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AN ASSESSMENT OF THE RISK ARISING FROM ELECTRICAL EFFECTS ASSOCIATED WITH CARBON FIBERS RELEASED FROM COMMERCIAL AIRCRAFT FIRES

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PREFACE

The work presented in this report was conducted under the direction of Dr. Ashok S. Kalelkar. Principal contributors to the project were Dr. Joseph Fiksel, Dr. Donald Rosenfield, David L. Richardson, and John Hagopian. The contributions of Israel Taback and Ansel Butterfield of Bionetics, Inc. are gratefully acknowledged, as are the contributions and guidance of Dr. Wolf Elber and Mr. Robert J. Huston of the National Aeronautics and Space Administration, Langley Research Center. Preparation of the manuscript was coordinated by Ms. Maureen Sullivan and Ms. Janet Mayer.

TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

LIST OF TABLES

LIST OF TABLES - Continued

LIST OF FIGURES

LIST OF FIGURES - Continued

1. EXECUTIVE SUMMARY

1.1 OVERVIEW AND OBJECTIVES

The increasing usage of carbon fiber (CF) composites in commercial aircraft has led to awareness of a potential, though not necessarily substantial risk. Air carrier operations will occasionally result in accidental fires and/or explosions. If the aircraft is carrying carbon fiber composites in the structure, then some of these fibers may be burned away by an intense fire, rise in the convection plume and be dispersed over a large area, depending upon the atmospheric conditions and the wind direction. If there are buildings or other facilities located in the path of the carbon fiber cloud, and if these buildings contain electronic equipment which is potentially vulnerable to the fibers, then there is a possibility that the fibers will penetrate these buildings, damage the equipment and thus result in economic losses to the residents or proprietors of these facilities.

The objective of the commercial aviation risk analysis was the assessment of potential economic losses due to CF releases through 1993. To meet this objective, several related objectives were formulated. In order to quantify the amount of carbon fiber that could be found on aircraft, it was necessary to project the potential usage of carbon fiber composites in commercial aircraft through 1993. In order to estimate the frequency with which such fibers could be released, it was necessary to investigate the incidence of commercial aircraft accidents with fire and/or explosion, in terms of both their location and frequency. In order to describe the physical mechanisms whereby fibers could be transported over the surrounding area, dispersion models were developed. Estimates were made of potential economic losses in situations where the accidentally released carbon fibers were able to penetrate buildings and equipment cabinets, creating damaging short circuits. In addition, it was necessary to explicitly show the uncertainties in the assumptions that entered into the risk analysis, and to test the sensitivity of the projected losses to those input parameters.

This report represents the second phase of a risk analysis program performed for NASA-Langley Research Center and incorporates some modelling techniques and data developed during the first phase. The major results of the risk assessment are described below:

1.2 CARBON FIBER USAGE

In order to describe the usage of carbon fiber composites in aircraft, we divided the commercial aircraft into three categories of jets--small, medium and large jets. Each of the jet aircraft produced by the major airframe manufacturers was assigned to one of these classes. The study did not consider other classes of aircraft, such as turbo-props, since there is expected to be little, if any, composite usage on this type of aircraft. The projections were based on estimates obtained from the three major U.S. airframe manufacturers, McDonnell Douglas, Lockheed and Boeing. They estimated both the fleet mix; that is the relative numbers of different sizes of aircraft in service in 1993, and the potential usage of carbon fiber composites for each of these classes. As indicated in Table 1-1, roughly half of the aircraft in service in 1993 will be large jets, the majority of which will be using carbon fiber composites. The projected weight of actual carbon fibers, including the epoxy binding, ranges from only 11 kg. on some of the small aircraft to as much as 15,600 kg. on some of the large aircraft. For the purposes of the risk analysis, these estimated ranges were used to develop a probability distribution for the amount of carbon fiber involved in an aircraft accident.

1.3 ACCIDENT CONDITIONS

The typical conditions surrounding a severe fire and/or explosion in the case of an air carrier accident were investigated through use of the National Transportation Safety Board accident and incident statistics for the years 1968-1976. Using their records, we created a data base of aircraft accidents that listed for each accident the phase of operation, the location of the accident, the weather conditions at the time of the accident, the nature of the fire, and other relevant details. This data base was augmented with the help of the airframe manufacturers who provided

TABLE 1-1

PROJECTED 1993 USAGE OF CARBON FIBER COMPOSITES IN COMMERCIAL AIRCRAFT*

	Size of Jet			
	Small	Medium	Large	TOTAL
Number of Aircraft in Service	560	780	1399	2739
Number of Aircraft Using CF Composites	100	754	1127	1981
Composite Mass per Aircraft (KG):				
Min.	11	215	155	
Max.	183	3787	15,652	

* Based on estimates of airframe manufacturers

additional data on accident characteristics, such as fire duration, that would affect carbon fiber release conditions. We then utilized these data to determine the distribution of possible accident characteristics.

We found that almost half of the severe accidents involving fire occurred during the landing phase. The take-off phase accounts for one-quarter of these accidents, with the remainder being distributed in either the static/taxi or cruise phase. Since most cruise accidents occur over unpopulated areas, we considered only a small fraction of cruise accidents in the analysis. However, the static, take-off or landing accidents were all associated with specific airport locations. From an analysis of the location of accidents relative to airport runways, we found that over 80% of accidents occur within 10 kilometers of the airport, and in fact 60% of accidents occur at the airport. We also investigated the angle between the accident location and the line of the runway to establish more precisely the potential locations of such accidents.

Historically, there have been about 3.8 accidents per year involving jet air carriers. Although air carrier operations are gradually increasing in number, the accident frequency appears to be relatively constant from year-to-year. Therefore, we did not project any increase in accidents through 1993. Based on the expected fraction of the air carrier fleet that would be carrying carbon fiber in 1993, the projected frequency of incidents involving fire on aircraft carrying composites of carbon fibers would be approximately 2.7 per year in 1993.

There were two different types of scenarios used to describe possible carbon fiber release situations in the aftermath of an air carrier incident. One of them was a simple fire plume in which the fibers were carried aloft by the plume and then dispersed. The second was the fire and explosion case in which there was a sudden rapid conflagration of fuel resembling an explosion, and therefore much more rapid burning of composite and a concentrated release of fibers over a short period of time. Based on the 92 accident data base compiled by the airframe manufacturers, we estimated conservatively that at most 5% of air carrier accidents would result in explosive release of carbon fibers of the type described.

1.4 CARBON FIBER RELEASE CONDITIONS

The extent of dispersion of carbon fibers from a burning aircraft and the level of resulting exposures to the surrounding area were influenced by the release conditions at the time of the accident. Release conditions include the weather conditions, such as atmospheric stability class, wind velocity and wind direction, as well as the duration and the intensity of the fire. With the help of the accident data base compiled by the airframe manufacturers we were able to develop distributions for several of the important release variables. These included the duration of the fire, the percent of fuel burned, and the percent of carbon fiber involved, all of which were found to be correlated. Roughly speaking, the greater the amount of fuel burned, the longer the duration of the burn, and the greater the potential carbon fiber involvement. In addition, the amount of fuel on board was estimated for different phases of operation and different aircraft size categories, and the amount of carbon fibers on board was estimated for the three size classes of aircraft. This allowed calculation of the actual amount of fuel burned and the actual amount of carbon fiber involved.

Even though an aircraft may be carrying over 15,000 kg. of CF composite, the amount of carbon fibers that could be released in a fire is significantly less, partly because of the fact that not all the carbon fibers can be released as single fibers in a burn, and partly because the tentire aircraft structure will not necessarily be involved in the fire. Based on experimental findings, it was estimated that not more then 1% of the carbon fibers involved in a fire would be released in most fire plumes, and that not more than 2.5% would be released in most fire and explosion scenarios. These are conservative estimates using the best judgment and interpretation of the experiments conducted by NASA and other groups on burning composite materials.

1.5 ECONOMIC LOSS ESTIMATES

To assess the potential consequences of carbon fiber-related equipment failures, an economic loss analysis was performed. A broad range of facility categories were identified as being potentially susceptible to equipment failure and/or business interruption, as shown in Table 1-2. Detailed site visits were performed at selected facilities corresponding to most of these categories in order to characterize the quantity, locations, and types of vulnerable equipment, to examine the ventilation and filtration systems in use, and to estimate the losses which might be incurred under various failure scenarios. In general it appeared that most facilities were well prepared for servicing routine equipment failures, and that important units of electronic equipment were usually protected from intrusion of foreign particles.

On the basis of the site visits, a set of loss estimates was constructed for each combination of equipment and facility type. The consequences of a single failure were generally low, rarely exceeding $50,000 in magnitude. Furthermore, the probability of failures was found to be low, given that maximum accidental carbon fiber exposures were expected to be on the order of 10^7 fiber-seconds per cubic meter. Airborne exposure transfer functions were estimated for the various facilities, and were generally found to reduce the outside exposure by at least two orders of magnitude. However, the mean inside exposures required to damage electronic equipment were estimated at 10^8 or more for most equipment categories. Hence, using an exponential failure model, the likelihood of a significant number of failures during a CF exposure would be negligible.

To apply the economic loss data for estimation of national risks, the 26 large hub airports as designated by the FAA were used as a basis for risk analysis. From census data, the numbers of facilities in each category were enumerated within a circular grid of forty sectors surrounding each hub airport. In this way, individual accidents could be simulated, dispersion models could be used to estimate the carbon fiber

TABLE 1-2

POTENTIALLY VULNERABLE FACILITIES

1. Residences	
2. Manufacturers	— Electronic Equipment
	— Computers
	— Aerospace
3. Transportation	— Aircraft and Air Traffic Control
	— Mass Transit
	— Railways
4. Communication	— Telephone
	— Radio/TV/Microwave
	— Post Offices
	— Fire/Police
5. Services	— Financial/Insurance
	— Software/EDP
	— Hospitals
6. General	— Retail Outlets
	— Office Buildings
	— Industrial Plants

exposures in each geographic sector, and the number of facilities affected could be determined. The actual simulation procedure is described below.

1.6 NATIONAL RISK PROFILE

The necessary inputs for the development of a risk profile for CF releases included the accident characteristics, the release conditions, the dispersion model, and the characteristics of vulnerable facilities. Once these elements had been assembled, we performed a Monte Carlo simulation of potential aircraft accidents at each of the 26 large hub airports. We used the Monte Carlo method to develop an individual risk profile for each airport and then these risk profiles were combined into a national risk profile. (A risk profile is a graph indicating the probability of exceeding various levels of dollar loss.) The Monte Carlo procedure worked in the following manner: It simulated a large number of accidents, on the order of hundreds or thousands of accidents, and for each one drew from probability distributions a set of conditions for that accident. The aircraft and incident details, such as the size of the plane and the phase of the operation, were randomly drawn, and these in turn influenced the probable accident location, the likelihood of a delayed explosion, and the assumed release conditions. By repeating the simulation many times, we generated the full range of possible accident types and thus developed a distribution of the potential accident results.

There were several important assumptions that entered into the risk analysis: First, atmospheric conditions were assumed to remain constant during the dispersion of the carbon fiber cloud, since it would be too complex to simulate different atmospheric conditions in different geographic sectors. The assumption is not expected to introduce any bias into the risk analysis since the variation of atmospheric conditions will sometimes increase and sometimes decrease the resulting exposures. We also assumed that there was no precipitation, which is a conservative assumption since if precipitation did occur it might wash out some of the fibers, resulting in lower airborne exposures on the ground. Another major assumption was that for a given facility category all facilities were equal in size, equipment inventory, and financial characteristics. The variation in facility characteristics would introduce a little more variation into the risk profile but should not affect the results too greatly because of the large number of facilities involved that would tend to average each other out. The last major assumption was that all equipment was activated and that failures occurred immediately after exposure. Since some fraction of the electronic equipment exposed will not be activated, this tends to be a conservative assumption. On the other hand, there is a phenomenon of post-exposure vulnerability, in which fibers that are deposited upon equipment do not cause a problem immediately but will affect the equipment when it is turned on at a later date. This phenomenon was not modeled explicitly, but it is taken into account by assuming continuous activation and failures immediately after exposure.

The resulting annual risk profile for economic losses due to air carrier fires involving carbon fibers is shown in Figure 1-1. The horizontal axis shows the total economic losses in dollars as a results of carbon fiber accidents during a given year. The vertical axis shows the annual probability of exceeding each dollar loss value. For example, an annual loss of approximately one thousand dollars would be exceeded with a probability of 10^{-1}, in other words once every ten years. An annual loss of ten thousand dollars would be exceeded about once every three hundred years. The expected annual losses due to CF released from air carrier fires in 1993 was about $470. It should be noted this included only those losses incurred by failures of equipment in the civilian sector.

1.7 CONFIDENCE ESTIMATES

The confidence bounds on the risk profile (Figure 1-1) show the sensitivity of the risk estimates to variations in the input parameters. These confidence bounds are based upon several different sources of uncertainty: the statistical error due to the simulation method, the statistical error in

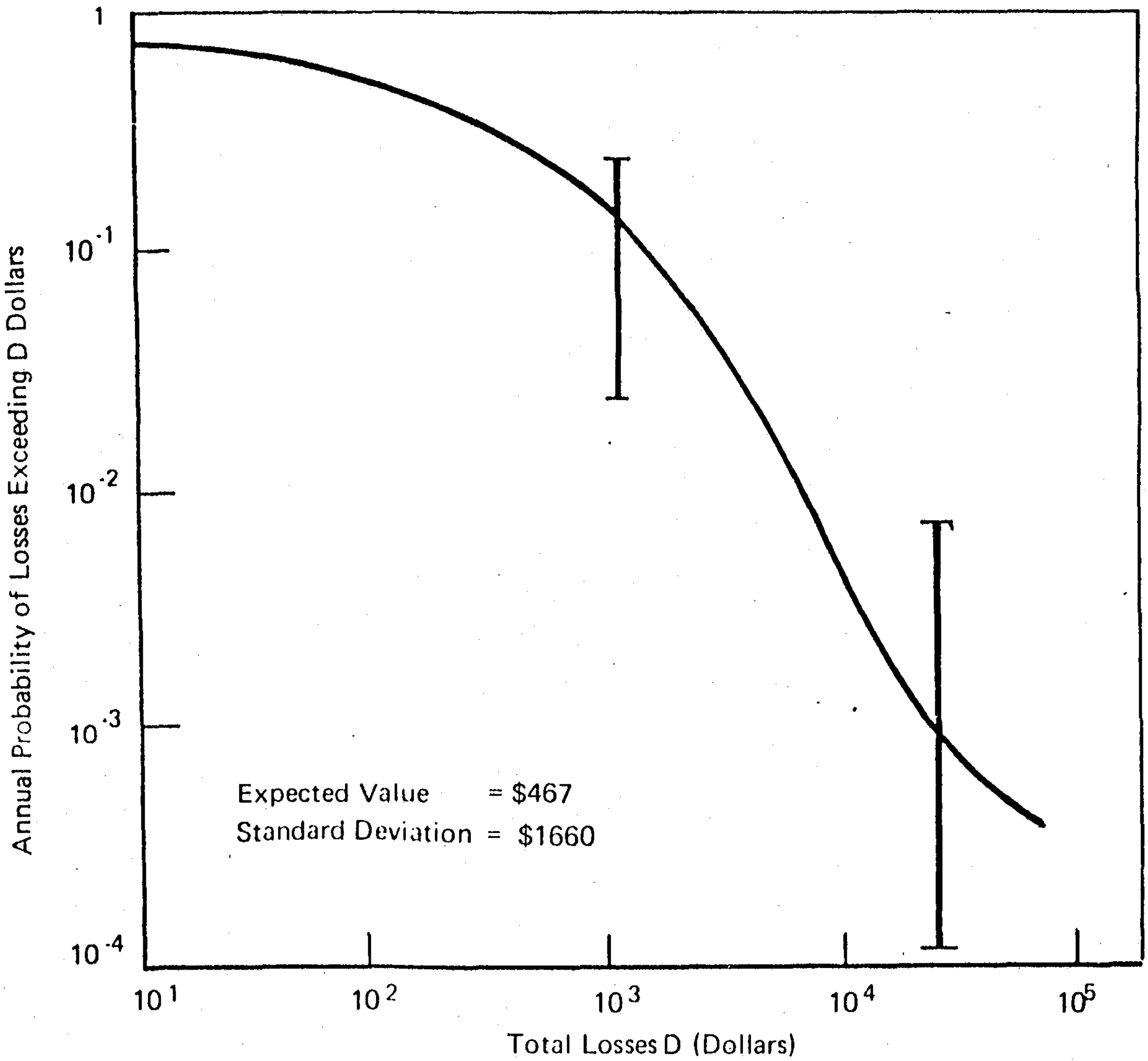


FIGURE 1-1

NATIONAL ANNUAL RISK PROFILE FOR CARBON FIBER
RELEASES FROM COMMERCIAL AIR CARRIERS
(1993 CF Utilization)

estimation of accident frequency, and the modeling errors due to uncertainty about input parameters. The former two sources of uncertainty were judged to contribute less than an order of magnitude to the confidence bound at the high-loss extreme, and considerably less than that at average loss values. The confidence bounds are wider at high loss values because the simulation may not have generated an extremely unlikely high-loss event even among thousands of simulated events.

To estimate the modeling errors, we performed a sensitivity analysis by varying several of the key input parameters. Of the three parameters tested, the largest increase in risk was obtained by setting the composite on the aircraft at its highest possible value, 15,652 kg. This increased the mean loss per incident by a factor of about 7. Restricting the simulation model to only explosive releases increased the loss statistics by a factor of 2 or 3, while setting the atmospheric stability class to E (moderately stable weather) increased the loss distribution only slightly. The two latter conditions are those which tend to result in highest exposures downwind of the release point. We concluded that modeling errors contributed less than an order of magnitude to the uncertainty of the risk profile. As a final verification of the simulation results, we compared the national conditional profile for dollar losses per incident against a risk profile obtained through an alternative analytic approach, based upon a Poisson model of equipment failures. The two methods agreed fairly well, with their mean values differing by a factor of less than 3.

2. INTRODUCTION

2.1 PROJECT OVERVIEW

Carbon fiber (CF) composites are being used to an increasing extent in commercial aircraft, due to their excellent structural properties. Since carbon fibers are highly conductive, a potential risk has been identified in the event that an aircraft with CF composite structures is involved in an accidental fire. If carbon fibers are released from the fire, they could disperse in the atmosphere and eventually cause damaging short circuits in electronic equipment at remote locations. This phenomenon could conceivably result in economic losses ranging from repair of failed equipment to interruption of business operations, and could affect many segments of society. The purpose of this study was to assess the risks presented to the nation as a whole by the use of CF composites in commercial aircraft, in terms of the potential economic losses from air carrier accidents.

To support the investigation, experimental data from a number of different sources were used, including tests of CF releases from burning composite structures and vulnerability tests for selected equipment. Accident reports for commercial air carrier fires were used to generate information about the frequency and severity of fires and/or explosions. Field surveys were conducted in the vicinity of several major airports in order to characterize the types of facilities that might be exposed to carbon fiber releases. Census data were employed to enumerate the numbers of residential and commercial establishments in the vicinity of the 26 large hub airports identified by the Federal Aviation Administration. These data formed part of the input to a Monte Carlo simulation model, which calculated the probability of different amounts of loss given that an accidental release of CF has occurred. Using these results, a national risk profile was developed, which estimated the annual losses due ts CF usage in commercial aircraft based upon the anticipated usage in 1993.

The present report represents an enhancement of an earlier Phase I risk assessment [1], incorporating both an improved technical approach and more accurate input data. The major areas of enhancement were as follows:

- Incorporation of improved forecasts of 1993 jet aircraft fleet mix and carbon fiber usage.
- Development of more accurate estimates for aircraft structural damage and CF release conditions.
- Detailed field visits and vulnerability analyses for specific facility categories, resulting in better loss estimates.
- Improvement of confidence in the risk profile through detailed sensitivity analyses and application of an alternate risk estimation methodology.
- Refinement of carbon fiber dispersion models to provide more accurate exposure estimates.
- Extension of the risk analysis to address CF usage in
  - General aviation
  - Surface transportation vehicles

The latter enhancement is described separately in two reports dealing with general aviation-related risks [2] and motor vehicle-related risks [3]. The present report documents the analysis of aircraft accidents, CF releases, and economic impacts of equipment failures, and then combines these results into a national assessment for air carrier-related risks.

2.2 OBJECTIVES

The major objective of the commercial aviation risk assessment was to develop a national risk profile for the potential economic losses through 1993 due to CF releases from commercial aircraft fires in the U.S. To accomplish this task, the following sub-ojbectives were formulated:

- Project the potential usage of CF composites in commercial aircraft through 1993.

- Investigate the incidence of commercial aircraft fires and/or explosions within the U.S.
- Model the potential release and dispersion of carbon fibers from a fire or a fire followed by an explosion.
- Estimate the resulting exposures in the area surrounding accident location due to dispersion of fibers in the atmosphere.
- Identify equipment and facilities in the vicinity of 26 large hub airports which are potentially vulnerable to damage from carbon fibers.
- Estimate potential economic losses due to carbon fibers penetrating and damaging electronic equipment.
- Create a national risk profile for annual dollar losses by extrapolating from the analysis of the 26 large hubs.
- Show explicitly the uncertainties and assumptions used in the risk assessment.
- Examine the sensitivity of the risk profile to changes in the input parameters.

2.3 METHODOLOGY

To satisfy the above objectives, a methodology was developed which analyzes the entire sequence of relevant physical events and then simulates these events repeatedly to obtain a probability distribution of the resulting losses. The methodology, which was largely created during Phase I, may be understood by referring to Figure 2-1.

