AN ASSESSMENT OF NATIONAL RISK

Arthur D. Little, Inc.

General Concepts and Overall Approach

Ashok Kalelkar

Our presentation reports on the analysis of risk presented by carbon fiber utilization in commercial aviation. At the outset, I would like you to note two things. First, although several speakers yesterday alluded to the entire civil aviation activity, today we are reporting only on one portion of the civil aviation activity, namely, commercial aviation. Second, this is a status report and some of the things that we will be presenting today may change somewhat as our study progresses. As shown in Figure 1, we have a three part presentation: Part I - General Concepts and Part 2 - Overall Approach, which I'm going to discuss; and Part three (which requires a majority of the time allocated to us) Risk Evaluation and Perspective, which will be presented by Dr. Fiksel. The last part of our presentation, which Dr. Fiksel will give, will show national risk profiles for carbon fiber usage in commercial aviation.

THREE PART PRESENTATION

1. GENERAL CONCEPTS
2. OVERALL APPROACH TO CARBON FIBER COMPOSITE RISK ANALYSIS
3. RISK EVALUATION AND PERSPECTIVE

Figure 1

General Concepts

Risk profiles are a very good way of expressing risks, especially where complicated mathematical models are involved. They express a risk in a relatively easy way and allow decision makers, who may not be interested in the detailed modeling, to make decisions based on what they see graphically. However, risk profiles can also be misinterpreted just as easily. I want to be absolutely certain that our results are not misinterpreted and in order to make sure of that, I'm going to take ten minutes to discuss certain general concepts.

Some of you may already be quite familiar with risk analysis and the concepts inherent in such analysis and for you this discussion may be repetitious. However, I think it is worthwhile because you will understand and appreciate our output better if you understand our terminology and objectives.

Now to begin with, I'd like in Figure 2 to very quickly define risk as we have used it in our analysis. Risk is the potential for realization of unwanted negative consequences of an event or an activity. Today, the event or activity of concern to us is the use of carbon fiber composites in commercial aircraft. The negative consequences, of course, were discussed yesterday. The fact that fibers can be released and can cause negative impacts

GENERAL CONCEPTS

DEFINITION OF RISK

RISK IS THE POTENTIAL FOR REALIZATION

OF UNWANTED, NEGATIVE CONSEQUENCES

OF AN EVENT OR ACTIVITY

Figure 2

on electronic equipment is well known. The question must be asked "What is the potential for realization or the likelihood of occurrence of those negative consequences?" As you can see, risk, as we have defined it, has two very definite components. There are probabilistic components, which deal with the likelihood of occurrence of various events, and deterministic components that deal with the actual level of impact that may be experienced. It is very important to keep in mind that "risk", as we use the term throughout our presentation, has these two components. It is meaningless to talk of risk only in terms of probability of occurrence or only in terms of the amount of damage that can occur. The two go hand in hand and are inseparable.

Now, as I'm sure you've gathered from the many presentations that were given yesterday, the use of carbon fiber composites in commercial aircraft does involve some risks. Where there are some risks there is need for an appropriate way of handling those risks through risk management as shown in Figure 3. In this particular case, the Federal Government is essentially placed in the role of being risk manager. A rational way of conducting risk management activities is by going through the three-step process shown: of, first, identifying the risk (again keep in mind the two components of risk); then measuring it quantitatively (it is very important to do it quantitatively); and finally by looking at the measured value to determine if control strategies are required or not, by

DEALING WITH RISK THROUGH RISK MANAGEMENT

RISK IDENTIFICATION

RISK MEASUREMENT

RISK CONTROL

Figure 3

comparing the measured risk against other risks and comparing the benefits to be derived by the use of the CF material against the risks that have been measured.

I don't think it necessary to spend much time discussing risk identification, the first step in the three-step process. Several speakers addressed different areas that deal with the risk associated with the use of carbon fiber composites in aircraft. There's been some past experience. There was an accident of sorts involving an incinerator. There's been substantial experimentation and dissemination testing, with actual burning of composite structures to see how much fiber can be liberated under different fire conditions, and studies of the effects of burns and explosions, of burns alone, and so on. The risk of the problem that we are looking at today has been pretty well identified in terms of the areas identified in Figure 4. There aren't too many unknowns in terms of conceptual identification of what can happen, what different consequences can result and the probabilistic pathways leading to what those consequences might be. In some cases where a certain piece of equipment may not have been properly tested, it is useful to use industrial experience-based judgement, engineering judgement, guesses if you will, to try to assess how things are going to fail, so their failure can be incorporated within the risk analysis. The risk identification step in this risk management scheme has, I believe, been quite well completed.

RISK IDENTIFICATION

- PAST EXPERIENCE – DIRECT OR RELATED
- EXPERIMENTATION
- INDUSTRIAL EXPERIENCE - BASED JUDGEMENT

Figure 4

The next step then is to measure the risk quantitatively as described in Figure 5. This requires that we assess the frequency

RISK MEASUREMENT

- FREQUENCY OF OCCURRENCE OF FAILURE EVENT
- CONDITIONAL OCCURRENCE OF SUBSEQUENT EVENTS
- CONSEQUENCES OF THE EVENT IN TERMS OF TOTAL IMPACT

Figure 5

of the occurrence of the failure event of concern. In our case this is an accident involving an aircraft that has carbon fiber composite structures on it and that is involved in either a fire or a fire followed by an explosion. This frequency can be assessed by looking at historical data on accidents and operations. Once that particular step has been completed, there are several conditional occurrences of subsequent events which must be examined. Given that the fiber is involved in a fire in the aftermath of an aircraft accident, what are the chances that it will be released? What are the chances that there will be wind blowing from a certain direction to carry the fiber a certain way? What are the chances that there will be certain classes of industrial facilities in its path? And so on. Finally, we need to assess deterministically the consequences of the event in terms of total impact. As Dr. Credeùr pointed out in her presentation, impacts can vary across a wide spectrum, depending on your interests. We're not that concerned about fatalities or environmental damage or chronic health problems today; we're more concerned with total dollar loss as a result of one of these occurrences.

In Figure 6 I'm going to show how the measured risk can be displayed. Now this is hypothetical, so please, these numbers

