SOURCE OF RELEASED CARBON FIBERS

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The first of the elements in the Langley risk analysis program is concerned with the source of released carbon fibers. Although there have been, to our knowledge, no crashes of civilian aircraft containing carbon composite parts, there have been several crashes of military planes carrying carbon composites which have demonstrated the high potential for the release of carbon fibers from the ensuing fires. With this military experience and the body of accident statistics for commercial aviation to draw on, we must face the inevitability of crashes and fires involving commercial aircraft with carbon fiber composites.

In the absence of actual experience, we have had to study ways to simulate the conditions of aircraft crash fires in order to predict the quantities and forms of fibrous materials which might be released from civilian aircraft crashes/fires. The following figures will describe some typical fiber release test activities which have been conducted, together with some very preliminary results of those activities. Following that, the status of our knowledge of carbon fiber release from simulated aircraft fires will be summarized, as well as some of the uncertainties in our knowledge of accidental fiber release.

Prior to NASA's involvement in the carbon fiber program, most of the knowledge of carbon fiber release resulted from investigations by the Navy. This testing is outlined in figure 1. Most of the fundamental studies of the burning of carbon fiber composites and fiber release were conducted at the Naval Research Laboratory, where the rates of composite combustion at low, moderate, and high fire temperatures were studied. The NRL researchers also noted the formation of a char, or "coke," resulting from the combustion of the epoxy resins. This char was observed to serve as a binder which tended to prevent the release of single carbon fibers from the burned composite residue. When single fibers were released, they were generally short. The NRL workers observed that some form of agitation was required to release any significant number of single fibers, and they also found an effect of thickness; that is, the thinner the composite, the more readily fibers were released.

The Navy's Dahlgren, Virginia laboratory developed a test involving a burn/explosion cycle for studying carbon fiber release. From the testing of one square foot flat composite plates in the chamber, they demonstrated there was a minimal release of carbon fibers when the composite was burned only, without the explosion. They showed that the same minimal release resulted when the

PRE-NASA CARBON FIBER RELEASE TESTING

NAVAL RESEARCH LABORATORY

- STUDIED COMPOSITE BURNING RATES
- NOTED EPOXY CHAR BINDER ON FIBERS
- OBSERVED SHORT LENGTHS OF RELEASED FIBERS
- NOTED TURBULENCE REQUIREMENT FOR RELEASE OF FIBERS
- NOTED COMPOSITE THICKNESS EFFECT

NAVAL/DAHLGREN CHAMBER

- DEVELOPED BURN/EXPLODE FOR COMPOSITES
- DEMONSTRATED MINIMAL RELEASE FROM BURN ONLY
- DEMONSTRATED MINIMAL RELEASE EXPLODED ONLY
- OBTAINED 15-20% SINGLE FIBER RELEASE FROM BURN/EXPLODE

Figure 1

composite was impacted explosively, without burning off the resinous binder. From the burning and exploding of the flat composite plates, they obtained 15-20% release of single fibers and lint (clusters of several single fibers), based on the amount of carbon fibers initially present in the composite.

This Navy work was pioneering and many of the results cited in the following presentation are in keeping with the Navy studies; the NASA results generally confirm or quantify those earlier findings.

The carbon fiber release test facilities listed in Figure 2 are those which have been closely coordinated into a NASA test program. The laboratory studies, which are of an exploratory nature, are being conducted at both the Langley and Ames laboratories of NASA. The chamber studies are those which not only burn and agitate or impact the composites, but also collect, measure, and count the fibrous residues which are produced. The only outdoor or range fiber release testing was done in the spring of 1978 by TRW, Inc., under the sponsorship of the Air Force and with the cooperation of the Navy at the Naval Weapons Center, China Lake, California. Presently, NASA has contracted with TRW to complete the reduction and analysis of the data resulting from

NASA CARBON FIBER RELEASE TEST FACILITIES

LABORATORY	-	NASA - LANGLEY NASA - AMES
CHAMBER	-	NASA - AMES NAVY - DAHLGREN AVCO CORPORATION
OUTDOOR	-	AIR FORCE/NAVY/TRW - CHINA LAKE

Figure 2

those tests, and for that reason, it is considered an ongoing test activity.

Some typical results from the simulated release of carbon fibers from laboratory testing will now be presented.

The information presented in figure 3 is intended to give a perspective on the thermal characteristics of carbon fibers. The comparative levels of heat resistance of several carbonaceous materials are presented by means of the thermogravimetric analysis of the carbon forms. Thermogravimetric analysis simply involves the heating of a material at a certain rate and in a particular environment (in this case at a rate of 5°C/minute in air) and measuring the subsequent weight loss. Obviously, diamond is the most thermally stable form of carbon, although it can still be burned if it is heated sufficiently high with enough air present. At the other extreme are the organic resins, in this case epoxy, which begin to lose weight when heated to a relatively low temperature, and which are almost completely burned up, except for a small amount of char, at about 400°C. Pyrolytic graphite is a relatively stable form of carbon, and some of the more "graphitic" fibers, such as GY 70, resist heat almost to the same degree as pyrolytic graphite. Fibers such as AS and T300 display thermogravimetric curves virtually identical to that of carbon

THERMOGRAVIMETRIC ANALYSIS OF CARBONACEOUS MATERIALS

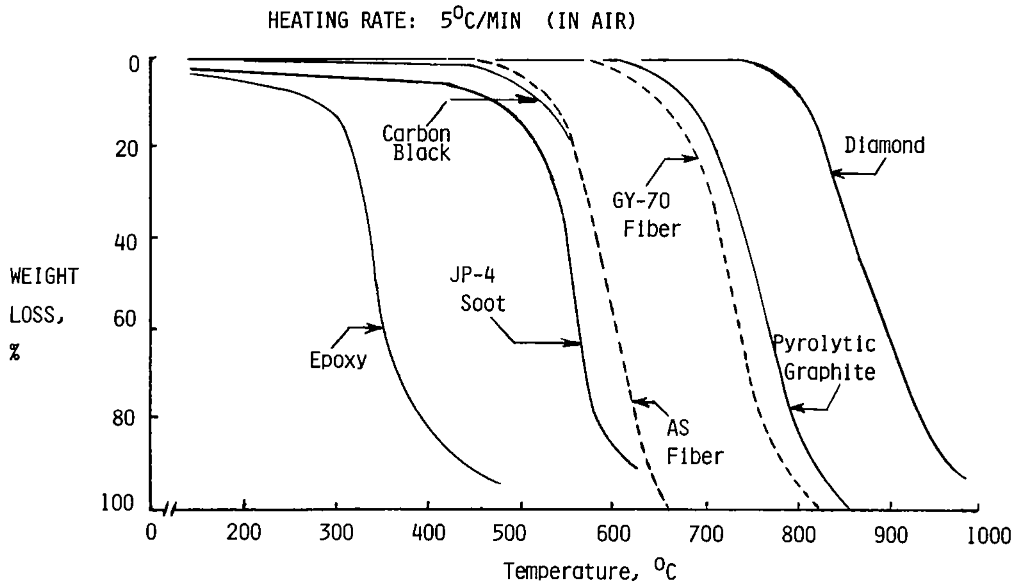


Figure 3

black, confirming the manufacturer's opinions that those products are carbon, and not graphite, in nature. The lower level of stability of JP-4 soot probably reflects the incomplete carbonization of the fuel precursor.

Although thermogravimetry is only a simple tool for studying thermal behavior of materials, some obvious things are apparent from this figure. In a fire, the first part of a carbon/epoxy composite to burn off will be the epoxy resin, and even the epoxy char will completely burn up before the fibers. Further, if JP-4 soot (or other jet fuel residues) are given off, it's an excellent bet that carbon fibers will survive the fire and be available for dispersion. And lastly, it is apparent that the thermal resistance of carbon/graphite fibers differ considerably, and that difference must be considered in assessing the potential release of fibers from a fire.

The apparatus shown in figure 4 is called the "Toonerville Trolley" at Langley, where it was built for the burning of composites with jet fuel. Most of the early composite burn work has been performed using "clean" propane fuel, because of the difficulty in analyzing the results of fiber release when composites are burned with messy, sooty, kerosene-based fuels. This

COMPOSITE BURNER

Figure 4

burner has been used fairly successfully at Langley to burn small composite samples, about 2" x 2" in size, with the oxidation products being carried through the inverted "U" stovepipe into the chamber at the bottom, where the fibers and large soot particles are filtered before exiting to the outside.

Figure 5 shows the results of burning several different virgin fibers, not composites, in the Langley oil burner. It is apparent that the two fibers most commonly used in aerospace composites, AS and T300, were completely oxidized in the short time of 1-1/2 minutes at 800°C, which is a moderate-to-low JP-4 fuel fire temperature. On the other hand, the more so-called "graphitic" fibers, Celion and HMS, are barely affected by the fire in the first 1-1/2 minutes, although prolonged exposures of 3 and 10 minutes at 800°C do burn them to a considerable extent. However, exposures of Celion and HMS to the hotter fire temperature of 1000°C causes large weight loss in rapid order, and at the very hot JP-4 fire temperature of 1200°C, even HMS can be burned completely in short order. These results support the proposition given previously that the differing thermal behavior of various fibers must be considered in studying carbon fiber release from fires.