The specific airports selected for detailed analysis were the 26 large hubs which account for a majority of air traffic in the U.S. As shown in Figure 2-2, the large hubs account for approximately 70% of domestic passenger enplanements. Using aviation statistics in conjunction with airport characteristics, the probability of an accident with fire involving a commercial jet aircraft was computed for each large hub. Probability distributions for accident characteristics and carbon fiber release conditions were developed, incorporating information about CF composite utilization and typical severity and duration of fires. These conditions formed the

FIGURE 2-1

OVERVIEW OF RISK ANALYSIS METHODOLOGY

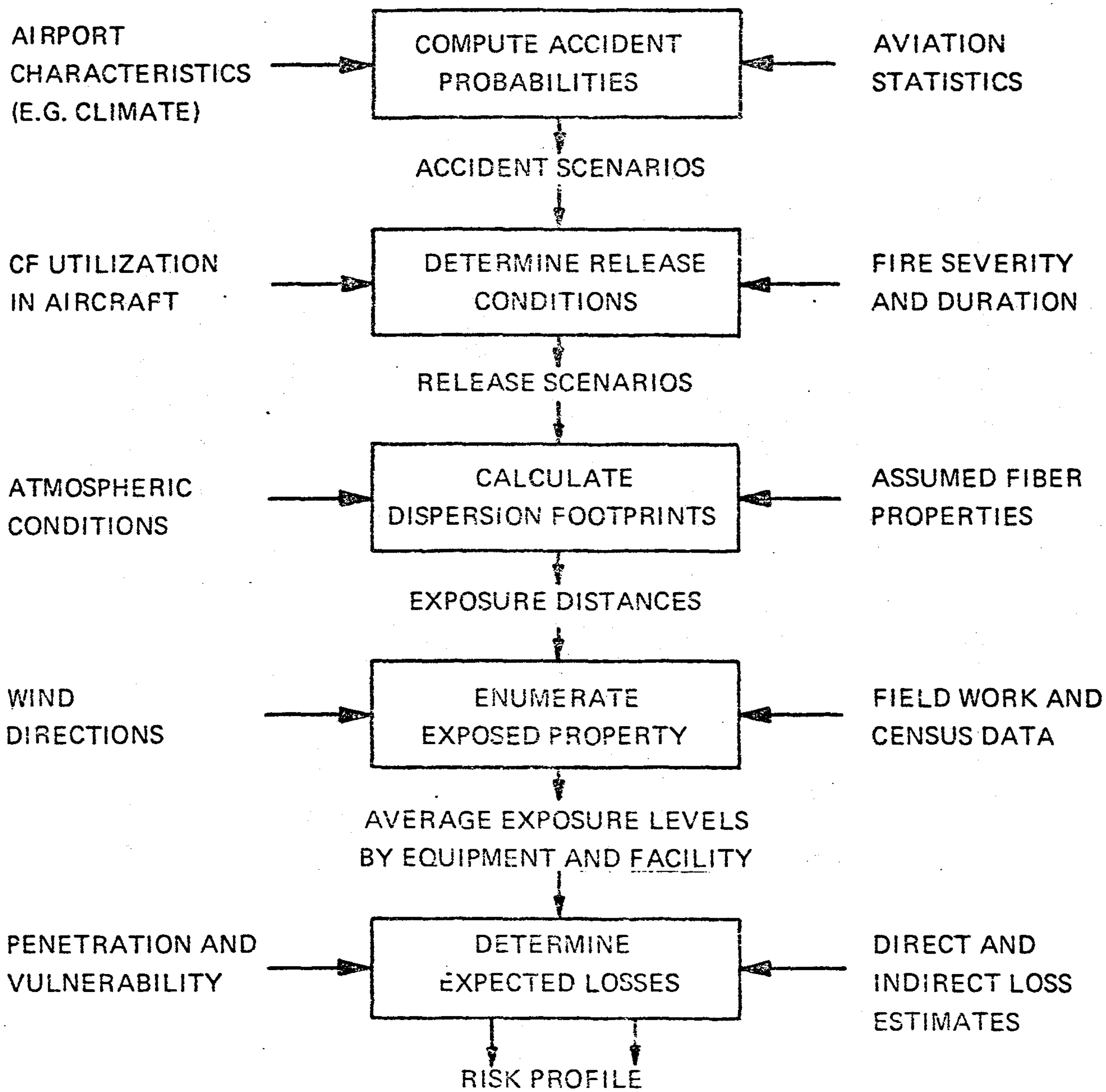
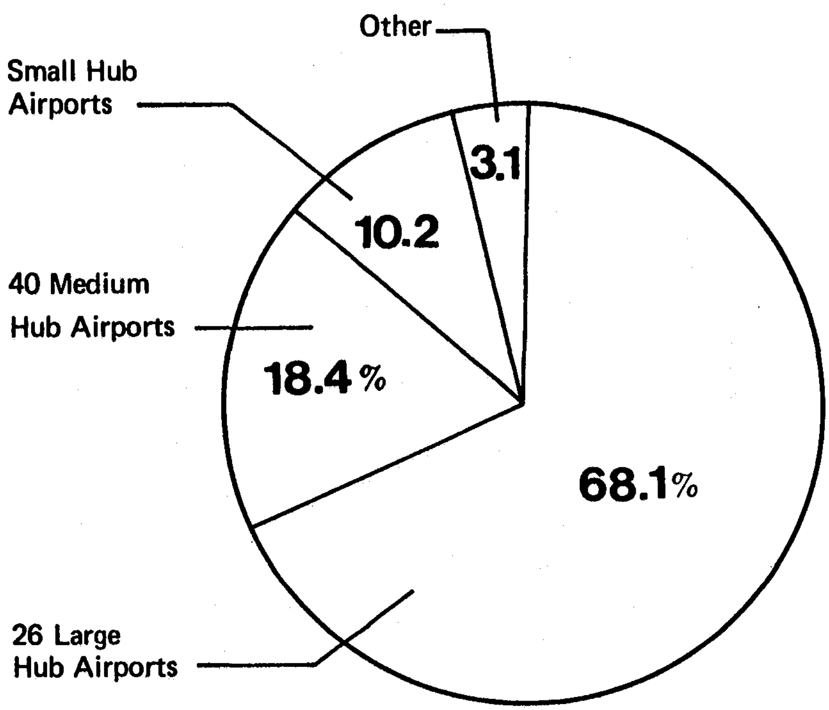


FIGURE 2-2

DISTRIBUTION OF AIR CARRIER ENPLANEMENTS



Percent of Passenger Enplanements

Source: 1977 Airport Activity Statistics - FAA, CAB basis for release scenarios, which included the location of the accident, the total CF mass released, and the type of release - either a fire plume or an explosive release.

The release scenarios were fed as input to either of two dispersion models, which took into account the probable atmospheric conditions surrounding the accident. Both the fire plume dispersion model and the fire-explosion dispersion model assumed that all CF was released as single fibers with a uniform settling velocity. Using Pasquill-Gifford dispersion parameters, these models calculated the resulting exposure at various distances from the accident locations. Exposure distributions were determined within 40 sectors of a circular grid centered at the airport. Wind directions played an important role in determining the sectors with maximum exposure.

By means of field work and census data, the potentially vulnerable facilities were enumerated in each of these geographic sectors. Facilities were divided into industrial categories, and private residences were also considered. The amount of electronic equipment exposed was then estimated by facility. Penetration of fibers into building interiors was analyzed, and the vulnerability of equipment to failure was modeled in probabilistic fashion, based upon experimental data. This permitted computations of the expected number of equipment failures. Finally, by means of an economic analysis of various possible losses, the total dollar damage resulting from CF exposure was estimated.

The simulation model generated a risk profile by repeatedly and randomly selecting accident scenarios and determining the resulting losses. This was done for each large hub, and then the 26 risk profiles were extrapolated to yield a national risk profile, which also incorporated the risk from cruise accidents between airports. The risk profiles that were generated involved a number of assumptions which have some uncertainty attached to them. The overall intent was to develop conservative risk estimates which would overstate rather than understate the risk, and to provide quantitative results which were useful for decision-making given our current state of knowledge. To test the effect of certain assumptions, some of the input parameters were varied in a sensitivity analysis. An alternative risk estimation method, based on a Poisson model, was also applied. The resulting risk profiles did not deviate greatly from the base analysis, indicating that the results can be interpreted as reasonably accurate.

2.4 REVIEW OF RISK ANALYSIS PRINCIPLES

The concept of risk can be defined as the potential for realization of unwanted negative consequences of an event or activity. In the case of this study, the unwanted negative consequences are the potential economic losses due to electronic equipment failure. The event or activity in question is the operation of commercial aviation aircraft utilizing carbon fiber composites. If risk is due to the presence of some causative agent, such as carbon fibers, then the degree of exposure* is measured by the amount of that agent which is potentially active.

In the past decade, an increasing amount of attention has been paid to problem areas involving activities with uncertain outcomes which might engender large risks. In order to deal with these problems the field of risk management has been created and developed. Risk management is a methodical scientific approach towards dealing with such risks. The quantitative aspects of risk management are often referred to as risk analysis. Examples of the application of this approach are in the areas of nuclear reactor safety and transportation of hazardous chemicals, such as liquefied natural gases.

The practice of risk management involves three basic steps: risk identification, risk measurement, and risk control. Potential risks can be identified through experience, judgment, or experimentation. In the case of the carbon fiber problem the nature of the risk is fairly

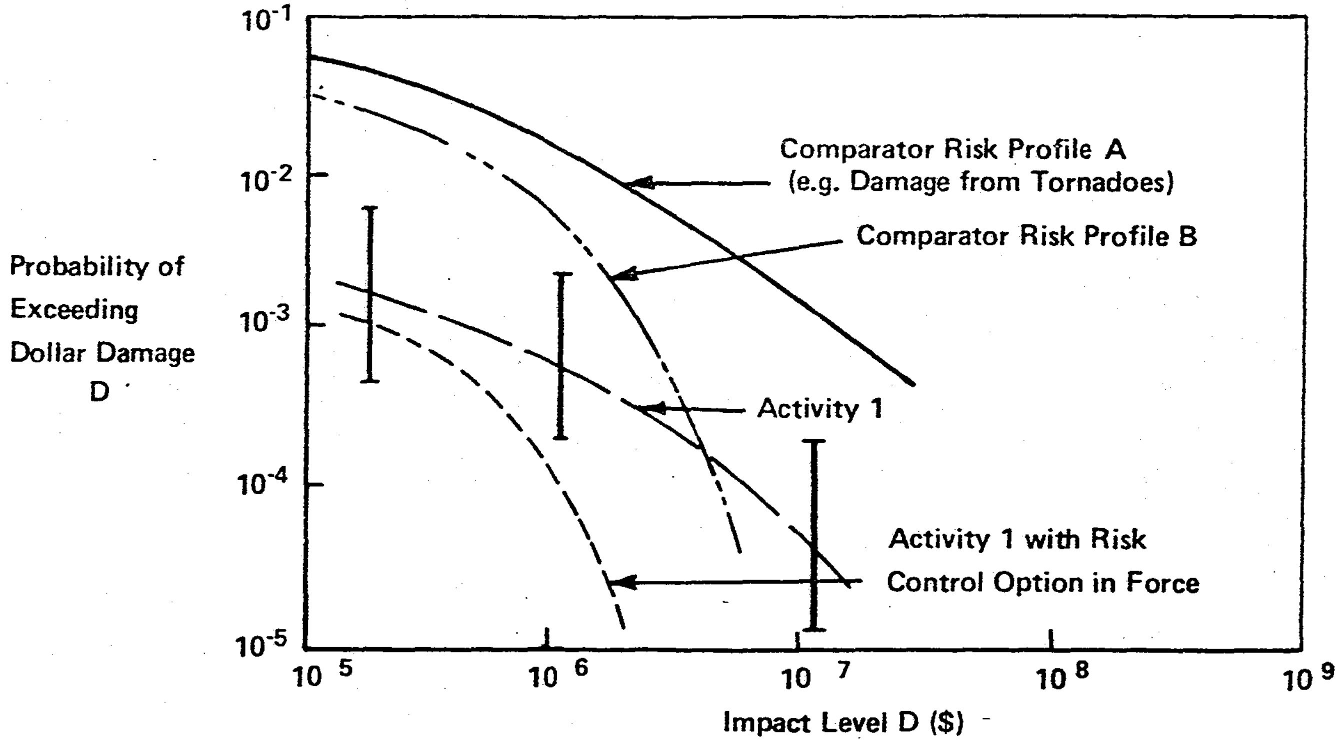
*In this case, exposure is the time integral of concentration, with units of fiber-seconds per cubic meter.

well understood. The major challenge lies in risk measurement, that is, in determining the frequency of occurrence of events. Thus, the purpose of risk analysis is to create an analytic framework permitting measurement of exposure and risk. Finally, if the measured risk is considered sufficiently great, control measures may be deemed necessary. Control measures would consist of any modifications to the mechanism of risk resulting in a reduction in the measured risk.

There are various possible representations which can be used to quantify risk. One possible representation is the expected value of losses over a given period of time. However, in order to deal with risks which may fluctuate over a wide range of losses and a correspondingly wide range of frequencies of occurrence, a preferred method of presentation is the risk profile. As discussed earlier, a risk profile is a graphical display of risk showing the probability distribution for exceeding various levels of unwanted impacts. A hypothetical example of a risk profile is shown in Figure 2-3. The activity in question is labeled Activity 1 and the risk profile for Activity 1 shows that economic impact can vary from $100,000 to $10 million with probabilities ranging from one in a thousand to one in ten thousand. This risk profile may be compared against other profiles for different types of events, such as the damage from tornadoes. In the diagram, two comparator risk profiles are shown. If risk control options are exercised, it may be possible to reduce the risk from Activity 1 as shown by the dotted curve at the bottom. The vertical lines are confidence bounds which show the uncertainty in the estimates of risk. Even though the actual risk may fall anywhere between these confidence bounds, the risk profile can still be used as an effective decision-making tool since it both quantifies in an absolute sense the risks imposed by Activity 1 and permits a comparison of these risks relative to other known risks.

FIGURE 2-3

HYPOTHETICAL RISK PROFILE



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[3] "An Assessment of the Risks Arising from Electrical Effects Associated with Carbon Fibers Released from Motor Vehicle Fires," Arhtur D. Little, Inc., Report to NASA, Contract No. NAS1-15380, (December, 1979). NASA CR-159207

3. CARBON FIBER USAGE FORECASTS

3.1 INTRODUCTION

This chapter presents the forecasts for U.S. aircraft fleet mixes and carbon fiber utilization in 1993, which were used as inputs to the release models described in Chapter 5. The forecasts given in this chapter were calculated directly from data supplied by the three major airframe manufacturers, Boeing, Lockheed, and McDonnell-Douglas. Some of these data have been reproduced in the tables in this chapter, including carbon fiber usage forecasts by section of the aircraft for each type of plane expected to be introduced by 1993. It is anticipated that many structural parts of commercial aircraft will be constructed from carbon fiber composites by 1993. These parts include horizontal and vertical stabilizers, rudders, elevators, flaps and supports, spoilers, ailerons, nacelles, secondary structures, wing boxes, floor beams and posts, wheel well doors, wing fairings, fuselages, and doors. Details of these usage forecasts are presented below.

3.2 1993 FLEET MIX AND GROWTH

Two significant trends in aircraft fleet mix will be observed between now and 1993, according to the predictions of the three airframe manufacturers. These are (a) a decline in the small jet fleet, and (b) a significant increase in the large jet fleet.

The fleet of large jets will include the present generation of jumbo jets: the Boeing 747, the Douglas DC-10, and the Lockheed L-1011. According to the airframe manufacturers, by 1993 the large jet fleet will number 1399, of which 1127 will be using carbon fibers.

Medium jets include those aircraft seating between 150 and 250 passengers. Medium aircraft that will be using carbon fibers by 1993 will consist largely of a new generation of medium jets. These include the Boeing 757, 767, and 777, as well as a newly-designed medium jet manufacturered by McDonnell-Douglas. According to the airframe manufacturers the medium size jet fleet will number 780 by 1993, of which 754 will be using carbon fibers.

The small jet fleet includes those aircraft carrying less than 150 passengers. Although this classification is a very large part of the present fleet it will represent only a small portion of the 1993 fleet. In addition, only a small portion of the 1993 fleet will be using carbon fibers. These planes will include newly manufactured versions of the Boeing 727, 737, and to a lesser extent, the Boeing 707. According to the airframe manufacturers, the small aircraft fleet will number 560 in 1993, of which 100 aircraft will use carbon fibers.*

These forecasts are summarized in Table 3-1.

3.3 DISTRIBUTION OF COMPOSITE BY AIRCRAFT TYPE

Each of the three airframe manufacturers developed forecasts for carbon fiber usage by structural component of the aircraft, for each aircraft type in the 1993 fleet. Some of these types are differentiated by production year. For example, one aircraft with over 15,000 kg. of carbon fiber composites will comprise 10% of the production years 1991 through 1993. Other production years of that aircraft will utilize different amounts of carbon fiber composites in various structural components of the aircraft. The CF utilization by structural component for all the different types of aircraft is summarized in Table 3-2.

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* Although some Boeing small aircraft carry more than 150 passengers (stretch version) they are placed in small aircraft classification. They do not, of course, represent a significant portion of the carbon fiber fleet as forecasted for 1993. It should be noted that the future generation of "medium" aircraft are larger than what many perceive today as medium aircraft.

TABLE 3-1

FLEET MIX IN 1993 BASED ON

AIRFRAME MANUFACTURERS' PROJECTIONS

	Total Fleet	Number of CF Aircraft
Large Aircraft	1399	1127
Medium Aircraft	780	754
Small Aircraft	560	100
Total	2739	1981

In order to perform a Monte Carlo simulation it was necessary to develop a probability distribution for the total amount of carbon fiber on an aircraft involved in an accident. A separate distribution was developed for each of the three aircraft size classifications. These distributions were derived from the data in Table 3-2 under the following assumptions established by NASA and the airframe companies:

- For large aircraft the 1993 fleet will be comprised of 1/3 each of Boeing, Lockheed, and Douglas aircraft.
- The 1993 medium jet fleet will be comprised of 1/2 each of Boeing and Douglas aircraft.
- The 1993 small jet fleet will be comprised entirely of Boeing aircraft.
- The Boeing medium jet aircraft using carbon fibers will be comprised 2/3 of 767/777 aircraft and 1/3 of 757 aircraft.
- The Boeing small jet carbon fiber fleet will be comprised of 737 and 727 aircraft in equal proportions.
- For each manufacturer and each aircraft type the production lots in the years from introduction of the aircraft through 1993 will consist of equal lot sizes.

These assumptions embodied certain simplifications; for example, we did not consider the impact of 707 jets using carbon fibers. Based on these assumptions, and on the data in Table 3-2, we developed probability distributions for total carbon fiber usage in the 1993 fleet, which are presented in Table 3-3 through 3-5. These distributions were used in the computer program that performed the Monte Carlo simulation.

TABLE 3-2

KILOGRAMS OF CARBON FIBER COMPOSITES
IN STRUCTURAL COMPONENTS OF COMMERCIAL AIRCRAFT

Aircraft #/Year	Rudder & Tabs	Vertical Stabilizer	Elevator & Tabs	Horizontal Stabilizer	Wing Flaps	Spoilers	Ailerons	Wing Trailing Edge*	Wing Leading Edge*	Wing Box	Nacelles	Wing Fairings	Wing Well Doors	Fuselage	Floor & Beams	Total
1: 1981-1983	98	-	199	-	595	-	103	-	-	-	132	-	158	-	-	1285
2: 1983-1985	98	213	116	742	595	-	103	-	-	-	307	-	153	-	713	3045
3: 1985-1990	98	213	116	742	595	-	103	410	555	-	613	329	158	-	713	4645
4: 1990-1993	98	213	116	742	595	-	103	410	555	-	1394	329	158	-	713	5426
5: 1990-1993	98	213	115	742	595	-	103	410	555	10227	1394	329	158	-	713	15653
	137	12	170	129	-	98	171	156	-	-	1857	362	29	114	560	3795
6: 1982-1983	50	17	-	180	-	137	-	219	-	-	-	507	-	-	911	2021
7: 1984-1986	50	17	-	180	-	137	-	219	-	-	3114	507	-	-	911	5135
8: 1987-1993	191	17	238	180	-	137	239	219	-	-	3114	507	179	150	911	6082
9:														91		91
10: 1979												11				11
11: 1980			45									11		127		183
12: 1980-1993												11		127		139
13: 1979-1980						55										55
14: 1981-1993						55								93		148
15: 1978-1982														155		155
16: 1982											131			155		286
17: 1983-1993							103				131			1002		1236
18: 1982-1984			45			68	23				45		34			215
19: 1985-1993			45			68	23				45		34	114		329
20: 1981-1983	73		107			55	25				45	16	32			353
21: 1984	73		107			55	25				45	16	32	216		569
22: 1985-1993	73		107		925	55	25				45	16	32	216		1494

*Secondary Structure

TABLE 3-3

PROBABILITY DISTRIBUTION OF WEIGHT OF
CARBON FIBER COMPOSITES

Small Jets-1993

Value (Kg.)	Probability that Total Weight in Kg. is Less Than or Equal to Value
11	.034
55	.077
139	.521
148	.995
183	1.00

TABLE 3-4

PROBABILITY DISTRIBUTION OF WEIGHT OF
CARBON FIBER COMPOSITES

Medium Jets - 1993

Value (Kg.)	Probability that Total Weight in Kg. is Less Than or Equal to Value
215	.04
329	.158
353	.237
569	.263
1494	.50
3795	1.0

TABLE 3-5

PROBABILITY DISTRIBUTION OF WEIGHT OF CARBON FIBER COMPOSITES

Large Jets-1993

Value (Kg.)	Probability that Total Weight in Kg. is Less Than or Equal to Value
155	.031
286	.052
1236	.334
1285	.387
2021	.443
3045	.496
4645	.629
5135	.712
5426	.795
6082	.989
15,653	1.0

4. PROBABILISTIC ANALYSIS OF AIR CARRIER ACCIDENTS

4.1 INTRODUCTION

In order to estimate the potential risk due to carbon fibers released from aircraft accidents, it was necessary to quantify the probability of accidents or incidents occurring at major U.S. airports. In addition, with each accident was associated a set of conditions termed an "accident scenario", that could affect the release of carbon fibers and the resulting risk. These factors included the phase of operation, the weather conditions, the occurrence of an explosive release, and the location relative to the center of the airport. To address these considerations, a comprehensive accident probability model was developed. This chapter presents the details of this accident model.

There were two sources of data used to develop the accident probability model. The first source of data was accident reports compiled by the National Transportation Safety Board (NTSB), which are available in summary form on computer tapes. The second source of data was a set of 92 detailed accident reports compiled for NASA by the three major airframe manufacturers. These reports, which were compiled only for fire or explosion accidents involving jet aircraft, provided data on the extent of the fire or explosion, weather conditions, phase of operation, location of accident, severity of damage, and other relevant details.

The NTSB reports were compiled for all air carrier accidents during the period 1968 through 1976. We considered all substantial damage and total destruction accidents or incidents in which there was a fire or explosion. NTSB distinguishes two cases: either the accident was caused by a fire or explosion, or a fire or explosion occurred after impact. Data extracted from the NTSB report included information such as location of accident, phase of operation, aircraft type, weather conditions, and level of damage.

A probabilistic accident model based primarily on NTSB data is presented in reference 1. The model presented in this chapter is very similar to that earlier Phase I model. However, there are some differences based on the information provided by the airframers, and these differences are noted as appropriate.

The most important output of the accident model was the annual frequency of accidents occurring in the United States involving jet aircraft and a fire or explosion. In addition, several factors were identified that either (a) influenced accident probabilities, or (b) influenced carbon fiber dispersion. These factors included:

- Conditional probability that an accident occurs at a given airport
- Phase of operation at the time of the accident
- Conditional probability of explosive release
- Distance of aircraft from center of runway
- Angle of runway and angle of accident site from runway
- Size of aircraft

For each of these factors, an appropriate probabilistic model was developed. The model for the number of accidents per year and the models for each of the above factors are presented below. A concise summary is also provided for each model parameter discussed.

4.2 ANNUAL ACCIDENT FREQUENCY

Based on the airframe manufacturer data base of 92 accidents there were fifty-three fire or explosion accidents that occurred in the U.S. in the last 14 years, which is equivalent to an average of 3.8 per year. This 3.8 figure represents U.S. accidents only (a large number of the 92 accidents occurred on foreign soil), and the 14 year period represents the time over which commercial transport fleets consisted predominantly of jets. The 53 accidents were selected by NASA as those which could presumably have released carbon fibers if the aircraft had been carrying CF composite structures.

The earlier Phase I analysis, based only on NTSB reports, estimated the expected number of U.S. jet fire or explosion accidents to be 4.5 per year (reference 1, p.63). However, under the assumption that most cruise accidents do not occur over metropolitan areas, only about 3.8 accidents per year would be expected to take place on or near a populated region. Inclusion of foreign carrier operations would represent a slight increase over this figure. Hence, the computations based on the two data sources are comparable, and for the purposes of the risk analysis it was assumed that there were 3.8 fire accidents annually for all jet aircraft.

Given an expected number of 3.8 accidents per year in recent history, we next projected the number of accidents that would take place in 1993. Both reference 1 (which used the NTSB data base) and the airframe manufacturer data base show a slight decrease in accidents per year from 1968 through 1976. Although total operations are increasing, the total number of accidents has remained relatively constant. Therefore, it was assumed that 3.8 represents the expected number of fire or explosion accidents in 1993.

Since the annual accident frequency required for the risk analysis was for fire or explosion accidents involving jets using carbon fibers, the 3.8 figure needed to be reduced to reflect the percentage of the jet fleet using carbon fibers. As noted previously, the projections for 1993 indicate that 72% of U.S. jet aircraft will be using carbon fibers. We therefore projected that the number of fire or explosion accidents involving U.S. jets with carbon fibers would be 2.7 per year in 1993.

Since aircraft accidents are a low-probability event, it is reasonable to assume that the actual number of accidents in any year is Poisson with a mean of 2.7. The data are not inconsistent with this assumption, and the Poisson model was therefore used to develop the national risk profile. Since the 3.8 figure was a statistical estimate, and was therefore subject to uncertainty, the sensitivity analysis in the development of the national risk profile (see Chapter 7) considered variations in the actual mean number of accidents.

- Summary

The expected number of fire or explosion accidents involving jet aircraft using carbon fibers and occurring on or near U.S. metropolitan areas will be 2.7 in 1993. The actual number of accidents is assumed to be a Poisson variable with a mean of 2.7.

4.3 LIKELIHOOD OF ACCIDENTS OCCURING AT A GIVEN AIRPORT

From an analysis of the various factors that could conceivably affect accident rates at different airports, reference 1 concluded that the only significant factor appropriate to a given airport was the relative frequency of IFR and VFR weather.* Since the proportion of IFR accidents was much higher than the proportion of IFR weather, it was concluded that the probability that an operation results in an accident is higher in IFR weather than in VFR weather. Based on a probabilistic model, a weather factor was developed for each airport which reflected the relative frequency of IFR weather.

To account for the weather factor, for the projected number of operations at each city, and for the percentage of operations in 1993 that would involve jets using carbon fibers, the following model was developed:

P_i = conditional probability that a carbon fiber jet accident with fire occurs at airport i given that such an accident occurs in the U.S.

