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THE POTENTIAL FOR DAMAGE FROM THE ACCIDENTAL RELEASE OF CONDUCTIVE CARBON FIBERS FROM BURNING COMPOSITES

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THE POTENTIAL FOR DAMAGE FROM THE ACCIDENTAL RELEASE OF CONDUCTIVE CARBON FIBERS FROM AIRCRAFT COMPOSITES

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SUMMARY

Carbon and graphite fibers are known to be electrically conductive. That property has resulted in damage to electrical equipment from the inadvertent release of virgin fibers into the atmosphere. The rapidly accelerating use of carbon fibers as the reinforcement in filamentary composite materials brought up the possibility of accidental release of carbon fibers from the burning of crashed commercial airliners with carbon composite parts. Such release could conceivably cause widespread damage to electrical and electronic equipment. This paper presents the experimental and analytical results of a comprehensive investigation by the National Aeronautics and Space Administration of the various elements necessary to assess the extent of such potential damage in terms of annual expected costs and maximum losses at low probabilities of occurrence. A review of a NASA materials research program to provide alternate or modified composite materials to overcome any electrical hazards from the use of carbon composites in aircraft structures is described.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) has been deeply committed to the research and development of advanced composites for aerospace applications for more than a dozen years. During the initial years of that research, the NASA followed an evolutionary, rather than revolutionary, approach toward the use of composites on civilian aircraft. Concurrent with several technology programs, NASA-sponsored flight service programs involved the selective reinforcement of conventional metallic structures (1). The modification of the tail cone of a CH-54 helicopter with stringers reinforced with strips of unidirectional boron/epoxy composites served to increase the vertical bending stiffness of the tail cone, while the addition of similar boron/epoxy reinforced stringers and wing planks to the center wing boxes of two C-130 transport airplanes served to reduce the stress levels and increase the fatigue life of the wing boxes. Both modifications were achieved at significant weight savings compared to the comparable metallic fixes.

Following an Air Force/NASA Long Range Planning Study for Composites (RECAST) in 1972 (2), several flight service programs which met the principal objectives of RECAST, to build confidence in the use of composites in aircraft and to point the way to lower costs, were begun. Several Kevlar/epoxy fairings were chosen for flight service evaluation on a number of commercial L-1011 transport aircraft, while aft pylon skins of boron fiber and aluminum were put into service on three DC-10 aircraft to replace production titanium skins. Two flight service programs involving secondary aircraft parts built of carbon/epoxy composites have successfully demonstrated the long term service capability of composite parts. Spoilers with carbon/epoxy skins have flown a cumulative total of more than 1½ million hours in active service on Boeing 737 airliners. DC-10 upper aft rudders built principally of carbon/epoxy materials have also been flown without any major problems in commercial airline service.

In 1975, NASA began a program to accelerate the development of several technologies for improving substantially the fuel efficiency of commercial air transports. A vital part of that Aircraft Energy Efficiency (ACEE) effort (3) is the composite structures development program. That composite program involves the development, under NASA contracts, of six aircraft components (Figure 1) by three major transport manufacturers, Boeing, Douglas, and Lockheed. Carbon fibers are the principal, though not sole, reinforcement material to be used in those composites. This follows the emergence from the early technology and flight service programs of carbon (also referred to in this paper as "graphite") fibers as the filamentary reinforcing material of choice for aircraft composite parts by reason of a combination of desired properties together with low cost, high production, and weight savings potentials.

NASA's accelerated efforts to promote the use of composites as a way to fuel-efficient commercial air transports have been matched not only by the progress achieved in utilization of carbon composites in new U. S. military aircraft, but also by independent programs by major U. S. airframe manufacturers designed to use advanced composites to save weight in their present and future airplanes (4). The concomitant emergence of carbon fibers as a useful material for other industrial production uses, such as in sporting goods manufacture, has led to the realization that this is a material destined for multi-million kilogram quantities within the next decade (Figure 2).

A possible barrier to the optimistic future for carbon fibers appeared with the report (5) that there was an uncertain risk associated with the widespread use of carbon fibers due to their good electrical conductivity. Since they are extremely fine (about 8 microns in diameter) and lightweight (about 1.7 grams per cm^3), they can be transported by the wind for great distances. In contact with electrical devices, they could create

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a number of adverse electrical effects, including resistive loading, short circuits, and arcing, which could lead to electrical outages or destruction (Table I) (6). Several actual such incidents gave credence to the potential for damage. Several crashes involving U. S. military aircraft with composite parts built of nonconductive boron fibers demonstrated (Figure 3) the likelihood that similar crash and subsequent fire events involving aircraft with carbon fiber composites might release free carbon fibers into the atmosphere after the restraining influence of the resin matrix was removed from the composites through oxidation by the fire. Furthermore, carbon fiber manufacturers and processors have been aware for some time of the electrical problems which could occur from the inadvertent release of carbon fibers during industrial operations, though they soon learned to include simple, yet necessary, preventative steps in their normal manufacturing procedures (7).

The United States Government has an extensive interest in the widespread use of carbon/graphite composite materials and any potential hazards resulting from their use. A number of recent programs have accelerated that interest. Some examples are: NASA's ACEE program to expand the use of composites in civil aviation, federal procurement requirements for lightweight composite materials in high performance military aircraft, and federal automotive fuel consumption standards which require weight reductions that may be met only by the significant utilization of composites. Consequently, the importance of those programs contributed to a decision to conduct a government-wide program to study and quantify any risks which would result from the widespread usage of carbon fibers.

The United States Federal Action Plan to deal with potential carbon fiber problems was begun in early 1978 (8). The overall program, which was coordinated by the Office of Science and Technology Policy (OSTP), involved about ten government departments and agencies shown in Figure 4. Although NASA was to assist other departments in several ways, its main responsibility was to conduct a thorough assessment of the risks of electrical and electronic damage that might result by the inadvertent release of conductive carbon fibers from crashes of civilian aircraft with carbon composite parts. That responsibility also carried an obligation to assess the need for protection of civil aircraft from free carbon fiber. An additional charter for NASA was to take part in, and coordinate, a program of research and development of modified or alternate composite materials which would be harmless from the standpoint of electrical hazards, yet which would satisfy the requirements of advanced composites for aircraft structures. While the R and D program for alternative materials was assigned to all of NASA's research centers, the task of assessing the possible hazards from the use of carbon fibers was assigned to NASA's Langley Research Center.

A Graphite Fiber Risk Analysis Program Office was formed at Langley to conduct the risk analysis. The scenario that was adopted as being of interest for the accidental release of carbon or graphite fibers from civil aircraft is illustrated in Figure 5. This scenario was hypothesized to encompass the consequences of accidents involving civil transport aircraft, usually near major airports, where the efflux from the burning of composite-carrying aircraft has the opportunity to be distributed downwind and thus to contaminate not only the nearby airport environs but also numerous distant facilities as pictured in the illustration. Another dimension of the risk analysis is afforded by the risk analysis flow chart, shown in Figure 6, which includes all of the elements of importance which can lead to damages from the release of conductive carbon fibers. Inasmuch as NASA's risk analysis was organized and conducted according to the elements in the flow chart, this paper will be presented in the same manner.

DISCUSSION OF RESULTS

Sources of Released Carbon Fibers

The Graphite Fiber Risk Analysis scenario assumed carbon fibers to originate principally from fires from crashed commercial aircraft with carbon composite parts, as represented in Figure 7. However, non-crash events such as in-flight or ramp fires were also considered. At the start of this program, there had been no known crashes of commercial aircraft with any carbon composites in their structures. In the absence of actual experience, an investigation of ways to simulate the conditions of commercial aircraft crash fires was deemed essential in order to predict the quantities and forms of carbon fiber residues which might be released.

The earliest experiments in release of carbon fibers from burned composites classified the principal types of fiber residues as shown in Figure 8 (9). Single fibers had the potential for the greatest range of distribution due to their very slow settling rate, while the clustering together of a number of single fibers gave a form of efflux which would fall much faster than individual fibers. A third class of residue consisted of yet faster settling strips of fibers, generally resulting from a single ply of a crossplied composite, with the fibers being bound together either by incompletely burned resin or the char formed by the burned resin. A fourth broad class of fibrous residue was fragments of the composite, widely varied in size and shape. These fragments, which were so dense that they were rarely found beyond the immediate vicinity of the fire, generally resulted only from a substantial impact to the burning or burned composite. Rarely were they formed as the result of a simple fire.

The emphasis of this carbon fiber source study was placed on the generation of single carbon fibers from fire tests. First of all, the spread of single fibers was considered to be the most extensive due to their buoyancy, and damage to electrical and electronic equipment spread over a broad area of population was felt to pose the greatest possible economic loss. And secondly, single fibers were considered to be the form of residue which would be most capable of penetrating the filters and cases of equipment to reach the vital interiors. Accordingly, most of the fiber release data was gathered and utilized as the percentage of single fibers released (over one millimeter in length) based on the mass of carbon fiber initially present in the composite test specimens. The initial experiments which defined the broad classes of residues involved the destruction of the burned composites with explosives (10). Obviously, such a procedure lacked credibility for representing the typical commercial aircraft crashes. Furthermore, although the fire plus explosive test showed substantial amounts of the highly buoyant single fibers being released, there was an uncertainty as to both the amounts and the forms of residues which might be generated from the simulated burning of composite aircraft parts without the explosion step.