OXIDATION OF CARBON FIBER WITH JP-4

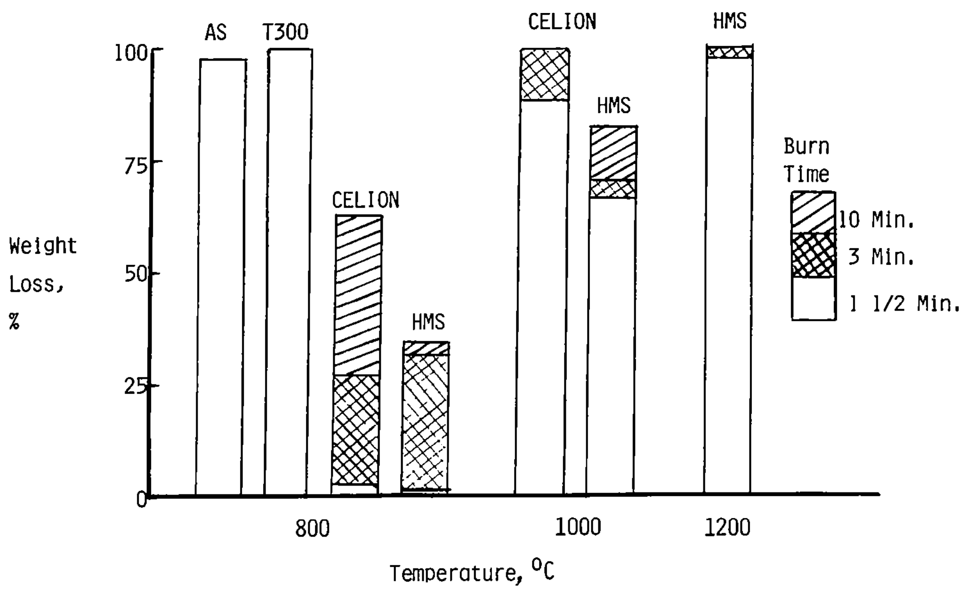


Figure 5

The previous figures have shown some results from laboratory testing, which has been relatively fundamental in nature. The next investigations to be reported deal with the simulated release of fibers by means of chamber testing.

The tests at the Naval Surface Weapons Center, Dahlgren, Virginia are conducted in a room within a large hemispherical chamber. The room is approximately 40 ft x 24 ft in size, with about 10 ft ceilings, as shown in figure 6. Composite specimens, preferably about 1 ft^2 in size, are mounted horizontally in the test fixture in the middle of the room. A propane burner, shown to the right of the test figure, is swung beneath the sample, which is burned for the desired time, up to 20 minutes. The burner is then swung away, and a conically-shaped explosive charge on the left is swung beneath the burned composite residue and detonated. The fibers and fragments from the composite are thrown throughout the room and deposited on 8" x 10" pieces of "sticky" paper laid out in a grid over the room. The sheets of paper are then removed and a representative sample of the grid is then counted by a statistical technique at Dugway Proving Ground in Utah. Only single fibers are precisely counted by that method, but a crude mass balance of the residue produced from each test is obtained via hand-pickup, sweeping, and vacuuming.

NAVY–DAHLGREN CHAMBER TESTS

SAMPLE SIZE:

6" × 6" OR 12" × 12"

FIRE TEMPERATURE:

HIGH (2100°F)

FIRE FUEL:

PROPANE

IMPACT:

HIGH (2 oz OF C-4 EXPLOSIVE)

BURN/EXPLODE RESIDUE:

SECONDARY IMPACTS; FULL RECOVERY

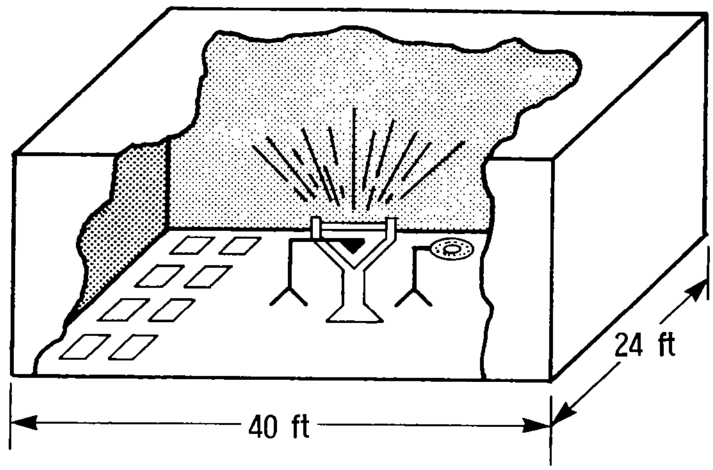
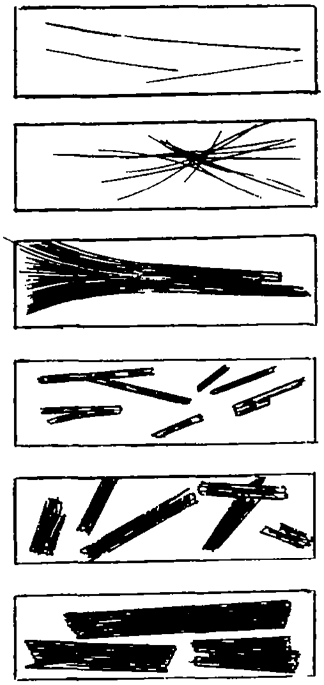


Figure 6

The conditions of this particular test method, from the standpoint of simulating an aircraft crash/fire scenario, are considered to be quite extreme. The fire temperature (2100°F) is fairly high, and certainly the impact produced by 2 ounces of C-4 explosive must be almost unrealistically high, at least for most commercial aircraft crashes. An undesirable effect of this test may be the fact that there is an opportunity for secondary impacts (against the ceiling and walls) of the blast fragments. However, a very desirable feature of the Dahlgren test is the complete recovery of all burn/explosion products.

Six representative fiber release categories designated by the Dahlgren test personnel are shown in Figure 7. Of most concern to date have been the first two, single fibers and lint consisting of several single fibers clumped together, due to their relatively low settling rates. The third category, the brush clump which looks rather like a paint brush, falls at such a rate to probably preclude its dispersion for long distances. The three blast fragment categories, arbitrarily divided up by sizes, probably represent a threat only to open electrical equipment in the immediate vicinity of the fire/explosion.

FIBER RELEASE CATEGORIES



Category	Fall Rates
1 - Single Fibers	3.2 cm/sec
2 - Lint	22 cm/sec
3 - Brush/clump	88 cm/sec
4 - Blast Fragments Width < 2 mm	152 cm/sec
5 - Blast Fragments Width 2-7 mm; Length < 25 mm	167 cm/sec
6 - Blast Fragments Width > 7 mm, Length > 17 mm	189 cm/sec

Figure 7

Prior to NASA's involvement, the Dahlgren test program had been confined to the burning of simple, flat composite plates. NASA then initiated a joint test program with the Navy to determine the relative tendencies for carbon fibers to be released when real composite aircraft parts are burned. Using the Dahlgren test chamber and burn/explosion sequence, a number of parts, as listed on figure 8, have been tested. Of those listed, only the results from the 737 spoiler and DC-10 rudder tests are complete.

This photograph of the 737 spoiler in figure 9 shows how the part was cut along the indicated grid of lines into a number of test specimens. The spoiler itself consists of 6-ply and 8-ply carbon/epoxy skins, with aluminum honeycomb between the skins. Since there was also a substantial amount of metal, in the form of the honeycomb, hinge fittings and frame, and close-out edges, etc., there was an opportunity to find if such factors as part thickness, metal content, etc. would influence the amount of single fiber released from the various specimens. The one-foot rule shown gives an idea of the size of the part, which is 22" x 52".