*IFR = instrument flight rules, VFR = visual flight rules

$$P_i = \frac{\text{Annual carbon fiber jet fire accidents at airport i}}{\text{Annual carbon fiber jet fire accidents in U.S.}}$$

$$= \frac{\text{Annual number of carbon fiber jet operations at airport i}}{\text{Total annual carbon fiber jet operations in U.S.}} \times W_i$$

where

W_i = Ratio rate of fire accident rate at airport i to the overall fire accident rate for the U.S.

However, W_i is equivalent to the weather factor which adjusts accident rates to account for airport differences. There is an implicit assumption in this analysis, of course, that accident rates for jet aircraft using carbon fibers is the same as the accident rate for all jet aircraft. The equation for the weather factor, as derived in reference 1, is

$$W_i = 4.52 \times P(IFR) + .58 \times P(VFR) \qquad (4.1)$$

The weather factors computed in Phase I ranged from .65 for Miami to 1.17 for Los Angeles and are presented in Table 4-1.

In estimating these factors, reference 1 noted that the proportion of non-static fire accidents in the NTSB data base occurring in IFR weather was 34 out of 70. The airframe manufacturers' data base for domestic accidents contained 53 accidents, of which 23 occurred in IFR weather. Since the difference in these proportions was judged not to be significant, equation (4.1) was used to compute the relative likelihoods of an accident occurring at any of the 26 large hub airports.

The overall model for incidence of accidents also required the estimated number of operations taking place in 1993 involving jet aircraft using carbon fiber composites at each airport. In order to develop these estimates for the 26 hub airports, it was necessary to forecast the operations mix at each airport and to adjust these to reflect the

TABLE 4-1

COMPUTATIONS FOR CONDITIONAL ACCIDENT PROBABILITIES OF 26 HUB AIRPORTS

City	Estimated 1993 Jet Operations	Weather Factor	CF Adjustment	Conditional Probability
Atlanta	433,434	1.09	0.54312	0.077106
Boston	171,897	1.06	0.62757	0.034362
Chicago	599,339	1.04	0.71862	0.1346
Cleveland	116,618	1.05	0.60523	0.02227
Dallas	288,369	1.00	0.7531	0.065259
Denver	201,927	.78	0.71074	0.033639
Detroit	142,166	1.09	0.74691	0.03478
Honolulu	100,788	.80	0.58995	0.014294
Houston	129,637	1.00	0.82543	0.032155
Kansas City	96,976	.99	0.81053	0.023384
Kennedy	289,275	1.05	0.82448	0.075253
Laguardia	213,724	1.05	0.50437	0.034012
Las Vegas	108,891	.79	0.77442	0.020019
Los Angeles	311,660	1.17	0.77792	0.08524
Miami	249,330	.65	0.68352	0.033287
Minneapolis	124,308	.95	0.64877	0.023023
Newark	116,208	1.04	0.57253	0.020793
New Orleans	100,806	.95	0.60615	0.017443
Philadelphia	138,520	1.04	0.59808	0.025891
Phoenix	91,179	.79	0.63926	0.013837
Pittsburgh	176,750	1.12	0.5698	0.033895
San Francisco	219,634	.89	0.49968	0.029351
Seattle	119,165	.95	0.74013	0.025178
St. Louis	165,764	.99	0.79583	0.039245
Tampa	114,088	.80	0.73209	0.020079
Washington	189,295	.87	0.63863	0.031604

proportion of operations in each size class involving jets carrying carbon fibers. The methodology for developing these forecasts is discussed below in Section 4.7. The estimated percentage of operations in each size class for each city was multiplied by the percentage of the total U.S. fleet for each size category using carbon fibers in 1993. The result was a carbon fiber adjustment factor to convert total jet operations into carbon fiber jet operations. Estimated 1993 operations were assumed to be proportional to present operations and were derived from the data in Reference 1. The resulting conditional probabilities are listed in Table 4-1.

- Summary

The conditional probability that a U.S. fire accident involving a carbon fiber-carrying jet occurs at a given airport in 1993 is assumed to be proportional to the weather factor and the estimated number of operations in 1993 involving jet aircraft using carbon fibers. The weather factor is given by equation (4.1) and the computed conditional probabilities for the 26 hub airports are presented in Table 4-1.

4.4 PHASE OF OPERATION

The data on phase of operation from the two data sources, NTSB and the airframe companies, are presented in Table 4-2. Although the airframe manufacturers' data base shows a decrease in the conditional probability that an accident is a take-off accident, the difference is not extremely large. Therefore, the reference 1 data were used as the basis of the conditional probability calculations. As the substantial damage and total destruction categorizations were not used explicitly in estimating any of the release conditions, this distinction was not considered. In addition, since most cruise accidents would occur over unpopulated areas, attention was restricted to the other three phases of operation.

TABLE 4-2

PHASE OF OPERATION DATA

Phase	Data Source: Reference 1 Total Destruction Accidents	Data Source: Reference 1 All Accidents	Data Source: Air Frame Manufacturers
Cruise	9	13	N/A *
Take-Off	13	20	32
Landing	31	37	48
Static or Taxi	3	11	8

* The airframe manufacturers classified some accidents as take-off or landing that NTSB might classify as cruise. These include accidents occurring within an airport area but at a distance greater than 10 km.

- Summary

The conditional probabilities for the three on or near airport phases were assumed to be

Take-Off	.294
Landing	.544
Static or Taxi	.162

4.5 LIKELIHOOD OF AN EXPLOSIVE RELEASE

The data base of the airframe manufacturers provided some useful information on the incidence of explosive release accidents. In the Phase I analysis (reference 1) there were no data available for these types of releases, and the probability that the release was of the explosive mode was estimated at between between 5% and 25% depending on the phase and damage category. The overall average was 8%. In the airframe manaufacturer's data base there were 22 out of a total of 92 accidents that involved explosions. 14 of the 92 explosions were explosions following fire. However, of these 14 it was judged that not all could cause an explosive carbon fiber release. It was assumed that in order for an explosive type of release to occur that the explosion would have to follow the fire by at least 3 minutes or that there would have to be a long burn with multiple explosions. Of the 92 fire accidents examined, only 4 fires were found to meet these criteria, with one additional one as a possibility. Thus the resulting probability estimate for an explosive type of release was 5 out of 92 or 5.4%.

The fire and explosion type of release was also sub-classified into two additional categories. In one of these categories the ADL explosive release dispersion model was utilized, which assumes an instantaneous release of fibers. In the second category the usual fire-plume dispersion model was used, but the amount released was set at the value used for the explosive type releases, which represents an increase over the standard plume release (See Chapter 5). The conditional probability of each of these two categories of releases was estimated to be 50% each, to account for the different possible CF dispersion scenarios in the aftermath of an explosion.

In the Phase I analysis, it was hypothesized that explosive releases would be more likely in take-off accidents occuring on the runway (or within 0.6 km. of the edge of the runway) and in static accidents. These assumptions were also used in the present accident model. The assumed probabilities for explosive type releases were 10% for take-off accidents occuring within 0.6 km. of the edge of the runway and 6% for static accidents. For all other types of accidents the probability of an explosive release was estimated to be 3%. The overall probability, averaged over all accidents, was 5.4%.

- Summary

The fire/explosion release mode was split equally between an instantaneous explosive release and a plume release involving a larger amount of carbon fibers than the fire-only case. The aggregate probabilities of these two types of releases combined were:

- 10% for accidents taking place within 0.6 km.from the edge of the runway.
- 6% for static accidents
- 3% for other accidents
- 5.4% overall

4.6 ACCIDENT LOCATION PARAMETERS

4.6.1 Distance From The Center of Runway

For each of the 26 large hub airports a centroid was located at the approximate center of all of the runways, and a probability distribution was developed to specify the location of the accident relative to this centroid. For static or taxi accidents, the location was assumed to be near the terminal area, and a distance value was measured from airport maps. For take-off and landing accidents the probability distribution developed in Phase I was used to detemine the distance from the edge of the runway. This probability distribution (which aggregated the total destruction and substantial damage cases) is presented below in the summary. If the distance value was greater than zero an additional 1.6 km. was added to reflect the distance from the edge of the runway to the center of the runway. If the distance value was zero the accident was assumed to occur at the center of the runway.

This model for distance from the edge of the runway was statistically consistent with the airframe manufacturers' data base, as shown in the comparison presented in Table 4-3. In the model calculations 13 out of 81 cruise accidents were assumed to take place at distances greater than 10 kilometers from the airport, and all static and taxi accidents were assumed to take place within the terminal area.

- Summary

Static and taxi accidents were assumed to occur in the terminal area and the appropriate distances were measured from airport maps. Take-off and landing accidents occurred at either the center of the runway or at a positive distance from the edge of the runway whose probability distribution was as follows:

TABLE 4-3

DISTANCE FROM EDGE OF RUNWAY COMPUTED BY MODEL COMPARED WITH AIRFRAME MANUFACTURERS' DATA BASE

	Model (NTSB Accidents)	Airframe Manufacturers' Data Base (60 Domestic Accidents)
On Ground	61%	63%
$<$ 1 km	68%	67%
$<$ 10 km	83%	82%

$$P(\text{Distance} > R) = \begin{cases} .16\, e^{-.43R} + .042\, e^{-.94R} & \text{(Take-offs)} \\ .38\, e^{-.43R} + .02\, e^{-.94R} & \text{(Landings)} \end{cases}$$

4.6.2 Angle of Accident Site From Runway

The second aspect of the probabilistic location model for aircraft accidents was the angle of the accident from the airport centroid. The angle of the accident consisted of the sum of two variables: the orientation of the runway and the angle of the accident relative to the runway. The probability distribution of the angle from the runway was based on the model in reference 1. The correlation coefficient between this angle and the distance from the edge of the runway was also used. This distribution is presented below in the summary.

The orientation of the runway was a city-dependent variable. Its distribution was based upon each city's runway usage frequencies and adjusted to account for the fact that approximately half of landing accidents are undershoots and half are overshoots. Runway usage frequencies were obtained from references 2 and 3. For eight cities we could not obtain usage frequencies, and for these cities a uniform distribution of angles was assumed based upon the known runway orientations. These distributions are presented in reference 1.

- Summary

The angle of the accident was the sum of the angle from the runway and the runway orientation. The probability distribution of the angle from the runway was assumed to be

$$P(\text{Angle} > \sigma) = .78e^{-\sigma/3.7}$$

with -20% correlation with distance from edge of runway

Orientation of the runway was based on runway usage frequencies where available, and on a uniform distribution of runway locations where unavailable.

4.7 SIZE OF AIRCRAFT

For each of the 26 hub airports we assumed that the probability of an accident involving an aircraft of a given size is proportional to the estimated percentage of 1993 operations involving jets using carbon fibers for the given aircraft size. According to the airframe manufacturers' predictions, the overall 1993 fleet mix for jets using carbon fibers will be 5%, 38% and 57%, for small, medium, and large jets, respectively. According to the analysis in reference 1, the existing U.S. jet fleet mix is 25%, 60%, and 15% for small, medium, and large aircraft, respectively.* The relationship between the 1993 forecasts for carbon fiber aircraft fleet mix and the present fleet mix for all jet aircraft represents a mathematical transformation that we applied to each airport's present operations mix in order to forecast the operations mix at airports in 1993. These forecasts are presented in Table 4-4.

As noted in Section 4.3, for a given airport it was also necessary to forecast operations mixes for all jet aircraft in 1993 for the 26 airports. This was performed by an analogous mathematical transformation using the total of the fleet mix for 1993.

- Summary

The aircraft size distribution was assumed to be equal to the forecast 1993 mix of operations for jet aircraft carrying carbon fibers. These forecasts are presented in Table 4-4.

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* The classification system in reference 1 classes Boeing 727 and 707 as medium size while the airframe manufacturers classify these craft as small. This does not affect the transformation procedure.

TABLE 4-4

FORECASTED OPERATIONS MIX FOR JETS USING CARBON FIBERS (1993)

Airport	Percentage of Aircraft Small	Medium	Large
Atlanta	15.7	42.3	42.0
Boston	10.0	41.5	48.5
Chicago	5.6	46.0	48.4
Cleveland	12.2	59.5	28.3
Dallas-Ft. Worth	5.2	68.2	26.6
Denver	6.4	55.4	38.2
Detroit	4.7	52.4	42.9
Honolulu	10.8	9.5	79.7
Houston	0.9	33.7	65.5
JFK	1.0	25.1	73.9
Kansas City	3.6	89.8	6.5
Las Vegas	19.1	45.8	35.1
Los Angeles	2.7	33.2	64.1
Miami	2.9	40.2	56.9
Minneapolis	7.3	47.4	45.3
Newark	9.3	51.8	38.9
New Orleans	14.1	54.1	31.8
LaGuardia	12.3	62.8	24.9
Philadelphia	12.2	50.0	37.9
Phoenix	10.2	59.7	30.1
Pittsburgh	15.2	73.2	11.6
St. Louis	20.5	66.3	13.2
San Francisco	4.4	40.2	55.4
Seattle-Tacoma	2.9	54.1	43.0
Tampa	5.5	56.2	38.4
Washington-National	11.6	88.4	0.0

4.8 Model Uncertainties

The overall accident model is based on statistical analysis of a large number of accidents, and consequently, some of the estimates are subject to statistical uncertainty. A discussion of the extent and the nature of this uncertainty is presented in reference 1. Most of the parameters of the accident model will not have a great impact on the risk analysis with the possible exception of the annual accident rate. As noted in Reference 1, 81 fire and explosion accidents occurred during the nine year period that was the basis of the analysis. Assuming that the actual number of accidents during the period was a Poisson random variable, then a 95% confidence bound for the true expected number of accidents during the period is 65 to 101. Similarly the 53 accidents in the airframer data base that occurred during the last 14 years correspond to confidence bounds of 40 to 69. The latter bounds range from 75% to 130% of the observed number of accidents. As these bounds represent a moderate departure from the observed accident rate, the levels of 75% and 130% were used as the basis of a sensitivity analysis in the development of the national risk profile. (See Chapter 7).

4.9 REFERENCE

1. "An Assessment Of The Risk Presented By The Use Of Carbon Fiber Composites in Commercial Aviation," Arthur D. Little, Inc., Report to NASA, Contract No. NAS1-15380, Phase 1, (January, 1979). NASA CR-158989

5. CARBON FIBER RELEASE CONDITIONS

5.1 INTRODUCTION

This chapter presents the methodology and data sources analyzed to determine the carbon fiber release scenarios for aircraft accidents. The scenarios consisted of a set of probability distributions for each of the variables, other than those described in Chapter 4, that were judged to have impact on carbon fiber release and dispersion in the aftermath of an aircraft fire. The set of probability distributions for all of the variables considered was used as input to the Monte Carlo simulation model described in Chapter 7.

In a general sense a release scenario consisted of all the variables that could possibly affect dispersion. The focus of this chapter is on those variables that were not incorporated within the accident model. These variables consisted of two distinct types. The first type was the set of weather variables that could impact carbon fiber dispersion. These included:

- Wind Direction
- Wind Velocity
- Pasquill Stability Class
- Ambient Temperature

The second type consisted of a set of variables relating to the nature and intensity of the accident. The distributions for these variables were derived primarily from the data base of 92 accidents analyzed by the airframe manufacturers. These distributions were used as input to the dispersion model which estimatated carbon fiber exposures following a release incident. The relevant variables were:

- Mass of carbon fibers released
- Amount of fuel burned
- Duration of the fire

There were a number of complexities involved in analyzing the carbon fiber release conditions. For example, the total mass of carbon fibers released depends on the amount carried on the plane, the amount involved in the fire, and the percentage that is actually released. To develop an appropriate model, we identified the following set of underlying variables, and wherever possible incorporated correlations among them.

- Total mass of carbon fiber composites on the aircraft
- Percentage of carbon fiber composites involved in the fire.
- Percentage of involved fibers that were released
- Amount of fuel carried on the aircraft
- Percentage of fuel consumed in the fire
- Duration of the fire

These variables together comprise the second set of release condition variables which we denoted as <u>accident variables</u>. The first variable above, mass of carbon fiber composites carried on the aircraft, is described in Chapter 3. The modelling assumptions for the other variables are described in this chapter.

The different release scenarios were developed under the explicit assumption that an accident had occurred. The simulation model actually simulated individual accidents and hence provided a conditional distribution of losses given an accident. The conditional distribution was then combined with the probability of an accident in order to develop unconditional distributions of losses. Thus, it should be recognized that release variables are conditional on an accident and that all the variables presented in this chapter are conditional variables.

The remaining two sections of this chapter desribed the modelling assumptions for each of the two types of variables described above. Section 5.2 describes the development of models for the four weather variables, and Section 5.3 describes the modelling of the other five accident variables, excluding the mass of carbon fibers on aircraft.

5.2 WEATHER VARIABLES

The four weather variables used in the simulation model included wind velocity, wind direction, temperature, and Pasquill stability class. The wind velocity, stability class and temperature were all direct inputs to the dispersion model, while the wind direction was used to locate the carbon fiber cloud on the geographic coordinate system developed for each of the 26 major hub airports. Actual distributions were drawn from reference 1 which compiled the data necessary for each of the distributions from airport climatological surveys and for the case of temperature, from the U.S. Statistical Abstracts. Wind velocity, wind direction, and temperature, of course, have direct numerical measures. Stability class could take on six possible values ranging from stable to neutral to unstable. In addition, to reflect the actual correlation between wind speed and stability class, a separate wind speed distribution was developed for each of the six stability classes and each of the 26 large hub cities.

5.3 PROBABILITY DISTRIBUTIONS OF ACCIDENT VARIABLES

5.3.1 Model Description

In the development of a probabilistic model for the various carbon fiber release conditions, a great deal of emphasis was placed on two sources of recently obtained historical and experimental data. An analysis of these data sources has led to modifications of Phase I models of accidental release conditions. The two sources of data consist of the 92-accident data base compiled by the airframe manufacturers and some recent experimental findings [2] on the possible amount of carbon fibers released in an accident. The 92-accident data base included, in addition to accident data such as the location and weather conditions, the duration of the burn, the amount or percentage of fuel burned, and the percent of structure consumed for each major component for the aircraft. These latter categories of data are generally not available in the standard NTSB accident reports.

In reviewing these data, one of our major conclusions was that even though aircraft may be carrying over 15,000 kilograms of carbon fiber composites, the amount of carbon fibers that could be released in a fire is significantly less. This is partly because not all of the carbon fibers can be released as single fibers in a burn, and partly because the entire aircraft structure will not necessarily be involved in the fire. These two considerations are reflected in two accident variables, namely the percent of carbon fibers released and the percent of composites involved in the fire.

To incorporate all of the variables within a model that could be used directly in dispersion calculations, the following equations were used.

Mass of Fibers Released = (Mass of Composite on Aircraft) x 70%

x (Percent of Composite Involved)

x (Percent of Involved Fibers Released)

Fuel Burned = (Fuel on Aircraft) x (Percent of Fuel Burned)

The amount of composite on the aircraft is based on the probability distribution described in Chapter 3, and this is multiplied by 70% to reflect the fraction of composite mass that consists of carbon fibers. The percent of involved fibers released is based on experimental findings and the percent of composites involved is based on the 92 accident data base. The amount of fuel on the aircraft is determined by the phase of operation and size of the aircraft. The percent of fuel burned and the third major release variable, the duration of burn, were based on the 92-accident compilation. It should also be noted that correlations were computed for the following three variables: percent of composite involved, percent of fuel burned, and duration of burn. These correlations were used in the Monte Carlo simulation for the purposes of generating release scenarios. As a general rule, the greater the amount of fuel burned, the longer the duration of the burn and the greater the percent of carbon fiber involvement.

The analyses of each of these variables, with the exception of the mass of composite carried by the aircraft, are described below.

5.3.2 Percent of Involved Fibers Released

Recent experimental findings [2] indicate that the percent of fibers involved in a fire that are released as single fibers is much lower than assumed in previous research. NASA estimates that not more than 1% of the fibers would be released in most fire plumes and that not more than 2.5% would be released in the fire and explosion scenarios. These are conservative estimates based on interpretation of multiple experiments conducted by NASA as well as other groups.

Consequently, as input to the simulation model, the following distribution was used to determine the percent of involved fibers that are released in an accident. In 94.6% of the cases, it was assumed that a fire plume would occur with a release of 1% of the mass of carbon fibers involved in the accident. In the other 5.4% of the cases a fire and explosion would occur resulting in a 2.5% release. The derivation of the 5.4% figure was also based on the 92 accident data base, and is described in Chapter 4. The cases corresponding to the larger release percentage were split into two types. In one type, the explosive release was assumed to cause an instantaneous release of fibers, while in the other type a continuous-release fire plume was assumed with an increase in the total amount of fibers released from 1% to 2.5%.

5.3.3 Percent Of Composite Involved

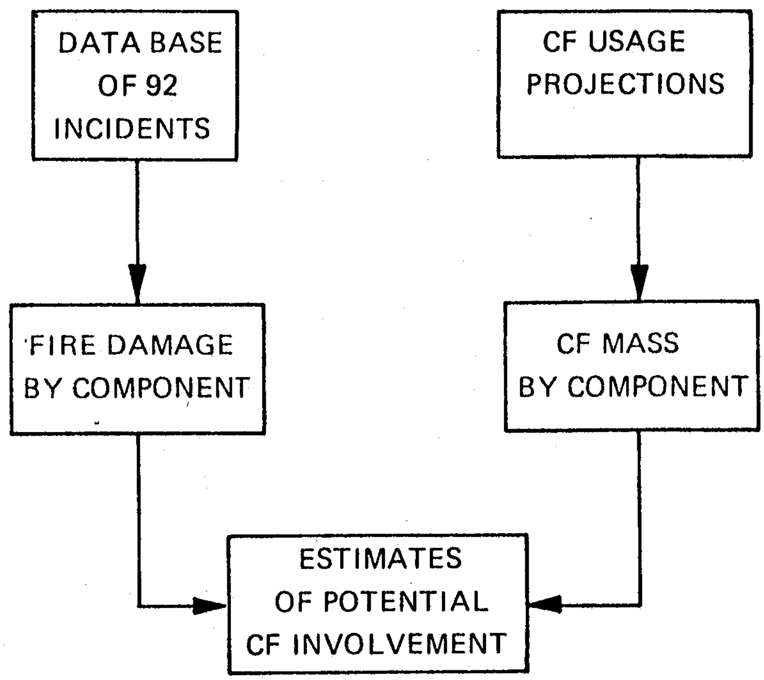
To analyze the percent of composite involved we examined the 92 accident data base which provided information on percent of structures involved in a fire accident. For each of the 92 accidents the percent involved in the fire was estimated for each of the 15 major components of the aircraft. In other words, a random sample was provided consisting of 92 events. Associated with each of these 92 events was a vector of 18 values, each representing the percent of the corresponding structure that was involved in the fire.

We then assumed that if a given component of an aircraft contained a certain mass of carbon fibers, that the CF mass would be involved in the fire to the same degree that the structure was involved in the fire. For example, if the nacelles were characterized by 50% involvement in the fire then any mass of carbon fibers in the nacelles would be 50% involved. Thus, a given distribution of carbon fiber mass by component of the aircraft could be combined with each of the 92 vectors describing structural involvement to yield a set of 92 values for the total amount of carbon fibers involved in the accidents. Dividing by the total mass of carbon fibers on the plane yielded a set of 92 percentages of carbon fiber mass involved.

A flow chart for the above procedure is presented in Figure 5.1. By using the distribution of mass by component of the aircraft for several of the major carbon fiber aircraft in 1993, we developed a probability distribution of the percent of carbon fiber involved in a fire. That is, we assumed that a certain mix of 1993 aircraft would be involved in the 92 historical accidents that were analyzed by the airframe manufacturers, and we calculated the percentages of carbon fibers involved based on this assumed mix.

FIGURE 5-1

POTENTIAL CF INVOLVEMENT IN AIR CARRIER FIRES:
ANALYSIS BY AIRCRAFT COMPONENTS



The distributions were developed separately for small, medium, and large aircraft: the results are presented in Tables 5-1, 5-2 and 5-3. The range of involvement varies from 0 percent, reflecting a fire which did not damage any of the structure containing carbon fibers, to 100 percent involvement, in which all portions of the aircraft containing carbon fiber composites were completely involved in the fire. Our median estimate of carbon fiber involvement was 54% for small jets, 32% for medium jets, and 34% for large jets. This variation is due largely to the different levels of carbon fiber usage that are anticipated in different aircraft size classes.

