

APPROACH TO THE ASSESSMENT OF THE HAZARD

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This paper is intended to provide an overview of the NASA approach to the assessment of the carbon fiber hazard. The objective of this overview is to place the later papers on the development of the data and analysis in the perspective of the entire program. I would like to point out that the first objective of the NASA program has been limited to the risk associated with accidental release of carbon fibers from civil aircraft having composite structures, that is, the potential risk to the civil sector including the general population (Figure 1). Our second objective was to assess the need for protection for civil aircraft from carbon fibers. We have identified an accident scenario for evaluation that involves crashes of civil aircraft, which in the case of large air-transport aircraft, usually occur near large airports (Figure 2). In this scenario, a burning aircraft containing carbon composites releases smoke, soot and carbon fibers to be wafted downwind from the fire and, depending upon the wind direction, have the potential of adversely impacting on transportation, manufacturing, and public service facilities as well as the home owner, commercial facilities and the power distribution systems. Another dimension of this potential hazard can be illustrated by the flow of analysis required to assess the risk (Figure 3). These are the elements that are involved in determining the risk that is associated with accidental release of carbon fiber. The subsequent papers (Figure 4) are generally organized along the lines of discussing each of these elements. The next four papers will discuss one or more of these elements either as isolated elements or combined elements. The next paper will provide a technical bridge between the laboratory and experiment evidence and the real world we are attempting to analyze. Finally, the eighth and ninth papers will show how the data and real world are combined mathematically in terms of a dollar cost impact on the U.S. economy. Dollars were chosen as the understandable common denominator measure of risk. As such it allows the addition of the costs of the failure of a single home television set with the cost of the failure of an industrial process control computer. The dollar value is more rationally understood than a statement that two electronic items failed.

Considering each element in turn, our third paper, presented by Dr. Bell, will discuss the source of the carbon fiber (Figure 5). Because carbon composites are not in widespread use today the first question we had to address is what is the future growth of carbon composites? We attack this problem by looking at the potential for various applications in the civil aircraft fleet. We found that general aviation, at this point in time, has only a single aircraft in production that uses carbon composite. That aircraft, a helicopter using less than 50 kg of carbon fiber, has only been in production a short time and current orders are only now approaching the 300 level. There is one airplane under construction and another in a preproduction stage which utilizes carbon composites. The viability of these two ventures is not yet proven. Both of these aircraft are turbine powered executive aircraft with a limited

potential for mass marketing. The remainder of the general aviation industry appears to be unprepared, for financial and technical reasons unrelated to the carbon fiber hazard, to begin to apply carbon composite technology to their designs. Therefore, we had to look at an industry that does not appear to be ready to adapt carbon composite applications and project the usage that they could have if they were encouraged to do so. I should point out that, for our purposes, general aviation is defined as all United States aircraft minus the air transport aircraft. That includes rotocraft, executive jet transports and the two seat trainer usually misnamed the "cub." We assumed a 30 percent a year growth in carbon fiber usage and projected the usage shown in Figure 6. Based on that projection, in about the 1993 time frame we would be looking at in excess of a million kilograms of carbon composite being flown in the general aviation fleet. Actually, that is a small amount of carbon fiber per aircraft in a very large fleet of aircraft.

In the air-transport area we took a different approach. We had the assistance of the major air-transport aircraft manufacturers in the United States. We analyzed the capability of these individual companies, considered their plans and the possibilities in which they could introduce carbon composites, and from that determined the date of various applications of carbon composites on their production aircraft for the next 15 year time period. Combining that information with an FAA study of the size of the air-transport fleet that is anticipated to be required over the next 15 years, we were able to develop the projection of carbon fiber usage on air-transport aircraft illustrated in Figure 6. The details of the 1993 estimate of air-transport fleet usage are illustrated in Figure 7. The carbon fiber usage is given as a function of the percent of the fleet exceeding a given level. We see that about 73 percent of the 1993 fleet would have some amount of carbon composite, even though it's a small amount, and one half percent of the fleet might have as much as 10,954 kilograms of carbon on the aircraft. It was this estimate of the carbon fiber usage that has been used in the analysis by Dr. Pocinki et al. (Reference 1) and Dr. Fiksel et al. (Reference 2).

In addition to the carbon fiber use projection, we have had to analyze the accident experience. The crash fire frequency is fairly easily obtained from the records of the National Transportation Safety Board (NTSB). However, that data is not completely adequate to determine the degree of damage involved. Many accidents that are listed as fire accidents in the NTSB data did not involve significant damage to the aircraft. In order to understand this area quite well, we had Boeing, Lockheed and Douglas analyze all of the jet transport accidents that have occurred since the jet transport was introduced. We were able to determine the magnitude of the fire damage for these accidents and determine the percentage of the various components consumed in the fire (Figure 8). The examples shown in the figure illustrate the damage to components exposures to fire as a function of the percent of accidents with fire. The rudder, for example, tends to be the least damaged component. Very rarely is a rudder totally destroyed and in most accidents it is only partially consumed. The components that are most heavily damaged are the fuselage or wing-body fairing. All other components tend to fall between the two extremes of the rudder and the fuselage.