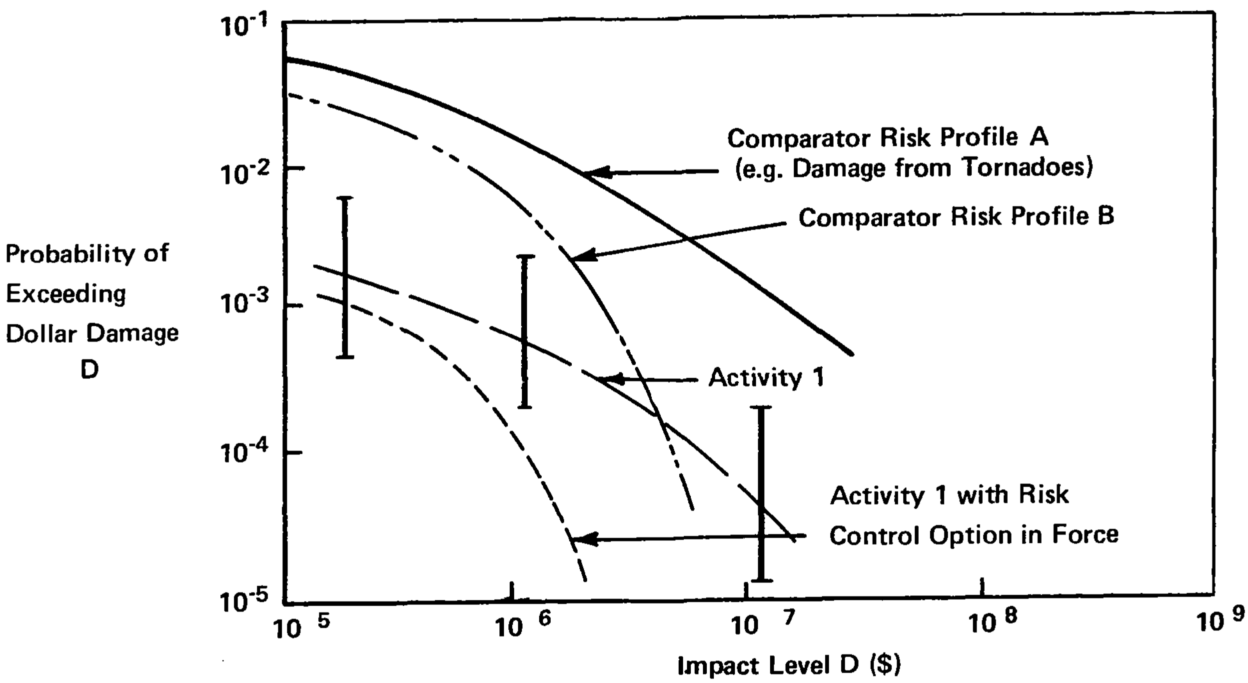


Figure 6

have no bearing on the presentation. I just want to use this for demonstration purposes, because I want to point out five or six things. First, look at Activity One. Suppose Activity One is an activity of concern to us and we evaluate it through our risk analysis scheme and we measure the risk. The measured risk would be portrayed in a fashion as shown depicting the probability of exceeding a certain dollar damage plotted against the dollar damage. For example, if Activity One had the risk profile as shown and you go up to the 10^{-3} probability (which is about one chance in a thousand), you find that the corresponding dollar loss is about a million dollars. If on the same risk profile for Activity 1, you look at an event that has a probability of occurrence of 10^{-4} (one in ten thousand chance), you see that the loss is about ten million dollars and so on.

Curves such as these are very useful when the probability of occurrence can vary over several decades as they usually do in problems like this and where the consequence of the impacts can also vary over several decades. It is better to show the risks in this way then just talk about "expected values," because an "expected value" really hides the fact that you can get substantially greater or lesser losses with different probabilities. We give our numbers in "expected values" as well, however. Expected values are useful when the degree of variation in both probability and impact are small. But when the degree of variation in impact and probability get this large, it is not necessarily the best measure of assessing the risk we're dealing with.

You notice I've shown uncertainty bounds, and the uncertainty bounds are rather substantial. They can vary by as much as an order of magnitude on either side. In risk analysis, we have generally found that we are not trying to find estimates within an accuracy of a factor of 50% or even a factor of 2. Very often, even with substantially greater uncertainties, very useful decisions can be made. As you will see later on, when you compare that risk profile with the uncertainties against other risk profiles A and B in Figure 6 (comparative profiles might be damage from tornadoes, hurricanes, high winds, or snow storms), you might find that, in spite of the uncertainties, one profile can lie substantially below another. Hence, you would be in a position to say that the risk from this activity, in spite of its uncertainties, is substantially less than the risk from whatever else. You might wish to compare it against manmade risks, because, after all, this is a manmade risk. It is a risk that man imposes on himself. It's not a natural event and you might want to compare it with things like transportation of hazardous chemicals, pesticide programs, nuclear power plants, liquified natural gas transportation.

Now after you've developed the risk profile for the activity of concern, if you find that the risk is unacceptable for whatever reason, you can go back and ask yourself what caused the risk in the area of concern to lie where it does lie. For example, if a decision maker finds that one portion of the risk profile is too high, he can look at options to reduce the risk. He can go back to his calculation to learn what contributed to those points on the curve and he can reduce the risk with risk control options. He can make that curve swing down with the control strategy by either reducing the probability of occurrence or reducing the consequences. This can be done by making changes in operations, by material modification, by engineering fixes or redundancy in the systems, by better inspections, etc.

The final thing I want you to note on Figure 6 is the x-axis, the impact level D. There are dollars, and there are dollars. Now you can talk about the losses caused by lost payroll, you can add to that the cost of repairing the equipment, you can add to that the business interruption which is very often the largest cost, you can add to that legal fees of defending against the accident, and so on. So you must understand very carefully what dollars you're talking about when you present a risk profile. Somebody might present it only in terms of direct loss incurred. Others, who want to explore the problem in more detail, might present it in terms of loss and the two can differ greatly for the same phenomenon. So keep in mind that the definition of the impact dollar D can vary. Note that for this same carbon-fiber problem, if one wanted to examine shock hazards and portray the shock hazards in terms of expected casualties, it is very easy to do so, and we are going to take a look at that in the next phase of our work. Today, however, we're only going to present our results in terms of national risk profiles with dollar damage as the impact parameter of interest.

I already talked about risk control. Recalling that risk is comprised of two elements, there are two ways in which you can reduce it, as shown in Figure 7. You can either reduce the probability of occurrence through better control systems, or you can reduce the level of impact. Which method you choose depends on how large the risk and benefits are and what the cost effectiveness of the various control strategies is

RISK CONTROL

- REDUCE PROBABILITY OF OCCURRENCE
- REDUCE LEVEL OF IMPACT

Figure 7

Overall Approach

I briefly want to review the overall approach that we used so that you understand how we procedurally went about solving this problem. As illustrated in Figure 8, utilizing aviation statistics, such as the number of accidents that have occurred in the