5.3.4 Fuel on Aircraft

The amount of fuel that is carried by an aircraft depends directly on two factors: the size of the aircraft and the phase of operation. Although there is some probabilistic variation in the amount of fuel on board at any time, we concluded that a deterministic function of the aircraft size and phase of operation would account for most of the actual variation observed in practice. The estimates that we used are presented in Table 5-4. These estimates were based on

- Fuel capacities of existing aircraft
- Anticipated fuel capacities of the new generation of jet aircraft, and
- Data from the 92 accident data base on amount of fuel on board as a function of phase.

It was conservatively assumed that in the take-off and in the static or taxi phase the aircraft would be fully loaded with fuel, whereas on landing the amount of fuel on board would be only a small portion of the capacity. The exact amounts are presented in Table 5-4.

TABLE 5-1

PROBABILITY DISTRIBUTION FOR PERCENT OF CF CONSUMED - SMALL JETS

Value	Probability That Percent is Less Than or Equal to Value
0	0.10
5	0.20
25	0.27
40	0.40
45	0.41
50	0.45
70	0.68
85	0.90
100	1.0

TABLE 5-2

PROBABILITY DISTRIBUTION FOR PERCENT
OF CF CONSUMED - MEDIUM JETS

Value	Probability That Percent is Less Than or Equal to Value
0	.0
5	.15
15	.32
35	.55
40	.62
45	.64
65	.85
90	.99
100	1.00

TABLE 5-3

PROBABILITY DISTRIBUTION FOR PERCENT OF CF CONSUMED - LARGE JETS

Value	Probability that Percent is Less Than or Equal to Value
0	.01
5	.17
15	.31
20	.34
40	.56
45	.59
75	.89
80	.93
100	1.00

TABLE 5-4

ASSUMED VALUES FOR TOTAL FUEL ON AIRCRAFT (Liters)

	Take-off, Static or Taxi	Landing
Small Jets	17,000	5,100
Medium Jets	40,000	12,000
Large Jets	150,000	25,000

5.3.5 Percent of Fuel Burned

The percent of fuel burned was drawn directly from the 92 accident data base by dividing the amount of fuel burned by the total amount of fuel on board, for those cases in which both entries were recorded. The resulting probability distribution is presented in Table 5-5. A relatively uniform distribution of percent of fuel burned was observed. However, this variable was correlated with both the percent of composite involved and the duration of the fire, as might be expected.

5.3.6 Duration of Fire

The duration of the fire was also computed directly from the 92 accident data base. It was recognized, however, that there would be some difficulty in interpreting the length of time recorded on the accident record. In most cases, it was assumed that the entire duration would be recorded, including a peak burn period followed by a gradual lessening of the fire intensity. On the other hand, the dispersion model used to determine CF exposure assumed a uniform burning rate during the burn period. Thus, using the burn period as recorded might result in an underestimate of the burn rate during the period when most of the carbon fiber structure is consumed. To address this issue we adjusted the distribution by dividing the recorded burn period by two, limiting the burn period to a maximum of 35 minutes and assuming that the burn period would be at least as long as 2 minutes. The resulting distribution is presented in Table 5-6.

5.4 CORRELATIONS AMONG ACCIDENT VARIABLES

Because of their mutual dependence, we measured correlations among the following three variables:

- Duration of fire
- Percent of fuel burned
- The percent of carbon fiber composites involved

TABLE 5-5

PROBABILITY DISTRIBUTION FOR PERCENT OF FUEL BURNED

Value	Probability That Percent is Less Than or Equal to Value
1	.15
5	.22
35	.33
50	.46
70	.54
75	.60
80	.84
85	.94
100	1.0

TABLE 5-6

PROBABILITY DISTRIBUTION FOR TIME OF BURN

Value	Probability That Time in Minutes is Less Than or Equal to Value
2	0.0
5	0.28
10	0.44
15	0.63
25	0.67
30	0.77
35	1.0

As mentioned earlier, the latter was calculated for each of the 92 accidents by estimating the distribution of carbon fiber composites by structural component for the major aircraft in the 1993 fleet. The resulting correlation coefficients were 76% between percent of composite involved and percent of fuel burned, 44% percent between percent of composite involved and duration of burn, and 47% between percent of fuel burned and duration of burn. These correlation factors were then used in the Monte Carlo simulation to reflect the observed relationship among the three variables.

5.5 DISPERSION ANALYSIS

The two dispersion models corresponding to the two accident and carbon fiber release scenarios are discussed in reference 1 of Chapter 2. In the fire and explosion case, we considered only those accidents in which there was a delayed explosion preceded by a period of burn during which the epoxy or resin surrounding the fibers would be burned away. This would expose the carbon fibers to an agitation by the force of the conflagration and thus would hypothetically result in a larger number of single fibers released. This scenario was modelled as an instantaneous release in the form of a cloud at a height of 10 meters above the site of the accident. In the fire plume model, rather than having an instantaneous release we assumed a continuous release of fibers over the period that the aircraft burns. The carbon fiber plume would rise until it met the inversion layer and then would be tilted or reflected back toward the ground. The direction and velocity of the wind determined the exposure contours over which carbon fibers would be deposited.

In the current Phase II analysis we have improved the continuous plume dispersion model and retained the same instantaneous release model as utilized in Phase I of work. The continuous plume dispersion model was improved as follows:

- As the buoyant fire plume rises to its maximum vertical ceiling height the plume half-width, as measured by the distance from the plume center to the velocity contour equal to 1/e of the centerline velocity, is calculated.

- The subsequent wind driven tilted plume is then assumed to originate at a virtual point source displaced ten half-widths upwind of the bouyant fire plume centerline at the ceiling height.

The net effect of this model improvement is to take account of the finite starting boundary conditions of the tilted plume portion of the model. This in turn displaces the high exposure footprints at ground level, bringing them closer to the fire source. The actual area of various exposure footprints is not appreciably altered.

5.6 REFERENCES

[1] "An Assessment of the Risk Presented by the Use of Carbon Fiber Composites in Commercial Aviation", Arthur D. Little, Inc., Report to NASA, Contract No. NAS1-15380, Phase 1, (January, 1979). NASA CR-158989

[2] "Assessment of Carbon Fiber Electrical Effects", NASA Conference Publication 2119 (December, 1979).

6. ECONOMIC LOSS ANALYSIS

6.1 INTRODUCTION

An important component of the risk assessment methodology was the estimation of economic losses resulting from CF releases in the aftermath of aircraft fires. This was accomplished by a computer subroutine which was called during each iteration of the Monte Carlo simulation of air carrier accidents. After the accident conditions were randomly drawn, a dispersion model was used to estimate CF exposures in the area surrounding the release location. The economic subroutine then utilized business and demographic data for the corresponding large hub airport, along with estimates of equipment vulnerability and failure costs, to compute the expected economic losses resulting from the given exposure distribution. The role of this subroutine within the overall methodology is illustrated in Figure 7-1.

The present economic loss analysis represents an enhancement of the original approach used in Phase I of the carbon fiber risk assessment.* As a result of detailed site visits to various types of facilities, including site visits performed by Bionetics, a more detailed and accurate description of potential failure modes and consequences was developed. The facility categories originally selected were reconsidered, with some being deleted and new ones being added. In addition, more recent test results allowed NASA to develop improved estimates of equipment vulnerability, which were incorporated into the facility descriptions. The calculation of airborne exposure transfer functions (AETF), which characterize building penetration properties of carbon fibers, was also revised as a result of more recent data and detailed site visits.

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*See reference 1 in Chapter 2.

This chapter presents a summary of the facility categories considered, the corresponding evaluations of potential loss, and the methods used to estimate aggregate economic losses resulting from a simulated CF release. A complete tabulation of the data utilized in the economic subroutine may be found in Appendix A. These data were also adapted for use in two parallel risk assessments* dealing with releases from accidental fires in general aviation aircraft and motor vehicles.

6.2 OBJECTIVES

The objectives of the Phase II estimation of economic losses were to:

- visit representative commercial, industrial, and service organizations and survey the types of equipment in operation, inspect the air conditioning and ventilation systems in use, make estimates of the repair costs associated with failures of these equipment, and estimate the business disruption costs that would be associated with identifiable failures of each type of equipment.

- For various facility types, estimate the transfer functions for determining the internal carbon fiber exposure.

- With the assistance of NASA, develop appropriate vulnerability estimates for different categories of equipment.

- Summarize the on-site equipment, the building transfer functions, and the repair and business disruption costs for the facilities visited during Phase II.

- Revise the equipment repair costs and facility disruption costs for those additional categories of facilities that were visited in Phase I but not visited in Phase II.

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*See references 2 and 3 in Chapter 2.

- Incorporate the four site visits performed by Bionetics Corporation* for purposes of comparison and supplementing of the data base.

- From the above findings, prepare quantitative estimates of potential losses for incorporation into the risk analysis computer model.

6.3 MAJOR ASSUMPTIONS

The following assumptions were used to permit the systematic assessment of economic losses over a wide range of facility categories:

- We assumed that equipment failure would cause losses associated with the most critical function that the equipment performed in the operation of the facility. The only exception was damage to inventory.

- We assumed that all firms or organizations within an industry had the same financial operating characteristics and revenues, using an industry average for each metropolitan area being considered.

- If several pieces of identical equipment operated simultaneously, failures were assumed to be independent. Thus, relative locations of equipment did not affect their individual failure probabilities.

- Economics were assessed by categories on the basis of statistical expectation, i.e., dollar loss estimates were assigned to the expected number of failures within an industry-equipment category.

- Failures were assumed to occur within a short period of time after the CF release, so that the phenomenon of post-exposure

* See reference 2 in Chapter 5.

vulnerability due to re-entrained fibers was not explicitly considered.

- Within each industry, facilities were assumed to be identically equipped for each city, and to have identical building transfer functions. In certain cases, facilities were divided into several classes of transfer function characteristics.

- Only "primary" costs to the facility in which equipment failure occurred were included. Secondary impacts, such as disruptions in the operations of firms relying on a service company which experiences a shutdown, were not considered.

These assumptions make it feasible to estimate economic losses in any major metropolitan area as a function of exposure to carbon fibers. The use of expectations and averages precludes extreme values of loss from being incorporated into the risk profile. However, the other economic loss assumptions were made conservative in an effort to ensure that potentially high risks were not ignored in the aggregate.

6.4 FIELD INVESTIGATIONS

6.4.1 Identification of Facility Categories

Potentially vulnerable facilities were considered to be any establishments or major pieces of equipment (such as aircraft) which house or utilize electronic equipment that have been shown to be susceptible to damage from carbon fibers. Since most large and medium hub airports are located in close proximity to heavily populated areas, a significant number of potentially vulnerable facilities fall well within the potential range of a carbon fiber cloud. Moreover, due to the widespread use of electronics, a large number of commercial and industrial business types had to be included in the economic analysis. Thus it was necessary to identify a finite set of important facility categories for which field investigations had to be conducted in order to estimate possible economic losses.

During the Phase I risk assessment, most of the pertinent industry categories had already been identified, and a number of field visits had been conducted. These previous investigations formed a basis for the Phase II economic analysis. In a few cases facility categories were dropped from consideration because the equipment in question appeared to be essentially invulnerable; in other cases new categories were added due to a recognition of their potential vulnerability. The final set of facility categories identified for economic analysis are shown in Table 6-1. Where possible, individual facility categories are identified by three and four-digit Standard Industrial Classification (SIC) codes. Those categories that were visited in Phase II are distinguished from those which were dealt with by updating the information gathered during the Phase I field visits. The four facilities visited by the Bionetics Corporation, for which detailed site visit reports are available, were also included in the overall analysis.

6.4.2 Detailed Site Visits

To gather information for the economic analysis, a number of site visits were arranged during which engineering personnel visited representative industrial, commercial, and public facilities that might be expected to be affected by carbon fiber infestation in the event of an accident at a major airport. Field investigations were made at each of the sites identified in Table 6-1, under Phase II. For each field visit, the facility was briefly described, details were obtained about air conditioning and ventilation systems in each area where potentially vulnerable equipment was found, and the equipment were identified that resided in each area. Information was obtained on how individual equipment repairs were made (in-house, outside contract, or combinations thereof). Information was also obtained to assist in the estimation of costs of facility disruption in the event that critical pieces of equipment failed. As noted in Table 6-1, all the necessary vulnerability and cost data for aircrafts at airports were obtained directly from the airframe manufacturers.

TABLE 6-1

FACILITY CATEGORIES FOR ECONOMIC ANALYSIS

	SIC No.	Site Visits Phase I	Site Visits Phase II	Bionetics Corp.
1. Households				
2. Fire and Police				
A. Large Metropolitan Police Central	9221		√	
B. Large Metropolitan Fire Central	9224		√	
C. Small Police Headquarters	9221		√	
D. Small Fire Headquarters	9224		√	
3. Post Office (Major Sorting Center)				
4. Subway, Railroad				
A. Subway	401	√		
B. Railroad	401		√	
5. Manufacture of Electronics and Mechanical Eqpt.	3714			√
6. General Manufacturers				
A. Organic Fibers, noncellulosic	2824			√
B. Electronic Equipment, television receivers	3651			√
C. Toilet preparation	2844		√	
7. Telephone Services				
A. Large Switching Center	481	√		
B. Small Switching Center	481	√		

Table 6-1 Continued

	SIC No.	Phase I	Site Visits Phase II	Bionetics Corp.
8. Radio/TV	483	√		
9. Electric Utility	491		√	
10. General Merchandise				
A. Main Store	531		√	
B. Branch Store	531		√	
C. Retail Grocer	541			
11. Finance and Insurance				
A. Brokerage house	621		√	
B. Computer services	737	√		
12. R & D, Universities		√		
13. Hospitals		√		
14. Automotive Assembly				
A. Automotive Assembly			√	
B. Small Truck				√
15. Aviation				
A. Aircraft*		√		
B. Control Tower		√		
C. Passenger Terminal		√		
D. ASR Field Radar		√		
E. LOC at Airport		√		
F. VOR at Airport		√		

*Inputs from airframe manufacturers

A capsule summary of the findings for each facility category is given in Appendix B.

6.4.3 Summary of Findings From Establishments Visited

Below are summarized what we considered to be the most important findings from the Phase II visits to different establishments:

- All of the electronic equipment and control equipment identified in the establishments visited could experience failures. Each establishment has developed procedures to follow in the event of equipment failures. In the large organizations, maintenance personnel are generally available to either make repairs on the spot, or else to remove a faulty piece of equipment and replace it with a spare. The faulty equipment would then be taken to an on-site repair shop and repaired by a company repair person, held for the repair person's next visit, or shipped out for repair. The inventory of spare equipment is dependent on the failure rate experience. For many organizations, repair and maintenance contracts are established on specialized electronic equipment such as computers, typewriters, communications, radios, point-of-sale terminals, and other equipment that may require servicing. Most of these contracts call for prompt service at any time of the day.

- Those organizations operating critical pieces of equipment whose failure would result in substantial loss of service, production, or revenue, give very special attention to equipment reliability. In some organizations, backup equipment is available on standby or, special precautions are taken for protecting the equipment from the hazards of environment. Most of the large computer facilities are housed in specially controlled rooms within air conditioned buildings. These rooms are particularly invulnerable to carbon fiber penetration.

- Some equipment, if properly maintained with the covers and access doors closed, is simply invulnerable. It was found that modern radio transceivers and much in-plant electrical switch gear are enclosed in tightly fitting cabinets that effectively reduce the transfer function between one and two orders of magnitude below the transfer function for the room within which the equipment are housed.

- All of the equipment with exposed printed circuit boards, which would normally suffer failures as a result of accumulation of dust and dirt, were well protected by cabinet filter systems on both natural and forced convection cooling systems, and by properly designed dust covers and enclosures.

- There were surprisingly wide differences between the amount of protection that individual commercial establishments provided in the air filtration system for seemingly similar activities. It was found that the type of filters used in the HVAC system was often determined by the lowest cost for filters.

6.5 ECONOMIC ANALYSIS METHODOLOGY

6.5.1 Penetration and Vulnerability Estimates

Data obtained during the field visits were used in the building penetration model that was developed in Phase I to compute ranges of Airborne Exposure Transfer Functions (AETF) values. AETF values are defined as the fraction of the outdoor carbon fiber exposure (in fiber-seconds per cubic meter) that will be experienced in a particular internal area of a building or other structure. The internal exposure relates to the area as a whole, and not necessarily to the conditions inside a particular item of equipment. In mathematical terms this is represented as

$$\text{Exposure indoors} = \text{AETF} \times \text{Exposure outdoors}.$$

Both Summer and Winter seasons were considered in determining transfer function characteristics. Under some circumstances it was necessary to account for windows and doors being open in pleasant weather, regardless of the fact that a forced air ventilation system was present and in use. A range of transfer functions were calculated for the best and worst conditions expected in each area investigated. In almost all cases, ranges were used because one or more of the penetration model's parameter values (e.g., infiltration rate) could not be precisely defined. Credit was taken for the possible beneficial effect of window screens in those establishments where screens existed. A complete listing of the AETF values used in the risk analysis may be found in Appendix A. The underlying penetration model is described in Appendix F of the Phase I report, Volume II.

The vulnerability of the equipment within a facility was quantified by the mean dosage for failure ($\bar{E}$). It was assumed that equipment failure probability would follow an exponential law, as given by:

$$\text{Prob (failure at exposure E)} = 1 - e^{-E/\bar{E}}$$

For low values of E, this probability is a nearly linear function of exposure. Values of $\bar{E}$ for various equipment types were estimated during the GFRAPO program by both NASA and other government organizations.* The final $\bar{E}$ values adopted for the risk analysis were provided by NASA-Langley after review of the equipment summaries developed from the individual site visits. These vulnerability estimates are also listed in Appendix A.

6.5.2 Estimates of Facility Costs

A carbon fiber exposure at an industrial, commercial, or public service facility may produce some amount of economic loss depending upon the type of equipment damaged and its function in the operation of the facility. In this analysis, we considered the costs associated with repairing the equipment and the costs associated with disruption of the facility's functions. The analysis revealed that given the external

*See reference 2 in Chapter 5.

carbon fiber dosage expected, the transfer functions, and the measured vulnerability of many classes of electronic equipment, large scale catastrophic disruption of normal functions would rarely occur. Rather, the type of failures that might be experienced with various classes of equipment would be extremely difficult to distinguish from the normal failure rate for these equipment. Facility costs were analyzed for two possible situations: first, the situation in which only equipment repairs were necessary, and secondly the situation in which the operation of the facility was disrupted.

For the first situation, we developed a schedule of estimated costs for repair that ranged from minor repair of small equipment such as home appliances and office equipment up to the repair of complex equipment such as large computers and telephone switching gear. This schedule of costs is summarized in Table 6-2. For each severity index from A to E, we described the type of equipment, the estimated time to diagnose and repair the equipment, the number of repair persons required, and estimates of labor costs and material costs required to effect the repair.

In a similar manner, we established facility costs for disruptions that ranged from minor service disruptions up to critical service disruptions; these cases were assigned a severity index from A to C. The estimated consequences of the facility disruptions were based upon the percent of the work force kept idle as well as identifiable loss of product (i.e., manufactured units that would need to be scrapped as a result of the disruption of manufacturing facilities). The schedule of facility costs for disruptions is summarized in Table 6-3. Estimates of average work force size and production volumes were obtained from business census data for each major hub airport and each facility category.

A master summary table was developed that includes all of the pertinent information assembled from the site visits and subsequent analyses. This summary is given in Appendix A and was used as input to the risk analysis simulation program.

TABLE 6-2

SCHEDULE OF COSTS FOR EQUIPMENT REPAIR

Severity Index	Description	Time to Diagnose & Repair (hrs.)	No. of Repair Persons	Labor Cost at Approx. $15/hr. ($)	Estimate of Material Costs ($)	Total Cost ($)
A	Minor repair of appliances and non-specified small equipment such as CRT displays, typewriters and small office equipment.	4	1	60	20	80
B	Minor repair of specified electronic and electromechanical equipment such as copiers, radio equipment and POS terminals.	5	2	150	100	250
C	Repair of complex small specified equipment such as small computers and PBX systems.	10	4	600	200	800
D	Repair of complex specialty equipment such as large computers.	20	6	1800	700	2500
E	Diagnosis and cleaning of telephone lines.	1% of lines will be affected; repair 10 lines per hour at $15/hour plus $5/line for materials.				

TABLE 6-3

COSTS FOR FACILITY DISRUPTIONS

Severity Index	Description	Consequence
A	Minor service disruption.	5% of work force loses 4 hours of production time at $15/hour; negligible loss of product.
B	Important service disruption.	10% of work force loses 8 hours of production time at $15/hour plus identifiable loss of product.
C	Critical service disruption.	50% of work force loses 8 hours of production at $15 hour plus identifiable loss of product.

7. MONTE CARLO SIMULATION OF SINGLE ACCIDENT RISK PROFILE

7.1 INTRODUCTION

A computer simulation model was developed for estimating the potential economic impacts of a carbon fiber release upon facilities within an 80 kilometer radius of a major airport. Assuming that an air carrier incident or accident involving fire or explosion had released carbon fibers, the model simulated the possible range of release conditions and the resulting dispersion of carbon fibers. Each iteration of the model generated a specific release scenario which would cause a specific amount of dollar loss to the surrounding communities. The simulation generated thousands of accidents, and for each one, random draws were performed from probability distributions describing the set of conditions for that accident. By repeating the simulation many times a full range of possible accident types was developed, along with a distribution of the potential accident consequences. Both the simulation model and the methodology used to synthesize a national risk profile are very similar to the model and procedures described in reference 1 of Chapter 2.

This chapter describes the mechanics of the simulation model which was applied to each of the 26 large hub airports in the United States. The risk profiles for these 26 cities each represented a distribution of economic losses conditional on there being an accident at the given airport. The development of the individual airport risk profiles was part of a multi-step procedure used for the computation of the national risk profile. The first step was the generation of the conditional profile for each of the individual airports. The second was the synthesis of these distributions into a single national distribution that was again conditional on there being an accident. In the final step, which is described in Chapter 8, the national probability of an accident was combined with the conditional national profile to generate a risk profile for annual national economic losses resulting from any number of accidents.

7.2 DESCRIPTION OF SIMULATION PROCEDURE

The general Monte Carlo procedure on which the model was based is presented in Figure 7-1. For each iteration, release conditions and relevant accident events were drawn from the appropriate probability distributions. This release scenario was fed as input to a dispersion model which calculated the dosage that would occur within each of forty sectors of a geographic grid whose center was located at the airport. An example of such a geographic grid is presented in Figure 7-2. From the exposure distribution we used the penetration and vulnerability characteristics of the facilities exposed and the economic anlyasis model described in Chapter 6 to estimate the resulting economic losses for each affected facility. The losses were then summed to determine the total economic losses resulting from the simulated accident. Once this procedure was complete the computer returned and simulated another accident, drawing a new set of accident/incident details. This procedure was repeated iteratively until enough samples had been taken to get a reasonably accurate distribution of the economic losses resulting from an accident. In this way we developed 26 individual risk profiles for the large hub airports.

A large number of probabilistic events were used as input to the Monte Carlo simulation procedure. The interactions between the various components of these distributions and the deterministic data inputs are illustrated by the flow chart in Figure 7-3. The question marks below several boxes in the flow chart represent the probabilistic input variables. These were the weather variables, the accident model variables described in Chapter 4, including the possibility of an explosive type of release, and the remaining variables described in Chapter 5, which determine the release conditions such as the amount of fiber released. The underlying probabilistic inputs used to determine the release scenario are fully presented in Chapters 3, 4 and 5. It is important to recognize that all of these underlying probability distributions resulted in separate random draws for each Monte Carlo iteration.