The results of the spoiler and rudder burn/explosion tests have been summarized in figure 10. A very definite finding was that the bulk of the single fibers released were very short - less

NASA/NAVY

COMPOSITE PARTS BURN TEST PROGRAM

- OBJECTIVE: DETERMINE RELATIVE TENDENCIES FOR FIBER RELEASE FROM ACTUAL COMPOSITE AIRCRAFT PARTS
- TEST FACILITY: NAVY CHAMBER AT DAHLGREN, VIRGINIA
- TEST PROCEDURE: BURN (PROPANE), BURN PLUS EXPLODE
- PARTS TESTED:
  - A. 737 SPOILER
  - B. DC-10 RUDDER
  - C. L-1011 AVF (MISCELLANEOUS TEST SPECIMENS)
  - D. 747 FLOORING
  - E. QCSEE FAN BLADE

Figure 8

737 SPOILER USED IN BURN TESTS

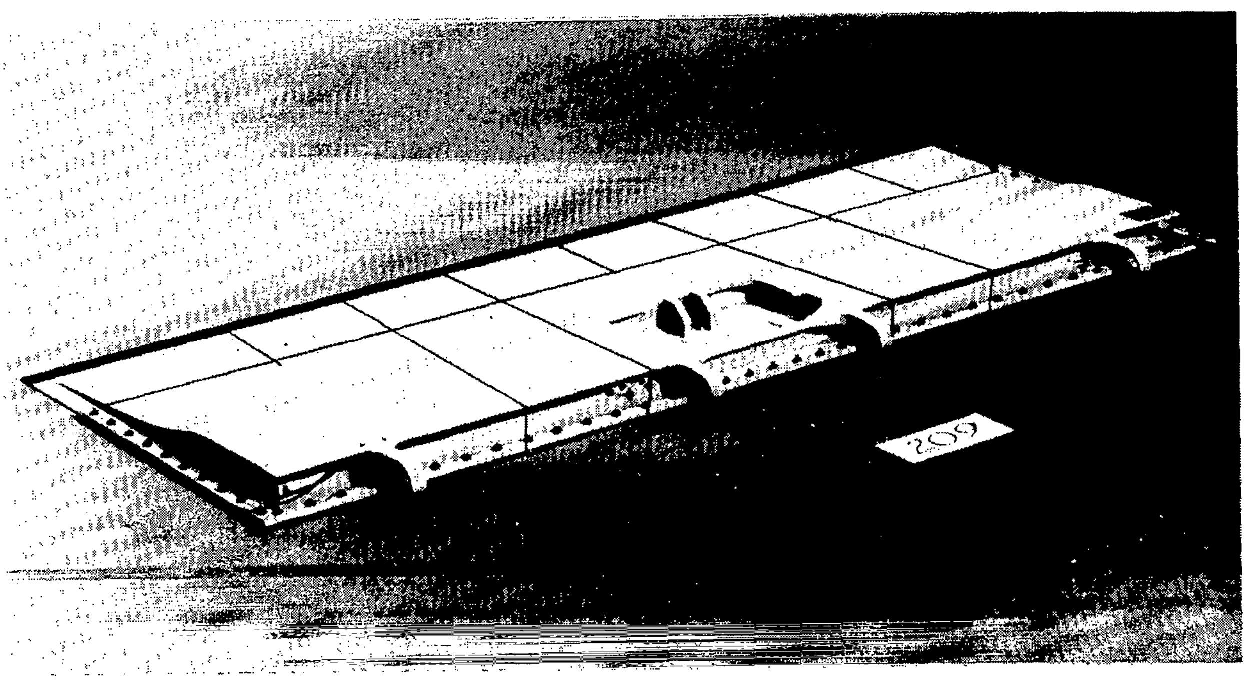


Figure 9

RESULTS OF BURN/EXPLODE TESTS ON
COMPOSITE SPOILER AND RUDDER

- SINGLE FIBERS ARE PREDOMINANTLY SHORT (< 3 MM)
- EXTENDED BURN TIMES YIELD LESS SINGLE FIBERS
- COMPOSITE PARTS WITH NON-COMBUSTIBLES YIELD LESS SINGLE FIBERS
- FEWER BLAST FRAGMENTS FROM SPOILER AND RUDDER THAN FROM THICK PLATES
- BURN/EXPLOSION OF RUDDER RELEASED 10% SINGLE FIBER
- BURN/EXPLOSION OF SPOILER RELEASED 12% SINGLE FIBER

Figure 10

than 2 millimeters in length. Qualitatively, it was noted that lengthy burn times resulted in the release of less single fibers, suggesting that the carbon fibers will burn up if given sufficient time. It also appeared that those specimens containing large amounts of noncombustible materials, such as metal and glass fiber, released less single fibers. The reason is not known, but perhaps the metal serves in some way as a heat sink to moderate the thermal effect on the composite; perhaps too, the aluminum honeycomb softens the impact of the explosive force on the composite skin.

Not surprisingly, fewer blast fragments were given off from the thin skins of the spoiler and rudder in contrast to the amount given off from thick composite plates. Although the amounts of single fiber released from individual test specimens varied widely, weighted averages of single fiber released from the rudder and spoiler tests were 10% and 12%, respectively. However, it should be emphasized that these quantities are single fiber only, and the results do not reflect the amounts of other fibrous residues which might represent a threat to electrical equipment.

A study to determine the effects of the various materials and structural parameters of composites on fiber release has also been conducted using the Navy's Dahlgren facilities. Fiber/resin compositions, laminate thickness, and layup configurations have been investigated by burning and exploding composite panels which have the variations indicated in figure 11. Although the actual tests have been completed, quantitative results which will reflect the relative amounts of fibers released are not yet available. However, we do have some indication of the relative importance of the parameters being studied.

COMPOSITE MATERIALS PARAMETERS STUDY

OBJECTIVE: DETERMINE RELEASE OF FIBER FROM RESIN/FIBER, THICKNESS, AND LAYUP VARIATIONS

APPROACH: BURN AND BURN/EXPLODE GRAPHITE/EPOXY PANELS IN NAVY/DAHLGREN CHAMBER; MEASURE RELATIVE AMOUNTS OF FIBER RELEASE

PARAMETERS:
- o FIBER/RESIN: T300/5208, AS/3501
- o LAMINATE THICKNESS: 1/16" , 1/8" , 1/4"
- o LAYUP: UNIDIRECTIONAL, CROSSPLY, WOVEN

Figure 11

Figure 12 is a photograph of the fiber residue which remained after a 2" x 2" unidirectional composite sample was burned with JP-4 fuel in the Langley "Toonerville Trolley" oil burner. The result is a rather firm, biscuit-like residue which retains the integrity of the fiber as it was laid up in the fabrication of the composite panel. It appears that fibers resulting from burned unidirectional composites naturally resist being released individually, either by virtue of the small amount of epoxy char which binds them together, or else as a result of the "cohesivity" of the fibers as they lay intimately in contact with each other for their entire length.

Figure 13 is a photo showing the results of impacting the unidirectional fiber residue "biscuit" with a .38 caliber prime load. An impact is required to cause such a fibrous residue to break up and permit the release of individual fibers.

FIBER RESIDUE FROM UNIDIRECTIONAL COMPOSITE

Figure 12

IMPACTED RESIDUE FROM UNIDIRECTIONAL COMPOSITE

Figure 13

The photo in figure 14 shows the manner in which the burning of the epoxy resin from cross-plied carbon/epoxy composites causes

RESIDUE FROM CROSS-PLY COMPOSITE

Figure 14

the individual plies to separate with no impact at all. It is apparent that the strength of cross-plied composite residues is very weak in the thickness direction, an observation in keeping with a knowledge of the mechanical properties of the unburned composites. Incidentally, the residues resulting from the burning of cross-plied composites in the crash fire of a military aircraft were virtually identical to those shown here from a test specimen.

The residue shown in the figure 15 photo resulted from burning a carbon/epoxy composite fabricated from woven carbon fiber, a method finding more and more use due to the ease of working with that form of fiber. Obviously, the weakness in this form of composite is also in the thickness direction of the composite, causing the individual plies to fall apart simply by burning off the adhesive epoxy resin. However, it also appears that the woven fiber residue must have a great tendency to resist the release of single fibers unless a substantial impact or agitation is applied to the burn residue.

Some preliminary results reflecting the effect of composite thickness on fiber release is shown in figure 16. Although fiber count from these tests is not yet available, a mass balance which

RESIDUE FROM WOVEN COMPOSITE

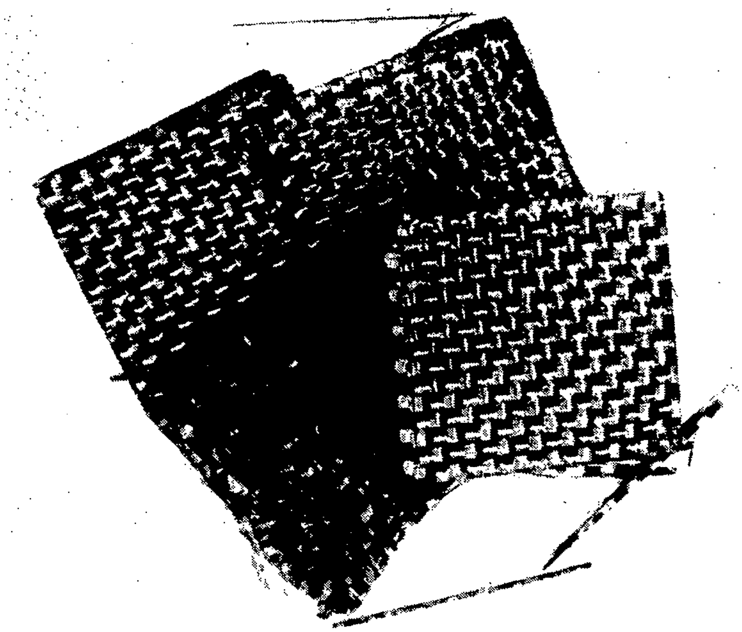


Figure 15

EFFECT OF COMPOSITE THICKNESS ON
RELEASE OF FIBROUS PARTICLES (PRELIM.)