We found that the fire dynamics and fire chemistry were not a well-understood subject. We found that we had to develop a suitable theory and obtain an experimental verification of that theory. We asked the Ames Research Center, which has been working in fire studies for a number of years, to take responsibility for development of a suitable theory and to obtain an experimental verification of the theory. As a part of that effort a series of tests were done at the NASA White Sands, New Mexico facility. Figure 9 shows one of these tests where a large pool fire was started and measurements were made in the fire at a number of elevations in the fire plume to determine fire temperatures, velocities, fuel-air ratios and other such elements that are important to understanding the potential for carbon fiber release. We used this kind of information to predict, for example, the percentage of released fiber that would be burned up in a fire plume.

Finally, we have had to quantify the composite fiber release characteristics. Dr. Bell's paper (Reference 3) discusses this in considerable detail, but let me just introduce this subject by this illustration of a sample specimen in a test chamber (Figure 10). This is a 6.35 cm by 15.24 cm (2 1/2 in. by 6 in.), 32-ply specimen in a radiant and gas-fired furnace. The illustration shows that the specimen has had layers of fiber and epoxy removed as it was gradually eroded away in the fire. In this particular series of tests, performed by AVCO, we found that as this charcoal glowing effect developed we could record with a camera the fibers being burned or oxidized away.

Considering the next elements in the flow of analysis, Dr. Elber will be discussing the areas of dissemination, redissemination and transfer function (Figure 11)(Reference 4). We had to relate the existing pollution dissemination models to carbon fiber transport. Dr. Trethewey at the Army Dugway Proving Ground had previously completed most of the experimental and theoretical work in this area and assisted us with what additional help we needed. In addition, we had to quantify the post release redissemination of carbon fiber. We again went to Dr. Trethewey at Dugway for an experimental study. Dr. Elber will discuss and interpret the results of that experiment. We have to quantify the potential for carbon fiber to be transported into buildings and into equipment. To do this, we had to develop test methods and acquire data in building and equipment transfer functions. Most of our data in this area was generated by the Army Ballistic Research Laboratory at Aberdeen or by the Bionetics Corporation using the Langley Fiber Chamber.

Our next element in the flow of analysis, equipment vulnerability, will be covered by Israel Taback in Reference 5. Once fibers have been transported through the atmosphere and into enclosures, we have to analyze the electrical effects on various equipment. In fact, we also have to identify the various types of equipment that we must consider in our analysis, and by our choice of an accident scenario, we have to consider a fairly wide range of equipment - ranging all the way from consumer products that occur in the home to aircraft components (Figure 12). Once we have identified a suitable sample, we need to conduct fiber exposure tests on these components and then analyze the results. We have at Langley a carbon fiber test chamber and we have been using similar facilities at the Army Ballistic Research Laboratory (Figure 13).

Basically, we place test specimens in an enclosed chamber. We run raw virgin fiber through a chopper, cutting the long length of fiber into prescribed short lengths of fiber, aspirate the fiber into the room and let it settle as it would in a normal atmospheric environment. Through monitoring, we determine the condition or the health of the equipment being exposed to fiber and through monitoring of the fiber concentrations and exposures, we determine the level of exposure at which failures can occur. A number of duplicate tests are required to obtain an adequate statistical sample of the failure rate. This method is used to develop data from which we can generalize for the equipment considered in the risk assessment. I should also point out that we have had to consider "failures" other than equipment malfunctions and Israel Taback will discuss, for example, the potential for shock hazard from some common, everyday equipment that you might have around your home, like a toaster. In addition to the fiber chamber test data we have utilized circuit analysis and a fiber simulator to investigate the susceptibility of equipment to fiber exposure. The National Bureau of Standards, in meeting their own responsibilities to the national carbon fiber program and to assist NASA in gathering data, has conducted extensive analysis on consumer products.

Next, in order to integrate some of the test activities and to verify the small scale tests we chose to do some large scale experiments (Figure 14). The objectives of the large scale experiments were to verify that the small chamber tests do adequately predict the fiber release characteristics and, also, to verify that the vulnerability of the equipment that we have been testing in the chamber with virgin fibers properly represents the vulnerability of equipment exposed to fire release fibers. One of these experiments that we performed was a large scale fire release of carbon fiber (Reference 6). Figure 15 is a photograph taken from about three miles away from the fire at the Dugway Proving Ground where we burned a variety of composite structural specimens containing from 32 to 50 kilograms of carbon. Through a wide range of monitoring devices and samplers, we were able to determine the fiber flux from the burning composite and the downwind depositions. One of the devices that we used to monitor the carbon fiber flux is a large Jacob's ladder, a 305 meter square rope grid carrying several hundred passive and active fiber collectors, that is supported by the two balloons shown in Figure 15. The Jacob's ladder is placed so that the fire plume intersects the ladder so that we can measure the flux all across that fire plume.