The testing program was conducted at six locations on contract to NASA-Langley. The majority of the small scale composite burn tests were carried out at the U. S. Navy's Dahlgren (VA) fire test facility, which was a completely enclosed environmental chamber, approximately 100 square meters in area, in which small samples (up to 0.1 square meter in size) were burned with a propane gas burner and a variety of disturbing effects were applied to the fibrous residue after consumption of the matrix resin. The test samples were generally either flat composite plates or small specimens cut from prototype composite aircraft structural components. The principal advantage of this test facility was the complete containment of all the fibers released, which were collected by allowing them to settle onto highly adhesive deposition papers laid out on the floor of the chamber. The fiber output from the tests was then counted, generally by optical microscopic methods, in order to analyze the test results. Additional small scale test support was provided by the AVCO Corporation's fire test facility in Lowell, MA (11) and a NASA-Ames/Scientific Services, Inc. test facility at Redwood City, California (12).

In addition to the small-scale laboratory test, valuable fiber release information was acquired from outdoor composite burn tests conducted by TRW Inc., Redondo Beach, California under U. S. Air Force sponsorship (13), for the purpose of studying not only the nature of fiber release from burning composites, but also to verify predicted dissemi nation patterns over broad areas. Confirmation of small-scale test data was also obtained from large-scale demonstration testing conducted in the U. S. Navy's Dahlgren, VA tube test facility and at the U. S. Army's Dugway (UT) Proving Ground.

Laboratory testing addressed the effects of the following variables on the amounts and characteristics of carbon fibers from burned composites:

Type of fire fuel (jet fuel, propane, natural gas)
Nature of fire (fuel-rich, fuel-poor)
Duration of fire
Disturbances to residue during and after fire
Composite thickness and configuration (crossply, woven, unidirectional, etc.)
Composite surface and edge effects
Types of composite materials (fibers and resins)
Composite quality

The most important findings of the fiber release investigation were:

1. The type and degree of disturbance to the burning composite or burned fibrous residue is the most critical variable for fiber release, as summarized in Figure 9. The quiescent burning of composites leads to the least amounts of single fibers being released, almost invariably less than 0.1% of the initial mass of fiber present. Internal disturbances to the fire residue, such as the type of flexing, twisting, vibrating, or dropping which could be expected in a burning crashed airplane also released relatively minor amounts of single fibers. While disruption of the fibrous residue applied as a mechanical impact gives off many large fragments but less than one-quarter percent as single fiber, the natural airflow of fires due to wind or fire-induced air currents resulted in amounts of up to 1% single fiber. Although ordnance-type explosives appeared to generate the greatest amounts of single fibers, near sonic airflows up to 250 meters per second, which could simulate the explosion of fuel tanks, released amounts of single carbon fibers almost as great.

2. Fire-generated single fibers were, in general, much shorter than expected. Most tests, both burn and burn plus disturbance, gave fiber length spectra where the great majority (two-thirds or more) were less than one millimeter in length. That length was considered to be the lower limit for fibers of concern from the standpoint of vulnerability of electrical equipment. For those fibers over one millimeter in length, the great majority ranged from one to four millimeters in length, with the observed mean length being between two and three millimeters. Seldom were fibers over ten millimeters long obtained.

3. Despite the oft-quoted "indestructibility" of graphite fiber, substantial masses of carbon fibers from composite aircraft parts were consumed in representative fuel fires considered to be typical of jet aircraft crash fires. This reflects the fact that the carbon/graphite fibers in use today are not graphite to any great extent. However, future use of the more graphitic, high modulus type would undoubtedly lead to less consumption of fibers in fires. The mass loss which was observed was manifested by a reduction in the thickness of the fibers, but there was probably some complete consumption of fibers when released in the hotter regions of the fire as well as from the burning composite itself.

A major objective of the investigation of the sources of accidentally released fibers was to guide the risk analysis efforts with reliable numbers on the predicted accidental fire-release of fibers. After a thorough analysis of carbon fiber release test results, the following criteria were assigned for use in the risk analyses. For those 85% of aircraft crash fires which accident records disclosed had no explosions, a figure of 1% of the mass of the carbon fibers initially present in those composites burned by the fire was considered to be released as single fibers. For the 15% of crash fires with accompanying explosions, a figure of 3-1/2% single fiber released was used. The fibers released were further defined as having an exponential distribution with a mean length of 2 millimeters for all the lengths, above and below 1 millimeter, resulting in a total of 5 x 10^9 fibers released per kilogram of carbon fiber. (Actually, the distribution was non-exponential for fibers less than one millimeter in length, which were of little concern from an electrical standpoint, due to the high mean exposures to failure for such short fibers).

Fiber Dissemination

The second of the risk analysis elements is the dissemination, or spread, of the carbon fiber, once it has been released from a burning composite into the environment. Before addressing the subject of dissemination, an explanation of the terms which describe the measure of fiber pollution of the environment is in order (Figure 10). The concentration C of carbon fibers is the number of fibers per cubic meter. Of even greater importance from the standpoint of carbon fiber pollution is the exposure E, which is the concentration times the period of time during which the concentration endures, or the time integral of the concentration. In some cases, the number of fibers that get deposited on the ground, or on some other surface, is a useful measure of pollution. This measure is the deposition D, the number of fibers deposited onto a unit area of surface. Vulnerability of electrical equipment is usually expressed in terms of exposure, as the time consequence of concentration.

The three main parameters which control the dissemination patterns for carbon fibers are the fire, the nature of source of the fibrous materials, and the weather. The fire begins the dissemination problem and it is influenced by such factors as the fire pool size, the amount of fuel, and the burning rate. The source has a great deal to do with the fiber exposure levels, since the source determines how many fibers can be given off, what lengths they are, and what other forms of fibrous debris are released. And of course the weather strongly controls the path and fate of the fibers, since it can determine the height to which the fiber-laden fire plume can rise, how much mixing and dilution of the fire plume can occur, the direction taken by the fall-out, and the settling of the fibers with precipitation such as rain and snow. Much dissemination research has been conducted over the past thirty years or so, including the dissemination of nuclear fall-out and the spread of aerosol pollutants into the environment. Existing Gaussian models for the dissemination of fire effluents, such as the Trethewey-Kramer (14) and EPA-Turner (15) models, were found to be acceptable for the carbon fiber risk analysis. The Gaussian models (Figure 11) provide for dispersion of the cloud in a conical sector downwind from the fire plume, with reflections from both the inversion layer and the ground. The dispersion coefficient, that is, the angles at which the cloud spreads, have been empirically determined for the various Pasquill-Gifford stability classes, ranging from a 10° cone for stable weather to a 40° cone for unstable weather.

The fiber materials released from a fire form a cloud which moves with the velocity of the wind and in the same direction as the wind. At a short distance from the fire, the effects of diffusion create Gaussian distributions in the concentrations of fibers along the direction of travel and across the spread of the cloud. The rate of spreading and also the maximum altitude of the fibers within the cloud are determined by the weather conditions. The ground level exposure can be described by a series of contours or "footprints" which link points of equal exposures to either single fibers or lint (clusters of fiber). As Figure 12 shows, overcast or nighttime conditions generally produce longer, narrower contours, with fall-out distances of up to 100 kilometers. Fall velocity has a direct effect on distance, with the heavier lint falling out in proportionately shorter distances. Conditions typical of sunny weather tend to give shorter but broader contours.

The single fiber coverage has been plotted in Figure 13 for a number of quantities of released carbon fibers and for a number of appropriate exposure levels. This exposure analysis allows the rapid determination of just how large a geographical region would be exposed to a certain exposure level of carbon fibers, as the result of the release of a specific weight of single carbon fibers. For example, if 40 kilograms of single carbon fibers with an exponential distribution and a mean length of 2 millimeters were released, an area about the size of the suburb of a city (about 10^7 square meters) would be exposed to 10^6 fiber-seconds per cubic meter. The fiber analyses represented in Figure 13 were developed from dispersion models. They showed that a certain quantity of released carbon fibers would be dispersed over a much broader area than had been estimated initially, but the fiber concentrations would be proportionately lower. The quantity of fiber released in the worst case prediction of this risk analysis is shown by the dotted line. Fiber exposure levels ranging from 10^5 to 10^8 fiber-seconds per cubic meter can be expected to result in some failures of electrical equipment. A more detailed discussion of equipment failures will be given in a later section on Vulnerability.

Fiber Life and Redissemination

Some initial thoughts concerning the lifetime of carbon fibers and their possible redissemination after being deposited on the earth's surface were rather uncertain and ominous. Due to the chemical inertness of carbon/graphite fibers, it was easy to imagine that the fiber would live forever and that following the initial dissemination and deposition onto the ground, they would be available to be lofted by winds into the atmosphere where they could continue to wreak havoc on electrical equipment. And each successive release of fiber would build up the pollution to a heavy concentration over huge areas. The subjects of carbon fiber lifetime and redissemination were investigated at the U. S. Army's Dugway Proving Ground, and the findings (16) have helped to alleviate those early fears.

The study involved the monitoring of free single carbon fibers which were spread out from the site of previous tests during which a total of 33 kilograms of virgin carbon fibers had been deposited onto a high desert plateau region with silty clay soil having about a 25% cover of small, high desert scrub vegetation. Fibers were collected by vertical fall-out onto "sticky paper" deposition samplers and also in a horizontal transport mode in mesh screen samplers located 2 feet above the ground. Sampling was conducted for a 24-hour period every two weeks after the initial fiber release for several months followed by less frequent sampling until three years had passed. The fibers which were initially released ranged from 6 to 12 millimeters in length, with a mean length of 8 millimeters.

The data shown in Figure 14 indicates a rapid decrease in the amount of resuspended fiber collected on the vertical mesh screen samplers within a month following the first sampling, after which the collection leveled out to a quantity of fibers numbering only about 5% as many as were found in the initial sampling. A second finding of the surveillance was the drastic change in lengths of the resuspended fiber (Figure 15), which decreased from over 9 millimeters mean length for the initial sampling to less than 1.5 millimeters for fibers collected after 3 years. Combining the decrease in numbers of deposited fibers with their decrease in length leads to the conclusion that after three years, the mass of carbon fibers which had been subjected to resuspension was very low indeed. Examination of the terrain revealed that the fibers were either buried partially or completely in the soil, or entrapped at the ground level by the scrub vegetation. The mechanism for the redissemination process is believed to involve wind-driven particles of soil impacting the entrapped fibers which, because of their inherent brittleness, break off into shorter segments.