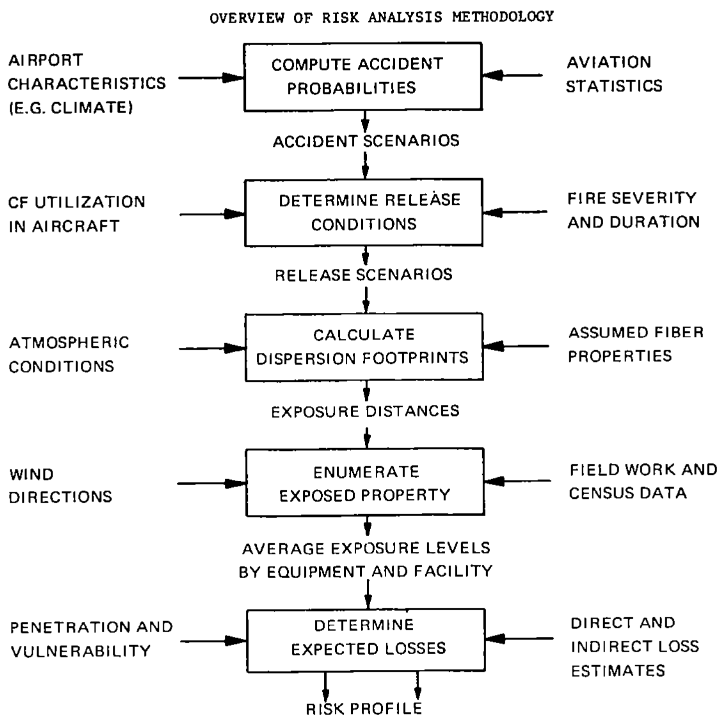


Figure 8

last ten years, the accidents that fall in the fire or fire and explosion category, and the number of operations, and tying those statistics in with airport characteristics (such as the type of climate it might have, the number of operations, any unusual features, the runway orientation, and so on), we compute the accident probability for aircraft. Out of that would be developed a series of accident scenarios which, when tied in with the amount of carbon fiber utilization in aircraft in different years and the fire extent and duration that can occur in accidents of different severity, would determine the release conditions--how much carbon fiber, if any, is released, and in what form. Then, we use that information, along with the prevalent atmospheric condition and the fiber properties (which have been reasonably well measured at this time) to calculate a dispersion footprint. The accident probability calculation (the top central box in Figure 8) will be addressed in some detail, because it was not addressed in much detail in previous presentations. The release conditions will not be addressed in too much detail because there has been a lot of discussion on the testing that has been done. As far as the dispersion footprint calculation is concerned, we use a method very similar to the one Dr. Wolf Elber talked about, so we are not going to spend too much time discussing that. Once we get the footprint, we can get exposure distances out of it; and depending on the wind direction and actual field work in areas of interest, we can find and enumerate the property that has been exposed. This again was not discussed in too much detail yesterday so we will be discussing it today. We did look at all the 26 major airports in developing our national risk profile. The information obtained then feeds into average exposure levels by equipment and facility and, depending on the transfer functions in different buildings and different systems (which depend on the penetration capabilities of the fibers and the systems they encounter), one estimates the direct and indirect loss. By tying the accident probability with the total loss, one develops a risk profile for this problem. Dr. Fiksel is now going to talk about the last item: Risk Evaluation and Perspective.

Risk Evaluation and Perspective

Joseph Fiksel

I would like to briefly summarize the objectives of our study as shown in figure 9. Our overall objective, as Dr. Kalelkar explained, was to evaluate the risk to the nation due to carbon fiber releases from commercial air carrier accidents involving fires. In order to do this, we gathered data concerning air carrier incidents. Our major source of data was the National Transportation Safety Board statistics which were discussed earlier. We gathered data concerning release and dispersion of fibers, including the experimental results which were referred to by Dr. Vernon Bell in his presentation. We also looked at the potential damage to electronic equipment and identified the types of equipment that might be vulnerable to carbon fibers. We developed methodologies using various techniques including statistical techniques, engineering models, and also a Monte Carlo simulation technique which is really at the heart of our methodology for developing a risk profile. Using the data and the methodology that I've described, we were then able to estimate the national risk.

OBJECTIVES OF ADL STUDY

GATHER DATA CONCERNING

- Air Carrier Incidents Involving Fire
- Release and Dispersion of Carbon Fibers
- Potential Damage to Electronic Equipment

DEVELOP METHODOLOGY USING

- Statistical Techniques
- Engineering Models
- Monte Carlo Simulation

ESTIMATE NATIONAL RISK, INCLUDING

- Projection of CF Market Growth
- Consideration of Major Airport Cities
- Identification of Potentially Vulnerable Facilities

Figure 9

This estimation involved a projection of the growth of the carbon fiber market from the present day up to 1993 and consideration of the major cities around the nation. We identified the large hub airports as described by the FAA, and we examined the potential risk to those airports in detail. We also looked at the additional airports in a more superficial manner to try to get an idea of the total national risk due to all air carrier operations in the U.S. Finally, we identified the different kinds of vulnerable or potentially vulnerable facilities that could exist. Because of the very large exposure distances involved, and because a carbon fiber cloud may extend over a very wide area, all segments of society and business activity may be influenced by this carbon fiber release.

The projections for utilization of carbon fiber composites in commercial aircraft were provided to us by the airframe manufacturers. We also developed our own projections, and we will soon be coordinating with the airframe manufacturers in trying to improve these projections. These projections are preliminary, but they give a good idea of the magnitude of carbon fiber masses that will be on aircraft in the future. We divided the aircraft that might carry carbon fibers into three classes. Since turboprops and propeller aircraft in general will not carry fibers, we concentrated on jet aircraft. Three categories were identified: small, medium, and jumbo jets.

On the first line of figure 10, the number of aircraft in service is projected for both 1985 and 1993 in each of these three categories. As shown, the total number of aircraft projected for

PROJECTED CARBON FIBER UTILIZATION					
	YEAR	SIZE OF JET			TOTAL
		SMALL	MEDIUM	JUMBO	
NUMBER OF AIRCRAFT IN SERVICE	1985	825	1980	495	3300
	1993	950	2280	570	3800
NUMBER OF AIRCRAFT CARRYING CF	1985	165	396	163	724
	1993	475	1368	285	2128
CF MASS PER AIRCRAFT (LB.)	1985	234	338	1017	
	1993	1000	1500	4500	

Figure 10

1985 is 3,300. By 1993, we expect 3800 aircraft. The fraction of these aircraft carrying carbon fibers varies from approximately one-quarter of the total fleet in 1985 to half the fleet in 1993. Thus, the total fraction of airplanes carrying fibers will increase. In addition, the amount of carbon fibers per aircraft will tend to increase. For example, on the jumbo jets in 1985, we expect an average of about a thousand pounds of carbon fiber per aircraft; by 1993 this amount is expected to increase to about 4500 pounds per aircraft. Incidentally, for the risk profile that I'm going to show you later, we utilized the 1993 figures. We concentrated on the 1993 data since we were attempting to upper bound the risk that could be caused by the carbon-fiber release phenomenon. It is also possible to generate a 1985 risk profile, but we won't present that today.

The sequence of events that we were obliged to look at in studying the carbon-fiber phenomenon is shown in figure 11. Of course, to get a feeling for the frequency of occurrence of the failure event, we had to look at the total number of air carrier operations and project these out to 1993. Once an air carrier operation occurs, there is a certain chance of an aircraft accident. Therefore, we identified the accident statistics corresponding to the kinds of accidents that we were concerned with, namely those with fire and/or an explosion. In the aftermath of an accident involving an aircraft which carries carbon