In addition to the outdoor tests, we have performed a large scale burn in a chamber. Figure 16 shows the Dahlgren shock tube. It has been converted to use as a fire facility to release carbon fibers from composites. We built a fire midway in its length and, through the use of exit fans on the large end, drew the fire efflux and carbon fibers through the tube across electrical equipment. The equipment exposed had been previously tested with virgin fibers and had known failure characteristics. Sufficient carbon composite was burned to release enough carbon fibers to deliberately fail the equipment. It would not be adequate to expose the equipment to carbon fiber levels that would not assure failure because that would prove nothing. We had to over-expose the equipment sufficiently to deliberately fail it. We were successful and Dick Pride will discuss that test in detail. It should be pointed out that there was no possibility of spilling of carbon fiber from the open end of

the tube because we used a water curtain at the end which we found quite effectively filtered out carbon fibers.

The seventh paper of the conference (Reference 7) will present the results of a series of surveys used to provide a variety of information necessary for assessing the public risk due to accidentally released carbon fibers. As such, the surveys become a bridge between the technical and laboratory data gathered on carbon fiber release, penetration, and vulnerability effects and the economic impact of these factors. The surveys were completed as a team effort. The surveys are not the results of one company or one organizational study. A. D. Little and ORI, which performed the risk calculations, found it necessary to tie the data available in census information to real installations. We used ORI, A. D. Little and the Bionetics Corporation, as well as our Langley staff, to survey a variety of installations that ranged all the way from public facilities, utilities, commercial to industrial facilities. This report was prepared by Ansel Butterfield of the Bionetics Corporation. In each installation the teams searched for the data that we needed to tie together our modeling problem (Figure 17). We had to acquire economic data and we had to search for the sensitivity areas that might involve life critical and emergency services. In addition we had to evaluate the protection afforded in-place operating equipment. Of course, the purpose of all this was to incorporate the survey result into our analysis model so that we would have a better tie between the theoretical calculations and the real economic environment that we are trying to simulate.

The next two papers will present the results of two studies performed independently by ORI Incorporated and A. D. Little Incorporated (References 1 and 2). One advantage offered by performing two independent studies is that different technical approaches, both considered a priori credible, may be compared. If either approach is faulty, for whatever reason, significant differences in the final analysis result will occur. For this introduction, I will emphasize the similarities in the basic approach used by both groups, though A. D. Little will present the results of a completely different approach for comparison (Figure 18). The basic approach is to simulate a single accident in the scenarios under question and compute the probabilities that are associated with the accident location and condition, determine the release characteristics, that is how much fiber is released, and compute the dispersion of that fiber through the atmosphere. The simulation is based on real localities where we can determine the type of equipment that would be exposed. Based on the level of exposure and the failure rate of the exposed equipment, the computation then determines the economic consequence. Now doing this calculation once gives you a sample answer but it does not address the total probability to the entire country. And so, therefore, we must repeat this simulation sufficient times to obtain a statistically significant answer. Now the approaches of the individual contractors are different, in detail, particularly with regard to assessing the economic consequence, but basically they follow this overall approach. In one case the simulation is performed for the nine major traffic airports in the United States and is extrapolated to the nation as a whole. In the other case, the simulation is performed for the 26 airports with the highest traffic volume and then extrapolated to the United States as a whole.

Finally, in the tenth paper, this author will attempt to put the NASA study results in perspective (Reference 8). A number of conservative assumptions will be pointed out as well as areas where we think we have some limitations on the assessment. There have been a number of implied assumptions that you may not have recognized and some conclusions that we have not put into the main discussion that will be shared in this discussion.

Finally, the various participants in the NASA risk assessment program are listed in Figure 19. Alongside of each name is the principal contribution of the organization to the NASA program. The NASA Graphite Fiber Risk Analysis Program Office is grateful to the individuals of these organizations that contributed to the various papers presented at this conference.

REFERENCES

1. Pocinki, Leon S.; Cornell, Merrill E.; and Kaplan, Lawrence: Assessment of the Risk Due to Release of Carbon Fiber in Civil Aircraft Accidents - Phase II Report. Assessment of Carbon Fiber Electrical Effects, NASA CP-2119, 1980. (Paper 8 of this compilation.)
2. Fiksel, J.; Rosenfield, D.; and Kalelkar, A.: Assessment of Risk Due to the Use of Carbon Fiber Composites in Commercial and General Aviation. Assessment of Carbon Fiber Electrical Effects, NASA CP-2119, 1980. (Paper 9 of this compilation.)
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7. Butterfield, Ansel J.: Surveys of Facilities for the Potential Effects From the Fallout of Airborne Graphite Fibers. Assessment of Carbon Fiber Electrical Effects, NASA CP-2119, 1980. (Paper 7 of this compilation.)
8. Huston, Robert J.: Perspective on the Results. Assessment of Carbon Fiber Electrical Effects, NASA CP-2119, 1980. (Paper 10 of this compilation.)

- QUANTIFY RISK ASSOCIATED WITH ACCIDENTAL RELEASE OF CARBON FIBERS FROM CIVIL AIRCRAFT HAVING COMPOSITE STRUCTURES
- ASSESS THE NEED FOR PROTECTION OF CIVIL AIRCRAFT TO ACCIDENTALLY RELEASED CARBON FIBER

Figure 1.- Carbon fiber hazard risk assessment - program objectives.