The current opinion, and that reflected in the risk analysis, is that redissemination of previously released carbon fibers would be a very small contribution to the entire amount. Certainly vegetated areas, such as grasslands, forests, and cultivated fields would not release any significant amounts of entrapped fibers. The only surface which can be envisioned as leading to a significant amount of redissemination would be hardtop surfaces typical of urban areas, such as paved streets and roads, roofs, parking lots, etc. Even then, precipitation effects could soon wash the fibers from the surfaces, and traffic on roads could also serve to grind many of the fragile fibers into an electrically-harmless powder. Of course, larger forms of carbon fiber debris, such as single-ply strips of burned out carbon composites, which have been shown to be transportable in the air for distances up to one mile from the fire site (13), may have to be cleaned from roadways soon after deposition to prevent the generation of a fresh supply of single fibers by the action of traffic.

Transfer Function

Transfer function is the element of the risk analysis dealing with the penetration of fibers through an interface. As applied to the transport of carbon fibers, the transfer function is the ratio of fibers which pass through an interface to those which encounter the interface. Examples of the interfaces which influence the carbon fiber risks are doors or window screens, filters, and equipment cabinets. The phenomenon of particle transport in air is well understood and a body of data employed for heating and air conditioning purposes was available. In addition, both analytical and experimental studies of the transfer of carbon fibers into buildings through filters, and into equipment boxes were made during this program. Much filter efficiency information was also available from the National Bureau of Standards for widely used types of filters. Typical results of the experimental studies have been shown in Figure 16 (17). The filter factor was determined for a number of different types of filters, such as ordinary household window screen and furnace filters, when exposed to fibers of different lengths. The chart at the right of the figure shows that in addition to the removal by window screen of many of the fibers with a mean length of 2 millimeters, another moderating influence on the potential for electrical damage is afforded by passage of the shorter fibers with a mean length less than 1 millimeter. Carbon fibers so short were considered harmless to virtually all electrical equipment, but that moderating effect was not included in the risk analysis.

In general, intentional or natural filtration of carbon fibers contributes a tremendous reduction in the concentration of fibers actually reaching the critical electrical equipment, with respect to the concentrations which encounter the filter barriers. While such a crude filter as window screen (Figure 16) removed nearly 90% of the 4 millimeter fibers, air conditioning systems for homes and factories give transfer functions of 10^{-3} to 10^{-4} for standard filters. On the other hand, some factors involved in filtration can partially nullify the benefits of filters. For example, filters must be properly mounted: even a small gap between the filter and its mounting can reduce the filter efficiency by an order of magnitude or more. Air velocity can also have a substantial effect on the number of fibers passing a filter, with a ten-fold increase in air velocity resulting in a similar increase in passage of fibers. Air filters (or water separators which serve the same purpose) in transport aircraft have extremely small transfer functions ($\sim 2 \times 10^{-5}$). However, as much as three-quarters of the fiber which approaches an open aircraft avionics bay door could pass into that compartment while the plane is on the ground. Entry of carbon fibers could be prevented, in the event of a nearby incident, simply by closing the door. Nevertheless, filtration and natural barriers to the transmission of carbon fibers were shown to provide alleviating effects to the electrical hazards of the fibers.

Vulnerability

The investigation of the elements dealing with the vulnerability, or susceptibility, of electrical and electronic equipment to damage from carbon/graphite fibers was preceded, perhaps, by the most speculation about the seriousness of the problem. While several incidents of damage caused by virgin carbon fibers in or near carbon fiber manufacturing operations were a matter of record at the onset of NASA's study, there was apparently no known instance in which fibers previously incorporated into a composite had been released in an accidental fire and had subsequently caused adverse electrical effects. Consequently, a number of unknowns regarding the non-virgin carbon fibers had to be studied and their effects on damage potential analyzed.

The types of effects that were expected from exposure of equipment to fibers were listed previously in Table I. The categorization shown is very gross, but serves to point out those general regions which were of the most concern. In the low voltage and low power region, a carbon fiber has the capability to maintain a high resistance short without burning out. In that event, the equipment could malfunction although the components incur no local damage. The region of medium voltage and high power causes some concern since the fiber acts as a trigger to potential arcing, and the arcing may be sustained. The result can be blown fuses, stressed components and flashovers at insulators. The third region of most concern is that of both high power and high voltage, where carbon fibers (as is the case for many foreign materials) can lead to corona, and initiate arcing severe enough to disrupt and to damage equipment catastrophically.

The electronic equipment failure model used to describe the vulnerability of electronic equipment to carbon fibers has been shown in Figure 17, where the probability (P) of failure is: $P = 1-\exp\left[-E/\bar{E}\right]$, where $\bar{E}$ is the mean exposure required to fail the equipment during testing and E is the exposure endured by the equipment. At the $\bar{E}$ exposure level, the probability of failure of a piece of equipment is 0.632, while at an exposure of one-tenth the $\bar{E}$, the probability is only .095, meaning about 9 or 10 pieces of equipment of the same type would fail out of 100 exposed.

The NASA Vulnerability Test Program relied principally on two test methods to assess the susceptibility of electrical and electronic equipment to carbon fibers. The simplest technique involved the use of a fiber simulator. This simple device was developed to simulate the electrical characteristics of a carbon fiber. If the electronics or the equipment to be tested had a limited number of nodes, 50 or perhaps no more than 100, it was possible to probe the equipment and so be able to tell if a carbon fiber (as represented by the fiber simulator) could cause the equipment to malfunction or fail. Representative electric appliances which were tested in that manner have been listed in Table II (18).

The most direct method to test electrical equipment for vulnerability to carbon fibers involved direct exposure of the equipment in a controlled chamber. An example of the several chambers used in this program is the one located at NASA's Langley Research Center, pictured in Figure 18. The operations scheme involved placement of the test article in the chamber, while a known quantity (monitored by fiber sensors) of carbon fibers of a desired length were chopped from continuous fiber tow and aspirated into the exposure chamber. The fibers were then kept in suspension until the test article malfunctioned or failed, or until a maximum exposure level (usually 10^8 fiber-seconds per cubic meter) was reached without failure. A number of replicate tests were conducted for each test item, whether it failed or not. A thorough cleaning of the equipment, such as by removal of fibers with a vacuum cleaner, was conducted between tests. A summary of the articles tested in the NASA or other chambers is presented in Table III (19).

Over 150 individual articles were tested for electrical/electronic susceptibility to carbon fibers by the fiber simulator and test chamber methods. The results in Tables II and III indicate that many pieces of equipment were invulnerable to carbon fibers. Most household appliances with 110-volt circuits proved to be unaffected. Enough pieces of consumer equipment were selected to be representative of about 75% of the market value of consumer goods. Very little 220-volt testing was done, but it was expected that 220-volt single-phase circuitry would be about as resistant to carbon fibers as 110-volt, since 440-volt single phase equipment was also proven to be relatively unaffected. (However, arcs could be sustained for 440-volt, 60 hertz industrial power using three phase transformer supplies capable of delivering currents in the range of 400 to 1500 amps, when arcs were initiated. An idea of the exposures leading to failure of some equipment can be seen from Figure 19 (19). Most equipment was vulnerable at 10^5-10^7 fiber-seconds per m^3 for longer fibers, and near 10^8 fiber-seconds per m^3 for very short ones. No equipment failed in the lower left hand region of the figure outlined by shading.

Figure 20 (19) illustrates an important factor influencing the effect of carbon fibers on electrical circuits. The tests were conducted with three different fiber lengths: short (∿3 mm), medium (∿7 mm), and long (∿12 mm). It is apparent that the longer fibers were much more effective in causing malfunctions than short ones. As was pointed out in the section on Source, most fire-generated carbon fibers are very short, with mean lengths usually between two and three millimeters. Therefore, the exposure levels causing equipment failure are quite high for the fibers released in real-life situations.

Another important relationship which was established by fiber chamber tests was that associated with the resistance of the carbon fibers themselves. Figure 21 (19) shows the effect that the fiber resistance had upon the critical exposure levels for three pieces of equipment. The stereo amplifier was an order of magnitude in exposure less vulnerable to DE 114, a high resistance, low temperature-processed carbon fiber, than it was to the T300 fiber in common use today. Similarly, a color television set and an air traffic control transponder were from 1-1/2 to 2 orders of magnitude of exposure less vulnerable to failure from T300 fiber than they were to two highly conductive, very high modulus fibers GY70 and HMS. Studies also concluded that fibers released from composites by fire had resistivities unchanged from virgin fibers and the damage potential of such fibers was the same as for the raw fibers. Another concern was that of post-exposure vulnerability. Most of the testing of equipment in Table III was done in the "on" condition. There was some concern about whether or not equipment which was exposed while "off" would fail subsequent to turning it "on". A test scheme involving 200 hours of testing of a color television set and a stereo amplifier, including many "on-off" cycles, indicated that post-exposure failure was not a significant problem.