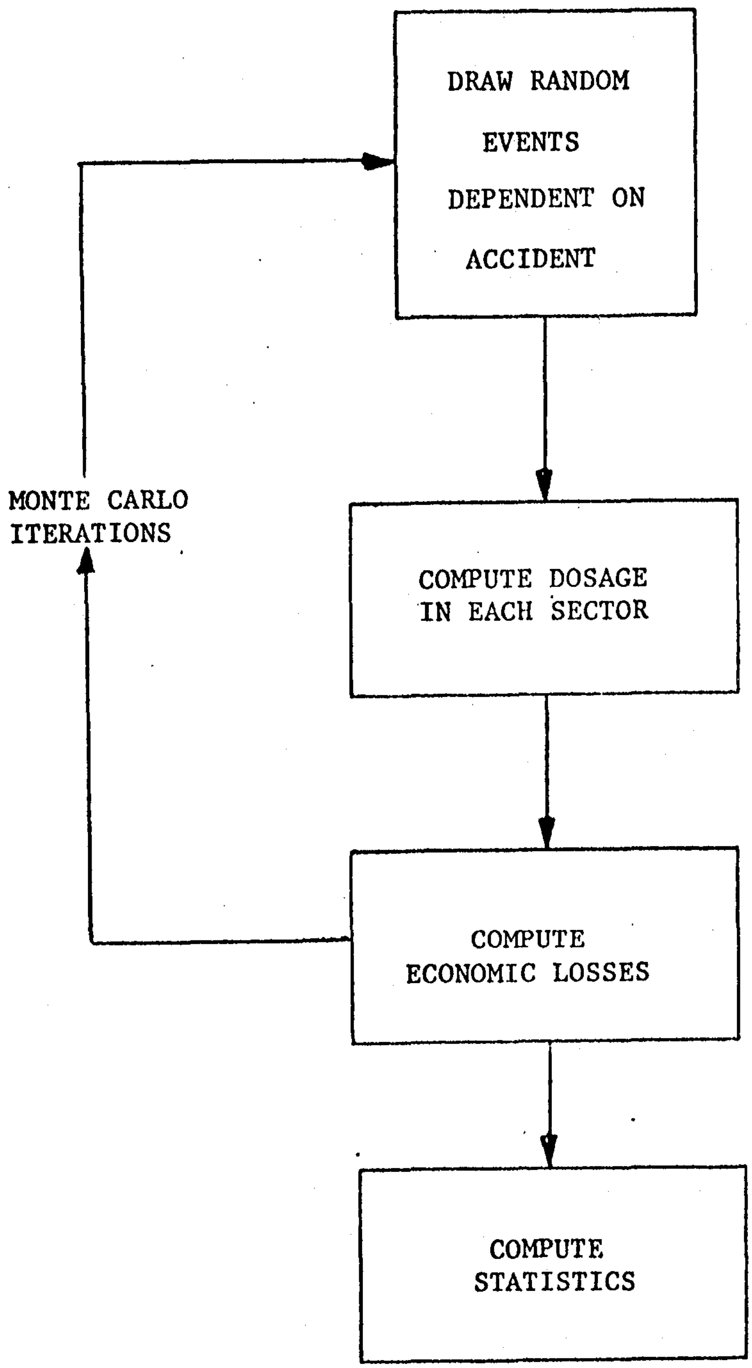


FIGURE 7-1

OVERVIEW OF MONTE CARLO PROCEDURE

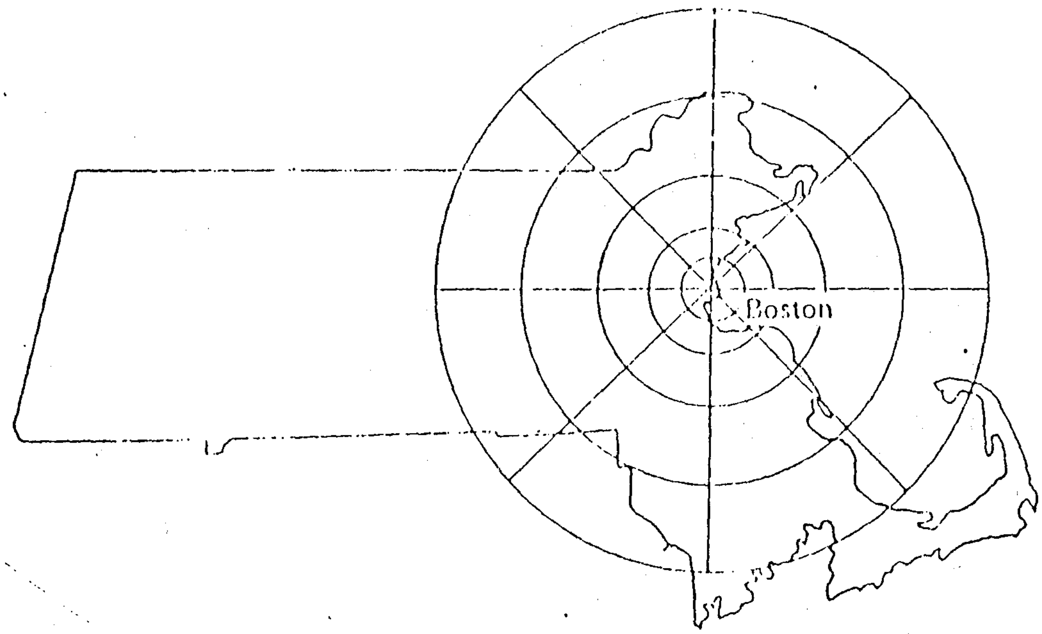
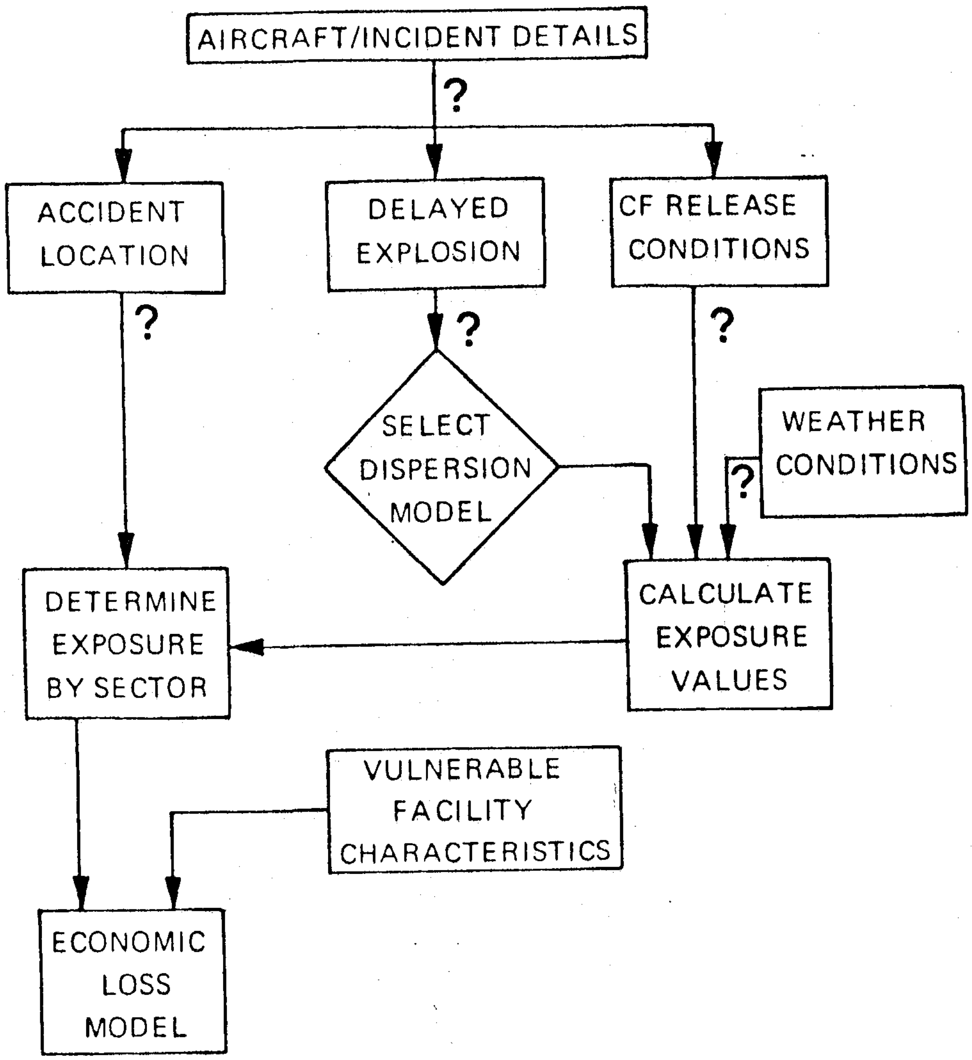


FIGURE 7-2

DISTRIBUTION OF SECTORS AROUND LOGAN AIRPORT, BOSTON, MA



? Denotes a random draw

FIGURE 7-3
MONTE CARLO SIMULATION PROCEDURE

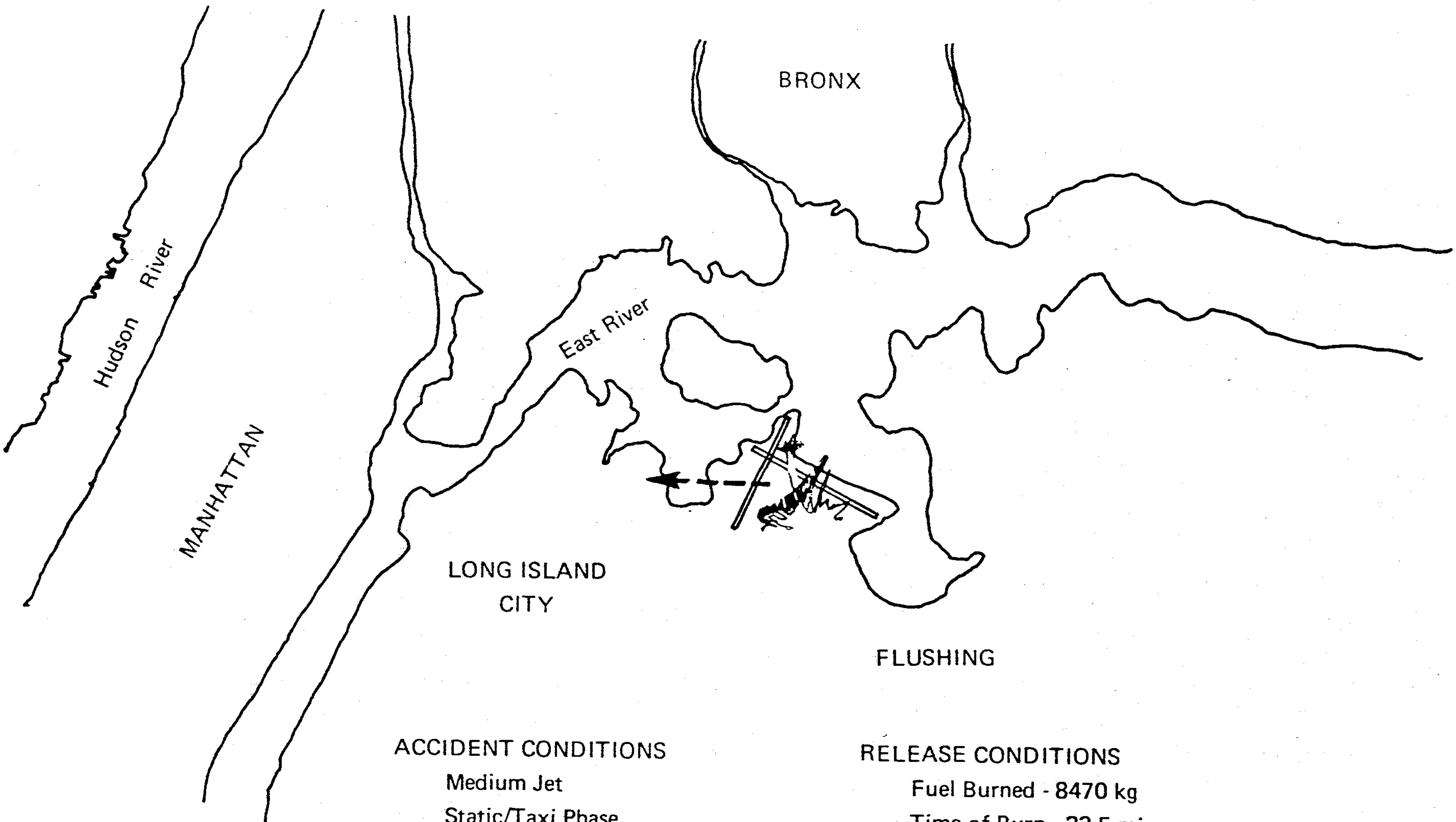
The individual random variables incorporated within the simulation procedure were the following:

- The probability of fire/explosive release (two distributions - one for static and certain types of take-off accidents and one for others).
- Probability of explosion given fire/explosive mode
- Aircraft Size
- Orientation of runway (two distributions - one for take-off and one for landing).
- Angle from runway
- Distance from end of runway (two distributions - one for take-off and one for landing)
- Stability Class
- Temperature
- Wind Direction
- Speed Class (six distributions - one for each stability class)
- Percent of carbon fibers consumed (three distributions - one for each size class)
- Duration of the fire
- Percent of fuel burned
- Carbon fibers on aircraft (three distributions - one for each size class)

To calculate the exposure distribution in each sector of the geographic grid a large number of exposure calculations were performed within the simulation. This was accomplished in two steps. In the first step exposures were calculated for each of four points uniformly distributed within the sector. The sectors with the maximum exposures were flagged and then exposures were calculated for 50 additional points in the five sectors lying in the same direction as the sector of maximum exposure. 50 points were determined by a five fold subdivision of each sector along the radial direction and a ten fold subdivision along the angular direction. After the exposures were computed along these lines the percentage of geographic area was computed in each decade corresponding to exposures from 10 to 10^{10} fiber seconds per cubic meter. These percentage distributions were used to directly calculate economic loss. In determining the appropriate decade of exposure corresponding to each sample geographic point, the base 10 logarithm of the exposure was evaluated and rounded to the nearest integer value.

The final part of the simulation was the computation of economic losses in each sector of the metropolitan area. To perform this step the number of facilities in each sector was obtained from census data for each city classified by facility categories. It was assumed that the fraction of facilities receiving different levels of exposure were given by the exposure distribution in that sector. By using these fractions and the building penetration and equipment failure rates presented in Chapter 6, the economic losses for each sector and then for each metropolitan area were computed.

An example of the outcome of a typical computer simulation is shown in Figure 7-4. In this case, the computer generated a hypothetical accident at LaGuardia airport relatively close to the center of the runway. The aircraft involved was a medium jet in a static or taxi phase which somehow caught fire. About 8,500 kilograms of fuel were burned over a period of 30 minutes, releasing 22 kilograms of carbon fibers. There was a delayed explosion during the fire. Based on randomly drawn weather conditions, the carbon fiber cloud moved westward, toward New York City, creating exposures as high as 10^8 fiber-seconds



ACCIDENT CONDITIONS

Medium Jet
Static/Taxi Phase
Explosive Release

WEATHER CONDITIONS

Neutral Atmosphere (D)
Wind from East at 7 m/sec
Temperature: 1°C

RELEASE CONDITIONS

Fuel Burned - 8470 kg
Time of Burn - 33.5 min.
CF released - 22 kg

CONSEQUENCES

10^8 Exposure at Airport
10^7 Exposure within 3 km of Airport
Total Dollar Losses $178
Household Losses $66

FIGURE 7-4

ILLUSTRATION OF A TYPICAL SIMULATION RUN AT LAGUARDIA AIRPORT per cubic meter at the airport, and 10^7 fiber seconds per cubic meter within three kilometers of the airport. The resulting losses due to equipment failures amounted to a total of $178 of which households accounted for $66. By performing hundreds of iterations like this one, the computer generated a risk profile for LaGuardia airport.

7.3 SIMULATION RESULTS FOR THE LARGE HUB AIRPORTS

Using the input probability distributions described in the previous section as well as the economic data described in Chapter 6, conditional risk profiles were developed for each of the 26 hub airports. The mean, the standard deviation, and several percentiles for these distributions are presented in Table 7-1. Note that the distributions are all skewed. That is, the tail corresponding to losses larger than the median is more extended than the tail corresponding to losses less than the median. As a result of this, the standard deviations are far greater than the means.

In performing the individual city simulations a different number of Monte Carlo iterations was used for each city. The total number of iterations for all 26 cities was 10,000. However, in order to develop the greatest accuracy in the national conditional risk profile given a total of 10,000 iterations, it was necessary to set the number of iterations for each city to a value proportional to the conditional probability that an accident occurs in that city given that an accident occurred somewhere in the U.S. (the reasons for this are discussed in Chapter 8). The appropriate conditional probabilities for each city are presented in Table 4-1. Because the conditional probabilities of the cities vary so widely, the number of Monte Carlo iterations ranges from 138 for the case of Phoenix, which had the lowest conditional probability, to 1346 for Chicago which had the highest conditional probability. Thus, for example, an accident was 1346/138 times as likely to occur in Chicago as it was in Phoenix, and because of this the national risk profile required more accuracy (and hence more iterations) for the Chicago risk profile than for Phoenix. The number of iterations used for each city is presented in Table 7-2.

TABLE 7-1

CONDITIONAL RISK PROFILES FOR 26 AIRPORTS

City	Mean	Standard Deviation	Minimum	5 Percent	10 Percent	25 Percent	50 Percent	75 Percent	90 Percent	95 Percent	Maximum*
Atlanta	24	53.5	0	0	0	1.0	5.0	20.0	60.7	113.1	433.2
Boston	53	115.1	0	0	0	0	6.0	56.5	171.2	251.5	1102.8
Chicago	222	543.5	0	0	0	9.5	57.5	166.9	541.9	848.6	7032.4
Cleveland	380	930.9	0	0	1.3	22.1	100.3	343.1	769.2	1355.9	6952.2
Dallas	33	72.4	0	0	0	.9	5.0	24.6	99.3	188.6	590.5
Denver	30	103.2	0	0	0	1.1	6.8	26.0	64.8	105.0	1559.7
Detroit	1184	2404.7	0	0	0	9.7	211.3	939.6	3728.5	5639.6	16429.0
Honolulu	7	21.1	0	0	0	0	.1	2.2	12.5	51.9	131.7
Houston	38	111.9	0	0	0	.1	1.8	13.8	124.4	183.8	1013.0
Kansas City	16	35.1	0	0	.1	.6	2.8	14.1	43.8	85.1	232.3
Kennedy	173	419.3	0	0	0	2.7	34.0	142.1	479.2	799.3	4644.0
LaGuardia	170	434.3	0	0	0	5.8	31.7	137.4	398.2	705.4	5113.7
Las Vegas	12	127.8	0	0	0	.1	.8	2.4	6.2	20.9	1806.8
Los Angeles	439	1030.6	0	0	0	1.8	80.8	511.4	1155.5	2092.6	20277.0
Miami	29	74.9	0	0	0	0	2.6	24.0	71.9	139.7	569.0
Minneapolis	349	4876.4	0	0	0	.5	4.1	17.6	62.8	141.7	73974.0
Newark	209	420.6	0	0	0	13.5	61.8	206.5	579.5	807.9	3399.4
New Orleans	14	43.6	0	0	0	.3	2.0	8.5	25.1	60.8	397.2
Philadelphia	89	209.9	0	0	0	3.4	19.1	63.7	258.3	464.2	1782.7
Phoenix	34	101.9	0	0	0	.2	3.3	19.6	83.8	169.1	950.4
Pittsburgh	61	115.4	0	0	.3	2.7	11.5	57.0	170.6	330.4	741.3

TABLE 7-1

CONDITIONAL RISK PROFILES FOR 26 AIRPORTS
(Continued)

City	Mean	Standard Deviation	Minimum	5 Percent	10 Percent	25 Percent	50 Percent	75 Percent	90 Percent	95 Percent	Maximum*
San Francisco	52	104.6	0	0	0	3.3	15.9	63.3	125.2	154.3	1149.8
Seattle	47	147.4	0	0	.2	1.5	9.1	42.3	105.9	151.0	1848.6
St. Louis	148	494.1	0	0	0	3.0	21.4	104.9	335.9	688.7	7889.1
Tampa	18	35.5	0	0	0	.9	5.3	19.5	50.6	68.0	223.7
Washington	35	87.5	0	0	0	1.7	8.0	30.1	105.9	137.8	1010.5

*Expected percentile is N/N+1, where N is number of iterations from Table 7-2.

TABLE 7-2

NUMBER OF MONTE CARLO ITERATIONS BY CITY

City	Iterations
Atlanta	771
Boston	343
Chicago	1346
Cleveland	223
Dallas	653
Denver	336
Detroit	348
Honolulu	143
Houston	322
Kansas City	234
Kennedy	753
LaGuardia	340
Las Vegas	200
Los Angeles	852
Miami	333
Minneapolis	230
Newark	208
New Orleans	174
Philadelphia	259
Phoenix	138
Pittsburgh	339
San Francisco	294
Seattle	252
St. Louis	392
Tampa	201
Washington	316

The conditional economic loss profiles for 26 hub airports constitute a major intermediate result in our risk analysis work. It should be noted, however, that the maximum observed losses represent sample maxima for this simulation. Statistically, if there are N Monte Carlo iterations for a given city, then on average the maximum represents the percentile corresponding to N/N+1. We therefore assumed these percentiles in the synthesis of the national risk profile. However, there was some question regarding maximum values obtained from the simulation. For any given city a loss higher than the maximum could conceivably occur. In order to develop a confidence bound for the probability of a loss higher than the maximum observed we utilized the binomial probability distribution. Suppose that the probability per accident of given loss is λ. Then using the binomial distribution the probability of not observing any such losses in N simulation trials is

$$(1 - \lambda)^N$$

To determine a 95% cofidence bound we set the above expression equal to 5% which yields a value of $\lambda = 3/N$. Thus, for example, a 95% confidence bound for Chicago, for which 1,346 iterations were run, is 3/1346 or 1 in 449. For the national profile analagous statements can be made and these are presented in Chapter 8.

7.4. SENSITIVITY ANALYSIS

The magnitudes and range of losses in Table 7-1 indicate that the losses in accidents at the 26 hub airports are moderate. In fact, the losses are significantly less than a previous analysis presented in Phase I (see reference 1 of Chapter 2). There are two major reasons for this significant decrease in losses. The principal reason is that present estimates of equipment vulnerability and economic loss are significantly less than those assumed in Phase I. In addition, of course, there have been additional data gathered and experimental findings on CF amounts release and on the relationships among the various release conditions. Both of these effects have tended to reduced the distribution of economic loss.

To test the relative importance of the two major modifications in modelling efforts, that is revised economic estimates and increased accuracy in the release condition models, the conditional risk profile for the city of Boston was run using the revised models for release conditions but maintaining the economic model used in Phase I. With these input conditions, the mean loss was $90,000 per accident, the standard deviation was $175,000, the 90th percentile was $336,000, and maximum was 1.46 million dollars. Although these numbers represent a decrease in the loss distribution compared with the Phase I Boston risk profile (A mean of $120,000, maximum of $3.1 million) the two risk profiles are comparable. However, with the introduction of revised economic data, the Boston profile decreased to the level presented in Table 7-1. We therefore concluded that the revised cost and vulnerability estimates have significantly reduced the risk of economic losses.

We also performed a sensitivity analysis to estimate modelling errors by varying several of the key input parameters. The results are shown in Figure 7-5. This analysis was run on the individual airport risk profiles which have the highest mean loss for the 26 hubs, namely Detroit. Of the three parameters tested, the largest increase in risk was obtained by setting the composite on the aircraft at its highest possible value - 15,652 kilograms. This increased the mean loss per incident by a factor of about 7 and increased the standard deviation and maximum value of the losses by a factor of about 4.5. Restricting the simulation models to only explosive releases increased the statistics by a factor of 2 or 3, while setting the atmospheric stability classes to E (moderately stable weather) increased the loss distribution only slightly. The two latter conditions are those which tend to result in highest exposure downwind of the release point. We concluded that modelling errors can contribute less than an order of magnitude to the uncertainty of the risk profile.

A final consideration of model sensitivity was the incorporation of other possible sources of randomness. A great many of the model calculations were made on a deterministic basis. For example, given a set of release conditions and an exposure distribution within a metropolitan area, we assumed that the economic losses would be equal to the expected

SENSITIVITY ANALYSIS

Changes in risk profile due to variation of input parameters, tested for the airport with highest mean dollar loss

	Resulting Increases from Base Case		
Parameter Tested	**Mean Dollar Loss ($1184)**	**Standard Deviation ($2409)**	**Maximum Dollar Loss ($16,429)**
Composite on Aircraft Set at Max. (15,652)	↑ by 7	↑ by 4.5	↑ by 4.5
100% Explosive Releases (no plume release)	↑ by 3	↑ by 2	↑ by 2.5
Stability Class Set at E (moderately stable)	↑ by 1.5	↑ by 1.2	↑ by 1.1

FIGURE 7-5
SENSITIVITY ANALYSIS

economic losses based on that exposure distribution. In fact, at low levels of exposure, the dominating source of randomness for the entire phenomenon was the randomness of the individual failure events of the various pieces of equipment exposed. To examine the effect of this source of variability within the overall context, an alternative method for generating risk profiles was developed. This method was used only for the national risk profile and is discussed in the following chapter.