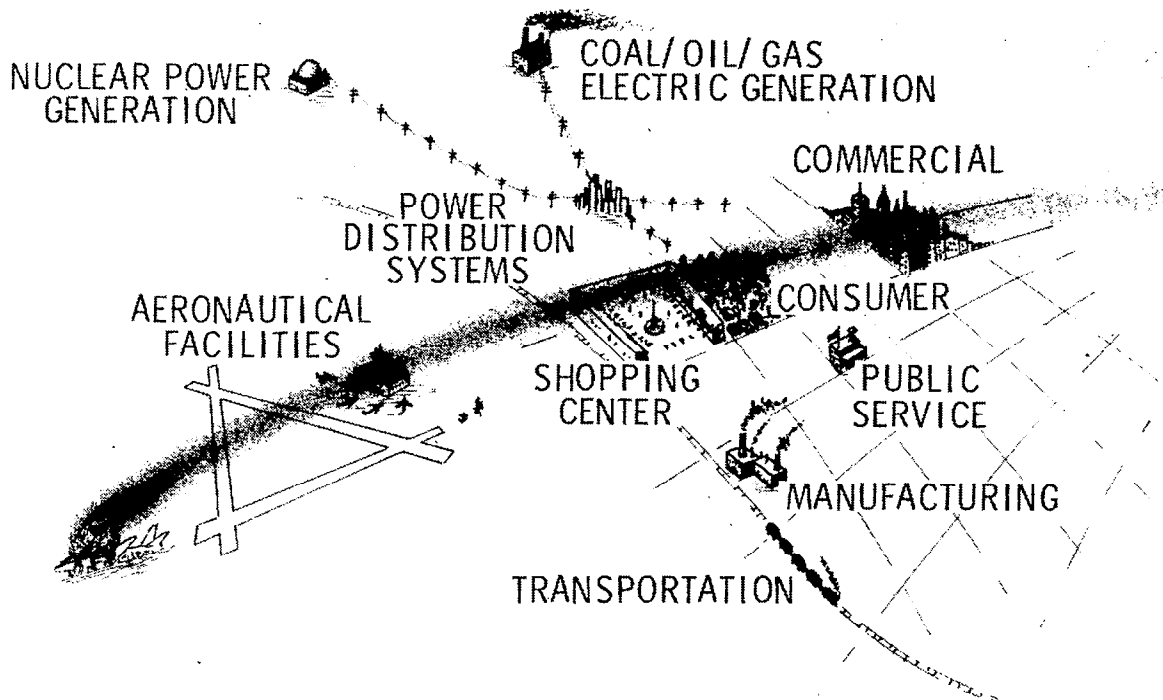


Figure 2.- The carbon fiber hazard potential.

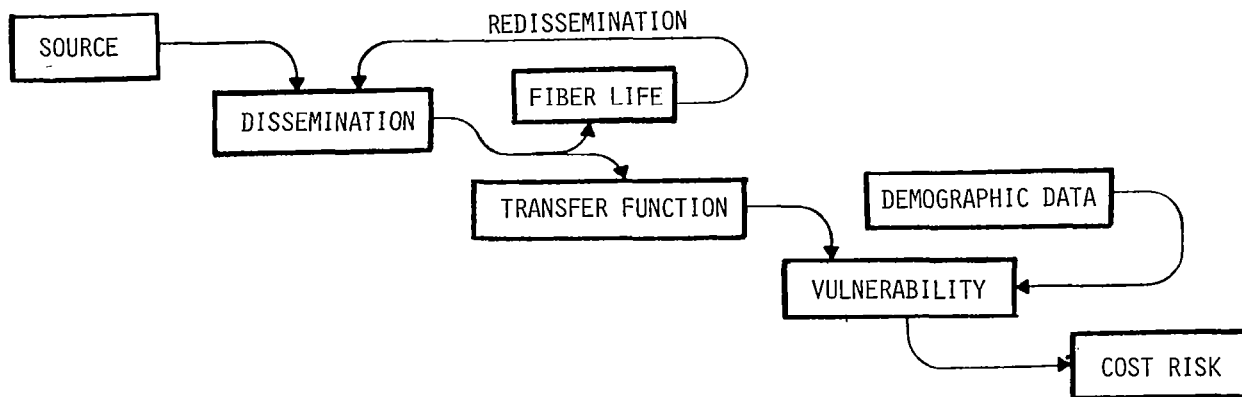


Figure 3.- Risk analysis flow.