SEQUENCE OF EVENTS TO BE MODELLED

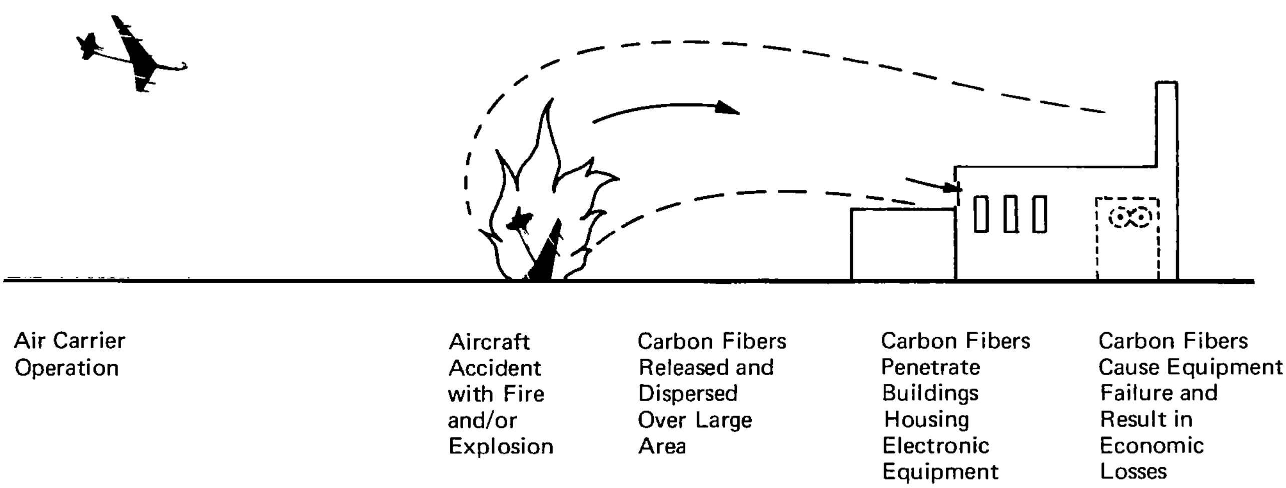


Figure 11

fibers, there is a possibility of the fibers being released and dispersing over a large area. This has already been discussed to a great extent by previous speakers. The fibers can penetrate buildings and damage electronic equipment. This damage can result in economic losses. Now, we'll go through each of these steps in turn and I'll try to summarize some of the results that we've obtained in looking at the different aspects of this release phenomenon.

The first event is the air carrier operation. If you look at figure 12, we have two circle charts. The one on the left indicates the percent of traffic which takes place at the major airports around the nation. As I mentioned, we concentrated on the large hub airports. According to the 1977 FAA statistics, there are approximately 26 such large hub airports, accounting for almost 70% of the total traffic. These large hub airports would therefore account for the majority of the risks. We also looked at the medium and small hub airports to a lesser extent, but our simulation concentrated on these 26 large hub airports. The circle chart on the right shows the national fleet mix projected for 1993 for the three types of jet air carrier operations. The national fleet mix was adjusted for individual airports since each airport has a slightly different fleet mix.

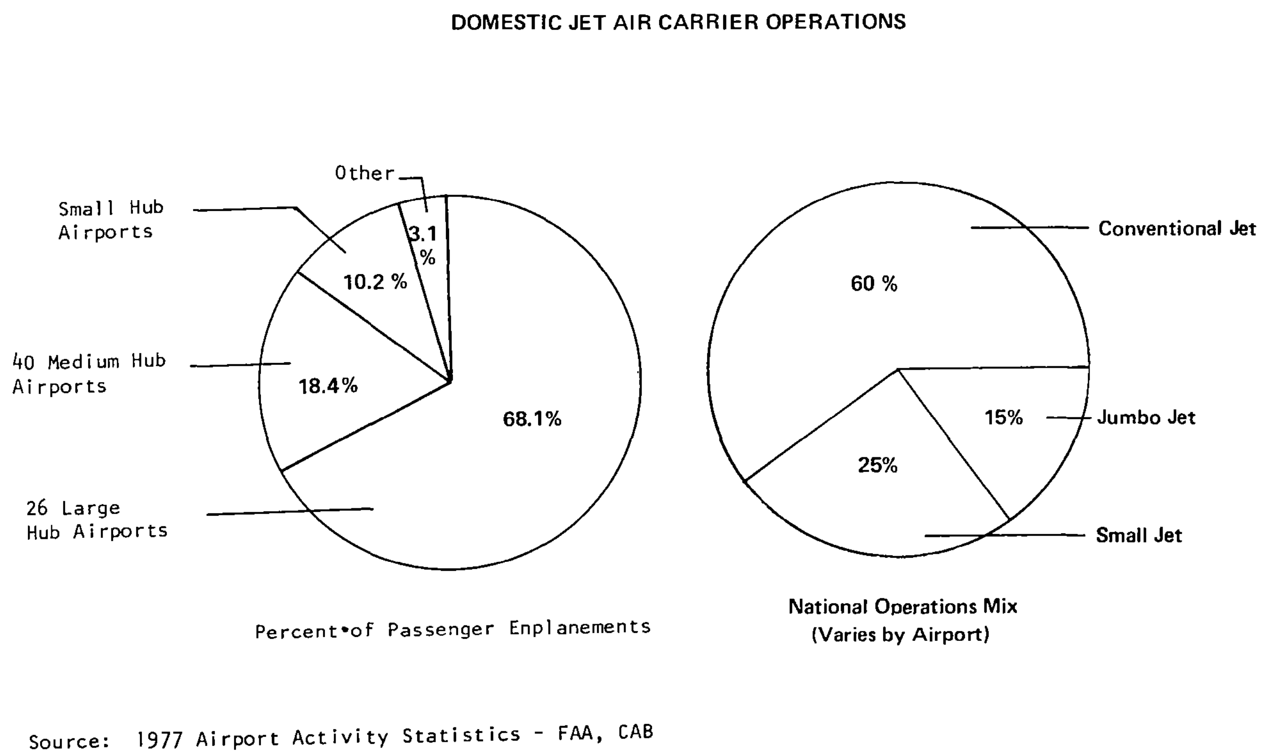


Figure 12

Figure 13 shows results from an extensive analysis of the National Transportation Safety Board data base using both the NTSB tapes and the hard copy records for that subset of the accidents that involved a fire. The data base contains approximately 260 accidents involving either total destruction of the aircraft or substantial damage. Total destruction means that the plane is essentially nonrecoverable. This chart shows the relative frequency of total destruction and substantial damage in the different phases of operation: takeoff, landing, cruise, and static/taxi. The largest potential for total destruction, which is generally the type of accident that involves the largest fires, occurred in the case of landing accidents, but there were also significant possibilities of total destruction in the other phases.