8. SYNTHESIS OF NATIONAL RISK PROFILE

8.1 INTRODUCTION

This chapter presents the methodology used and results obtained in computing the national risk profile. The computation was performed by use of the 26 individual conditional risk profiles under the conservative assumption that all U.S. air carrier accidents occur at the 26 hub airports. The risk profile was obtained using the 1993 carbon fiber utilization forecast, but numbers of facilities were taken from 1972 and 1975 census data, while the losses were expressed in 1977 dollars.

As noted in Chapter 7, we developed two kinds of national risk profiles in the analysis. One of them was the risk profile for a single incident which gave a distribution of dollar losses resulting from any one air carrier accident, and this was derived by taking a mixture of the individual risk profiles for a single incident weighted by the probability that an accident takes place at each airport. The second type of profile was a national annual risk profile which showed the distribution of the total annual losses due to accidents involving carbon fibers. This annual risk profile incorporates the possibility of 1, 2, 3 or more accidents involving carbon fiber releases during one year. To derive the annual risk profile we began with the national risk profile for a single incident and performed a convolution procedure based on a Poisson distribution of accidents with mean equal to the annual frequency of such accidents. The procedural steps are illustrated in Figure 8-1.

We also developed an annual risk profile based on a Poisson model for the number of equipment failures. This procedure was used by Arthur D. Little in development of the dollar loss distribution relating to carbon fiber releases from general aviation accidents.* The purpose of the approach was to accurately account for the randomness due to the failure process. The trade-offs involved in the use of this procedure are discussed in Section 8.6, but the risk profiles using the two methods

* See reference 2, Chapter 2.

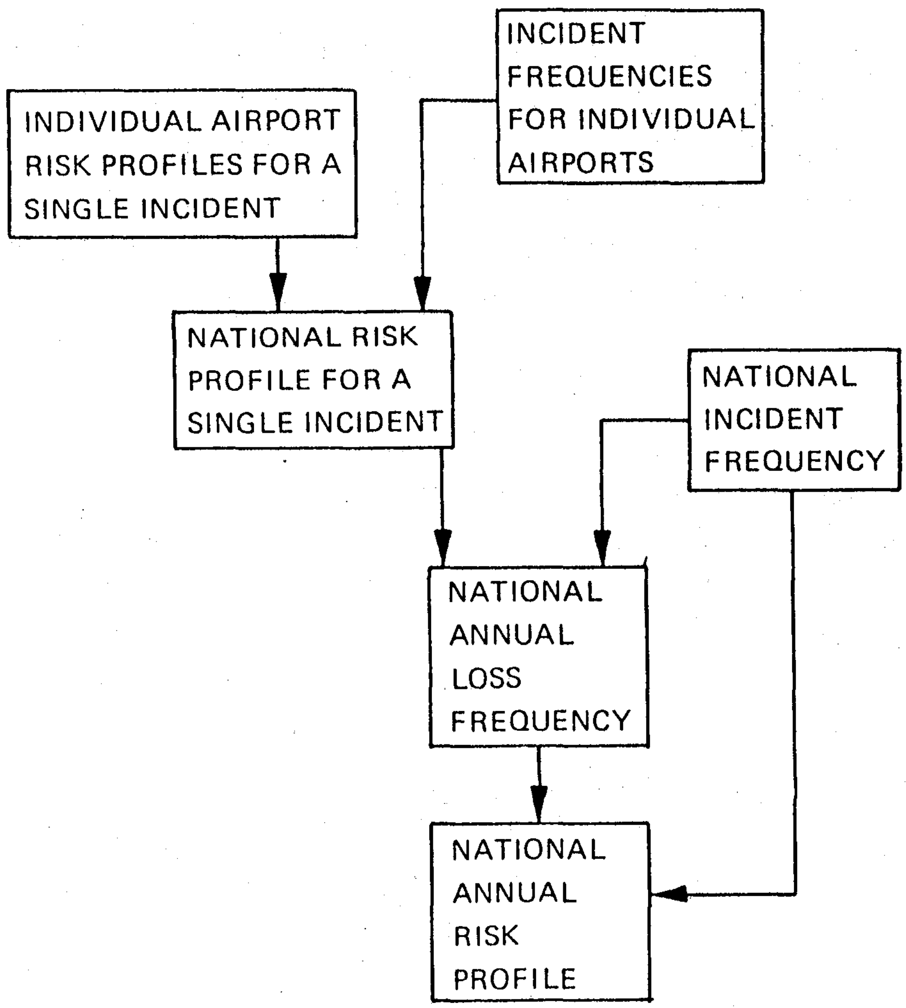


FIGURE 8-1
DERIVATION OF NATIONAL RISK PROFILE

did not show substantial differences. An additional advantage of the Poisson analytic procedure is that it overcomes problems related to statistical estimation of high loss events. The probability of such high loss events are low, and as a result the statistical confidence bounds relating to these probabilities show a moderate deviation from the estimated values.

8.2 Major Assumptions

Before proceding to the results of the risk analysis, it is important to note the major assumptions that entered into the analysis. The first major assumption was that all U.S. air carrier accidents occur at the 26 hub airports. Since large hubs account for 68% of passenger enplanements and about 59% of airplane departures, this assumption is not unreasonable. It is conservative in the sense that larger hubs tend to show a higher conditional risk since they are generally associated with higher densities of facilities.

The second major assumption was that atmospheric conditions were assumed to remain constant during the dispersion of the carbon fiber cloud. This is a somewhat unrealistic assumption since weather conditions are constantly changing and a cloud moving at a rate of a few kilometers per hour could take as much as a day to cover 80 kilometers. However, it would be too complex to simulate different atmospheric conditions in different geographic sectors, and therefore this assumption was made. The assumption is not expected to produce any bias into the risk analysis since the variation of atmospheric conditions will sometimes increase and sometimes decrease the resulting exposures.

The third assumption was that there would be no precipitation, which is conservative since if precipitation does occur it may wash out some of the fibers, resulting in lower airborne exposures on the ground. It was found that there was a high likelihood of rain or other forms of precipitation being associated with aircraft accidents, since many of the accidents in the historical data base occurred in IFR (instrument flight rules) weather.

The fourth assumption was that for a given facility category all facilities are equal in size, equipment inventory, and financial characteristics. Again, this is a necessary assumption due the enormous volume of data that would have to be processed in order to identify all the different sizes and scales of facilities that do exist. Instead we took the average case based on regional statistics for each facility category and attempted to model a typical vulnerable facility. The variation of facility characteristics would introduce a little more variation into the risk profile, but should not affect the results too greatly because of the large number of facilities involved that would tend to average each other out.

The fifth major assumption was that all equipment is activated and failures occur immediately after exposure. This assumes, first of all, that equipment which is exposed is in an activated state and is vulnerable to the fibers at the time of exposure. Since some fraction of electronic equipment exposed will not be activated, this tends to be a conservative assumption. On the other hand, there is a phenomenon of post-exposure vulnerability, in which the fibers that are deposited upon equipment do not cause a problem immediately but will affect the equipment when it is turned on at a later date. This phenomenon was not modelled explicitly but was taken into account by assuming continuous activation and failure immediately after exposure.

The final major assumption was that the number of failures for a given scenario would be equal to the expected number of failures based on equipment vulnerabilities and the exposure distribution. As noted, the number of failures was a random variable based on this expectation. To determine the sensitivity of the results with respect to this assumption the alternative Poisson analytic model was developed.

8.3 DEVELOPMENT OF A CONDITIONAL NATIONAL RISK PROFILE

The first step in the synthesis of the national profile was to develop a conditional distribution for loss given an accident anywhere in the country. That is to say, if there was an accident somewhere in the U.S. involving a jet aircraft using carbon fibers and resulting in a fire or explosion, the distribution of losses is given by this conditional profile. The profile is obtained by a simple probabilistic mixture of the 26 individual conditional risk profiles.

Formally,

$$F(X) = P_1F_1(X) + P_2F_2(X) + . . . + P_{26}F_{26}(X)$$

Where

$F(X)$ = Probability that total loss is greater than or equal to X given an accident in the U.S.

$F_i(X)$ = Probability that loss is greater than or equal to X given an accident at airport i

P_i = Conditional probability that an accident occurs at airport i given that it occurred in the U.S.

To compute the conditional national risk profile we computed F(X) from the above equation for several dollar values. This computation involved two technical tasks before the equation could be evaluated. These were

- Computation of P_i
- Computation of the $F_i(X)$ for given values of X

The determination of the P_i is presented in Chapter 4 and the values are presented in Table 4-1. The 26 individual risk profiles were expressed in terms of fixed percentiles rather than the fixed dollar values required by the equation. To determine the $F_i(X)$ for fixed dollar values, we performed a logarithmic interpolation of the points in the inidividual risk profiles. That is, a straight line was connected between the fixed percentile data on a logarithmic basis. Logarithmic interpolation was preferred to linear interpolation because of the concave nature of the risk profile. The maximum dollar value for each city represented an expected percentile of N/N + 1, where N was the number of Monte Carlo iterations for that city. We terminated the computation at a value of $75,000 as this was approximately the maximum loss calculated in the 26 original simulations. (It was observed for Minneapolis.) To extrapolate the 25 risk profiles for which this value was not observed, a log-linear relationship was again utilized.

The national conditional risk profile computed by the above procedure is shown in Table 8-1 and is presented graphically in Figure 8-2. The mean value or expected loss per incident was $173, but there was a large variation in loss; the standard deviation was $969. While one-quarter of the accidents exceeded approximately $75 in loss, only 2% exceeded $1500 in loss.

Although we could not develop valid statistical confidence bounds for the annual risk profile, statistical confidence bounds for the conditional national risk profile were developed. A discussion of the methodology involved in deriving such a confidence bound is presented in Appendix H of reference 1, Chapter 2. As an example of this type of confidence bound, a 95% upper confidence bound for the conditional probability that an accident results in a loss in excess of the maximum observed in the simulation is equal to

$$3 \times \max_{i=1 \text{ to } 26} (P_i/N_i) \tag{8.1}$$

where P_i is defined above and N_i is the number of simulation trials for city i.

TABLE 8-1

NATIONAL CONDITIONAL
RISK PROFILE
(1993)

Losses X	Cumulative Probability of Losses Less Than X	Probability of Losses Greater Than X	Expected Annual Frequency* of Incidents With Losses Greater Than X
10	.49	.51	1.4
75	.75	.25	.68
300	.897	.103	.28
500	.929	.071	.19
800	.958	.042	.113
1,500	.980	.020	.054
3,000	.991	.009	.024
6,000	.9968	.0032	.0086
10,000	.9987	.0013	.0035
15,000	.9993	7×10^{-4}	1.9×10^{-3}
40,000	.9998	2×10^{-4}	5.4×10^{-4}
70,000	.99985	1.5×10^{-4}	4.1×10^{-4}

*Based on an average of 2.7 jet accidents per year involving CF composites and fire

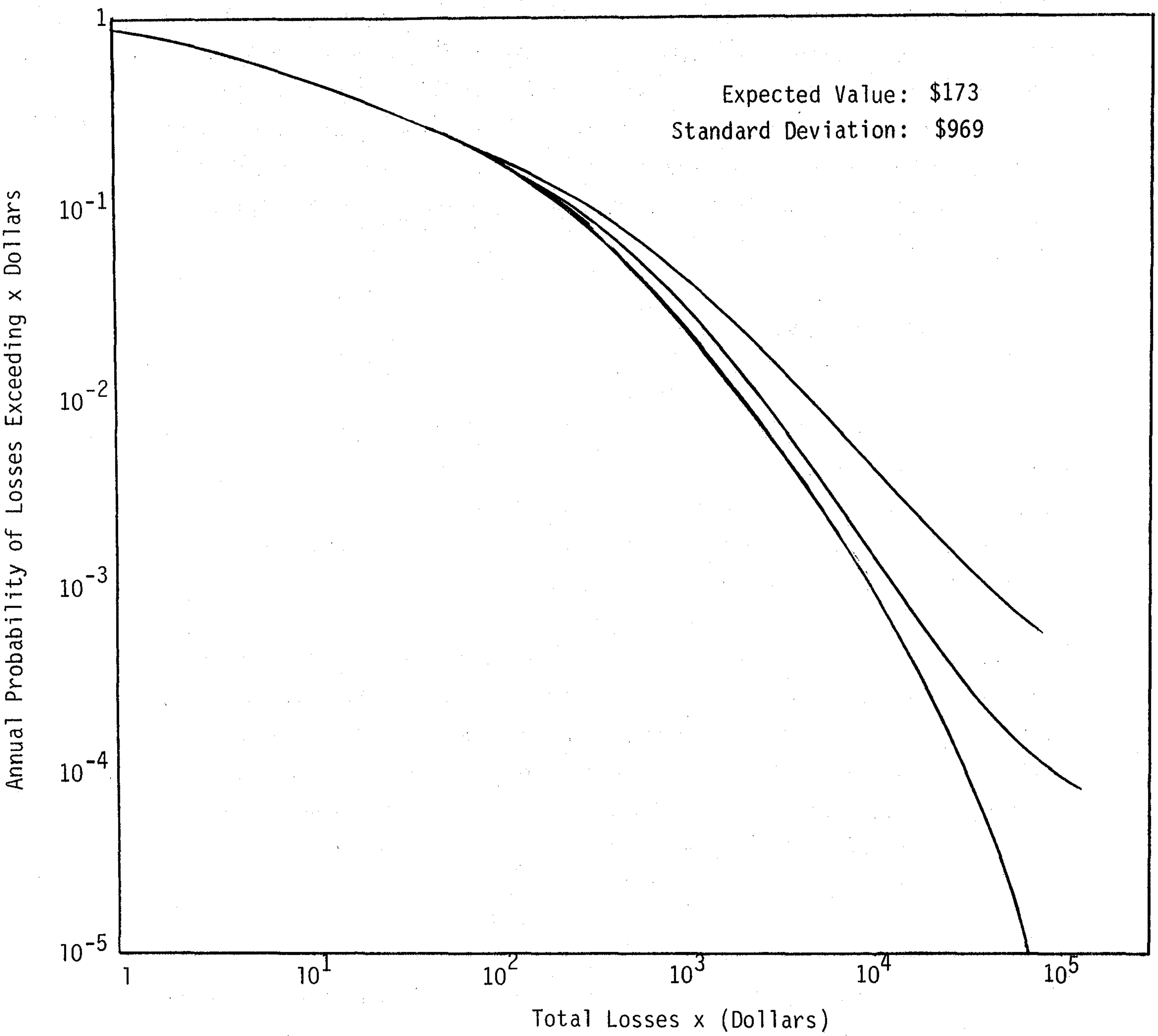


FIGURE 8-2

AIR CARRIERS 1993 NATIONAL CONDITIONAL RISK PROFILE AND
UPPER AND LOWER 95% CONFIDENCE BOUNDS DUE TO STATISTICAL ERRORS IN SIMULATION

In order to ensure maximum accuracy in our simulation, we determined values of N_i such that this upper confidence bound probability would be minimized but the total number of simulation trials would not be excessive. (We set the total number to 10,000). We therefore designed the simulation so that all 26 values of P_i/N_i would be approximately equal. For Chicago, for example, which represented a P_i of .1346, the highest number of Monte Carlo simulations (1346) was generated. Note that 1,346 trials drawn from a segment representing 13.46 percent of the possibilities is equivalent to

$$\frac{1346}{.1346} = 10{,}000$$

for 100% of the possibilities. In other words our simulation was designed to be accurate to an equivalent 10,000 iterations for a non-stratified sample. Based on 8.1, the upper confidence bound for a loss in excess of maximum observed is 3/10,000.

The above considerations were used to develop the confidence bounds for the risk profile. Based on the number of observations exceeding any loss value, confidence bounds were developed assuming a Poisson probability distribution. The stratification of the sample was taken into account in these calculations. The resulting confidence bounds are also depicted in Figure 8-2 and presented in tabular form in Table 8-2.

8.4 CONVOLUTION PROCEDURE FOR NATIONAL PROFILE

To develop a national risk profile for the total annual losses without regard to the number of accidents, the following formula was used:

$$F(X) = P(1)F^{(1)}(X) + P(2)F^{(2)}(X) + \ldots$$

TABLE 8-2

CONFIDENCE BOUNDS (5% OF EACH TAIL)
FOR CONDITIONAL NATIONAL RISK PROFILE
DUE TO STATISTICAL ERROR IN
SIMULATION AND NO OTHER UNCERTAINTY

Dollar Value	Lower Confidence Bound on Probability of Loss Exceeding Value	Upper Confidence Bound on Probability of Loss Exceeding Given Value
75	.24	.26
300	.098	.108
800	3.9×10^{-2}	4.5×10^{-2}
3,000	7.6×10^{-3}	1.07×10^{-2}
10,000	8.4×10^{-4}	2.0×10^{3}
40,000	7.5×10^{-5}	6.4×10^{-4}
75,000	0	3×10^{-4}

where

$P(i)$ = Probability that i accidents occur per year, which equals the probability that a Poisson variate with parameter 2.7 is equal to i

$F^{(i)}(X)$ = Probability that loss exceeds X given i accidents

$F(X)$ = Probability that total annual loss exceeds X

The procedure to compute the $F^{(i)}(X)$ involves a mathematical integration procedure known as convolution. A computer program was developed to convolve the conditional national risk profile up to 21 times (at which point the remaining terms in the above expression were negligible.) The resulting unconditional risk profile is presented in Table 8-3 and Figure 8-3. It expresses the probability distribution of total annual losses from all carbon fiber accidents regardless of the magnitude of any individual accidents. The horizontal axis shows the total economic losses in dollars as a result of carbon fiber accidents during a given year. The vertical axis shows the annual probability of exceeding each dollar loss value. For example, the annual loss of approximately 1,000 dollars would be exceeded with a probability of 10^{-1}, in other words, once every 10 years. An annual loss of $10,000 would occur about once every 600 years. The expected annual losses due to carbon fiber released from air carrier fires in 1993 is about $467. It should be noted that this includes only those losses incurred by failures of equipment in the civilian sector.

8.5 CONFIDENCE BOUND FOR NATIONAL RISK PROFILE

Figure 8-3 also presents confidence bounds for the national annual risk profile. One of the more important issues concerning the risk profile is its statistical accuracy. For example, one may inquire about the true probability of a loss in excess of $50,000 dollars. To answer such questions we derived the confidence bound depicted in Figure 8-3.

TABLE 8-3

NATIONAL ANNUAL RISK PROFILE - 1993

Losses X	Probability That Annual Losses Exceed X
75	.57
150	.43
300	.39
500	.24
800	.16
1,500	.07
6,000	.019
10,000	.0016
70,000	.0006
100,000	3.5×10^{-4}

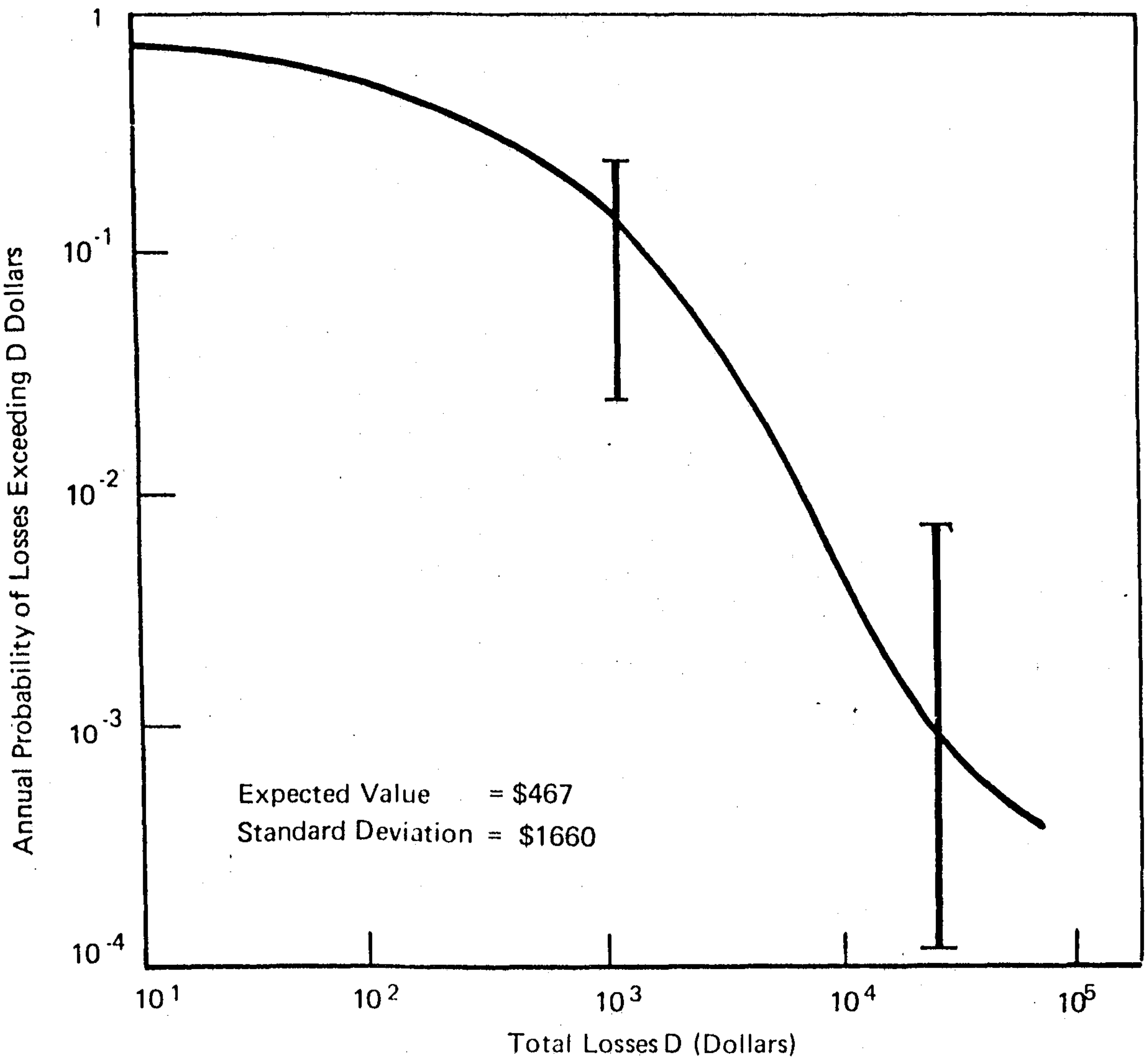


FIGURE 8-3

NATIONAL ANNUAL RISK PROFILE FOR CARBON FIBER RELEASES FROM COMMERCIAL AIR CARRIERS (1993 CF Utilization)

The possible sources of errors in generating the risk profile consist of

- Statistical accuracy of the conditional profiles

- Statistical errors in the estimates of sample parameters

- Errors in assumptions about values of constants

- Possible variability in parameters

Any errors in the various stages of the analysis will therefore impact one or both of the risk profiles. All of the above sources of errors are discussed in this section.

The first and second sources of errors represent the statistical errors in the construction of the risk profile. If the model is valid, that is if there is no variability in parameters and if there are no errors or biases in assumptions about values of constants, then a statistical confidence bound reflects all of the errors in the estimation of the national risk profile. Figure 8-2 and Table 8-2 present the statistical confidence bounds for the conditional national risk profile. Note that the error in this risk profile is small at the low and medium sections of the loss range but can be substantial at the high end of the loss range due to the low frequency of simulated accidents involving high losses. At the high end of the loss range the width of the confidence bound is still less than an order of magnitude, although this may be compounded in the annual national risk profile.

With regard to the sources of error due to statistical errors in the estimates of sample parameters, most parameter estimates are based on a large body of statistical data. For example, the number of operations used to estimate the values of P_i and the weather statistics used in development of the airport profiles are based on large numbers of observations, and hence there is generally very little error in the estimates. There is one variable, namely the estimated number of accidents per year, that has a significant impact on the annual risk profile and is subject to some uncertainty. As noted in Chapter 4, a confidence bound for the expected number of potential CF release accidents per year ranges from 75% to 130% of the estimated value. Since the estimated value is 2.7 accidents per year, the confidence range for the expected number of fire accidents per year is 2.0 to 3.5. This range could also add uncertainty at the high loss end of the annual risk profile.

With respect to the third possible source of error, the various assumptions of the model have been documented in this report. For some of these assumptions, such as constant atmospheric conditions, the impacts are unclear. Confidence bounds for many of these assumptions will necessarily be judgmental. However, for some of the constants the sensitivity analysis presented earlier in the chapter gives an indication of the relative impact of the assumption. In particular, these analyses show that even under extremely conservative assumptions, possible dollar losses will not be extremely large.