SOURCE OF RELEASED FIBERS

DR. V. L. BELL

DISSEMINATION, REDISSEMINATION, AND TRANSFER FUNCTIONS FOR RELEASED FIBERS

DR. W. ELBER

EQUIPMENT VULNERABILITY, ANALYSIS AND TESTS

I. TABACK

LARGE-SCALE FIBER RELEASE AND EQUIPMENT EXPOSURE EXPERIMENTS

R. A. PRIDE

SURVEY OF INDUSTRIAL, BUSINESS AND PUBLIC FACILITIES TO ESTABLISH FIBER INDUCED FAILURE CONSEQUENCE

A. J. BUTTERFIELD

AN ASSESSMENT OF THE RISK DUE TO THE RELEASE OF CF FROM CIVIL AIRCRAFT ACCIDENTS

DR. L. POCINKI

AN ASSESSMENT OF RISK DUE TO THE USE OF CARBON FIBER COMPOSITES IN COMMERCIAL AND GENERAL AVIATION USE

DR. JOSEPH FIKSEL
D. B. ROSENFELD

PERSPECTIVE

R. J. HUSTON

Figure 4.- Carbon fiber hazard - NASA assessment of the risk from the accidental release of carbon fibers from civil aircraft.

PROJECT CF USAGE OVER THE NEXT 15 YEARS

ANALYZE ACCIDENT EXPERIENCE

CRASH/FIRE FREQUENCY

CRASH/FIRE DAMAGE

UNDERSTAND FIRE DYNAMICS AND CHEMISTRY

QUANTIFY COMPOSITE FIBER RELEASE CHARACTERISTICS

Figure 5.- Source.

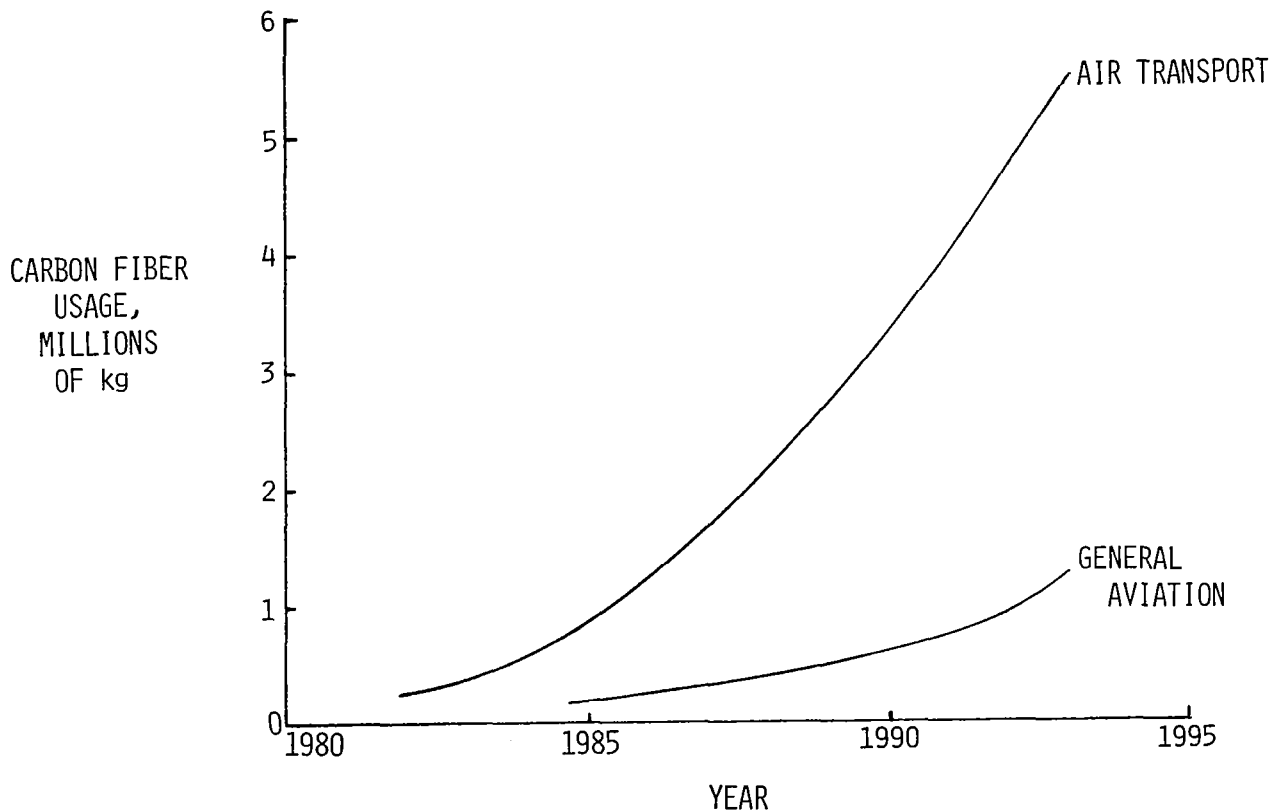


Figure 6.- Civil aircraft CF usage projection.