DAHLGREN BURN/EXPLODE TEST
AS/3501 CROSS PLY PANELS

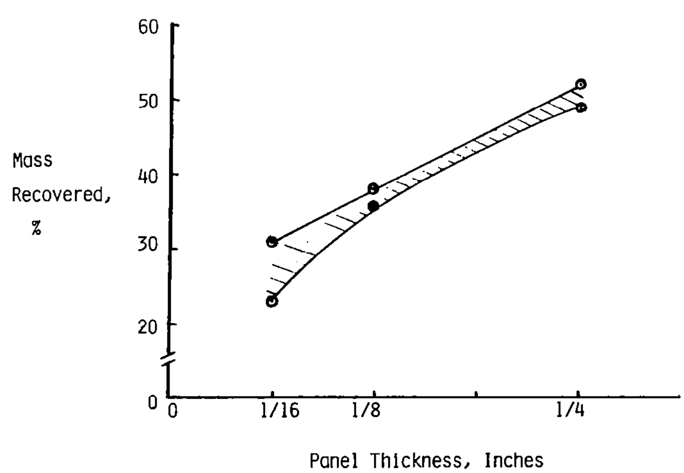


Figure 16

includes all forms of fiber residue resulting after the burn/explosion of six composite panels of three different thicknesses clearly indicates that the thinner the composite skins, the more fiber will be burned away. It should be stressed that this would be expected given the identical flame conditions. Nevertheless, it lends substance to early observations made by a number of researchers, included those at the Naval Research Laboratory.

Figure 17 diagrams the fiber release test facility at Redwood City, California which is being operated for NASA - Ames, and is just beginning to generate useful fiber release data. The major portion of the facility is at the right and includes a burner system using highly radiant gas burners, with provisions for nitrogen to cool the temperature or to modify the fire environment. The sample, preferably a 1 foot by 1 foot composite panel, is mounted horizontally as shown in the fire chamber. After the sample has been burned for the desired period of time, a projectile of a chosen weight is dropped from a chosen height and impacts the center of the burned composite sample. Immediately upon impact, a cover falls over the impacted sample to contain all the impact residue. The residue is then collected and counted to complete the test. At the present time, this facility is designed only to study burn and impact test cycles. However, NASA-Ames does plan to modify it to study burn-only situations. The scrubber-cooler is utilized to remove any carbon fiber which might be inadvertently carried in the gas flow stream, and a high

FIBER RELEASE TEST FACILITY AT REDWOOD CITY, CALIF.

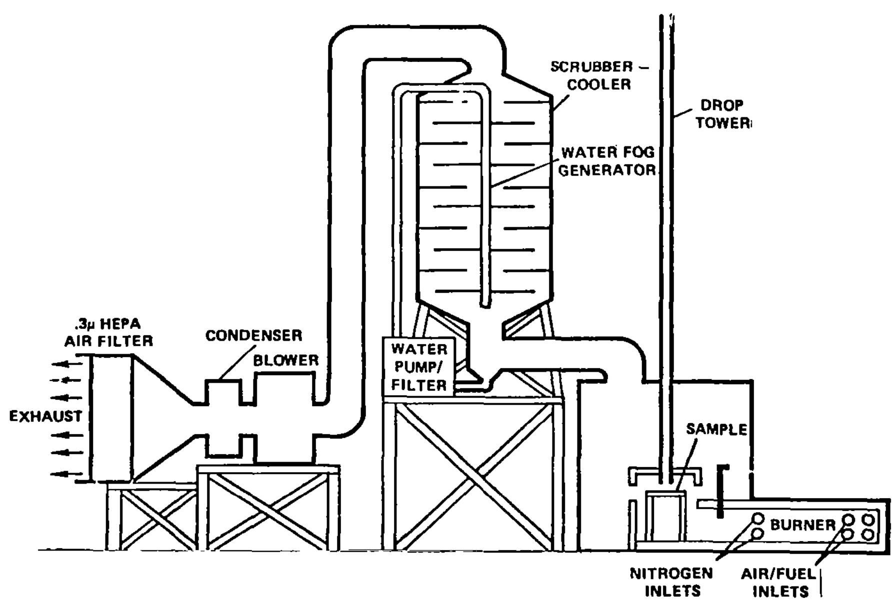


Figure 17

efficiency filter serves to make certain no fiber is released to the outside environment.

The photograph in figure 18 shows the state of a burned composite test panel after the impact. The cross-plied composite is seen to be severely shattered by the impact, suggesting the presence of some residual epoxy char has tended to hold the individual fibers together.

BURNED COMPOSITE TEST PANEL AFTER IMPACT

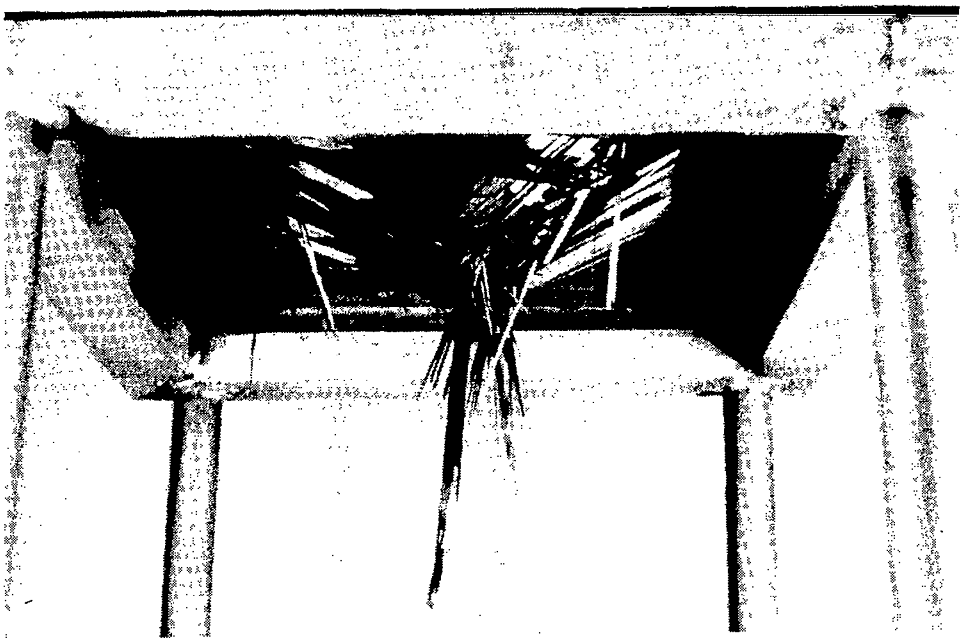


Figure 18

The photo in figure 19 shows the types of fragments which were released from the impacted composite panel shown previously. Not visible to the eye in this photo are any single carbon fibers which might have been released.

Figure 20 shows the spectrum of lengths of single fibers which were released from a cross-plied composite burned and impacted in the Redwood City facility. The histogram clearly shows that the large majority of fibers released in this test were very short, less than 3 millimeters in length, and this finding is in agreement with those results obtained in the Dahlgren test chamber. However, in this particular test, the energy of impact of less than 60 foot-pounds must be considered to be very low in comparison to the explosive impact of the Dahlgren test, and indeed the amount of single fibers released in this test was very slight: less than 0.1% of the weight of carbon fiber initially

FRAGMENT TYPES RELEASED FROM IMPACTED COMPOSITE PANEL

Figure 19

FIBER LENGTH SPECTRUM

Tested at NASA/Ames-Redwood Facility

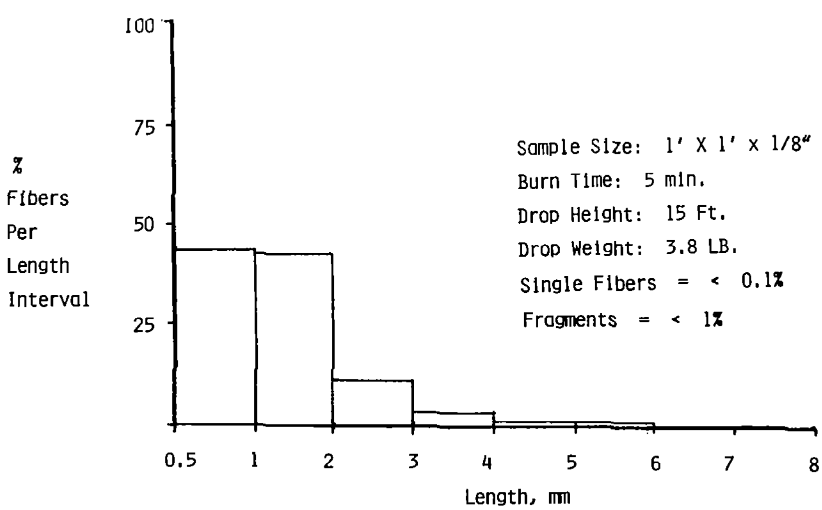


Figure 20

present in the composite panel. Furthermore, the quantity of total fragments released in this test, less than 1% of the total carbon fiber in the composite, was far less than the total fragments released in the Dahlgren test.