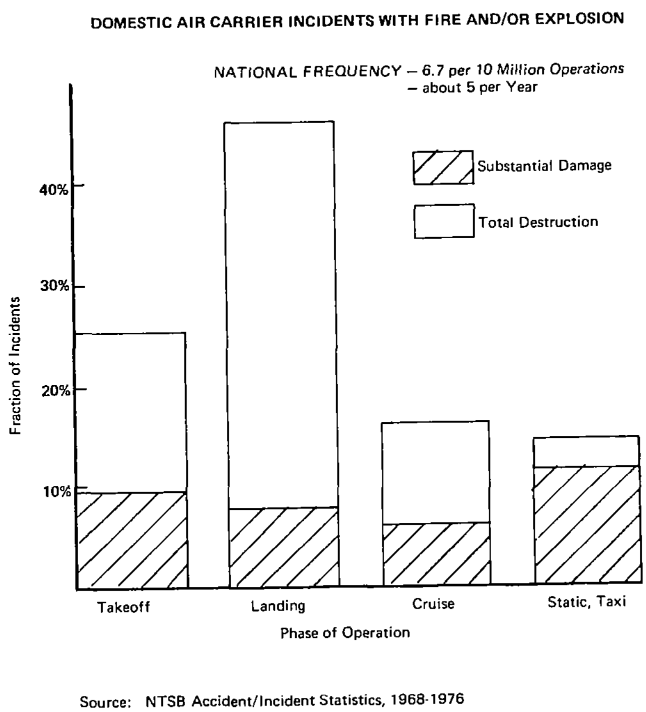


Figure 13

Weather conditions at the time of an accident are generally classified into IFR - which stands for Instrument Flight Rules - and VFR - which stands for Visual Flight Rules. There is also a Below-Minimum classification. We took the IFR and Below-Minimum statistics for accidents and compared those against the accidents which occurred during VFR weather. We learned that an accident is eight times more likely in IFR or below-minimum weather. Accordingly, we normalized the national accident frequency (about 6.7 accidents per 10 million operations involving a fire and/or explosion and total or substantial damage, which is equivalent to about 5 accidents per year) by the IFR/VFR weather frequency in each of the major airports to obtain an adjusted accident rate for each of these airports.

In addition, we estimated the occurrence of explosions in these accidents. Explosions are relatively rare; only about 8% of all accidents with fire result in some kind of explosion. However, it is not a true explosion. Rather, after a period of burn the fire may reach the fuel tanks, at which point there is a very rapid burning or deflagration of the fuel in the fuel tanks, similar to an explosion. This deflagration or "explosion" can cause an agitation of the structure, promoting the release of a large number of fibers. In his presentation, Dr. Vernon Bell showed some of the experimental results that we used to estimate fiber release. Based on these results, we estimated the fraction of fibers that were released from an aircraft. These fractions ranged from approximately 5% in the case of substantial damage accidents to as much as 25% in the case of a total destruction accident with an explosion.

Because of the two situations under which carbon fibers can be released, we used two different models, as shown in figure 14, to account for the release phenomenon. The first model was an instantaneous release model, corresponding to the explosion case. In this model, we assumed an instantaneous release of a certain mass of carbon fibers corresponding to the mass that was onboard

DISPERSION MODELS

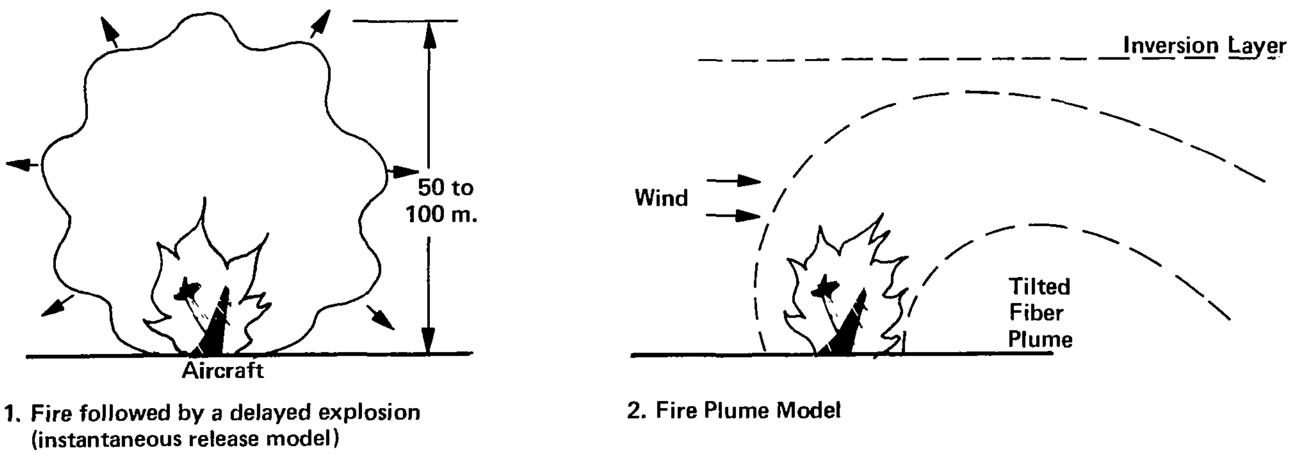


Figure 14

the aircraft. A certain percentage of this mass was then assumed to be released as single fibers. The resulting carbon fiber cloud then drifted downwind. The other type of model, in the case where no explosion occurred, is the fire plume model, where the fire causes a plume which rises and reaches a certain maximum height. The carbon fibers are then dispersed downwind. The plume, however, is tilted due to the settling velocity of the fibers. I won't go into the details of these dispersion models, since Dr. Elber gave a very thorough discussion, but these models are similar to the ones that he described and they have been verified in different experimental situations.

Our accident-statistics investigation also permitted us to calculate a probability distribution for the location of an accident and to describe the proportion of the accidents that fell within various distances of the runway. We found that the fraction of accidents that occur off the airport was fairly large in the case of landing accidents, as much as 45%. With most other operational phases, the proportion of accidents occurring off the airport was smaller. In the case of off-airport accidents, as illustrated in Figure 15, we established distributions for the distance and the angle from the runway, and we also utilized runway orientations to pinpoint the location of the accident within the vicinity of each airport. Once the incident location was established, the dispersion model was used to

EXPOSURE FOOTPRINTS AFTER CF RELEASE

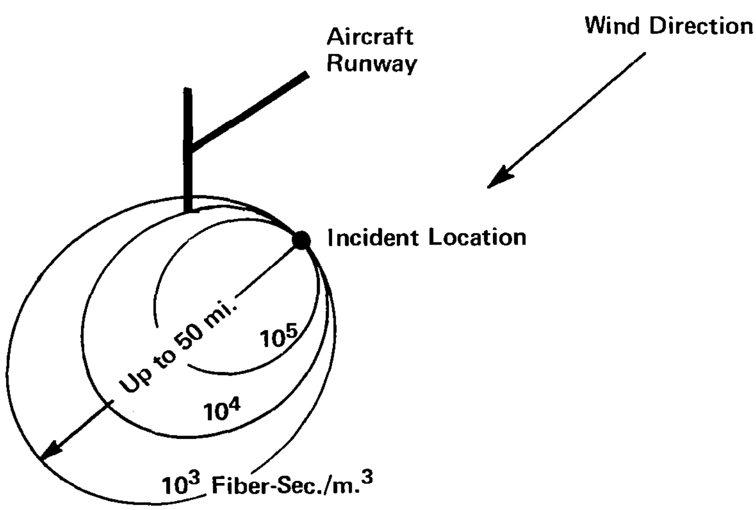


Figure 15

calculate exposure contours in the downwind direction. I should point out that these contours are not drawn to scale. Obviously, the aircraft runway is not that large; the contours can be up to 50 miles in extent, and, generally speaking, they tend to be elongated. That is, they are much longer than they are wide, and not elliptical or almost circular as shown in Figure 15.