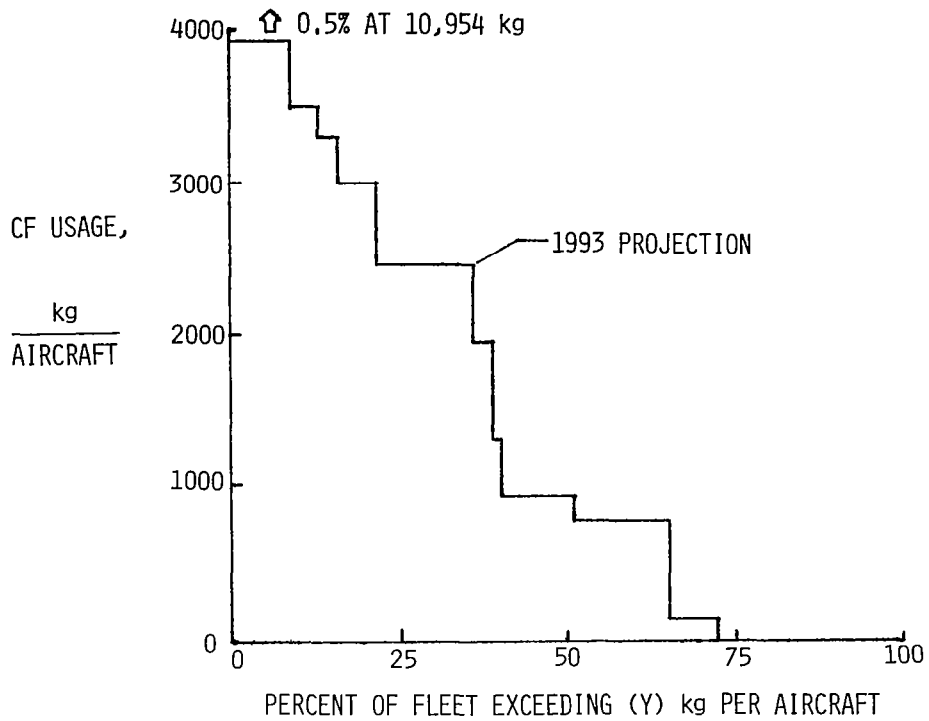


Figure 7.- Air transport fleet CF usage.

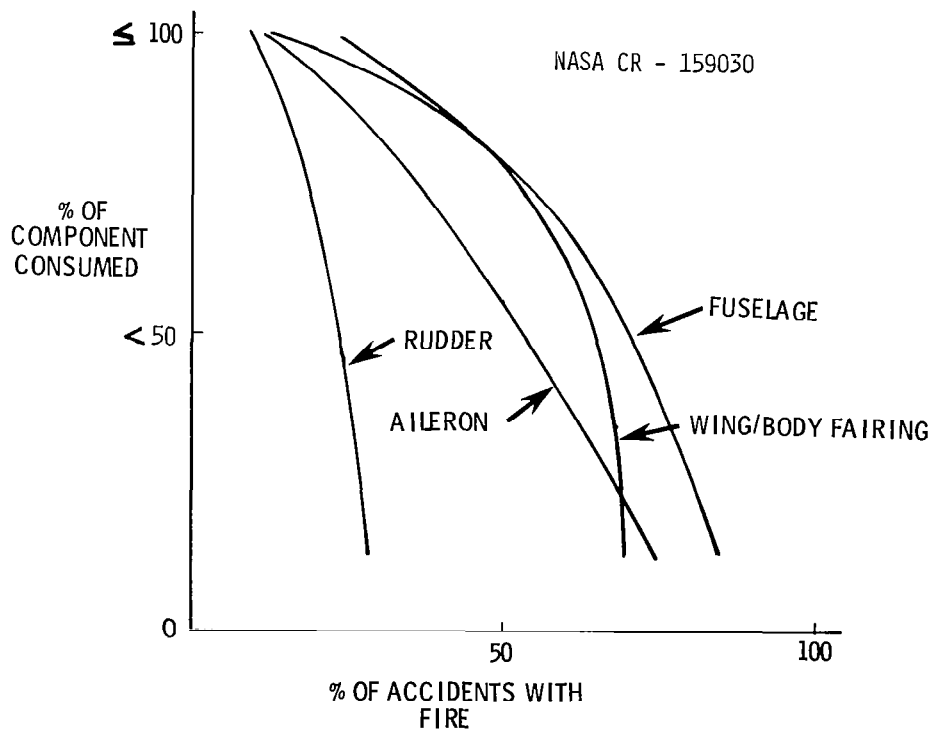


Figure 8.- Frequency of fire damage for 88 accidents (examples).