Figure 21 pertains to a very interesting and potentially useful test activity being conducted at the Navy's Aircraft Survivability Laboratory at China Lake. Some of the conditions which might be present during an in-flight fire are simulated by placing a 6" x 6" x 1/2" composite panel, which in some cases has a round hole or notch cut through it and in others has a slot cut across the entire leading edge of the panel, over a fire box containing burning jet fuel. Air at various velocities is passed over the test panel and the rate of composite material loss is determined. The results shown in this figure show that the rate of mass loss increases with exposure time and then reaches a constant rate for each air speed. Presently, the test only determines mass loss, but plans are being made with the assistance of NASA - Ames personnel to monitor carbon fiber loss from the burning panels. Such a test could be very useful in answering future questions regarding release of carbon fibers from composite-containing aircraft which would be burning in flight.

SIMULATED IN-FLIGHT COMPOSITE FLAMMABILITY TEST

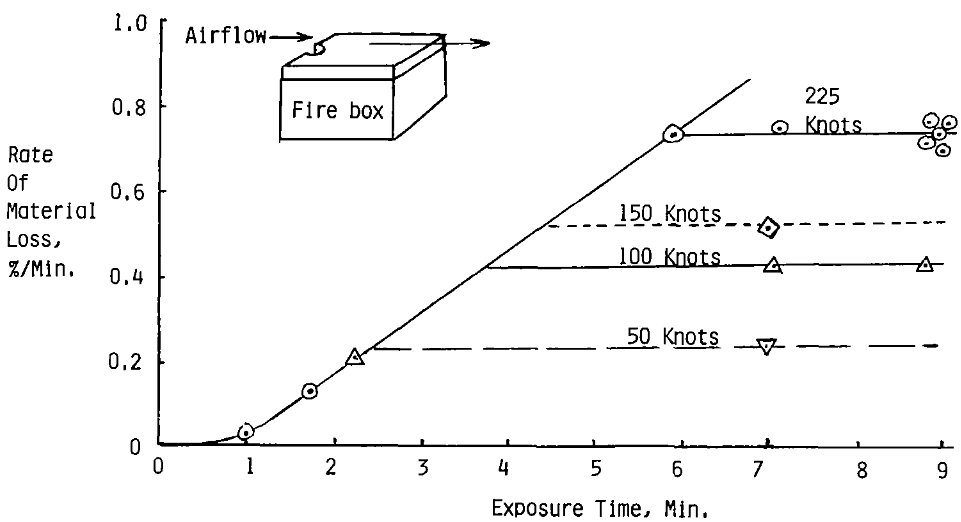


Figure 21

The next series of figures will describe the results of the only large scale outdoor composite burn tests to have been carried out to date.

These tests are outlined in figure 22. TRW began its series of outdoor burn and fiber release tests for the Air Force by burning three standard one square foot composite plates in separate tests, followed by an explosion to impact the fibrous residue in a unique but simple outdoor facility at their Capistrana, California Test Site. These tests, which were intended to parallel the conditions of the Dahlgren test, were conducted in a 15 foot by 15 foot tent with screen walls, thus allowing for the retention of all but the finest burn/blast fibers and fragments.

AIR FORCE/TRW OUTDOOR

COMPOSITE BURN AND FIBER RELEASE PROGRAM

- CAPISTRANO

  THREE 1 ft^2 X 1/4" PLATES (PROPANE FUEL)

- CHINA LAKE
  - THREE COMPOSITE PLATES, 1 ft^2 X 1/4" (Propane fuel)
  - THREE COMPOSITE BARREL BURN TESTS (PROPANE, JP-5 FUEL)
  - COMPOSITE SPOILERS BURN TEST (JP-5)
  - F-16 COCKPIT BURN TEST (JP-5)

Figure 22

Following those preliminary tests, eight more tests were carried out at China Lake. First three individual flat plates were burned with propane, and then a 2 foot diameter by 3 foot tall composite barrel, consisting of thin 2-ply filament wound inner and outer skins containing a Nomex honeycomb core, was burned with propane. That was followed by the burning of two half-barrels, segmented in the length direction, one first with propane, and the second with JP-5. The next test involved the burn of three 737 test spoilers at one time in a very large JP-5 pool fire. Finally, an experimental F-16 cockpit containing several types of carbon composite pieces was burned in a JP-5 pool fire.

The photograph, figure 23, of the test site at the Naval Weapons Center, China Lake, California shows why such a range was chosen. It was obviously suited for releasing fibers into the open environment without fear of affecting electrical equipment. The asphalt test pad at the left was heavily instrumented with appropriate fiber detection and measuring equipment, and the desert to the left of the pad was also instrumented for distances up to 6000 feet.

NAVAL WEAPONS CENTER TEST SITE

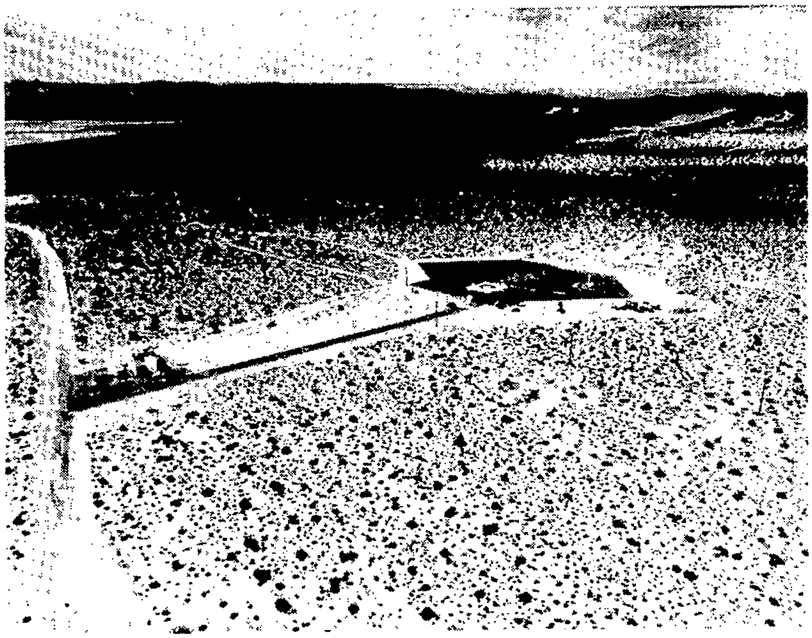


Figure 23

The various methods used by TRW to accumulate fiber release data is summarized in figure 24. The passive methods at the left resulted in a measure of the deposition of fibrous residues, while the active instrumentation on the right gave a time resolution of the fibers released. The sticky paper, which caught and held the falling fibers, were used as 8" x 10" sheets, 8" x 6' strips, and 8" wide rolls as long as 200 feet. The fine-meshed bridal veil fabric was used in several ways. Small cans about the size of tuna fish cans had both ends removed, and bridal veil was mounted over one end. The tuna cans were then placed vertically, normal to the direction of the air flow so that any fibers in the air flow would pass through the open end of the can and be trapped on the bridal veil. Bridal veil was also placed over 8" x 10" vugraph frames and mounted vertically, and it was even placed over 9' x 10' frames. For one particular test, a "Jacob's Ladder" 90' x 90' in size was used to suspend 342 bridal-

METHODS USED TO

DETECT, MEASURE, AND COLLECT CARBON FIBERS

PASSIVE	ACTIVE
STICKY PAPER (SHEETS, STRIPS AND ROLLS)	LIGHT EMITTING DIODES
BRIDAL VEIL OVER OPEN-END "TUNA" CANS	MICROWAVE
BRIDAL VEIL VUGRAPHS (8" X 10")	BRASS BALL DETECTORS
BRIDAL VEIL FRAMES (9' X 10')	LADAR
BRIDAL VEIL VUGRAPHS ON 90' X 90' "JACOBS LADDER"	THERMOCOUPLES (SAMPLE AND FLAME)
HAND PICKUP FROM TEST PAD	FLAME VELOCIMETER
RANGE SWEEP BRIGADE	PLUS
	PHOTOGRAPHY (INFRARED AND VISUAL)
	METEROLOGICAL EQUIPMENT

Figure 24

veil vugraphs to monitor a large cross-section of the air flow. Hand pickups by test personnel gathered burn and blast fragments from the asphalt test pad, while a "sweep brigade" of all test personnel covered the desert for up to 6000 feet after the spoiler burn test, collecting fibrous residues which had been lofted for such distances.

Of the active techniques, the first three (light emitting diodes, microwave, and brass ball detectors) monitored the passage of individual fibers, while the remainder in the list monitored the fiber and fire clouds. The principle and operation of the novel brass ball detectors has been presented in an exhibit at the rear of this hall.

The enlarged photograph of the fibers collected on the bridal veil of a tuna can collector, figure 25 illustrates the nature of the fibers given off and collected from the composite barrel burn test. The size of the mesh is approximately one millimeter, so you can see that in general, the single fibers are quite short, perhaps mostly 2-3 millimeters or less (with a few exceptions). The clustered mass of fibers in the lower right are typical of many clusters which resulted from the barrel burn test, and could probably be considered the hallmark of that particular test.