As pointed out in the Introduction, one of NASA's responsibilities in the conduct of its carbon fiber risk analysis was to assess the need for protection of civil aircraft from released carbon fiber as warranted by the vulnerability of those aircraft to carbon fibers. A detailed analysis of the civil transport aircraft built by three domestic U. S. manufacturers was carried out. The analysis included testing of several specific types of avionics equipment typically used in those aircraft and having some expectancy, for various reasons, of being susceptible to damage from carbon fibers. Five pieces of avionics were tested extensively in the Langley test chamber (20): an air traffic control (ATC) transponder, an instrument landing system (ILS) receiver, a very high frequency (VHF) transceiver, distance measuring equipment (DME), and a flight director system. Except for the DME, none of the equipment was conformally coated. The equipment was exposed to fibers with three lengths: 1, 3, and 10 millimeters. All of the values for $\bar{E}$ (mean exposure to failure) were above 4×10^6 fiber-seconds per cubic meter, with the ATC transponder having the lowest value. That represented the oldest electronic design for a piece of equipment tested; it was introduced in the 1960's. It had the greatest open area available for ingesting fibers, with two sides of the dust cover completely perforated with 3.18 millimeter (1/8 inch) holes. Because of the gap sizes in the equipment and the filtering action of the dust covers, 3 millimeter fibers were the most significant in terms of contamination. As a result of detailed analysis based not only on the fiber exposure tests, but also on internal airflow analysis for the aircraft and various operational duty states of the aircraft, it was concluded that ground-exposed aircraft at an airport with a carbon composite crash fire would experience a much lower avionics equipment failure rate from carbon fibers than current normal operational failures. Because of the redundancy required for the current operational failure rate, no further protection for civil aircraft avionics was anticipated to be required.

A final concern in the area of vulnerability was that of carbon fiber-induced shock hazards. Under NASA sponsorship, the National Bureau of Standards examined a large number of household equipment items for susceptibility to failure and/or shock hazard. As mentioned before, 110-volt household appliances were generally invulnerable to carbon fibers. However, at extreme exposure levels some appliances were susceptible to carbon-fiber induced shorts to the external appliance case where potential shock hazard can exist. The most susceptible equipment for the shock potential was found to be the common household toaster (21). An analysis based on the projected carbon fiber usage and accident rates in 1993 (the year for which the risk analysis was performed), indicated less than one potential shock hazard per year would be caused by accidental carbon fiber release. Furthermore, it was predicted that the short current would not be lethal since the fiber would burn out (that is, using the 30 million psi modulus fibers in use in 1980).

Demonstration Testing

A series of tests were conducted (22) in a large, tubular fire facility to demonstrate an agreement between the susceptibility of electronic equipment to carbon fibers generated from burning composites in a jet fuel fire and the vulnerability of the same equipment to clean, virgin fibers in the Langley exposure chamber. The unique fire chamber was a modification of a portion of a long, shock tube located at the Naval Surface Weapons Center, Dahlgren, Virginia. A photograph of the 750-meter long tube is pictured in Figure 22. A 275-meter section of the tube was utilized, with a 1.22-meter square commercial jet A fuel fire being burned at a location where the tube was 4.6 meters in diameter. Composite specimens were burned in the fire and the fire plume was pulled through the last 275 meters of the tube by up to six large fans. A water fog spraying down from the top of the tube served to remove carbon fibers from the smoke plume, which exited from the 7.3-meter (24-foot) diameter end of the tube. During the equipment exposure tests, six identical fan-cooled, unfiltered stereo amplifiers were situated on a target table at 220 meters (700 feet) from the fire. The amplifiers were in an operating mode during the fiber release fire test. Strips of carbon fiber/epoxy composites were placed in a wire mesh basket, which was rotated in the middle of the fire during the entire period of the test. The actual failure of the amplifiers have been represented in Figure 23 by the step-wise solid line plot. The first four amplifiers had failed after the first 600 seconds of the test. Those failures have been indicated by the step-up at an exposure of about 6.5×10^5 fiber-seconds per cubic meter, with a fifth failure occurring when an exposure of 2.4×10^6 fiber-seconds per meter^3 had been reached, and the final amplifier failed at a level of about 3.3×10^6 fiber-seconds per meter^3. The experimental failures in the shock tube test matched very well the failures predicted from the Langley chamber-derived exponential probability curve superimposed on the figure.

A series of large scale outdoor demonstration tests was conducted at the U. S. Army's Dugway Proving Ground in Utah (23). The series consisted of two types of tests: source tests designed to measure the extent of fiber release from burning carbon/epoxy composites in a large JP-4 fuel fire and plume tests which were intended to not only capture carbon fibers and so determine the amounts released, but also to disseminate the released fibers over an area so large as to realistically simulate the dispersion expected from the crash and burning of a commercial air transport with carbon composite parts. The tests were carried out using a 10.7-meter diameter fuel pool size and 11.4 cubic meters of JP-4 aviation fuel. Duration of the fires was nominally 1200 seconds. About 45 kilogram quantities of real and test aircraft parts of carbon/epoxy composites were placed on an elevated steel mesh table above the fire pool.

The source tests were conducted during periods of very low wind speeds (less than 0.4 meters per second) in order to allow the fire plume to rise vertically from the fire. A large number of steel mesh sampling devices which captured released carbon fibers on the mesh screen within a cannister were suspended in an array above the fire. The samplers were suspended from cables rigged from four 60-meter high towers, arranged in a 65-meter square around the fire pool.

The dissemination tests were conducted in the same manner except that wind speeds from 2.7 to 5.4 meters per second were desired, and a wind direction of $320^\circ \pm 35^\circ$ was required. This permitted the fire plume to pass through a huge "jacobs ladder" (Figure 24). (The 169-meter high Washington Monument has been shown to scope the size of the undertaking). This "jacobs ladder" was constructed from 2.54 mm Kevlar ® rope with horizontal and vertical spacings of 15.25 meters. The 305-meter by 305-meter network was suspended from a catenary which was lofted by two U. S. Air Force 1270 m^3 balloons, with stabilizing tether lines placed out in all directions. The net was placed 153 meters from the fire. Many sampling devices of several types were mounted on the net. These included flat plastic rectangular frames, with their 0.29 m x 0.23 m openings covered with 1 mm mesh fabric coated with a sticky substance to cause fibers to adhere to the mesh when the samplers were placed at the intersections of the rope, normal to the flow of the smoke plume. Other samplers included mesh filters in cardboard cannisters similar to the steel samplers suspended over the fire, eight high voltage electrified grids instrumented to discharge when contacted by fibers, open-ended 0.085 meter diameter cans with adhesive-coated fabric mesh spread over one of the open ends, fiber collection pumps and filters used to monitor the air for excessive concentrations of respirable-sized fibers, and light emitting diode detection devices. As the fire plume passed through the suspended "jacob's ladder", the fibers were detected or collected by the array of monitoring apparatus which was then analyzed subsequent to the test. In addition, the dissemination of fibers was monitored by means of both deposition sticky papers and vertically mounted open-ended mesh can samplers spread out at appropriate intervals for distances of up to 19 kilometers from the fire in the direction of the wind flow.

A summary of the results of both the source and the dissemination tests has been presented in Table IV. Variance from the laboratory tests reported in the Source section of this report was noted only for the average fiber lengths. The average lengths of 5.0, 4.4 and 5.2 millimeters from the three dissemination tests were somewhat higher than the lengths obtained for the laboratory tests. However, the average length (3.2 mm) from the source test was in keeping with the laboratory test findings. The average fiber diameters of 4.1 to 4.7 micrometers indicated a substantial oxidation of the fibers from their normal 6 to 8 micrometers in the virgin state. The weight percent of fiber release was in concert with many of the laboratory results.

Conclusions pertinent to the risk analysis, based on the results of the large scale demonstration tests at Dahlgren and Dugway Proving Ground, are summarized below.

A maximum of 0.5% of carbon fiber, based on the amount initially present in the composite specimens exposed to the fire, was released in the best Dahlgren shock tube fire and equipment exposure test. However, since that was a long duration fire (over 12,000 seconds) and the fiber release was forced, the maximum of 0.19% released from the Dugway demonstration tests was considered more representative of predicted fiber release from commercial air transport fires. Therefore, the figure of 1% carbon fiber release used in the risk calculations was quite conservative. The mean fiber length (2 mm) from the Dahlgren test was in close agreement with the value used in the risk analysis, but some of the mean lengths from the Dugway large scale tests were somewhat longer than the mean length used for the risk analysis. And finally, the Dahlgren demonstration

® Registered trademark for DuPont's Aramid fiber tests established that the vulnerability of equipment to fire-released fibers agrees with the vulnerability of the equipment to virgin, unburned carbon fibers, thus justifying the use of fiber chamber test data in the risk calculations.

Facility Surveys

Surveys of 62 public, utility, commercial and industrial installations in the United States were conducted (24) in order to develop a sound foundation for the use of census data generated in the analysis of the overall risk to the community from the use of carbon fibers in civilian aviation. A summary of the number and types of installations of the four major classes has been summarized in Table V. Emphasis was placed on three main elements:

(a) Determination of data for use in modeling the economic impact of fiber-induced failures;

(b) Identification of the sensitivity of life-critical or emergency services to the fiber hazard; and,

(c) Definition of the sensitivity of in-place equipment to airborne fibers.

Analysis of the results of the surveys indicated that life-critical services already have sufficient in-place protection for isolation from the environment so that further protection against airborne carbon fibers was not required. For example, hospital operating rooms and critical care areas use such "absolute" levels of air filtration to guard against airborne infections and contaminations that fibers would not enter those areas. Another finding was that more than half of the 21 industrial installations surveyed had strong in-place barriers against the ingestion of airborne carbon fibers, such as high efficiency filters or coated circuit boards, due to the needs to protect against atmospheric or self-generated contaminants. Assembly lines and other continuous process type operations represent cases where operations could be halted by on-line equipment failures. Quite generally, such operations have preventative or protective in-place measures adequate to resist carbon fiber damage. And finally, many industrial installations have the ability to shift operations or to work around failures in equipment. Where equipment failures caused by other adverse factors are the rule, quickly installed parts are kept in readiness.