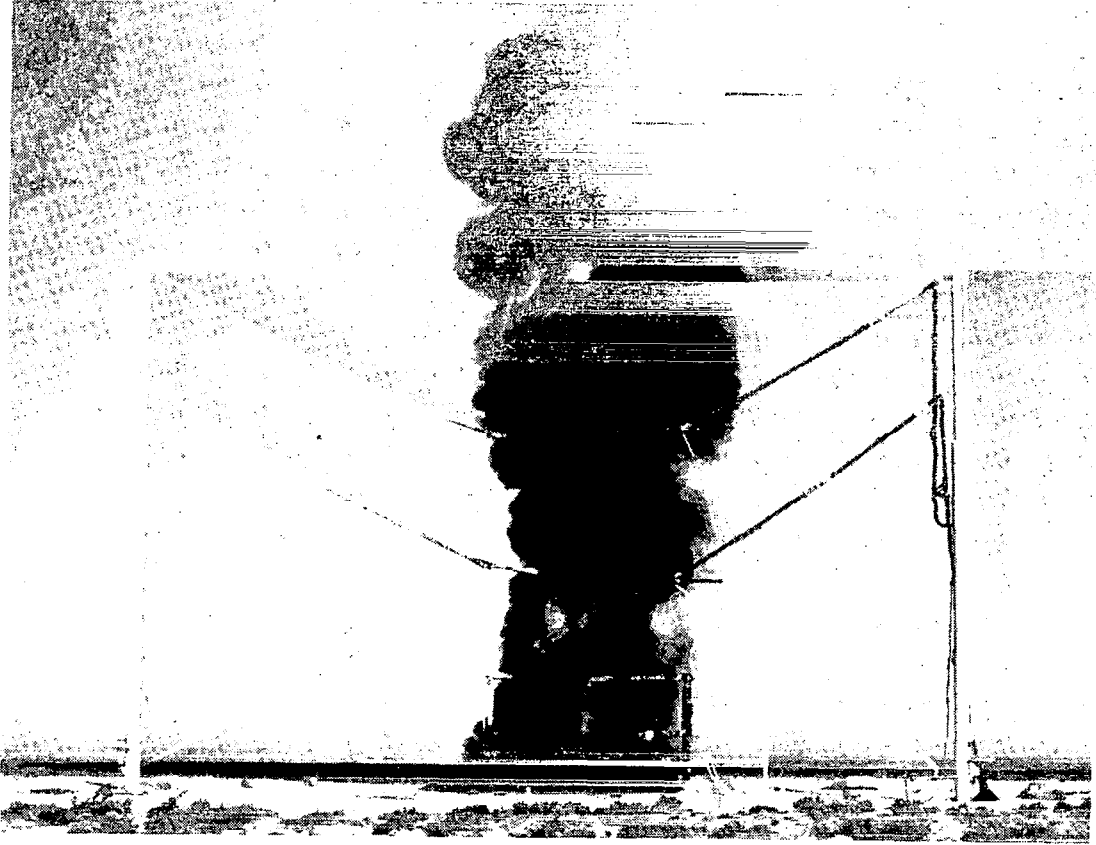


Figure 9.- Fire plume model verification tests at
White Sands, New Mexico.



Figure 10.- Test specimen.

RELATE EXISTING POLLUTION DISSEMINATION MODELS TO CF TRANSPORT

QUANTIFY POST RELEASE REDISSEMINATION OF CARBON FIBER

QUANTIFY BUILDING AND EQUIPMENT TRANSFER FUNCTIONS AND PENTRATION FACTORS

Figure 11.- Dissemination, redissemination, transfer function.

IDENTIFY AND TEST REPRESENTATIVE SAMPLES OF EQUIPMENT

CONSUMER PRODUCTS

INDUSTRY

BUSINESS

AIRCRAFT

ANALYZE TEST RESULTS AND GENERALIZE FOR THE RISK ANALYSIS

Figure 12.- Vulnerability.