BARREL TEST 8 - TUNA CAN RECORD

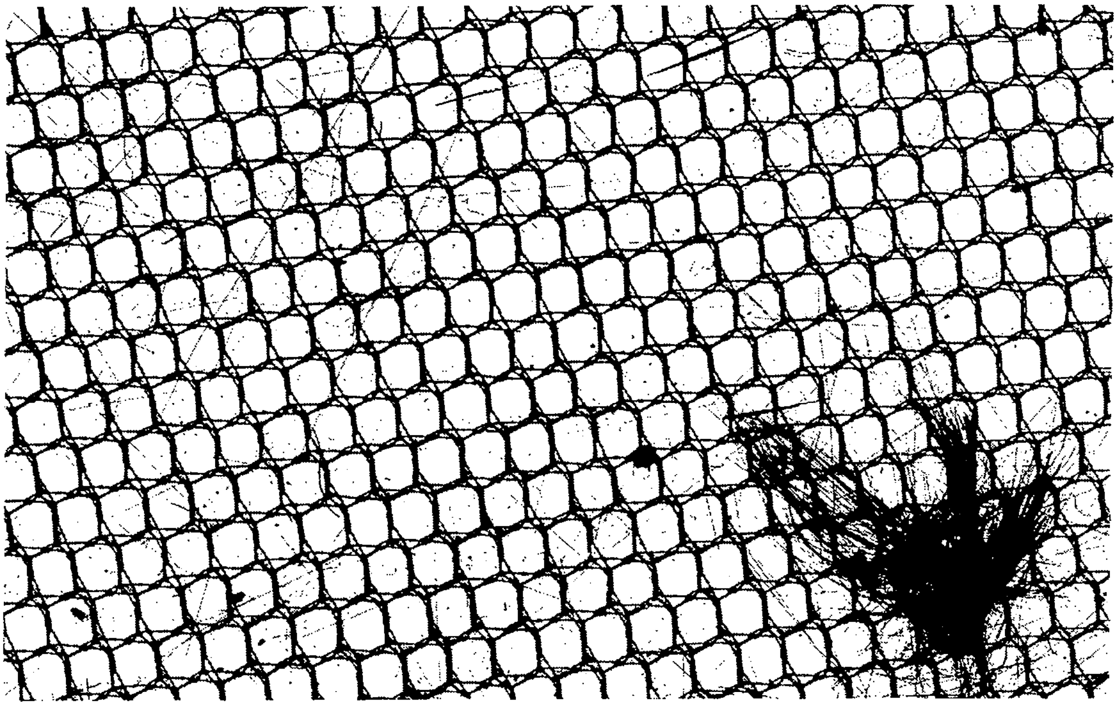


Figure 25

Figure 26 is a histogram showing the single fiber length spectrum resulting from the China Lake barrel burn test (no. 8). Once again, as has been noted for other fiber release tests, the single fibers collected on sticky paper 3000 feet from the fire were quite short, the big majority being less than about 5 millimeters.

As mentioned before, the unusual feature resulting from the burning of the composite barrel with its very thin 2-ply composite skins was the large number of clusters of individual carbon fibers. These clusters, which apparently somewhat resembled "chicken feathers", probably represented more potential numbers of fibers than the single fibers actually detected. The distribution of the cluster dimensions in figure 27 shows them to be generally from about 1/2" x 1/2" in size up to 3-4 inches on a side.

The photograph in figure 28 is of the smoke plume from the large (40 feet x 60 feet) JP-5 pool fire which was used to burn the three composite spoilers at China Lake, and it is apparent that the fire should be considered representative of a rather vigorous fuel fire which could result from an aircraft crash.

Figure 29 is a diagram of the "Jacob's Ladder" array of bridal veil vugraphs which was mentioned previously as one of the