Conclusions which resulted from a comprehensive analysis of the survey were, as follows:

o Life critical functions could be excluded from any impact on the risk analysis.

o Emergency services would suffer no interruption. Any economic impact would be limited to specific items of equipment.

o Utilities would suffer no system loss. The economic impact would be confined to local outages and repairs.

o Commercial institutions, such as banks, stores, etc., would incur no interruptions to critical operations. Any adverse impact from carbon fibers would be limited to peripheral equipment.

o Industrial operations: A number of class operations, such as food processors, textile mills, paper mills, printing, chemicals, and others, representing 40% of the national value-of-shipments, would create no adverse impact on the risk analysis because of protection from their present operating environment. Another group (machinery, some transportation) comprising 15% national value-of-shipments would contribute no impact on the carbon fiber risk because their operations require local protection from cutting fluids and contaminants. Other installations representing 10% of value-of-shipments, such as electrical and instrument plants, would create minimal impact on the risk due to their critical need for air conditioning or other control of ambient conditions. And a fourth group of industrial installations, comprising plants having 7% of the national value-of-shipments from their operations, would also contribute a minimal risk impact because their operations are supported by ready spares.

Risk Computations

The primary objective of the risk analysis was to estimate the risk to the nation over the next 15 years (from 1978) resulting from the use of carbon composites in civil aircraft. A secondary purpose was to provide a framework for decision making on composite material usage, material modification, and protection schemes. Two contractors, ORI and Arthur D. Little, Inc. were selected to develop independently methods to numerically evaluate the potential losses due to failures of electrical equipment from airborne carbon fiber contamination originating from civilian aircraft crashes. The risk computations were conducted in two phases. ORI developed a risk model based on the 9 largest hub airports in Phase I (25) and proceeded to translate the risk profiles for a number of individual airports into a national model in Phase II (26). Arthur D. Little, Inc. developed a preliminary national profile from 26 major airports in the first phase (27) and followed up with a number of refinements to the national risk profile in Phase II (28).

The available commercial air transport accident records of the National Transportation Safety Board (NTSB) were augmented by information from the three major U. S. airframe manufacturers. They supplied detailed data on accident characteristics, such as fire duration and severity of damage to aircraft, that would affect carbon fiber release conditions. Projections on the extent of carbon fiber usage on U. S. commercial aircraft were also generated by the aircraft manufacturers. Such projections included the numbers of planes expected to be in service in 1993, by three types: small, medium, and large jets, as well as the ranges of quantities of carbon fiber composites which were predicted to be used on those planes. Among the criteria for determining the aircraft crash scenarios were the operational phases during which the accidents occurred. Figure 25 summarizes NTSB data for 1968-1976 (29) indicating that almost half of the severe accidents accompanied by fire occurred during landing, while a quarter of the accidents with fire occurred during takeoff. Furthermore, 60% of the accidents happened at the airport and 80% were within 10 kilometers of airports. Attention was also focused on 26 large hub airports which accounted for nearly 70% of U. S. emplanements. And lastly, 3.8 severe fire accidents were predicted annually in the United States. Based on predictions that 70% of the jet fleet would be using carbon composite parts by 1993, 2.7 fire accidents per year were projected for 1993 for such aircraft.

Figure 26 (27) shows the sequence of events which were modeled in order to describe the carbon fiber risk phenomenon. The simplified event tree logic which was followed to arrive at the local risk profile has been depicted in three sequential figures, Figures 27a, 27b, 27c (30). Random selections are used during many phases of this event tree for selecting the paths. At various points, the random selection leads to inputs from various elements of the entire program. For example, if an accident is randomly selected (Figure 27b) which involved an explosion in addition to a fire, then 3-1/2% single fiber release will be used. If the accident chosen involved fire only, then 1% single fiber release was used in the model of that accident. When the path of the event tree reaches Figure 27c, the areas of the city and/or countryside affected have been defined. Input from the elements of transfer function, vulnerability, and facility surveys then permit the determination of cost impacts from the accident. Examples of costs are repair or replacement of equipment, downtime, product losses, etc. Using a selected historical number of accidents each year (∿3 to 6), the random selection of nodes in the event tree and the cost calculations are repeated for each accident and the cost is summed to obtain one estimate of the national cost. One estimate, however, is insufficient to obtain a statistical distribution of estimates, so the national risk calculations must be repeated a large number of times.

The results of the annual risk profiles for economic losses due to commercial air transport fires involving carbon fibers have been given in Figure 28. The Phase I profile was assessed one year earlier than those from Phase II. The markedly lower risks in Phase II were attributable to a number of refinements in single fiber release (5% fire, 25% fire-explosion in Phase I vs. 1% fire, 3-1/2% fire-explosion in Phase II), a ten-fold decrease in infiltration due to use of experimental transfer function data, and extreme diminishments in equipment susceptibility due to shorter fiber lengths and higher mean exposures to failure. An increase in predicted carbon fiber usage in aircraft manufacturing made a slight positive contribution to the risk profile.

As the risk profiles in Figure 28 show, the expected annual risks to the United States due to the predicted use of carbon composites on civil aircraft in 1993 are certainly less than $1000 per year. The chances of national losses reaching significant levels are extremely small. For example, both the ORI and Arthur D. Little (ADL) models indicate (at the crossover for the plots) that an accident resulting in $5000 damage from carbon fibers would only occur every 40 years! Although a trend toward significant use of carbon fiber composites on general aviation aircraft has not yet emerged, separate risk computations dealing with forecasts of up to 55 kilograms of such composite per plane were made. The conclusion from that study was that it was extremely unlikely there would be a substantial dollar loss due to carbon fiber releases in general aviation accidents. Further diminishing the concern for carbon fiber hazards is the fact that loss of life from carbon fiber electrical events is virtually non-existent.

Material Modification

As pointed out in the Introduction, a secondary responsibility assigned to NASA under the Federal Action Plan was to investigate alternative or modified composite materials which would lessen or eliminate electrical hazards as a consequence of the use of composites. This responsibility was assigned to NASA's research centers since new materials research and development fit into the existing charters of the centers' base technology programs. All of the installations (Langley, Ames, and Lewis Research Centers, Marshall Space Flight Center, and the Jet Propulsion Laboratory) had knowledgeable line organizations with composite materials expertise so that a minimal impact on their existing research programs resulted.

The general objective of the resulting program was to develop composites which reduce carbon fiber electrical risks while retaining or improving the structural properties of resin matrix composites which make them desirable for use in aircraft structures. A NASA workshop on modified and alternate materials was held at Langley Research Center (31) in March 1978 as a means of making the composite materials community aware of the carbon fiber hazards program and to solicit the ideas of government, industrial and academic representatives. The cooperative efforts of the workshop resulted in a program with the following elements:

Test Methods
Hybrid Composites
Fiber Gasification
Modified Epoxy Resins
Fiber Coatings
Alternate Matrices
High Resistance Fibers
New Fibers

The element of test methods was given the highest priority since it was essential that investigators be able not only to determine the effectiveness of their new or modified materials, but also be able to compare them with other modified materials. However, since research could not be delayed pending the development of standardized test methods, several different tests were developed for determining fiber release at several of the research centers. One rather simple test device was developed at NASA's Ames Research Center (32) and it was utilized to a limited extent for comparing the relative amounts of single fibers which were released from burning composites. The device burned relatively small composite specimens, approximately 25-30 cm^2 in size, with a heat flux fairly realistic for a fuel fire, after which the composite was impacted with a pneumatically driven steel ball. The released fibers could then be collected and measured.

The concept of hybrid composites to minimize the release of conductive fibers was considered to be the most promising approach by the workshop participants. The hope that outer, or alternating, plies of a nonburning fiber reinforcement used together with plies of carbon fiber would help contain free carbon fibers appeared to be valid in preliminary tests, especially for composites which were just burned without any severe disturbance. Although the concept has not been evaluated conclusively, there are indications (33) that the type of disruption applied to the residual post-burned fibrous mass may be critical in determining the validity of the hybrid concept.

Fiber gasification was a novel approach which involved the deposition onto carbon fibers of certain metallic ions which would catalyze the complete consumption of the fibers when exposed to flame. Preliminary results (34) with such contaminants as calcium and barium acetates were promising, although much additional research was required to prove the practicality of this potential solution to the problem.

The modification of the epoxy resins used in composites was attractive from the standpoint of promising a minimum disruption of current applications and the least requalification of the modified composites. It was early recognized in the determination of fiber release from carbon-epoxy composites that epoxies are always converted in fires to a small amount of char which serves to bind individual carbon fibers together, thus preventing their release for some time. Some promising modified epoxies were uncovered by changing the chemistry, catalysts, and blending to give much higher char yields (35). The same thrust toward higher char yield resins was the basis for much of the attention paid to another element in the program, that of alternate matrices.

The general objective of the fiber coatings element of the program was to deposit coatings onto existing carbon fibers and thus to render them nonconducting. Among several coating materials such as silicones, boron nitride, silicates, boron carbide and silicon carbide (36), (37) the latter offered the most promise. A ten-fold increase in resistance of carbon fibers was afforded by a 0.1 micrometer coating, but oxidation of the silicon carbide to silicon dioxide at 1273 K gave six orders of magnitude increase in resistance. However, preliminary tests indicated some undesirable effects on the properties of composites made from the coated fibers.

The last two elements of the materials modification program, nonconductive fibers and new fibers, were considered to be the most long-term in nature and, thus, were relatively low in priority. When the carbon fibers were oxidized to carbon oxide fibers, the resistivities of the resulting fibers were much higher (up to 10^5 ohm/cm). However, the degradation of fiber properties was excessive. As a nonconductive fiber with mechanical properties quite similar to carbon, boron nitride fibers were being studied prior to the emergence of carbon fiber electrical hazards and those early efforts were revived and augmented as a result of this new program. At least one high modulus, nonconductive organic fiber was studied as a hoped-for replacement for carbon fibers.