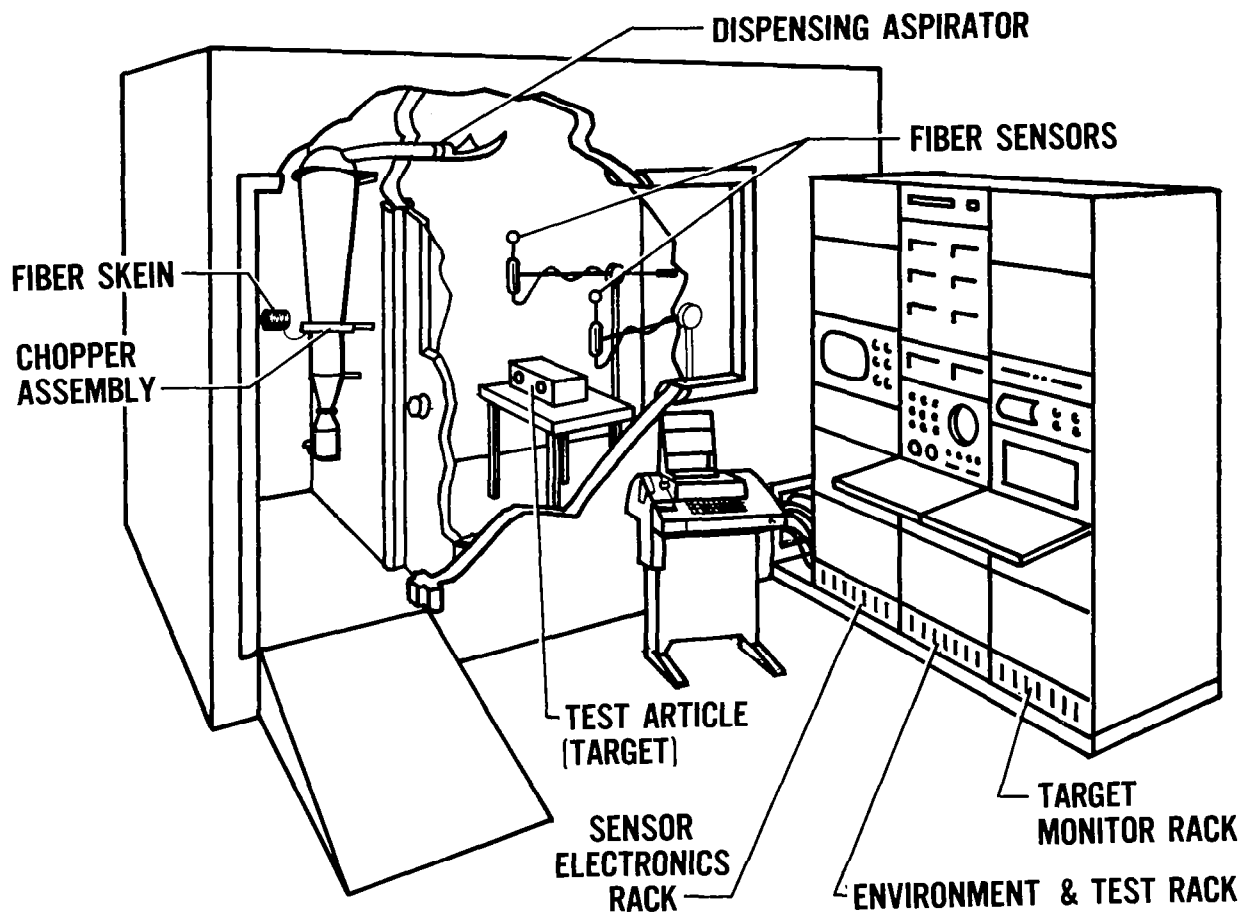


Figure 13.- Langley carbon fiber test chamber.

VERIFY THAT FIBER RELEASE CHARACTERISTICS ARE ADEQUATELY
 ESTIMATED BY SMALL-SCALE TEST RESULTS

VERIFY VULNERABILITY OF EQUIPMENT TO FIRE RELEASED FIBERS

Figure 14.- Large-scale experiments.



Figure 15.- Fire at Dugway Proving Ground.



Figure 16.- Dahlgren "shock tube" burn test.

SCOPE OF SURVEYS

- 62 SURVEYS OF PUBLIC, UTILITY, COMMERCIAL, AND INDUSTRIAL INSTALLATIONS

PURPOSE

- ACQUIRE DATA FOR USE IN ECONOMIC MODELING
- IDENTIFY SENSITIVITY TO AIRBORNE CARBON FIBERS OF:
LIFE CRITICAL OR EMERGENCY SERVICES
IN-PLACE OPERATING EQUIPMENT
- INCORPORATE SURVEY RESULTS IN ANALYSIS MODELS

Figure 17.- Survey of facilities.

SIMULATE SINGLE ACCIDENT IN SCENARIO UNDER QUESTION

- COMPUTE ACCIDENT CONDITIONS AND PROBABILITIES
- DETERMINE CARBON FIBER RELEASE CONDITIONS
- CALCULATE CARBON FIBER DISPERSION FOOTPRINTS
- ENUMERATE EXPOSED EQUIPMENT
- DETERMINE EXPECTED LOSSES

REPEAT SIMULATION SUFFICIENT TIMES TO OBTAIN STATISTICALLY SIGNIFICANT ANSWER

Figure 18.- Risk computation - overall approach.

AIR FORCE GEOPHYSICS LABORATORY	-	LARGE-SCALE TESTS	
AMES RESEARCH CENTER	-	FIRE DYNAMICS AND CHEMISTRY	
SCIENCE APPLICATIONS, INC	-	THEORY DEVELOPMENT	
WHITE SANDS TEST RANGE	-	FIRE MEASUREMENTS	
AVCO	-	SOURCE	
BALLISTICS RESEARCH LABORATORY ABERDEEN	-	VULNERABILITY, TRANSFER FUNCTION	
BIONETICS CORPORATION	-	PATHFINDER STUDIES, VULNERABILITY, SURVEYS	
BOEING	}	-	
DOUGLAS			SOURCE, AIRCRAFT VULNERABILITY
LOCKHEED			AIRCRAFT OPERATIONAL SURVEYS
DAHLGREN, NAVAL SURFACE WEAPONS CENTER	-	SOURCE, LARGE-SCALE TESTS	
DUGWAY PROVING GROUND	-	DISSEMINATION, REDISSEMINATION, LARGE-SCALE TESTS	
JET PROPULSION LABORATORY	-	INSTRUMENTATION	
A. D. LITTLE	}	-	
ORI			ANALYSIS METHODS, SURVEYS, RISK COMPUTATIONS
GEORGE WASHINGTON UNIVERSITY			
NATIONAL BUREAU OF STANDARDS	-	VULNERABILITY	
TRW	-	DATA ANALYSIS, LARGE-SCALE TESTS	

Figure 19.- NASA carbon fibers risk assessment - program participants.