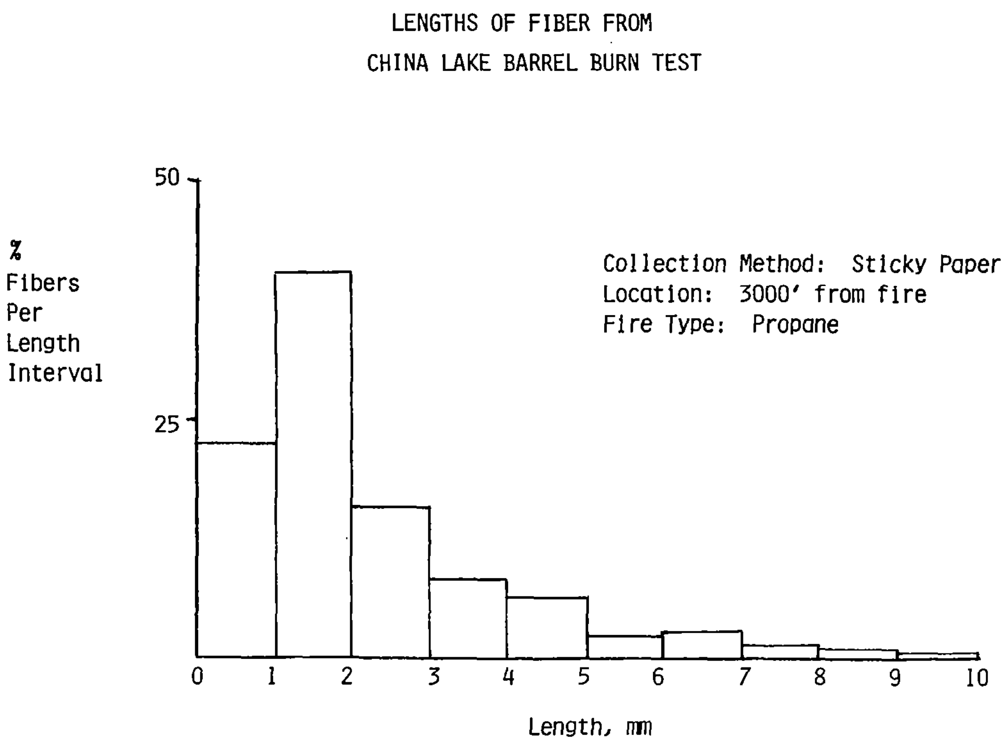


Figure 26

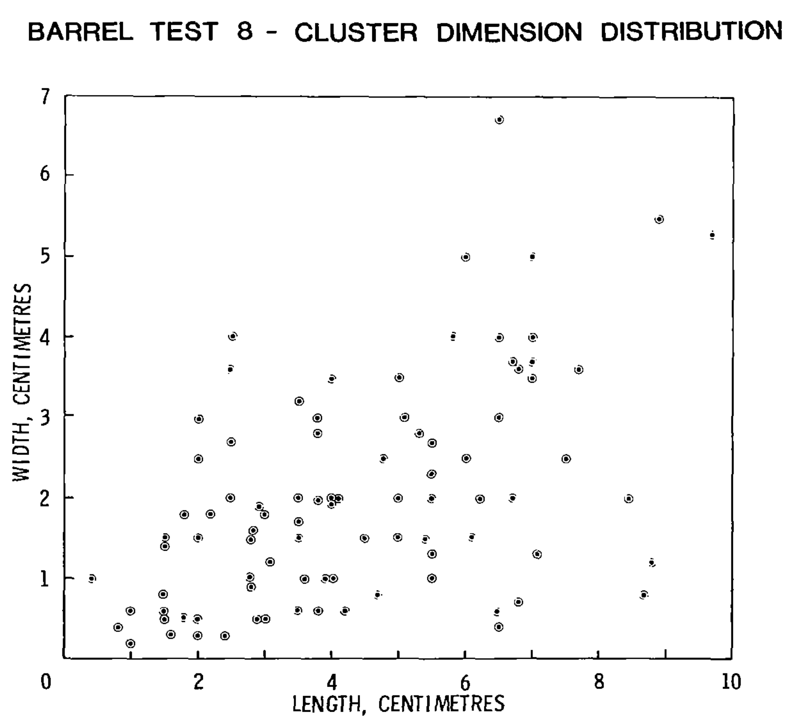


Figure 27

SMOKE PLUME FROM JP-5 FIRE

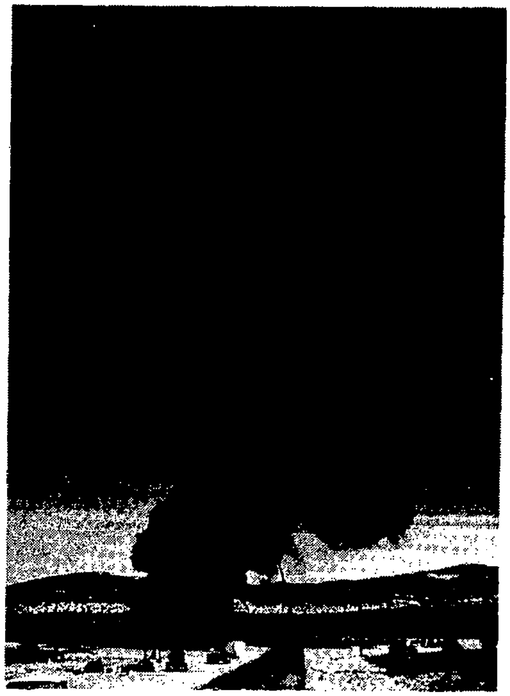


Figure 28

SPOILER TEST 11 - JACOB'S LADDER
PASSIVE INSTRUMENTATION ARRAY

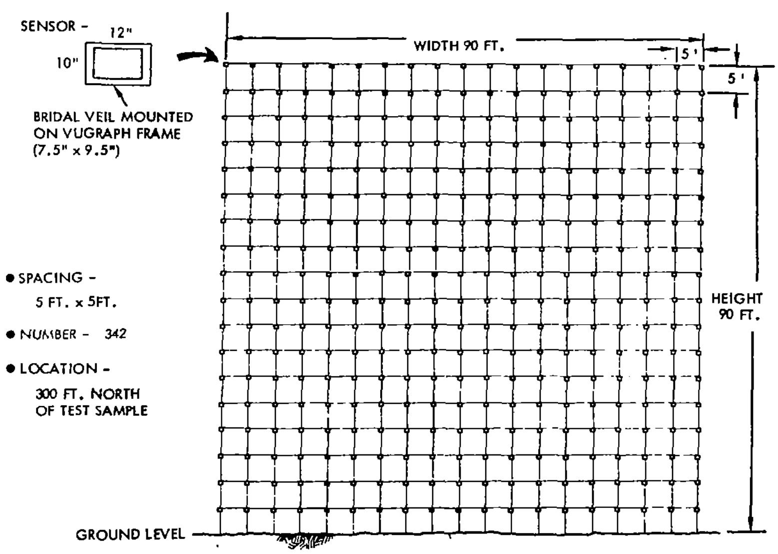


Figure 29

types of passive fiber detection methods. As noted in the figure, the vugraph frames covered with bridal veil were spaced every five feet, both horizontally and vertically. Thus, an excellent monitoring of the fiber concentration in the air is possible. In the spoiler burn test, it was found that the highest concentrations of fiber were detected by the vugraphs in the lower half of Jacob's Ladder, and up toward the upper right side of the Jacob's Ladder.

The spectrum of lengths of fibers which were collected from the spoiler burn test by bridal veil vugraphs on the Jacob's Ladder are presented in figure 30. The histogram clearly shows, as with several previously cited tests, that the majority of the fibers collected were very short, less than 4 millimeters, with a very small proportion being over 10 millimeters in length. In this case, no fibers less than 1 millimeter in length were counted, since they would have passed through the 1 millimeter mesh of the bridal veil.

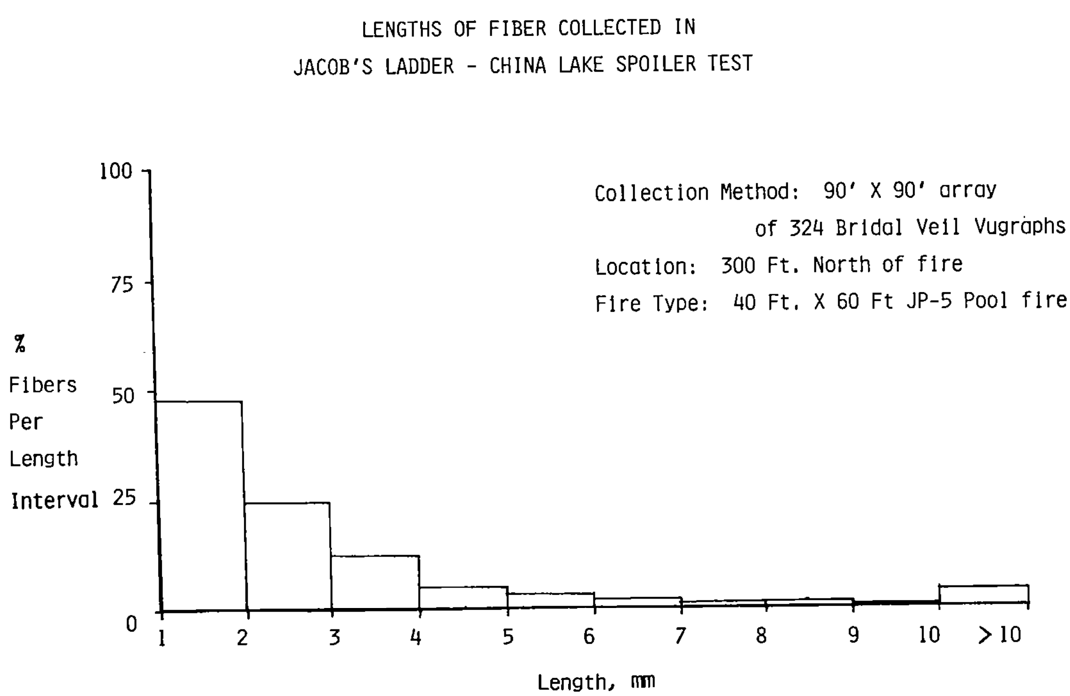


Figure 30

If the hallmark of the composite barrel burn test was the release of a large number of "chicken feather" like fiber clusters, then the unusual result of the burning of the three 737 spoilers in the large JP-5 pool fire was the release of a large number of long, narrow, thin carbon fiber strips shown in figure 31. These were collected at distances up to 6000 feet from the

SPOILER TEST 11

REPRESENTATIVE STRIP-TYPE PARTICULATE

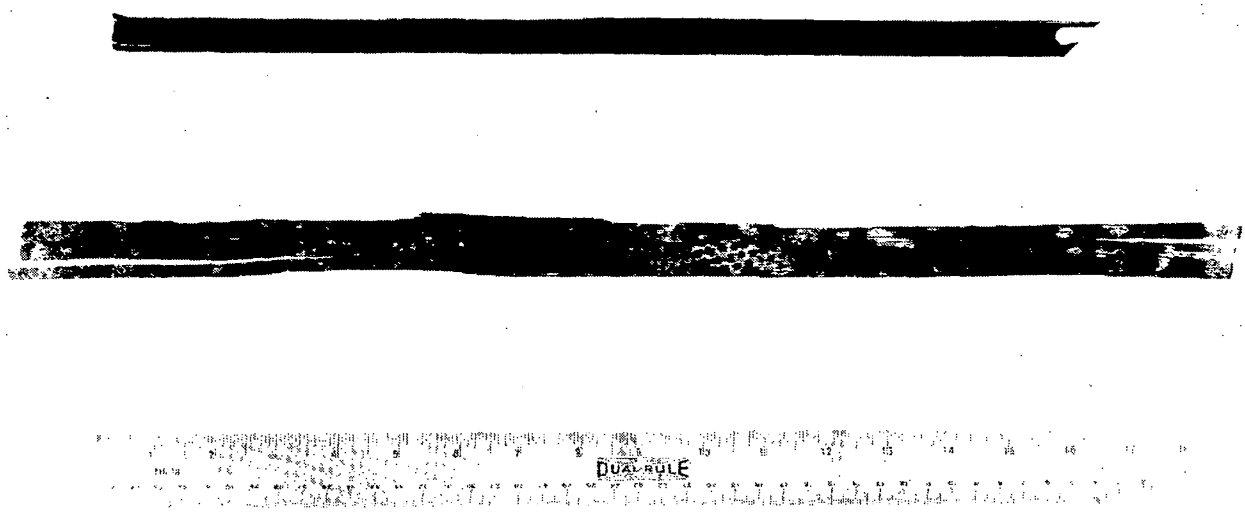


Figure 31

fire. They were generally of a thickness very close to a single ply, and were believed to have resulted from the almost explosive delamination of the cross-plied carbon/epoxy skins of the spoilers as the resin was violently burned in the intense heat of the jet fuel. The lengths of the strips, scaled by the 18 inch rule in the figure, seemed to be close to the length, width, and diagonal dimensions of the plies within the composite skins. These strips were lofted to extreme heights (the fire and smoke plume was estimated to have reached in excess of 2000 feet in altitude) and then were transported by the wind for up to 6000 feet downwind of the fire site.