The final source of errors was the probabilistic variability of values assumed to be constant. We believe that most of the sources of such variability will not have a great impact on the annual risk profile. There is one area of variability, however, that could be significant and this deals with the random nature of the failure of events. Recall that within the simulation model, the actual number of failures in any economic loss category is assumed to be equal to the expected number of failures given the exposure distribution for the given release and the geographic distribution of facilities. In fact, the actual number of failures will be a Poisson random variable with the expectation as its mean, and this can be significant when the number of expected failures is small. To investigate the effect of this source of variability an analytic model was developed which is described in the next section.

Due to all of these sources of error, we estimated the confidence bounds as depicted in Figure 8-3. Confidence bounds are wider at the high loss values to reflect the statistical error in the conditional national risk profile discussed previously.

8.6 ANALYTIC APPROACH TO THE NATIONAL RISK PROFILE

Because of the possible sources of error using a Monte Carlo simulation approach, an alternative methodology was developed to compute the national risk profile. There are several issues involved in determining which of the two types of methodologies might be appropriate. A simulation model was appropriate for large releases which would result in large numbers of failures. In this case, the simulation model allows detailed identification of the geographic distribution of the facilities as well as the different possible accident and release conditions. The higher the number of failures, of course, the lower the relative impact of statistical fluctuations of the actual number of failures relative to the expected number of failures. As noted previously, however, the simulation approach results in statistical uncertainty at the high loss tail of the risk profile.

In an analysis of the possible economic losses resulting from carbon fiber releases from general aviation fire accidents*, it was noted that the number of failures per incident was expected to be extremely small and the dominant variation in economic losses would appear to be caused by the random failure process rather than by variations in physical conditions. In addition, there were not sufficient data available to allow detailed modelling of release and dispersion scenarios. For these reasons an analytical model was developed to analyze losses due to general aviation accidents. We then investigated the appropriateness of this model for the analysis of air carrier-related losses.

The details of the analytic model will not be presented here, but the important assumptions required are as follows:

- Exposure values are nearly always substantially lower than outside exposures to failure.

- Variations in expected number of failures due to variations in accident location within a metropolitan area, weather conditions, and all release conditions except total amount of carbon fiber

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* See reference 3, Chapter 2

released, are small compared with the variation due to the randomness of failure.

- If the second assumption is invalid then it is assumed that equipments are uniformly distributed within the metropolitan area in question.

It is shown in reference 2 of Chapter 2 that the first two assumptions are valid for releases up to several kilograms. For the case of air carrier accidents, the total amount of carbon fibers released can be as large as several hundred kilograms. However, such large releases are uncommon and even in the event of a large release the equipment categories for which the second assumption is not completely valid can be characterized by generally uniform distributions of locations. The most important example of such an equipment category is household goods.

Assuming that the assumptions of the analytic model are valid, it then follows that the number of failures conditional on an accident occurring is a Poisson random variable with a mean value directly proportional to the amount of carbon fibers released and the density of facilities, and inversely proportional to the mean outside exposure to failure. On this basis a probability distribution can be developed for the total number of failures given an accident or the total number of failures that occur nationally in a year.

In order to develop the analytic model, we used the data on probability of an explosive release, maximum percent of carbon fibers released, percentage of composite consumed, probability of each size aircraft, and distribution of total mass of carbon fibers on various aircraft in 1993. Synthesizing all of these distributions, we developed a probability distribution for total number of fibers released per accident in 1993. This distribution, which is presented in Table 8-4, also incorporates the assumption that there are 5×10^9 single fibers per kilogram of carbon fiber mass.

TABLE 8-4

APPROXIMATE PROBABILITY DISTRIBUTION
FOR NUMBER OF
FIBERS RELEASED

Number of Fibers X	Probability That Number of Fibers is Less Than or Equal to X
4×10^{7}	.0001
3.9×10^{8}	.005
1.4×10^{9}	.029
3.3×10^{9}	.069
6×10^{9}	.152
1.4×10^{10}	.242
2.2×10^{10}	.307
3.6×10^{10}	.402
4.8×10^{10}	.512
6.4×10^{10}	.637
8.9×10^{10}	.714
1.2×10^{11}	.849
1.5×10^{11}	.939
2.1×10^{11}	.989
4.1×10^{11}	.9998
1.2×10^{12}	1.0

Using the same computer program to analyze the Poisson model that was used for the general aviation analysis, we developed a probability distribution for the number of equipment failures occurring per accident (Table 8-5). Within the program, facility densities were required by county and we assumed a uniform distribution of accident locations among all the counties in each of the 26 metropolitan areas. We then converted this distribution for number of failures into a distribution for dollar losses by multipling each value of dollar loss by the average dollar loss per failure of $330. This average dollar loss per failure was also an output from the computer program that performed the Poisson analysis. Because individual dollar losses can exceed the average dollar loss, the actual national risk profile will show more variance than the risk profile that we developed in this manner. However, we believe that this excess variance is relatively small, especially at the tail end of the distribution which correspond to larger numbers of failures.

The risk profile developed in this manner is depicted in Figure 8-4 along with the profile developed from the Monte Carlo procedure. It may be seen that the two profiles are roughly comparable, with their mean values differing by only a factor of 3. The Poisson model gave an expected loss per accident of $452, which is equivalent to an annual expected loss of $1220, assuming 2.7 accidents per year involving CF releases.

TABLE 8-5

PROBABILITY DISTRIBUTION FOR NUMBER OF FAILURES PER ACCIDENT (1993) BASED ON POISSON MODEL

Number of Failures X	Probability That Number Of Failures Exceeds X
0	.28
1	.15
2	.10
3	.073
4	.057
5	.047
10	.024
15	.015
20	.011
30	.0063
50	.0027
70	.0016
90	.001
200	7.4×10^{-5}
800	6.2×10^{-7}
1000	9×10^{-9}

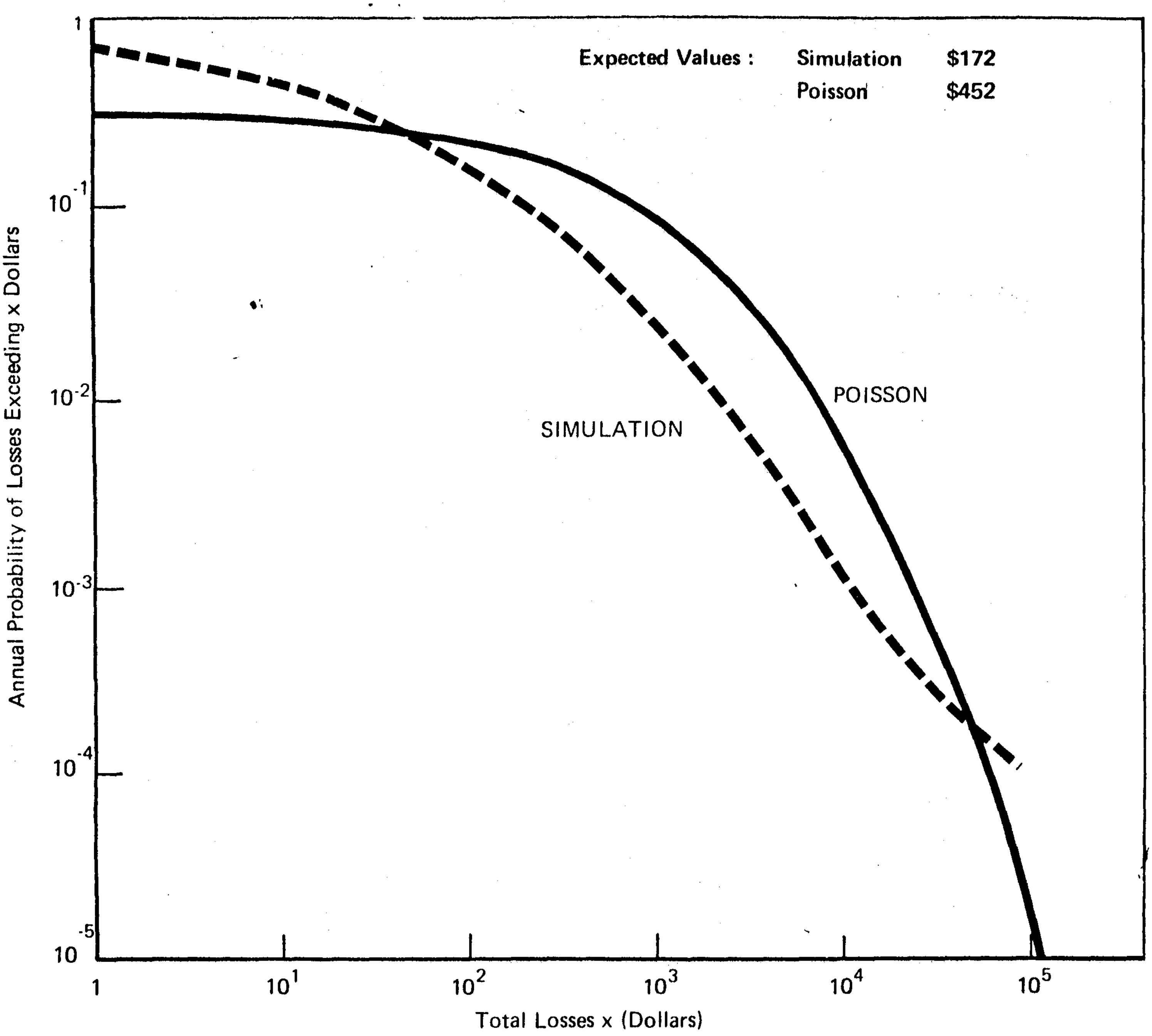

FIGURE 8-4

COMPARISON OF NATIONAL CONDITIONAL RISK PROFILE FOR POISSON AND SIMULATION MODELS

9. CONCLUSIONS

9.1 NATIONAL RISK

The results of the risk analysis described in the preceding chapters indicate that the potential economic losses due to electrical effects of carbon fibers released from commercial aircraft fires are relatively low. This is mainly due to the low probability of a significant number of equipment failures resulting from an accidental release, and the moderate costs associated with such failures. The expected national annual risk was only $467 (measured in 1977 dollars) based on an estimated 2.7 accidents with fire per year involving commercial aircraft carrying carbon fiber composites in 1993. These results, obtained by a Monte Carlo simulation approach, were verified using a simpler analytic model, which yielded expected annual losses of $1220 (or $452 per accidental fire). Thus, at least on an expected value basis, the risks due to CF usage were found to be much lower than other risks associated with the operation of commercial aircraft.

In performing a risk assessment, however, it is not sufficient to compute an expected value. One must also consider the possibility of highly unlikely events involving extremely large losses. We therefore devoted considerable attention to quantifying the probability of high-loss events which form the "tail" of the risk profile shown in Figure 8-3. It was estimated that annual losses of $10,000 would occur about once every 600 years. The maximum loss observed from any one simulated accidental release was $75,000, but it is conceivable that higher losses could occur if a large release of CF took place in a densely populated area. Confidence bounds were estimated which indicate that annual losses in excess of $75,000 would occur at most once every 100 years. This level of risk is still relatively low when one considers the frequency of natural or man-made disasters involving millions of dollars in economic losses. (See Reference 1, Chapter 2 for a further discussion of comparative risks.)

The risk analysis of CF releases from commercial aircraft incorporated a number of important assumptions which contributed to the uncertainties in the risk profile. Even with these uncertainties, the sensitivity analysis procedure was able to quantify the national risks within an order of magnitude confidence interval, except for the high-loss tail of the risk profile. major assumptions that entered into the analysis are described in the next section.

9.2 IMPORTANT ASSUMPTIONS AND UNCERTAINTIES

Certain assumptions were necessary in the risk analysis either because precise information was not available in certain areas, or because the scope of the study did not require a more exact determination. The most important of these assumptions are listed below, and the anticipated effect of each one upon the resultant risk profile is indicated. These effects fall into three categories: Conservative, implying an overestimation of risk; non-conservative, implying an underestimation of risk; and unclear, implying that no definite effect upon the risk can be expected in either direction. Most of the assumptions that were adopted are conservative, but particularly in the area of economic loss estimation there may be additional costs which were not included.

- When CF composites are exposed to fire and/or explosion, up to 2.5% of the CF mass can be released in the form of airborne fibers.
  Effect: Conservative. Experiments by NASA and other groups indicate that much lower release levels are likely.

- All CF released from a fire would be in the form of single fibers, rather than groups or clumps of fibers.
  Effect: Conservative. Single fibers will disperse farthest, and have the greatest potential for penetrating to equipment. (The one possible exception is the vulnerability of power stations to clumps of fiber.)

- All fibers released would have a length of 3 mm.
  Effect: Conservative. Shorter fibers will have less chance of damaging equipment, whereas longer fibers will not be able to penetrate vents and filters as effectively.

- Atmospheric conditions remain constant during dispersion of the carbon fiber cloud.
  Effect: Unclear. Though weather will fluctuate, the net effect on dispersion should average out over many simulation trials.

- The presence of precipitation was ignored in the dispersion analysis.
  Effect: Conservative. Precipitation would tend to wash out airborne fibers and reduce downwind exposures.

- Within a facility category, all facilities were assumed to be similar in terms of penetration properties and economic characteristics.
  Effect: Unclear. Considerable variations will exist among facilities, but these will average out when losses are aggregated over a large area.

- Equipment was assumed to be in an activated state during exposure.
  Effect: Conservative. Reactivation of equipment after exposure may produce failures, but vulnerability in such a case is most probably reduced.

- Secondary impacts of business interruption were not included in the economic loss estimate.
  Effect: Non-conservative. The shutdown of one facility may have subsequent impact upon other sectors of business or society at large (e.g., mass transit, telephone system).

- The amount of vulnerable electronic equipment was assumed to remain at current levels.
  Effect: Non-conservative. Rapid growth is expected in the electronics industry during the next decade.

- Costs associated with decontamination and precautionary procedures were not incorporated.
  Effect: Non-conservative. The cost of anticipating failures due to CF release or of preventing additional failures subsequent to a release may be significant, especially at vital installations such as airports.

APPENDIX A

SUMMARY OF ECONOMIC LOSS DATA FOR THE RISK ANALYSIS

The complete set of penetration, vulnerability, and cost data used in the economic analysis is presented in Table A-1. These data were compiled from a number of different sources. Trip memoranda were prepared describing the findings from the facilities visited during the Phase II program. In addition, information gathered for certain facilities during Phase I was reviewed and updated for incorporation into summary Table A-1. We also included in this table the economic data that were obtained by Bionetics, Inc. in their four site visits. Summary Table A-1 includes a description of the facility, a measure of the size of the facility (number of persons or employees, square footage, number of telephone lines, etc.), the Standard Industrial Classification number (SIC), and descriptions of the types and numbers of electronic and electrical control equipment found within the facilities. For each type of equipment, we have assigned a severity index for both repair and disruption, except for the facilities visited by Bionetics (see Table 6-1), since they did not make such a distinction.

The mean dosage for failure ($\bar{E}$) for each type of equipment was obtained from discussions with NASA-LRC and Bionetics personnel. The range of airborne exposure transfer functions (AETF) values were calculated from the information gathered during each site visit, and the procedure used for calculating the AETF values was summarized in the Phase I Report. (Reference 1, Chapter 2). The ranges of transfer functions are presented both for summer and winter seasons. Under some circumstances, it was necessary to consider a situation when windows and doors might be open during pleasant weather.

For the severity indices assigned to the individual equipment in each facility, there is a directly related repair and facility disruption cost. The schedule of costs for repairs is summarized in Table 6-2, and the schedule for facility costs as a result of disruption is summarized in Table 6-3. A discussion of the findings resulting from site visits to a number of typical facilities is provided in Appendix B.

TABLE A-1: Summary of Economic Data for Risk Analsyis

Data Source	Facility and Equipment Type (Scale Factor)	Level for Repair	Level for Disruption	Number of Equipment	Mean for Failure $\bar{E}$	Range of Transfer Functions Summer	Range of Transfer Functions Winter	Direct Cost Repair Each Eqpt.	Direct Cost Facility Disrupted	Remarks
County & City Data Book	1-Households					Windows Open				
	TV/Stereo	A	-	1	10^8	6×10^{-3} to 0.1		80	-	No HVAL, windows have screens
	White Goods	A	-	3	10^8	Windows closed		80	-	
	Furnace	A	-	1	10^8	0.0 to 9.6×10^{-3}		80	-	
	2-Fire & Police									
SIC 9221	2-A Large Metropolitan Police Control System (3000 persons)									
	CRT terminals	A	-	38	10^8	4.4×10^{-4} to 0.15	4.4×10^{-4} to 1.4×10^{-2}	80	-	
	Teletype machines	B	-	2	10^7	4.4×10^{-4} to 0.15	4.4×10^{-4} to 1.4×10^{-2}	250	-	
	Miscellaneous equipment	A	-	10	10^7	4.4×10^{-4} to 0.15	4.4×10^{-4} to 1.4×10^{-2}	80	-	
	Radio control console	B	-	9	10^8	4.4×10^{-4} to 0.15	4.4×10^{-4} to 1.4×10^{-2}	250	-	
	Small computer line printer	A	-	4	10^8	8.3×10^{-4} to 0.34	4.7×10^{-4} to 1.5×10^{-2}	80	-	
	Large computer	D	A	1	10^7	8.3×10^{-4} to 0.34	4.7×10^{-4} to 1.5×10^{-2}	2500	9000	
	Small computers	C	A	2	10^8	8.3×10^{-4} to 0.34	4.7×10^{-4} to 1.5×10^{-2}	800 -	9000	
	Radio transceivers in vehicles	A	-	540	10^8	0.8	0.2	80	-	All over city
	Motor generator (large)	C	A	1	10^6	1.0	1.0	800 -	9000	Seldom used, tested wkly usage factor 0.01
	PBx (small)	C	A	14	10^7	4.7×10^{-4} to 1.5×10^{-2}		800 -	9000	
	Radio transceivers	B	-	35	10^8	0.0 to 6.7×10^{-3}		250	-	Each precinct
SIC 9224	2-B Large Metropolitan Fire Control Center (20 persons)									
	Radio control consoles	A	-	5	10^8	9.7×10^{-2} to 0.3	9.7×10^{-2} to 0.3	80	-	
	PBx (small)	C	B	1	10^7	7.4×10^{-2} to 0.2	7.4×10^{-2} to 0.2	800	240	
	Motor generator (large)	C	A	1	10^6	0.3 to 1.0	0.3 to 1.0	800	80	Seldom used, tested wkly usage factor = 0.01
	Motor generator (small)	A	C	2	10^7	0.3 to 1.0	0.3 to 1.0	80	1200	
	Radio transceivers	B	-	3	10^8	5×10^{-3} to 0.2	0.0 to 9.5×10^{-3}	250	-	
	Radio transceivers in vehicles	A	-	200	10^8	0.8	0.2	80	-	All over city

TABLE A-1: Summary of Economic Data for Risk Analsyis

Data Source	Facility and Equipment Type (Scale Factor)	Level for Repair	Level for Disruption	Number of Equipment	Mean for Failure $\bar{F}$	Range of Transfer Functions: Summer	Range of Transfer Functions: Winter	Direct Cost: Repair Each Eqpt.	Direct Cost: Facility Disrupted	Remarks
SIC 9221	2-C Small Police Headquarters (10 persons)									
	Radio control console	B	-	1	10^8	8.8×10^{-5} to 0.6	8.8×10^{-5} to 1.4×10^{-2}	250	-	
	Radio transceiver	B	-	1	10^8	4.9×10^{-4} to 1.1×10^{-3}	0.0 to 1.1×10^{-3}	250	-	
	Motor generator (small)	A	B	1	10^6	0.5	0.5	80	120	Seldom used, tested wkl usage factor = 0.01
	PBx (small)	C	A	1	10^7	8.8×10^{-5} to 0.6	8.8×10^{-5} to 1.4×10^{-2}	800	30	
	Radio transceivers in vehicles	A	-	10	10^8	0.8	0.2	80	-	
SIC 9224	2-D Small Fire Headquarters (20 persons)									
	Radio control console	B	-	1	10^8	Windows Open: 6×10^{-3} to 0.1		250	60	
	PBx (small)	C	A	1	10^7	Windows Closed: 0.0 to 9.5×10^{-3}		800	60	
	Radio transceivers	B	-	1	10^8	4.9×10^{-4} to 1.1×10^{-3}	0.0 to 1.1×10^{-3}	250	-	
	Radio transcievers in vehicles	A	-	10	10^8	0.8	0.2	80	-	All over city
	Motor generator (small)	A	B	1	10^6	0.5	0.5	80	240	Seldom used, tested wkl usage factor = 0.01
	3-Post Office (Major sorting area, cities > 10^6 people)									
	Sorter without optical character reader	C	-	11	10^7	4.3×10^{-4} to 3.9×10^{-2}		800	-	
	Sorter with optical character reader	C	-	1	10^7	4.3×10^{-4} to 3.9×10^{-2}		800	-	
SIC 401, Am Publ. Transit Association	4A-Subway									
	Radio	A	-	190	10^8	1×10^{-2} to 0.8		80	-	
	Drive Motors									
	Schedule System (computer-small)	C	-	1	10^7	4.3×10^{-4} to 7×10^{-2}		800	-	
	Auto fare coll.	B	-	3	10^7	1.2×10^{-2} to 0.6		250	-	
	PBx (small)	A	-	1	10^7	4.3×10^{-4} to 7×10^{-2}		800	-	

TABLE A-1: Summary of Economic Data for Risk Analsyis

Data Source	Facility and Equipment Type (Scale Factor)	Level for Repair	Level for Disruption	Number of Equipment	Mean for Failure E	Range of Transfer Functions Summer	Range of Transfer Functions Winter	Direct Cost Repair Each Eqpt.	Direct Cost Facility Disrupted	Remarks
SIC 401	4-B Railroad									
	CRT terminals	A	-	12	10^8	2.4×10^{-3} to 2.3×10^{-2}		80	-	
	Radio control console	B	-	3	10^8	2.4×10^{-3} to 2.3×10^{-2}		250	-	
	Transceivers	B	-	3	10^8	2.4×10^{-3} to 2.3×10^{-2}		250	-	
	PBx (small)	C	-	1	10^7	7.0×10^{-3} to 3.0×10^{-2}		800	-	
	Mobile transceivers	A	-	20	10^8	7.0×10^{-3} to 0.5		80	-	Not vulnerable on trains
SIC 3714	5-Manufacturer of Electronic and Mechanical Equipment									
	Transformer substation switch	(Critical)		2	10^8	1.6×10^{-2}		65,800		
	Control circuit in process streams	(Disruptive)		1	10^8	4×10^{-5}		2,800		
	" " " " "	"		1	10^8	5×10^{-4}		500		
	" " " " "	"		1	10^8	3×10^{-4}		500		
	" " " " "	"		1	10^8	3×10^{-4}		500		
	" " " " "	"		1	10^8	2×10^{-5}		500		
	" " " " "	"		1	10^8	6×10^{-4}		300		
	" " " " "	"		1	10^8	6×10^{-4}		52,700		
	" " " " "	"		1	10^8	8×10^{-4}		300		
	" " " " "	"		1	10^8	2×10^{-3}		10,000		
	" " " " "	"		1	10^8	2×10^{-3}		5,000		
	PBx (small)	(Repair)		1	10^7	5×10^{-4}		800		
SIC 2824	6-General Manufacturers									
	6-A Organic Fibers, Non-Cellulosic									
	Transformer switch or direct 'eaker	(Disruptive)		6	10^8	1×10^{-3}		93,000		
	" " " " "	"		1	10^8	1×10^{-3}		98,000		
	" " " " "	"		1	10^8	1×10^{-3}		41,000		
	Variable frequency controller	"		6	10^6	1×10^{-3}		15,200		
	Motors and controller - chemical	"		24	10^7	1×10^{-3}		28,400		-
	Hydraulic power unit controller	"		6	10^7	5×10^{-4}		6,600		
	Temperature controller	"		60	10^8	5×10^{-4}		3,400		
	Reference cells	"		24	10^7	5×10^{-5}		6,700		
	Chemical control	"		36	10^7	5×10^{-4}		5,300		
	Digital speed control	"		2	10^6	5×10^{-4}		1,700		
	PBx	(Repair)		1	10^7	1×10^{-3}		800		