Figure 16 gives some sample results from the fire plume model just to give you an indication of the kind of results that we

SAMPLE OUTPUT FROM FIRE PLUME MODEL

Scenario: 500 KG of Carbon Fibers Released Over a 10-Minute Period

EXPOSURE LEVEL	CONTOUR DIMENSIONS (M.)	NEUTRAL ATMOSPHERE 4M./SEC. WIND VELOCITY	MODERATELY STABLE ATMOSPHERE 2M./SEC. WIND VELOCITY
10^5 FIBER-SEC/M^3	NEAREST DISTANCE	0	39,150
	FARTHEST DISTANCE	0	57,150
	MAXIMUM WIDTH	0	4,247
	AREA (KM^2)	0	60
10^3 FIBER-SEC/M^3	NEAREST DISTANCE	6,300	28,150
	FARTHEST DISTANCE	94,300	63,150
	MAXIMUM WIDTH	16,107	8,363
	AREA (KM^2)	1,110	230

Figure 16

obtained for the exposure contour. Two different types of atmospheres are shown: a neutral atmosphere and a moderately stable atmosphere. These are two of the Pasquill-Gifford stability classes. In the case of the neutral atmosphere we had a four meter per second wind velocity; and for the moderately stable atmosphere, a two meter per second wind velocity. In both cases, 500 kilograms of carbon fibers were assumed to be released over a 10 minute period. The distances shown in figure 16 are in meters except for the area which is shown in square kilometers. For example, the 10^5 exposure contour extended over a distance of 57 kilometers and had a maximum width of four kilometers, so it was a fairly elongated contour. Interestingly, in this case the neutral atmosphere showed no 10^5 exposure contour. There are cases in which the maximum exposure will not necessarily exceed 10^4 or 10^5.

The 10^3 contour for the neutral atmosphere was fairly long. It went out a distance of 94 kilometers, which is slightly in excess of the 50 mile distance that we discussed earlier.

Given these contours, we can establish the exposure in the case of an accident occurring in the vicinity of an airport. Figure 17 gives, as an illustration, a map of Massachusetts showing

DISTRIBUTION OF SECTORS AROUND LOGAN AIRPORT, BOSTON, MASS.

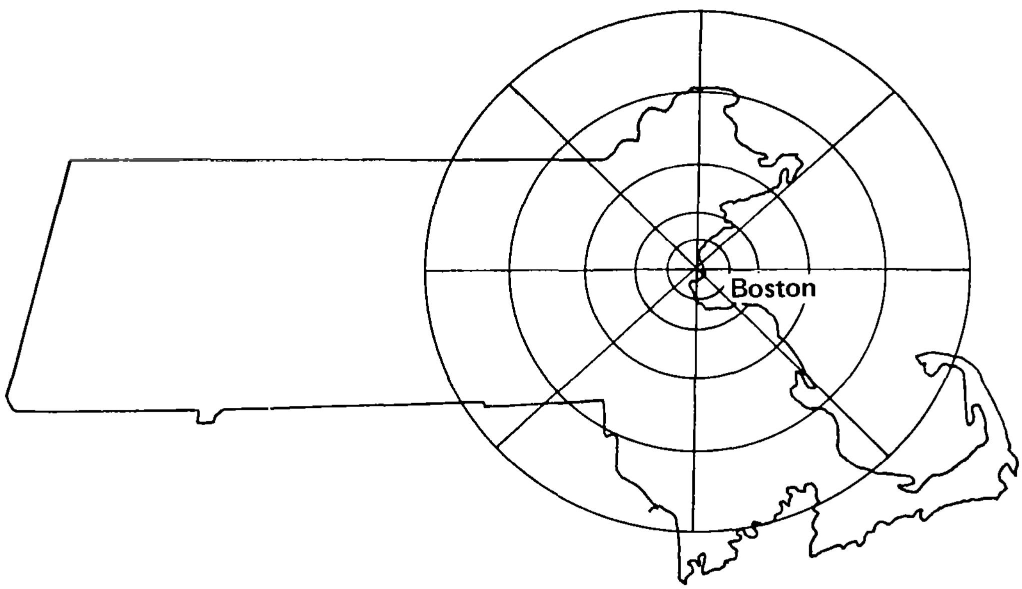


Figure 17

the location of Logan Airport in Boston. We first establish a grid, or a map, in polar coordinates surrounding each major airport. We then place concentric circles at distances of 5, 10, 20, 35, and 50 miles from the airport center and divide the circles into 8 equal segments. This procedure effectively divides the area into 40 sectors. Once the exposure contour is determined and the incident location is identified, we can find the exposure distribution in each of these forty sectors. Notice that if you go out 50 miles, you cover a good half of the state of Massachusetts. Therefore, many different communities are involved. A number of other, smaller, airports are also covered. So, as I mentioned earlier, there are an enormous number of facilities which are potentially vulnerable and subject to exposures of greater than 10^3 carbon fiber seconds per cubic meter.

To establish the kinds of facilities present in exposed areas, we did a great deal of work in terms of field surveys as well as investigations of census data. As shown in figure 18, we

POTENTIALLY VULNERABLE FACILITIES

1. Residences	
2. Manufacturers	– Electronic Equipment – Computers – Aerospace
3. Transportation	– Aircraft and Air Traffic Control – Mass Transit – Motor Vehicles
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

Figure 18

identified the potentially vulnerable facilities in these areas, starting with households. We were able to get a count of the number of households in each geometric sector from 1972 census data. We also used the 1972 census data to examine standard industrial classifications to determine the number of facilities in various types of industries. We enumerated manufacturers of electronic equipment which might be sensitive, including computers and aerospace manufacturers, and we also looked at general manufacturers who might use electronic equipment in process control or for other applications. We looked at the transportation industry; in particular, aircraft and air traffic control were of great interest, and we also examined mass transit systems and motor vehicles. We looked at communications in terms of telephone, radio, T.V., microwave, Post Offices, and fire and police communications. In terms of service industries, we looked at finance and insurance industries, software and electronic data processing centers as well as hospitals. Finally, in the general category, we looked at various types of retail outlets, office buildings and industrial plants corresponding to the general manufacturing category. Mr. Ansel Butterfield described some of the main field surveys that we made. There have been some additional surveys since then; so that we now have a fairly good coverage of some of the more important facilities in these different categories. As I mentioned, we established a data base which essentially describes the number of facilities existing in the fifty-mile radius area surrounding each of the 26 major airports. I should reiterate that these results are based on 1972 census data and that we did not attempt to project the number of facilities that exist presently into the future.

Given that the facilities have been identified, suppose that a facility is exposed to carbon fibers. How many of these fibers enter the building, and what is the effect of exposure inside the building? Mr. Israel Taback gave us a good discussion of the notion of penetration and transfer functions, so I won't go into that in much detail. The model and main variables are shown in figure 19. The filter efficiencies, window openings, interior dimensions of buildings, ventilation rates, recirculation of air, and infiltration rates through walls and through cracks can all be estimated based upon heating and ventilation handbooks and construction codes, so we can get a fairly good idea of what the rate of entry is for fibers into a building. We can then calculate an inside exposure based upon this information and the outside exposure.