The strips from the spoiler burn test were collected by a range "sweep brigade" composed of the test personnel who, spaced at arm's length, searched the desert downwind from the burn site. As they collected each strip, the size of the strip and its precise location on the desert was noted. Thus, an excellent record and thorough characterization of the strips was obtained. This unusual strip deposition spectrum shown in figure 32 describes four dimensions of the spectrum. In the foreground is noted the location of the range where the strips were found, on the left is the classification of the lengths of the strips, and the vertical scale gives the additive numbers of strips found in each length interval. And then a key to the strip width

SPOILER TEST II - STRIP DEPOSITION SPECTRUM

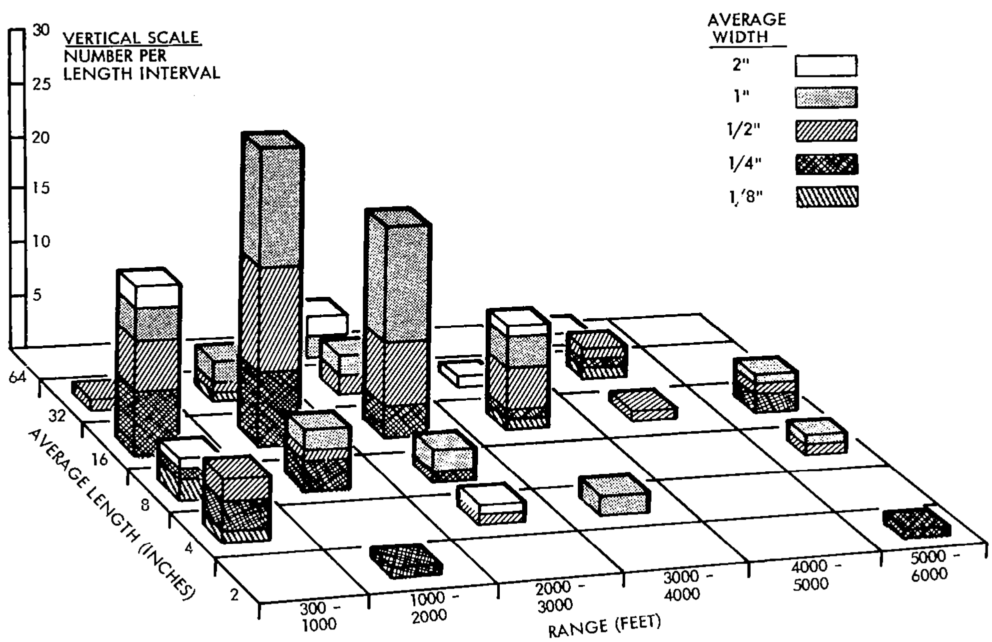


Figure 32

spectrum, from 1/8 inch to 2 inches is given in the upper right portion of the figure. Actually, a large number of strips were collected from the test pad and also at up to 500 feet from the fire site, before a record of the strip size and location was begun. Therefore, if these had been included in the pictured strip deposition spectrum, they would have increased the numbers in the left hand portion of the figure to give a more normal decrease in numbers of fibrous strips from left to right (decreasing distance from the fire).

Although there is some question as to the degree of success that was achieved in tracking the dissemination of single fibers from the China Lake tests, there is no doubt that the formation and dispersion of large numbers of clusters of fibers (as in the barrel burn) and the generation and transport of long strips of fibrous residue (from the spoiler test) created a new awareness of types of carbon fiber materials other than single fibers which could, under entirely imaginable situations, represent substantial threats to outdoor electrical equipment.

Now, it is appropriate to present a summary, a little bit quantitative but mostly qualitative, of some of the findings to date from our simulated carbon fiber release testing.

First of all, as shown in figure 33, we believe that the burning of representative aircraft parts which use relatively thin composite skins, such as the DC-10 rudders and 737 spoilers, will release about 10% of the weight of the carbon fiber initially present in the composite in the form of single carbon fibers with a very high energy impact such as an explosive detonation and probably less than 1% for a low energy impact, such as a short fall of the burning structure to the ground. Secondly, and quite conclusively to date, the majority of single carbon fibers released under most fire conditions are very short, generally less than 3 millimeters. This finding probably will have an effect on the electrical equipment vulnerability test program.

CONCLUSIONS FROM SOURCE STUDIES

(PRELIMINARY)

- BURNED AIRCRAFT PARTS(DC-10 RUDDER, 737 SPOILER) USING THIN COMPOSITES RELEASE:

  ABOUT 10% SINGLE FIBER WITH HIGH ENERGY IMPACT

  LESS THAN 1% SINGLE FIBER WITH LOW ENERGY IMPACT

- UNDER MOST FIRE CONDITIONS, MAJORITY OF RELEASED SINGLE FIBERS ARE VERY SHORT (< 3 mm)

- THIN CARBON COMPOSITES RELEASE SINGLE FIBERS EASIER THAN DO THICK COMPOSITES

- SUBSTANTIAL AMOUNTS OF CARBON FIBERS IN THIN COMPOSITES MAY BE OXIDIZED IN VERY HOT FIRES

- CARBON FIBERS (AS, T300) IN COMPOSITES OXIDIZED EASIER THAN "GRAPHITE" FIBERS (HMS, HTS, GY-70, ETC.)

- AGITATION OF COMPOSITE DURING OR AFTER THE FIRE IS REQUIRED TO RELEASE FREE FIBER

Figure 33

A general observation is that thin carbon composites release single fibers more readily, in general, than do thick composites; this probably comes as no surprise to anyone. Furthermore, there is strong evidence that substantial amounts of carbon fibers in thin-skin composites may be completely oxidized in very hot fires. Along these lines, it has been shown that the carbon fibers AS and T300, which at this time are most often used in aerospace composites, are oxidized in fires more readily than are those higher performance fibers such as HMS, HTS, GY-70, etc. which may have some graphitic content. And perhaps very importantly, testing to date has demonstrated most definitely that some as yet undefined amount of agitation, turbulence, or impact during or after a fire is required to release any significant numbers of free single carbon fibers.

At this time there remain a number of uncertainties concerning the accidental release of carbon fibers from burning composites which must be resolved before reliable predictions can be made of how much fiber might be released from actual crash fires of composite-containing civilian aircraft. These uncertainties are summarized on figure 34. One uncertainty is that of just how much of the fiber in a burning composite can be completely consumed by the fire, and thus be eliminated from concern. It is planned to study this uncertainty very hard in testing in the near future. A second uncertainty lies in the amounts and sizes of single fibers which can be released from

UNCERTAINTIES OF CARBON FIBER RELEASE

- AMOUNT OF CARBON FIBER OXIDIZED IN AIRCRAFT FIRES
- AMOUNT AND SIZE OF SINGLE FIBER RELEASED FROM FIRES OF VARYING INTENSITY
- CHARACTER OF CARBON FIBER RESIDUES (SINGLES, LINT, CLUSTERS, STRIPS) RELEASED FROM FIRES OF VARYING INTENSITY
- CORRECT SIMULATION OF AGITATION AND TURBULENCE EFFECTS UPON BURNED COMPOSITE RESIDUES
- OPTIMUM TECHNIQUES OF FIRE-FIGHTING AND CONTAINMENT OF COMPOSITE RESIDUE AT ACCIDENT SITE

Figure 34

fires of varying intensity. Next, the China Lake burn tests have made us look beyond our initial prime concern with single fiber release to an equal consideration of other forms of released fibrous species, such as lint, clusters, and strips which, while not as transportable through the atmosphere to the great distances that single fibers will reach, nevertheless may pose substantial hazards to exposed outdoor high voltage power equipment. In view of the emerging criticality of turbulence and agitation to the amount of fiber which can be released from burning composites, it is clear that a knowledge of just what form and intensities of disruption to the burned composite residues can be considered to be realistic.

The last uncertainty on the list, one which has not been mentioned until now, pertains to the need to find the optimum techniques to fight the aircraft crash fires and worthwhile methods to contain and dispose of the wreckage containing composite debris to minimize the release and spread of carbon fibers. However, an investigation of those factors is being initiated by the military services, with some NASA participation; and it is expected some important and useful information will result from that program in the near future.

QUESTIONS

Question: The question is related to the photograph showing the residues from the woven composite sample where the individual plies had come apart. Would the release of single fibers be less from woven material than from unidirectional or cross-plied material?

Response: Our feeling is that that is probably true in the absence of any very high impact. There have been tests run in the Dahlgren chamber with very high impacts and some of the results indicate quite the opposite. There are weaknesses built in the weaving operation which might tend to cause more fiber to be released. In just the burn situation, with the very low impact, it looks like the woven material is better as far as inhibiting fiber release.

Question: Was reduction in fiber diameter observed?

Response: Yes, from the numbers I've been given in both the China Lake barrel and the spoiler tests, the fibers went from an average of 6 1/2 to 7 microns in diameter down to about 4 microns which represents about a 50% reduction in the cross section of the fiber.

Question: Are we getting into a health hazard at those diameters?

Response: I don't know. I think other government agencies are looking into that matter. I think they're drawing the guidelines at around 1 micron in diameter for these particles. However there's a region between 1 and 3 microns where some people have indicated concern so it may be a consideration in the future.

Question: Question related to the minimum lengths of fibers measured.

Response: In some cases where the fibers were collected by deposition they were counted down to half millimeter in length. In other cases where they were collected with the bridal veil, they stopped at one millimeter because that was the mesh size of the veil. In many of the tests there are very small particles, almost identical with soot which must have come from the blasting of the residue. There are fine particles but we have not addressed the size of them.

Response by Dr. Sessels of TRW: In the Capistrano tests that were performed by TRW, they did analyze fibers with lengths down to 5 to 10 microns in length and the information is available.

Question: Who is the contact for the China Lake tests?

Response: Mr. Quentin Porter of Rome Air Development Center and Dr. Paul Lieberman of TRW.