The materials modification program was undertaken with the full knowledge that the chances of replacing, improving, or even modifying, an existing industrial product such as carbon fiber which had undergone years of industrial development were very remote. It is not possible to claim any positive results from this program at the present time since the program has been underway for less than two years, and some of the leads are still being actively pursued. The findings of extremely low risks as a result of the afore-described carbon fiber risk analysis has certainly diminished the necessity for new materials research. Nevertheless, the incentive which engendered the modified materials research program could well prove to have been the driving force instrumental in the successful development of one or more exciting new composite materials in the future.

Concluding Remarks

A comprehensive assessment of the possible damage to electrical equipment caused by accidental release of carbon fibers from burning civil aircraft with composite parts has been completed. The study concluded that the amounts of fiber expected to be released were lower than initially supposed: conservative quantities of 1% and 3-1/2% were employed in the risk computations for aircraft crash fires and crash fires plus explosions, respectively. Footprints of carbon fibers determined from dispersion models were found to be much larger in area than originally estimated, but were much lower in fiber concentrations. Redissemination, as a source for fiber, was shown to be insignificant. The susceptibility of electrical equipment to carbon fibers was low for current structural fibers. Consumer appliances, industrial electronics, and aviation instrumentation were relatively invulnerable to carbon fibers. The overall risk costs were shown to be extremely low: the expected annual cost was less than $1000 and it was predicted that there was only one chance in two thousand of exceeding $150,000 equipment loss in 1993. Furthermore, the potential shock hazard from carbon fibers was insignificant, so risk of life from electrical fiber effects was not considered to be a factor in the overall risk associated with the widespread use of carbon fiber composites in commercial aircraft structures.

The results of the NASA risk assessment program are such that the electrical effects of carbon fibers should not be considered an impediment to further development of carbon composites in aircraft use. In addition, a program to develop alternate materials specifically to overcome that perceived hazard is not necessary.

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TABLE I.-TYPICAL ELECTRICAL EFFECTS FROM CARBON FIBERS

Voltage Range	Low Power (Up to 100W)	High Power (Above 100W)
Low (0 to 30 Volts)	Sustained shorts Fiber not burned Malfunctions No local damage	Sustained shorts Fiber not burned No equipment damage
Medium (30 to 1000 Volts)	Sparking or shorts Possible fiber burn Transients Blown fuses Stressed components Low damage potential	Some sustained arcs Fiber burns Transients Blown fuses Stressed components Damage usually repairable
High ($>$1000 Volts)	Sparks, no sustained arcs Low voltage corona Transients Interruptions	Sustained arcs Corona Flashover May be severe damage

TABLE II.-APPLIANCES TESTED WITH FIBER SIMULATOR

With No Significant Failures*

- Refrigerators
- Freezers
- Ranges
- Dishwashers
- Clothes washer
- Clothes dryer
- Vacuum cleaners
- Irons
- Fry pans
- Bed covers
- Coffee makers
- Percolators
- Food mixers
- Can openers
- Portable heaters

With Failures

None

*Significant failures are those resulting in equipment damage or loss of function.

TABLE III.-EQUIPMENT TESTED IN FIBER TEST CHAMBER

With No Failures

- Telecommunicator
- Black & white television
- Air Surveillance Radar (ASR-3)
- Calculator
- Calculator and printer
- Tape recorder
- Electric motors (6) 110 V.
- Thermostats (2)
- Cash registers
- Portable heater
- AM/FM Radio
- Home music system
- Clock radio
- 10 Band radio
- Car radio
- Toasters
- Instrument Landing System receiver
- Distance Measuring Equipment
- Smoke alarms

With Failures

- Military equipment (70) (High modulus fibers, restricted lengths)
- Computer
- Color television
- Digital voltmeter
- Air Traffic Control transponder
- Very High Frequency transceiver
- Flight director
- Connector blocks
- Quick disconnects
- Relays
- Generic circuits
- Power amplifier
- Microwave oven

TEST IV.-SINGLE CARBON FIBERS RELEASED FROM DUGWAY OUTDOOR FIRE TESTS

Test	Carbon Fiber Mass in Fire, kg	Total Number	Average Length mm	Average Diameter µm	Single Fibers Released g	Single Fibers Released %
D-1	31.8	1.5×10^8	5.0	4.7	50	0.16
D-2	31.8	2.1×10^8	4.4	4.4	62	.19
D-3	52.0	1.1×10^8	5.2	4.1	38	.07
S-1	34.9	2.9×10^8	3.3	4.7	64	.18
S-2	31.8	2.2×10^8	3.2	4.6	47	.15

TABLE V.-SUMMARY OF FACILITIES SURVEYED

1) Public Support	No.
Hospitals	7
Air traffic controls	6
Airports-Airlines	3
Police headquarters	2
Fire dispatch	2
Post offices	1
Traffic control	1
2) Utilities	
Telephone exchanges	3
Power generation and distribution	3
Refuse incinerators	2
AMTRAK Railway System	1

3) Commercial Installations	No.
Department stores	2
Financial institutions	2
Radio and TV stations	6
Analytical laboratories	1
4) Manufacturing Operations	
Meat packing	1
Textile mill	1
Garments	1
Pulp and paper	1
Publishing	2
Textile fibers	1
Toiletries	1
Steel mills	2
Wire, cable	1
Electrical equip.	6
Automotive fab/assy	4

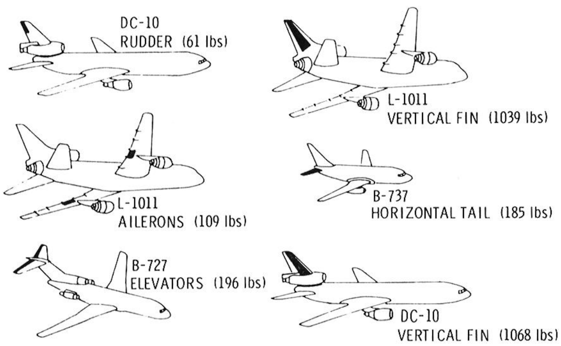

Figure 1. Aircraft Energy Efficient (ACEE) composite components.

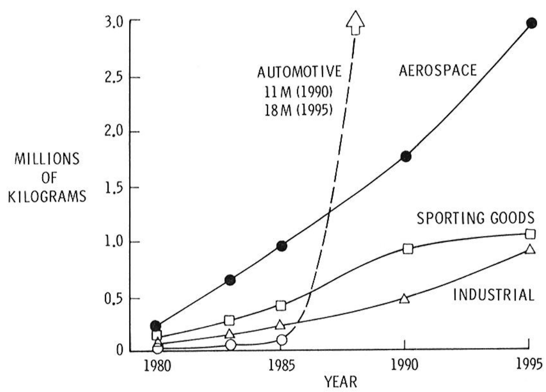

Figure 2. Projected U. S. consumption of carbon fibers.

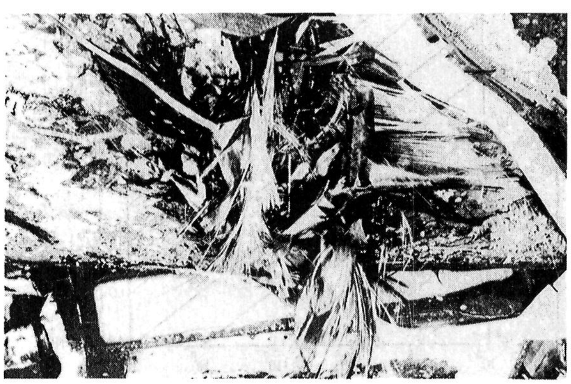

Figure 3. Boron fibers released from aircraft crash.

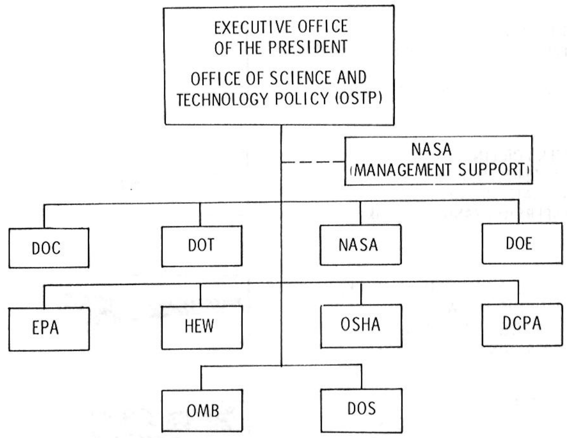

Figure 4. Organization of U. S. Carbon Fiber Study.

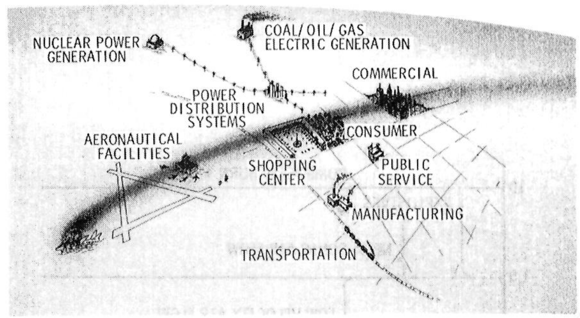

Figure 5. Scenario of the carbon fiber risk analysis.

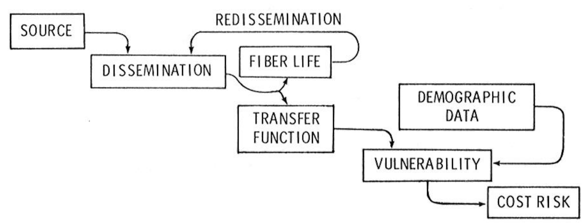

Figure 6. Elements of carbon fiber risk analysis program.