TABLE A-1: Summary of Economic Data for Risk Analysis

Data Source	Facility and Equipment Type (Scale Factor)	Level for Repair	Level for Disruption	Number of Equipment	Mean for Failure $\bar{E}$	Range of Transfer Functions Summer	Range of Transfer Functions Winter	Direct Cost Repair Each Eqpt.	Direct Cost Facility Disrupted	Remarks
SIC 3651	General Manf-(cont'd)									
	6-B Manufacturers of Electronic Equipment Television Receivers									
	Master oscillator controllers			1	10^6	7×10^{-3}		16,360		
	Incoming inspection test equipment			3	10^6	7×10^{-3}		6,330		
	Small computer			2	10^7	8×10^{-3}		940		
	Assembly line signal interconnect			14	10^7	4×10^{-2}		30		
	Injection mold temp. and pressure controllers			20	10^7	2×10^{-2}		1,800		
	Encapsulation controller			1	10^8	2×10^{-3}		1,040		
	Transformer switch or circuit breaker			16	10^8	6×10^{-5}		26,200		
	In-process-plaster parts contamination			1	10^6	5×10^{-2}		2,420		
	-spray paint contamination			1	10^6	8×10^{-2}		3,760		
	-electronic component contamination			3500	10^6	4×10^{-3}		1.10		
	-burn in			3500	10^6	4×10^{-3}		1.00		
	-life test			100	10^7	3×10^{-3}		250		
	PBx system (small)			1	10^7	1×10^{-3}		800		
	Embossing temp. and press controllers			20	10^7	6×10^{-4}		230		
SIC 2844	6-C Toilet Preparations (600 employees)									
	Fork lift trucks	A	-	10	10^6	0.0 to 0.12		80		
	Battery charger for trucks	A	-	10	10^6	0.0 to 0.12		80		
	Programmable palletizer	B	-	1	10^7	0.0 to 0.12		250		
	Transformer substation		C	3	10^8	0.0 to 6×10^{-3}		32,000	36,000	
	Injection mold heater controls	A	-	24	10^6	0.0 to 6×10^{-3}		80		
	Quality control instruments	B	-	20	10^7	0.0 to 6×10^{-3}		250		
	Computer facility (small)	C	-	1	10^7	0.0 to 6×10^{-3}		800		
	PBx (small)	C	-	1	10^7	0.0 to 6×10^{-3}		800		

TABLE A-1: Summary of Economic Data for Risk Analsyis

Data Source	Facility and Equipment Type (Scale Factor)	Level for Repair	Level for Disruption	Number of Equipment	Mean for Failure E	Range of Transfer Functions Summer	Range of Transfer Functions Winter	Direct Cost Repair Each Eqpt.	Direct Cost Facility Disrupted	Remarks
SIC 481	7-Telephone Services									
	7-A Large Telephone Switching Centers (200,000 lines)									
	Main switching center	E	-	2	10^7	0.0 to	7.4×10^{-3}	13,000	-	
	Dedicated telephone system	C	-	1	10^7	0.0 to	7.4×10^{-3}	800	-	
	Microwave link	C	-	1	10^8	0.0 to	7.4×10^{-3}	800	-	
SIC 481	7-B Small Telephone Switching Centers									
	Tel. PBx	E	-	1	10^7	0.0 to	7.4×10^{-3}	1,300	-	
SIC 483	8-Radio/TV									
	Studio equipment	C	-	1	10^7	0.0 to	5.0×10^{-2}	800	-	
	Transformer and transmitter	C	-	1	10^7	0.0 to	5.0×10^{-2}	800	-	
	Mobile mini-camera	D	-	3	10^7	5.0×10^{-2} to	1.0	2,500	-	
	Control room	D	-	1	10^7	0.0 to	5.0×10^{-2}	2,500	-	
	PBx (small)	C	-	1	10^7	0.0 to	5.0×10^{-2}	800	-	
SIC 491	9-Electric Utility (185 Employees)									
	Control room	C	-	2	10^7	0.0 to	1.2×10^{-3}	800	-	
	Control computer (small)	C	-	1	10^8	0.0 to	1.0×10^{-3}	800	-	
SIC 531, 56, 57, 59	10-General Merchandise Retailers									
	10-A Main Store (1000 Employees; 656,000 ft^2)									
SIC 531	POS terminals	B	-	200	10^8	6×10^{-3} to	2×10^{-2}	250	-	
	Computer (large)	D	-	1	10^8	0.0 to	2×10^{-4}	2,500	-	
	HVAC controls	A	-	4	10^8	6×10^{-3} to	2×10^{-2}	80	-	
	PBx (small)	C	-	1	10^7	6×10^{-3} to	2×10^{-2}	800	-	
	Motor generators (large)	C	-	2	10^6	0.1 to	1.0	800	-	Seldom used, tested weekly factor = 0.01

TABLE A-1: Summary of Economic Data for Risk Analsyis

Data Source	Facility and Equipment Type (Scale Factor)	Level for Repair	Level for Disruption	Number of Equipment	Mean for Failure F	Range of Transfer Functions (Summer – Winter)	Direct Cost: Repair Each Eqpt.	Direct Cost: Facility Disrupted	Remarks
SIC 531	10-B Branch Store (250 Employees, 120,000 ft^2)								
	POS terminals	B	-	130	10^8	0.0 to 3×10^{-3}	250	-	
	Computer (small)	C	-	1	10^8	0.0 to 3×10^{-3}	800	-	
	Motor generators (large)	C	-	2	10^6	0.1 to 1.0	800	-	Seldom used, tested weekly, factor = 0.01
	HVAC controls	A	-	2	10^8	0.0 to 3×10^{-3}	80	-	
	PBx (small)	C	-	1	10^7	0.0 to 3×10^{-3}	800	-	
SIC 541	10-C Retail Grocers								
	POS terminals	B	-	12	10^8	9.4×10^{-5} to 0.1	250	-	
	HVAC controls	A	-	2	10^8	9.4×10^{-5} to 0.1	80	-	
SIC 602, 621, 63	11-Finance and Insurance								
	11-A Brokerage House (100 persons)								
SIC 621	Computer (small)	C	C	5	10^8	0.0 to 1.0×10^{-4}	800	6,000	
	Computer (small)	C	-	1	10^8	0.0 to 6.0×10^{-3}	800	-	
	CRT & Keyboard display	B	-	37	10^8	1.3×10^{-4} to 1.0×10^{-2}	250	-	
	PBx	C	-	1	10^7	0.0 to 6.0×10^{-3}	800	-	
	General Office Equipment	A	-	50	10^8	1.3×10^{-4} to 1.0×10^{-2}	80	-	
SIC 737	11-B Computer Services (100 persons)								
	Computer (large)	D	C	1	10^8	0.0 to 7.0×10^{-2}	2,500	6,000	
	General Office Equipment	A	-	100	10^8	4.0×10^{-4} to 7.0×10^{-2}	80	-	
	PBx (small)	C	-	1	10^7	4.0×10^{-4} to 7.0×10^{-2}	800	-	
	12-R&D, Universities								
	Instruments	A	-	100	10	0.0 to 6×10^{-3}	80	-	
	PBx (small)	C	-	1	10	0.0 to 6×10^{-3}	800	-	

TABLE A-1: Summary of Economic Data for Risk Analsyis

Data Source	Facility and Equipment Type (Scale Factor)	Level for Repair	Level for Disruption	Number of Equipment	Mean for Failure E	Range of Transfer Functions Summer	Range of Transfer Functions Winter	Direct Cost Repair Each Eqpt.	Direct Cost Facility Disrupted	Remarks
	13-Hospitals									
	PBx	C	-	1	10^7	0.0 to 6.6×10^{-3}		800	-	
	Generator (large)	C	-	1	10^6	0.2 when running		800	-	Seldom used, tested weekly, usage factor 0.01
	X-Ray	C	-	6	10^7	0.0 to 3.3×10^{-3}		800	-	
	Gen. Instr. in Patient Area	B	-	200	10^7	Windows open 2.8×10^{-3} to 5.6×10^{-2}		250	-	
						Windows closed 0.0 to 6.6×10^{-3}		250	-	
	Gen. Instr. Operating Room	B	-	50	10^7	0.0 to 3.5×10^{-4}		250	-	
SIC 3711	14-Automotive Assembly									
	14-A Automobile Assembly (4000 Empl.)									
	Computer system (large)	C	A	1	10^7	1.5×10^{-3} to 1.5×10^{-2}		800	12,000	
	Programmable automotive welders	C	A	2	10^7	6.4×10^{-2} to 0.14		800	12,000	
	Spray paint drying tunnel	A	A	1	10^1	0.0 to 3.5×10^{-4}		80	12,000	
	Assembly line controllers	C	A	2	10^7	6.4×10^{-2} to 0.14		800	12,000	
	Transformers & switchers		B	8	10^8	1.5×10^{-4} to 1×10^{-2}		32,000	48,000	
	PBx (small)	C	-		10^7	1.5×10^{-3} to 1.5×10^{-2}		800		
SIC 3711	14-B Truck Assembly									
	Transformer switches	(Critical)		9	10^8	1×10^{-3}		430,000		
	Transformer circuit & breaker	"		9	10^8	1×10^{-4}		42,000		
	110 v. auxillary transformer	(Repair)		12	10^8	5×10^{-3}		6,800		
	Spot welder controls	"		50	10^6	3×10^{-1}		1,700		
	Welder controls	"		2	10^6	2×10^{-2}		1,900		
	Teletype printer controls	"		15	10^7	2×10^{-5}		900		
	Electronic harness contr. tester	"		1	10^8	1×10^{-2}		1,700		
	Electrostatic paint controller	"		8	10^8	1×10^{-4}		1,700		
	PBx (small)	"		1	10^7	1×10^{-2}		800		
	Automatic welder controls	"		2	10^7	2×10^{-5}		42,000		

TABLE A-1: Summary of Economic Data for Risk Analsyis

Data Source	Facility and Equipment Type (Scale Factor)	Level for Repair	Level for Disruption	Number of Equipment	Mean for Failure F	Range of Transfer Functions Summer	Range of Transfer Functions Winter	Direct Cost Repair Each Eqpt.	Direct Cost Facility Disrupted	Remarks
	15-Aviation									
	15-A Aircraft					Doors closed (95%)				
	Cabin Inst.	C	-	20	10^8	0.0 to 9×10^{-4}		800		
	Avionics	D	-	40	10^8	Doors opened (5%) 0.16 to 0.68		2,500		
	15-B Control Tower @ Airport									
	Computer (small)	C	-	1	10^7	0.0 to 6.5×10^{-3}		800		
	Radios	B	-	10	10^8	0.0 to 6.5×10^{-3}		250		
	Consoles	B	-	10	10^7	0.0 to 6.5×10^{-3}		250		
	CRT	A	-	10	10^8	0.0 to 6.5×10^{-3}		80		
	15-C Passenger Terminal @ Airport									
	X-Ray	C	-	14	10^8	0.0 to 1.0×10^{-2}		800		
	TTY	B	-	89	10^7	0.0 to 1.0×10^{-2}		250		
	Printers	A	-	30	10^8	0.0 to 1.0×10^{-2}		80		
	CRT	A	-	48	10^8	0.0 to 1.0×10^{-2}		80		
	15-D ASR-Field Radar at Airports									
	ASR	D	-	1	10^7	0.0 to 1.0×10^{-2}		2,500		
	LOC at Airport									
	LOC	D	-	3	10^8	0.0 to 1.0×10^{-2}		2,500		
	VOR at Airport									
	VOR	D	-	1	10^8	0.0 to 1.0×10^{-2}		2,500		

APPENDIX B

VULNERABILITY OF MAJOR FACILITY CATEGORIES

B.1 MANUFACTURING

- Manufacturer of Electronic and Mechanical Equipment

  For this manufacturer, surveyed by Bionetics, Inc., of printed circuit electronic control units, automotive fuel injectors, and automotive air injection pumps, the two main power transformers were considered critically vulnerable to carbon fibers. Loss of either transformer would cause disruption in production that could not readily be made up, some product loss, and considerable repair and/or replacement costs. Key control circuit elements in the process streams in this plant could be disruptive should they become infested with carbon fibers. The specific circuits, should they fail, would result in widely varying costs for disruption depending upon the equipment affected, the complexity and value of the product, and the replacement and/or repair costs. The facility telephone system was vulnerable.

- Manufacturer of Organic Fibers

  This facility, surveyed by Bionetics, Inc., contained a continuous flow process for manufacture of carpet fibers that would be extremely expensive in terms of manufacturing disruption and cleanup should the plant power be disrupted or key control elements damaged by carbon fibers. Eight enclosed transformer switches and/or circuit breakers were found to have high potential for losses but only at extremely high carbon fiber exposures. Process controls located throughout the plant were identified which had potential for disruption of production or loss of product, and would require substantial repair and/or replacement costs. Some of the equipment had low values for $\bar{E}$ and relatively high transfer functions which would indicate that the facility is vulnerable to carbon fiber exposures.

- <u>Manufacturer of Television Receivers</u>

  This facility, visited by Bionetics, Inc. contained the assembly line for a full range of domestic black and white and color television receivers. The sixteen main transformer switches and circuit breakers had a high potential for disrupting the production at considerable cost, but had an extremely high $\bar{E}$ and a very low transfer function, which combined to require an extremely high exposure before losses could be expected. Although there were a large number of in-process manufactured items that were vulnerable to contamination by carbon fibers, the repair costs per unit were very low. Several key pieces of calibration and test electronic equipment were found which had low $\bar{E}$ but were located within carefully controlled environmental areas with low transfer functions. The factory telephone system was found vulnerable to carbon fiber exposure.

- <u>Manufacturer of Toilet Preparations</u>

  This modern formulation and packaging factory contained almost 100% explosion proof electrical control equipment in the product filling areas, and a superior air filtration system throughout the factory (with the exception of the warehouse) that made the whole facility virtually impervious to carbon fiber exposures. A programmable automatic box palletizer located in the unfiltered air of the warehouse was considered slightly vulnerable but the repair costs were minimal.

- <u>Automobile Assembly Plant</u>

  The facility visited employed approximately 4,000 persons and received in bulk all of the components required for assembly of large domestic automobiles. No manufacturing of components is done in the plant. The large computer system used for scheduling the details of how each automobile is assembled and for handling all of the production scheduling and paper work associated with such a large assembly plant, was vulnerable to carbon fibers. A similar computer located at another facility within the same city was available for back-up. Facility disruption costs would be expected as well as diagnostic and repair costs. The programmable automatic spot welders for assembling body panels were vulnerable. The spray paint drying tunnel would be vulnerable if any carbon fibers could get past a triple air filtration system of very high quality. The paint on as many as 12 automobiles could be damaged by an instantaneous infestation by fibers. Each unit would then have to be individually spot repaired in order to complete final inspection. The assembly line speed controllers, located in sealed cabinets are critical to the operation of the assembly line and productivity would be lost during a prolonged outage. However, outages from a few minutes to several hours are experienced regularly. Eight transformers and switches located throughout the plant are critical to the operation and facility disruption cost can be expected as well as sizeable repair costs for carbon fiber damages. However, as with all transformers and switch gear, the $\bar{E}$ for this equipment is extremely high and the probability of loss is extremely low. As with most organizations, the telephone system was vulnerable.

- Truck Assembly Plant

  This facility, visited by Bionetics, Inc., assembles light duty full sized pick-up trucks for one of the major U.S. manufacturers. The nine main transformer switches and circuit breakers are critical to the plant operation, and loss of individual units will result in very high disruption costs associated with loss of production, loss of wages, and diagnostic and repair costs. This equipment, although not particularly vulnerable to carbon fibers, was enclosed and provided good year round protection against infestation. The automatic welder controls for body panel assembly appeared to be vulnerable but were located within an area where the transfer function for carbon fibers was extremely low, implying low probability of failure. A variety of other equipment including spot welders, welder controls, a teletype printer, electronic harness continuity testers and the electrostatic paint spray control would all be subject to interruption with carbon fibers and had identifiable facility disruption and diagnostic and repair costs. Some of the equipment such as welder controls had low $\bar{E}$'s and were not very well protected against dirt and carbon fiber infestation. The probability of this equipment failing was high, but back-up units were available both on the line and in the repair shops, principally because normal failure rates for this equipment is high. Loss of the equipment would result in diagnostic and repair costs with minimal loss of productivity.

B.2 TRANSPORTATION AND COMMUNICATION

- Post Offices

  Major post office sorting centers have two types of mini-computer-controlled letter sorters: optical character readers and more conventional visual-read sorting machines. Failure of equipment for a short period of time would result in delayed service but no revenue loss or cost increases of any significance. Therefore, only repair costs were considered for this category.

- Subway, Railroads

  The vulnerability of a subway system depends upon whether it is a "new" system (constructed in the 1970s or later) or an older system. New systems like the BART system in San Francisco, the WMATA in Washington, D.C., or the MARTA system in Atlanta, all rely upon sophisticated electronic control equipment for operation of the system and the individual cars. Great reliance is placed upon a central computer for controlling and scheduling the various trains. Such systems will be at higher risk potential as a result of carbon fiber exposure. Disruptive losses of service can be expected and some loss of revenue will occur, especially if emergency backup systems cannot be brought into action and if manual control of trains and systems cannot be activated. Repair costs will be high.

Subway, Railroads - Continued
However, most subway systems are much older, and have manually operated trains with simple basic control systems that are virtually immune to dirt and thus to carbon fibers. The computer systems in both new and old subway systems are usually maintained in modern clean facilities where care is taken to protect the equipment from dirt and dust.

The rolling stock of railroads, whether diesel or electrified, is virtually invulnerable to carbon fibers. Modern diesel locomotives derive the cooling air for all of the electronic controls from the well-filtered air that feeds the diesel engines. Miscellaneous two-way radio control systems are used for direct communication with trains both on the road and in the yard. These systems have proven low vulnerability to carbon fibers. The railroad signal control system (the block system) is almost impervious to carbon fibers and, should a failure occur, would simply cause minor schedule delays on all but the most heavily travelled corridors. Repair costs would be low, especially when compared with the annual budget of the signal and communication department of most railroads.

All of the telephone equipment, especially the switching control rooms, are vulnerable to carbon fibers. Some disruption in service can be expected and repair costs (to be charged against the telephone company and not against the specific business establishment) are expected.

- Large Telephone Switching Centers (200,000 lines) and Small Telephone Switching Centers

For all of the centralized telephone systems, the switching equipment is vulnerable to both single and multiple carbon fibers. Infestation will cause widely scattered disruption in service that is characterized by the inability of a

Large and Small Telephone Switching Centers -Continued circuit to complete a call. Alternative circuits may come into action or the customer may simply be diverted until an alternative circuit can be found. Costs associated with disruption will be for diagnosing and cleaning the contacts on relays and multiple-pin junction boxes.

- Radio/Television

  In this industry, the studio equipment, the control room, the mobile mini-cameras and the main transmitter are all vulnerable to carbon fibers. The studio equipment, the transmitter and the control room are all located within fully air conditioned areas, where exposure to fibers is expected to be low. The mobile equipment is subject to heavy exposure when in use. In the event of facility disruption, back-up equipment can be used and there is no loss in revenue. Costs are associated with the diagnosis and repair of individual equipment when exposed.

B.3 GENERAL MERCHANDISE RETAILERS

- Major Department Store

  In the modern facility that was visited, there were approximately 200 point of sale (POS) terminals that were considered vulnerable to carbon fibers. These units were connected to a large computer that keeps track of individual sales, the merchandise sold, the inventory, and a host of other information required for operating such businesses. The loss of individual POS terminals was not considered disruptive but would only cause some loss of efficiency. Multiple POS terminals in each department could be used in the event that one is out of action. A number of back-up units were maintained in the repair shop. The computer was located in an environmentally controlled room where exposure to carbon fibers was extremely low. The HVAC controls and the telephone system

Major Department Store - Continued

were considered vulnerable but they are both enclosed within fully air conditioned and filtered areas within the building. The probability of significant disruption of a main store by carbon fiber infestation is very low.

- Branch Store

  A branch store of the main store located in a suburban setting also had a low probability for disruption by carbon fibers. In the event of carbon fiber infestation, some repair costs might be expected.

- Retail Grocers

  Retail grocery stores also have point of sale terminals and HVAC controls. Normally they do not have a centralized computer. Some POS terminals now have automatic equipment for reading the universal product identification code and automatic computation of the bill. Loss of individual POS terminals would result in delay at check-out but no significant disruption in productivity or loss of revenue. Costs for carbon fiber infestation would be restricted to the diagnosis and repair of equipment.

B.4 FINANCE AND INSURANCE

- Brokerage House

  The facility visited was a branch office of a large national company with a staff of about 100 persons. The office contained two small computers. One critical to the operation contained the account information for local patrons. Loss of this computer would disrupt activities in the local area and make it difficult for brokers to rapidly review the content of clients accounts. Brokers could still place orders through a keyboard terminal that is directly connected to the New York office. Several back-up terminals were available for

Brokerage House - Continued

overload or breakdown. Each pair of brokers had a keyboard and CRT display for access to the computer. These terminals are critical to the operation. However, loss of individual units due to carbon fibers could be handled by doubling up on the remaining units. Several spare units were available at unoccupied desks and others were readily available through an outside service organization.

The telephone system is vital to the operation of a brokerage house and it is maintained by the local telephone company. All of the telephone equipment was judged vulnerable to carbon fibers. Much of the switching equipment was located in out-of-the-way rooms that were part of the building structure where the brokerage house is located. In the event of carbon fiber infestation of the computer, facility disruption costs can be expected. All other carbon fiber damage would simply reduce the efficiency of the office slightly and would result in costs for diagnosis and repair of equipment.

- Computer Services

As in the case of the brokerage house, computer service companies usually have one large computer that is critical to their operation and unscheduled loss of the computer for periods longer than a few hours can be disruptive to the operation. Both disruption and diagnosis and repair costs could be expected. General office equipment and the telephone equipment are also vulnerable to carbon fibers and they would require diagnosis and repair costs.

B.5 PUBLIC SERVICES

- Electric Utility

A major generating station for a metropolitan electric utility was visited. All of the outside transformer and switch gear

Electric Utility - Continued

were judged invulnerable to all but yard-long strands of carbon fibers. The control room for the boilers and the turbine generators in each unit of the generating station contained a large number of electronic, electro-pneumatic and mechanical control circuits and read-out devices whose disruption by carbon fibers would require that the operators switch to other back-up control systems for maintaining service. Affected equipment could either be repaired on the spot or replaced with standby units from the instrument repair shop. A small control computer was used as a supplement for controlling the operation. The whole facility appeared to be almost insensitive to carbon fiber infestation.

- Electronic R&D Labs, Universities, Colleges

  In these institutions, scientific and support-type instrumentation was judged to be vulnerable. However, since these organizations are not profit-oriented and the pace of activities is often moderate, equipment failures would lead at worse to activity delays. Thus, only diagnostic and repair costs can be expected for equipment in these facilities.

- Hospitals

  Several categories of support equipment were included for hospitals. While in rare instances some combinations of equipment failures would put human life at risk, probabilities of such occurrences could not clearly be identified because of various back-up procedures. Similarly, increases in direct cost resulting from failure could not be clearly identified. Therefore, only the diagnostic and repair costs were included in the economic analysis.

- <u>Fire and Police Services</u>

  A distinction was made within this category between large metropolitan police control systems and small police headquarters, and between large metropolitan fire control centers and small town fire headquarters. The major distinction between large and small police control centers are that the large police control centers use computers, both large and small, for storage and manipulation of critical information and for monitoring the activities of the various precinct stations located throughout a city. CRT terminals and displays are used extensively as input/output modules for these computers. Multiple radio control consoles are used for communication with various precincts and with individual patrol cars. A large PBX telephone exchange is a key element that is vulnerable to carbon fibers.

  In smaller police stations, all activities are monitored by a single police dispatcher who will utilize one or two radio control consoles and remotely located radio transceivers. The telephone equipment is limited to a few trunk lines. Disruptions in the service of both large and small police stations occur if the telephone system is interrupted, or if their emergency standby generators are not operational when there is a need for them (this is a very rare occurrence). For large metropolitan police departments, disruptions will occur if any of the computer systems become inoperable.

  Large metropolitan fire control centers and small town fire headquarters are not particularly vulnerable to communication system failures because there are three separate channels for communication, 1) the hard-wired fire alarm system which was judged to be invulnerable to carbon fibers, 2) the public telephone system, and 3) the fire and police radio communication networks. The telephone system is by far the most vulnerable of these three communication links and, minor service disruptions can be expected.

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16. Abstract

The risks associated with electrical effects arising from carbon fibers released from commercial aviation aircraft fires were estimated for 1993. The expected annual losses were estimated to be about $470 (1977 dollars) in 1993. The chances of total losses from electrical effects exceeding $100,000 (1977 dollars) in 1993 were established to be about one in ten thousand.

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