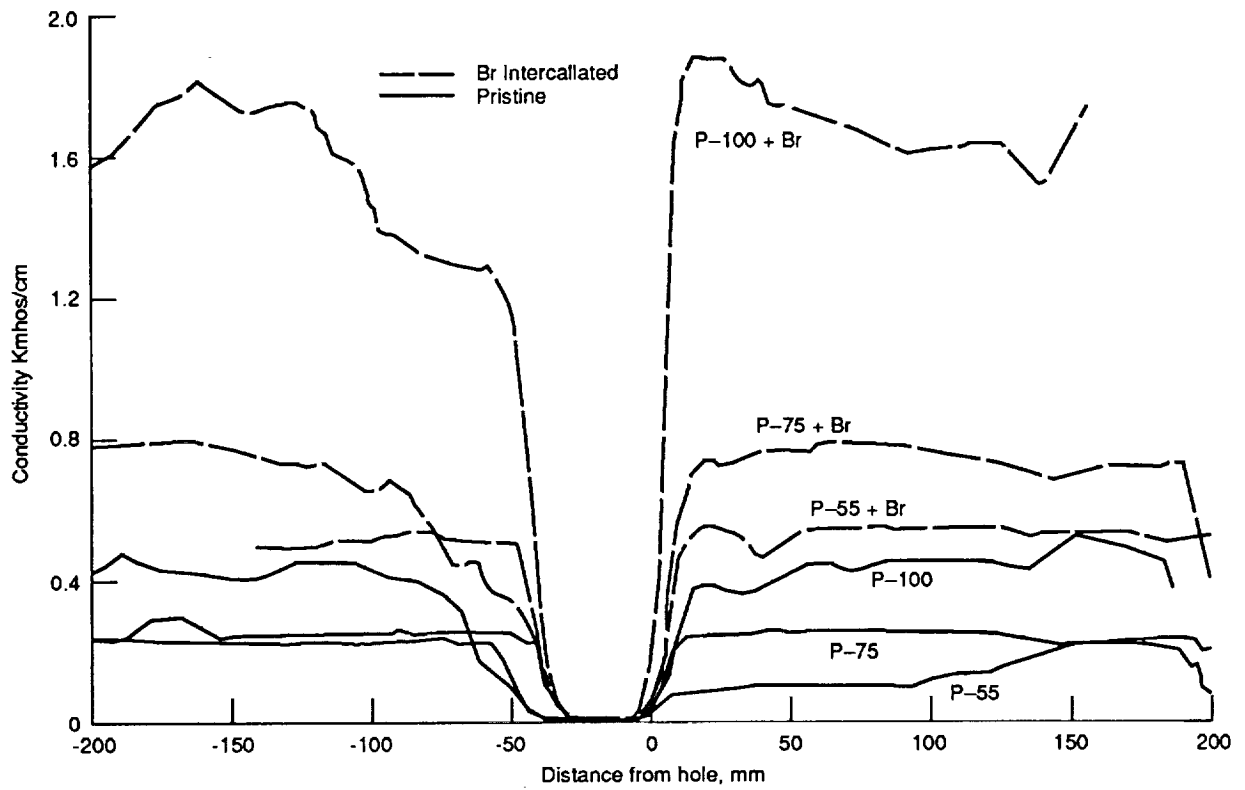


Figure 12.—The conductivity of composite samples near the lightning strike point.



National Aeronautics and
Space Administration

Report Documentation Page

1. Report No. NASA TM-104507		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Effect of Lightning Strike on Bromine Intercalated Graphite Fiber/Epoxy Composites				5. Report Date August 1991	
				6. Performing Organization Code	
7. Author(s) James R. Gaier, Melissa E. Slabe, and Norman O. Brink				8. Performing Organization Report No. E-6370	
				10. Work Unit No. 506-41-41	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001				14. Sponsoring Agency Code	
15. Supplementary Notes James R. Gaier, NASA Lewis Research Center; Melissa E. Slabe, Cleveland State University, Cleveland, Ohio 44115; Norman O. Brink, Rohr Industries, Inc., Chula Vista, California 92012. Responsible person, James R. Gaier, (216) 433-2311.					
16. Abstract Laminar composites were fabricated from pristine and bromine intercalated pitch-based graphite fibers. It was found that laminar composites could be fabricated using either pristine or intercalated graphite fibers using standard fabrication techniques. The intercalated graphite fiber composites had electrical properties which were markedly improved over both the corresponding pitch-based and PAN-based composites. Despite composites resistivities more than an order of magnitude lower for the pitch-based fiber composites, the lightning strike resistance was poorer than that of the PAN-based fiber composites. This leads to the conclusion that the mechanical properties of the pitch-fibers are more important than electrical or thermal properties in determining the lightning strike resistance. Based on indicated lightning strike tolerance for high elongation to failure materials, the use of vapor-grown, rather than pitch-based graphite fibers appears promising. POLYACRYLONITRILE					
17. Key Words (Suggested by Author(s)) Carbon fibers Graphite-epoxy composites Lightning protection Graphite intercalation compounds			18. Distribution Statement Unclassified - Unlimited Subject Categories 03 and 24		
19. Security Classif. (of the report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 18	22. Price* A03