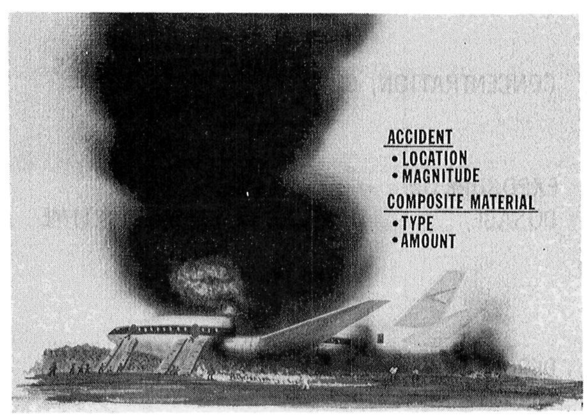

Figure 7. Scenario for crash of civilian airliner.

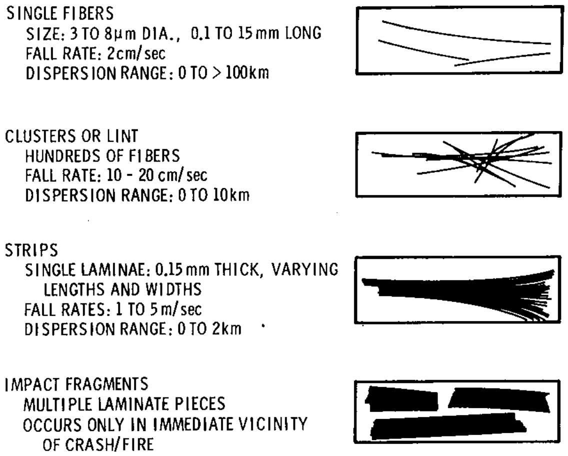

Figure 8. Carbon fiber residues released from fires.

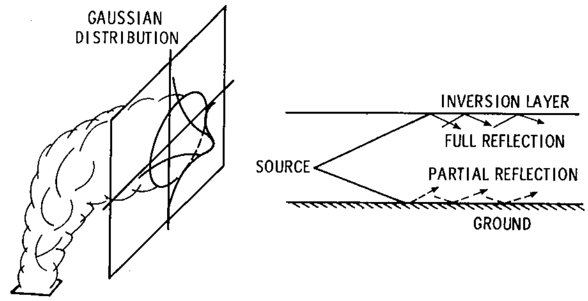

Figure 11. Gaussian distribution of pollutant in drifting cloud, with inversion layer and ground reflections.

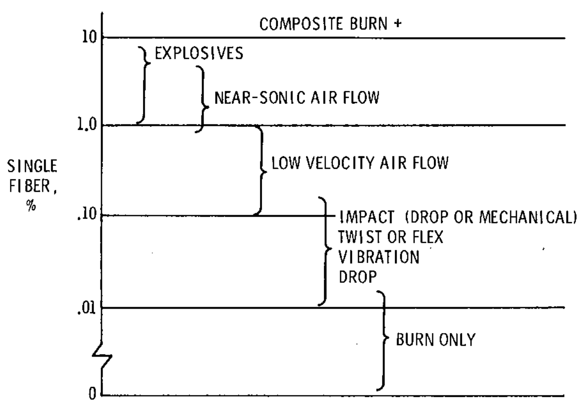

Figure 9. Summary of disturbance effects on single fiber release.

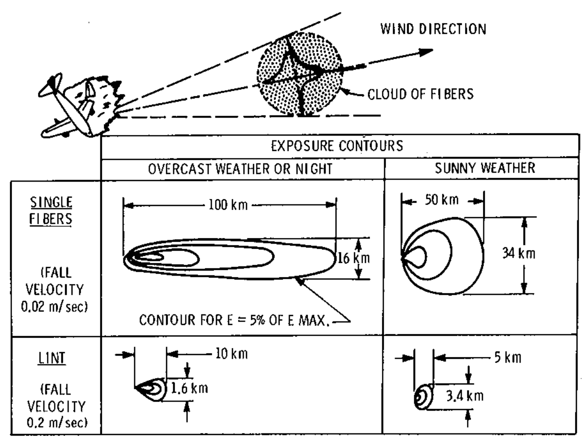

Figure 12. Weather conditions and fiber dispersion.

1. CONCENTRATION, $C = \dfrac{\text{NUMBER OF PARTICLES}}{\text{VOLUME}}$

2. EXPOSURE OR DOSAGE, $E = \text{CONCENTRATION} \times \text{TIME}$

$$= \int C\,dt$$

3. DEPOSITION, $D = \dfrac{\text{NUMBER OF PARTICLES}}{\text{AREA}}$

Figure 10. Measures of carbon fiber pollution.

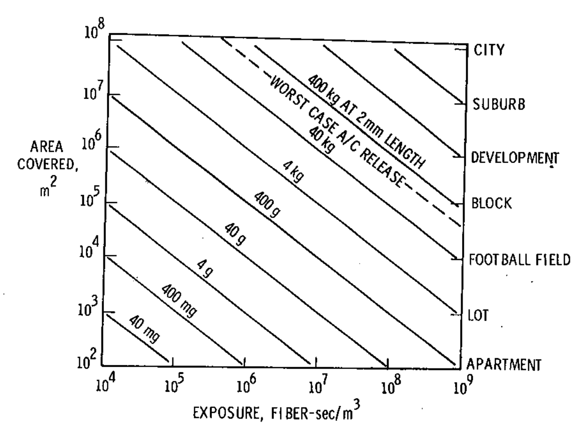

Figure 13. Parametric plot of carbon fiber area coverage.

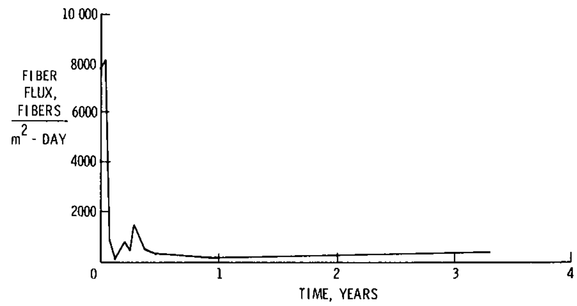

Figure 14. Extent of carbon fiber re-suspension with time.

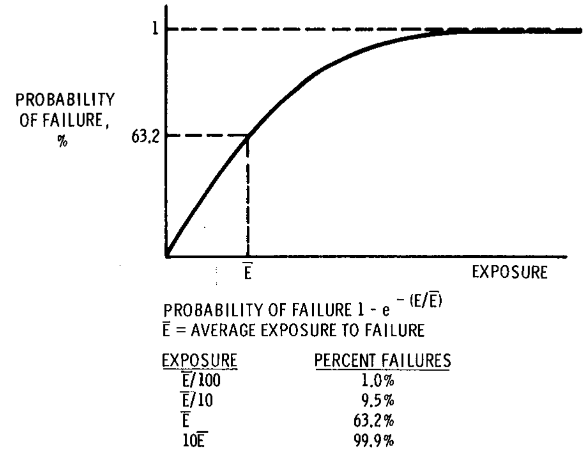

Figure 17. Electronic equipment failure mode.

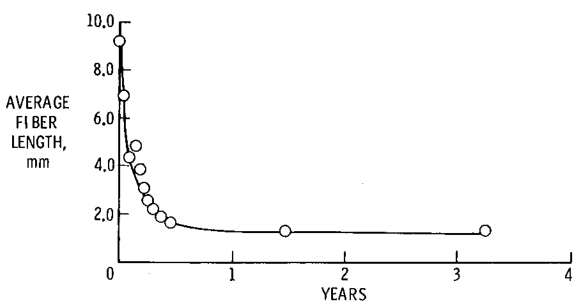

Figure 15. Change in fiber lengths with resuspension.

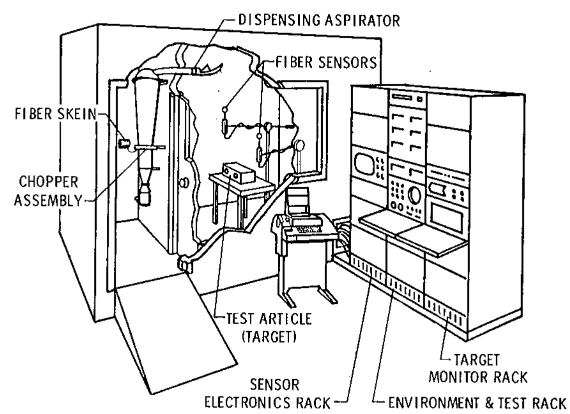

Figure 18. NASA carbon fiber exposure chamber.

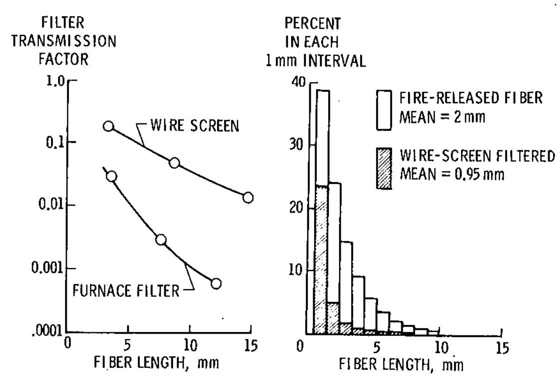

Figure 16. Carbon fiber filtration data.

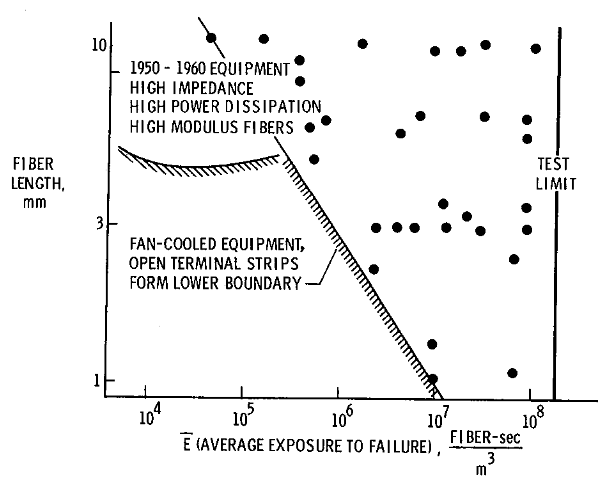

Figure 19. Average exposure to failure for vulnerable equipment.