BUILDING PENETRATION MODEL

$$\left(\text{Inside Exposure}\right) = \left(\text{Outside Exposure}\right) \times \left(\text{Transfer Function}\right)$$

TRANSFER FUNCTION DEPENDS ON

- Filter Efficiencies
- Window Openings
- Interior Dimensions
- Ventilation Rates
- Recirculation of Air
- Infiltration Rate

Figure 19

Figure 20 gives an overview of some of the results we got for transfer function, which we call an airborne exposure transfer function (AETF). We've shown a range from minimum to maximum. The reason that we show a range is that there is some uncertainty in the estimation of a transfer function. There are two sources to

AIRBORNE EXPOSURE TRANSFER FUNCTION
OVERVIEW OF RESULTS

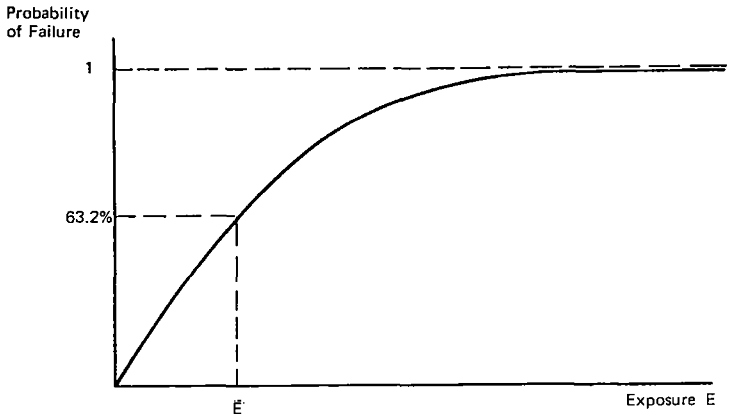
AREA DESIGNATION	AETF Range Min.	AETF Range Max.
AIRCRAFT – CABINS, DOORS OPEN	0.16	0.68
– CABINS, DOORS SHUT	0	9×10^{-3}
– EXTERNAL COMPARTMENTS	10^{-3}	9×10^{-2}
AIRPORT – BAGGAGE AREAS	7×10^{-2}	0.87
– CONTROL TOWERS, WINDOWS SHUT	0	6×10^{-3}
– PASSENGER TERMINALS	0	10^{-3}
COMPUTER ROOMS	0	3×10^{-3}
EMERGENCY GENERATORS	0.1	0.7
HEALTH FACILITIES – GENERAL AREAS, NON SEALED	1.5×10^{-2}	0.44
– OPERATING ROOMS	0	3×10^{-4}
INDUSTRIAL BUILDINGS – OLD BUILDING	0.3	0.7
– MODERN, AVERAGE FILTERS	7×10^{-5}	0.13
OFFICE AREAS – WINDOWS SHUT	4×10^{-4}	7×10^{-2}
RESIDENCES – WINDOWS OPEN	10^{-2}	0.7

Figure 20

this uncertainty. One is the fact that each of the variables is somewhat uncertain. For example, filter efficiencies do have some uncertainty band; they can't be estimated precisely. Another source of uncertainty is that in each type of facility there is an enormous variation in the different building characteristics, from modern buildings to old buildings, from very well controlled buildings to poorly ventilated buildings. So within this range of variation, we're able to estimate a transfer function range from each of the facility categories that I showed earlier. Some samples of the ranges we identified are given in Figure 20. You can see that they range over many orders of magnitude. We looked at aircraft and the airport terminal areas. In computer rooms, for example, you have a fairly low transfer function, anywhere from zero to about 10^{-3}. For residences the transfer function tends to be high, ranging from 10^{-2} to about 0.7 in a situation where it's summer time and all the windows are open.

Figure 21 gives the failure model for electronic equipment. By using this exponential failure distribution and vulnerability

ELECTRONIC EQUIPMENT FAILURE MODEL



Probability of Failure = $1 - e^{-\frac{E}{\bar{E}}}$

$\bar{E}$ = Mean Exposure for Failure

EXPOSURE	PERCENT FAILURES
$\bar{E}$ /100	1.0%
$\bar{E}$ /10	9.5%
$\bar{E}$	63.2%
10 E	99.9%

Figure 21

estimates based upon the experimental data that were described by Mr. Israel Taback, we were able to develop a failure distribution for each category of equipment that was identified. It's interesting to note that, on the horizontal axis, at two decades below $\bar{E}$, the mean exposure for failure, the probability of failure is 0.01; or about 1% of the equipment exposed at that level will fail. At one decade below $\bar{E}$, about 10% of the equipment will fail. At $\bar{E}$, about 63% of the equipment will fail. However, at one decade above $\bar{E}$, nearly all the equipment exposed at that level will fail.

Figure 22 gives some examples of the facility categories that we've identified, along with particular types of equipment that are present in those facility categories and the mean exposure estimates which were derived for those types of equipment. Notice that one column is called "Failure Category". In order to estimate the economic losses, we identified for each type of category what the function was for the equipment within that facility. In other words, how would the failure of equipment affect the operation of the facility as a whole? We identified three such classes, namely equipment which would require only repair in the case of failure, equipment which might disrupt the operation of

SELECTED VULNERABILITY ESTIMATES

Facility Category	Equipment Type	Failure Category	Mean Exposure (Fiber-Sec./M.^{3})
HOUSEHOLDS	TV / STEREO	REPAIR	6.4×10^8
AIRPORT CONTROL TOWER	ATC CONSOLES	REPAIR	7×10^5
AIRPORT CONTROL TOWER	ATC COMPUTER	REPAIR	4.9×10^9
SHIPYARDS	CRANES	REPAIR	4.0×10^5
POST OFFICE	ELECTRONIC SORTERS	REPAIR	5.0×10^5
AIRPORT TERMINAL	CRT DISPLAYS	REPAIR	1.6×10^7
MANUFACTURERS	TELEPHONE PBX	DISRUPTIVE	7.0×10^5
AIRCRAFT	AVIONICS INSTRUMENTS	DISRUPTIVE	1.0×10^6
RADIO/TV STATION	CONTROL ROOM	CRITICAL	3.0×10^5
RETAIL OUTLETS	POINT OF SALE TERMINAL	DISRUPTIVE	1.0×10^7
BUSINESS SERVICES	GENERAL OFFICE EQUIP.	DISRUPTIVE	5.0×10^5
HOSPITALS	POWER GENERATOR	REPAIR	9.8×10^5
EDP SERVICES	COMPUTER	CRITICAL	4.9×10^9

Figure 22

the facility (called a disruptive failure), and equipment, such as a control room in a radio/tv station, where, if the equipment fails, the operation is obliged to shut down until the equipment can be repaired. This latter is called a "critical failure". Shown are two types of critical failure: one for the control room and another for the computer in an EDP service industry.

Notice that the exposure estimates for computers to fail are fairly high; they're about 5 times 10^9. The reason is that our vulnerability estimate for computers included a transfer function for the computer room. Most facilities have a transfer function corresponding to the building exterior, but, since computer rooms tend to be very well protected, there is an additional transfer function corresponding to the passage of the fibers from outside to inside the computer room and also corresponding to the cabinet protection of the computer. In general the vulnerability estimates tend to range between 10^5 to 10^9 fiber seconds per cubic meter. Generally speaking these values are well above the external exposures that we saw from our dispersion analysis, and, due to the transfer functions, the inside exposures will usually be even further below these levels.