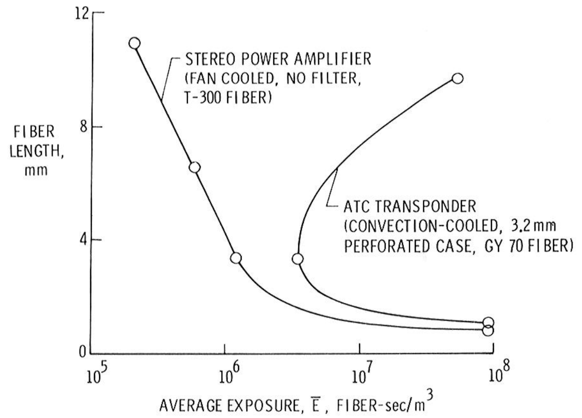

Figure 20. Effect of fiber length on equipment vulnerability.

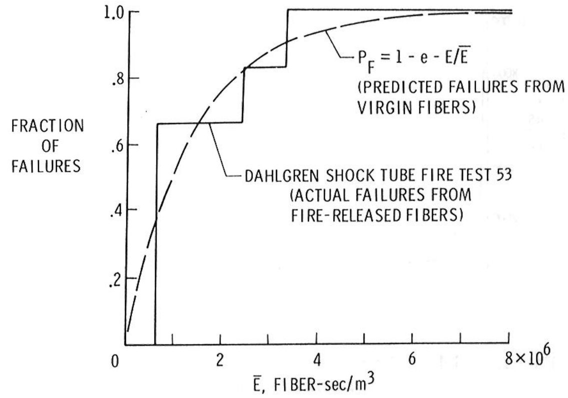

Figure 23. Probability of failure of stereo amplifiers to fire-released fibers in comparison to virgin fibers.

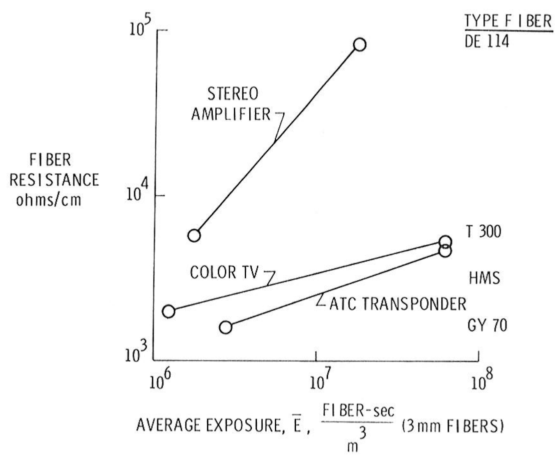

Figure 21. Effect of fiber resistance on equipment vulnerability.

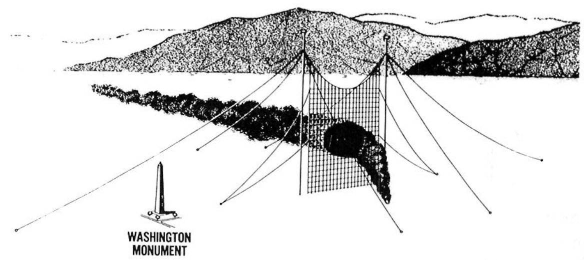

Figure 24. Balloon-supported "jacob's ladder" fire plume sampling net.

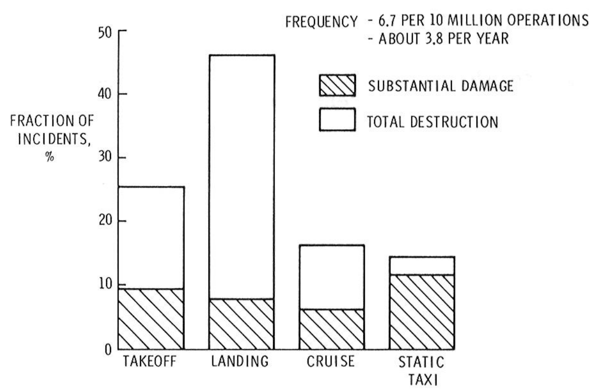

Figure 25. Domestic air carrier incidents with fire and/or explosion, 1968-1976 (Source: NTSB)

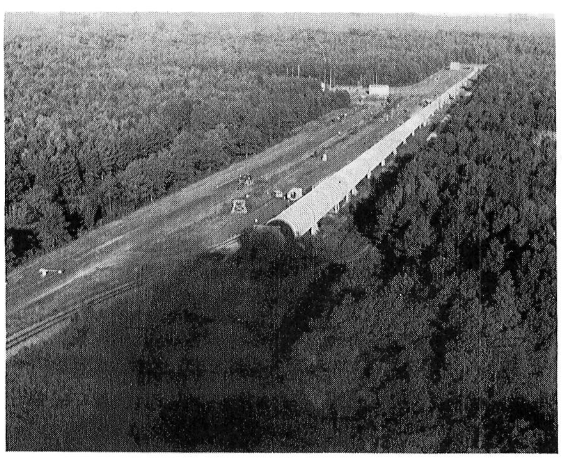

Figure 22. Shock tube fire facility at Dahlgren, Virginia.

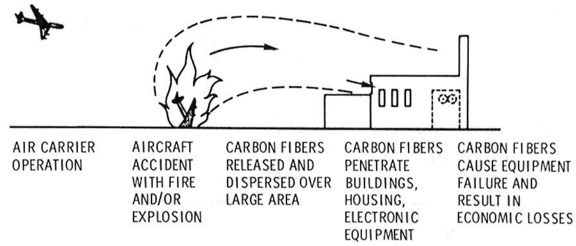

Figure 26. Sequence of events modeled in risk analysis.

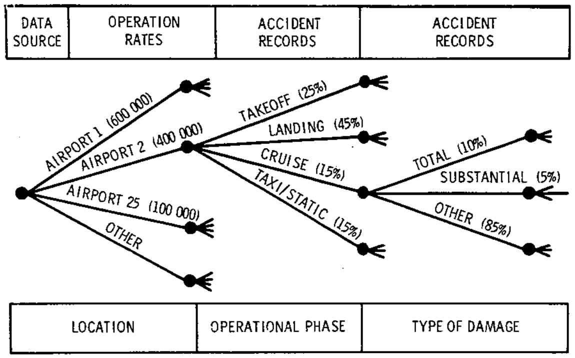

Figure 27a. Simplified event tree logic.

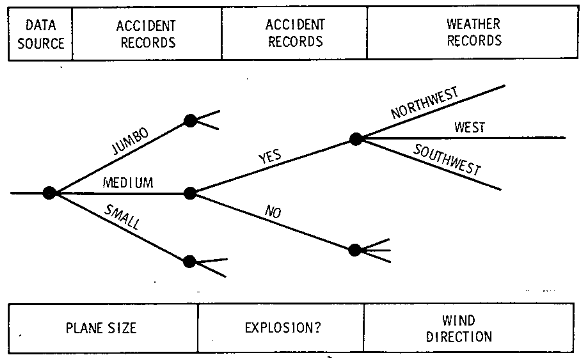

Figure 27b. Simplified event tree logic.

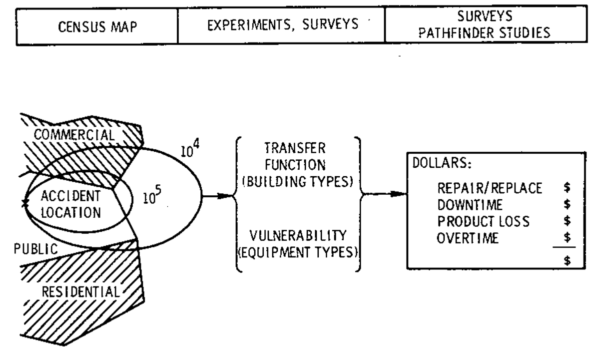

Figure 27c. Simplified event tree logic.

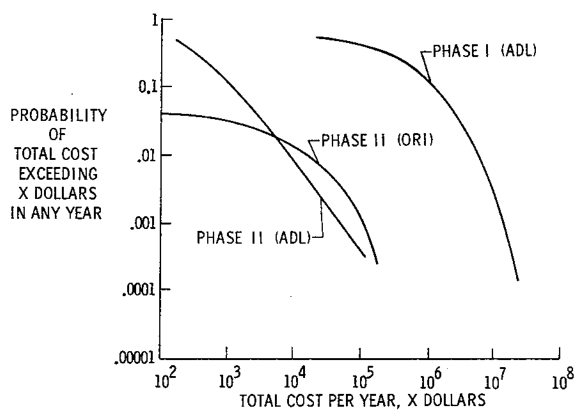

Figure 28. Phase I and Phase II risk profiles.

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15. Supplementary Notes
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16. Abstract
Carbon and graphite fibers are known to be electrically conductive. That property has resulted in damage to electrical equipment from the inadvertent release of virgin fibers into the atmosphere. The rapidly accelerating use of carbon fibers as the reinforcement in filamentary composite materials brought up the possibility of accidental release of carbon fibers from the burning of crashed commercial airliners with carbon composite parts. Such release could conceivably cause widespread damage to electrical and electronic equipment. This paper presents the experimental and analytical results of a comprehensive investigation by the National Aeronautics and Space Administration of the various elements necessary to assess the extent of such potential damage in terms of annual expected costs and maximum losses at low probabilities of occurrence. A review of a NASA materials research program to provide alternate or modified composite materials to overcome any electrical hazard from the use of carbon composites in aircraft structures is described.

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