Figure 23 gives economic consequences of the carbon-fiber problem for industries. Recall that we identified three categories of failure type. Corresponding to each of these failure types, we had a different approach towards estimating the economic

ECONOMIC CONSEQUENCES FOR INDUSTRIES

TYPE OF FAILURE	DIRECT LOSSES	INDIRECT LOSSES
Minor	Equipment Repair or Replacement	
Disruptive	Equipment Repair or Replacement	Additional Operating Costs
Critical	Equipment Repair or Replacement	Shutdown, Loss of Revenue

Figure 23

losses. In the case of a minor failure, which amounts to only the repair of the equipment, the cost of the failure was assumed to be the cost of replacing or repairing the equipment. In the case of a disruptive failure we have the equipment repair costs, plus the additional operating costs due to alternate procedures for operating the facility. Although it was assumed that the facility could continue operation while the equipment was being repaired, some additional operational procedures would be necessary. Finally, in the critical failure we assumed a shutdown of the facility, in which case there would be a loss of revenue during the estimated downtime for the equipment under consideration. To get revenue figures and operating cost figures for the various facilities, we used average financial statements for an industry based upon each metropolitan area. We were able to obtain these average financial statements for areas near each of the major airports that we examined.

We've gone through the sequence of events that was to be modeled, and I've shown the approach we've taken towards modeling each step in that procedure, from the initial air carrier operation to the potential release of fibers, through the penetration, to the possible failure of the equipment, and ultimately the economic losses that could result. Now what did we do with all these data? In her presentation, Dr. Karen Credeur gave a good description of the simulation approach that was used. Our approach was slightly different, but essentially similar in character; it was based upon the roulette wheel analogy that Dr. Credeur described. We used each of the data types that were generated in each of the steps that I described, and input them to a Monte Carlo simulation model, illustrated in figure 24, which performs random draws to simulate the occurrence of an accident.

MONTE CARLO SIMULATION PROCEDURE

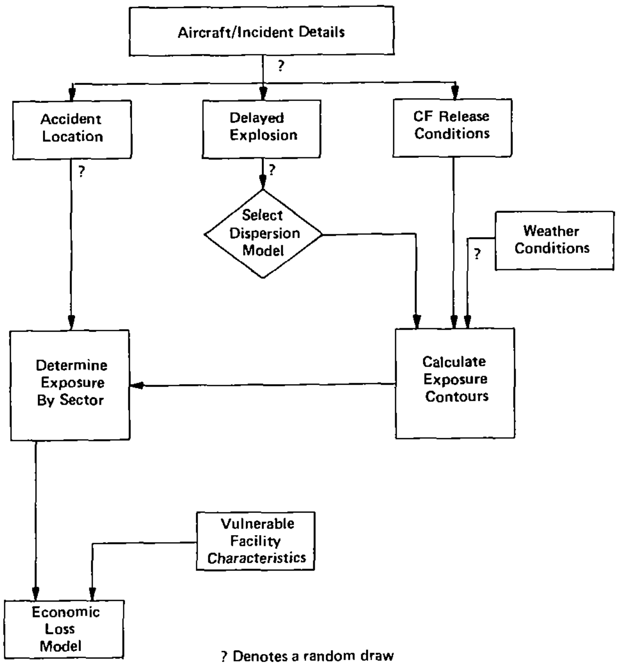


Figure 24

We simulated the occurrence of a large number of accidents for each of the major airports under consideration. We input frequency distributions for each of the different accident characteristics: the aircraft/incident details such as aircraft type, operational category, whether the damage was total destruction or substantial damage--all these details were derived from the aircraft accident statistics. For example, there's a certain chance of total destruction, there's a certain chance that the destruction will be off-airport, there's a certain chance that there will be a fire, and there's a certain chance that there will in fact be an explosion following this fire. A question mark indicates a situation in which we had a random draw from a frequency distribution. We selected the appropriate dispersion model. For example, if there was a delayed explosion, we selected the instantaneous release model. The carbon fiber release conditions were based upon the aircraft/incident details; these described the mass of fibers that were released. The weather conditions were drawn from data supplied by the National Climatic Service, which describes the wind direction and the atmospheric stability classes at each of the airports under consideration. Given all these details, we then call upon the dispersion model to calculate the exposure contours. The accident or incident location tells us where the exposure contours originate, and we then determine the exposure by sector for each of the 40 sectors surrounding the airport. Once the exposure distribution has been determined, we look at the potentially vulnerable facilities within each of the sectors and calculate the total expected economic losses.

The simulation that I described establishes a distribution for the losses given a single accident at a particular airport. To develop a national risk profile for a single accident, we combined the incident frequencies, as indicated in figure 25. Having the national risk profile for a single incident and knowing the frequency of incidents in the nation, which as I said was approximately 5 per year, we then can calculate two types of representations of the total national risk. One representation

DERIVATION OF NATIONAL RISK PROFILE

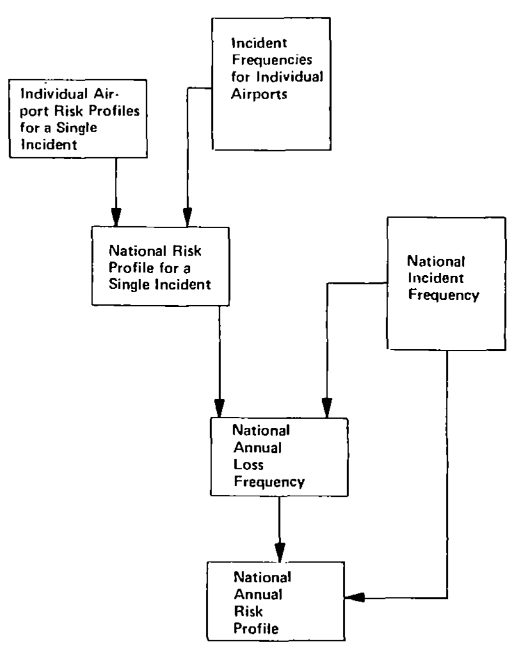


Figure 25

is the national annual loss frequency, which tells us how often events occur with various levels of damage. For example, how often would a ten thousand dollar accident occur? How often would a million dollar accident occur, and so forth? Another representation of the risks, which is a better representation for decision-making purposes, is the national annual risk profile which doesn't look at specific events, but instead gives the range of loss due to carbon fibers for the nation as a whole. This risk representation incorporates the assumption that there may be 1, 2, 3 or more accidents.

Before showing results, however, I want to review the assumptions that enter into this calculation. There are five major assumptions that should be mentioned. These five are shown in figure 26. First, if an aircraft carries composites, we assume that the composite will always be involved in the fire. In fact, this assumption is not necessarily true and the airframe manufacturers are currently investigating the actual probability of the fiber being involved in the fire and thus being released.

MAJOR ASSUMPTIONS

1. IF AN AIRCRAFT CARRIES COMPOSITE, AND A FIRE OCCURS, THE COMPOSITE WILL ALWAYS BE INVOLVED
2. ATMOSPHERIC CONDITIONS REMAIN CONSTANT DURING DISPERSION OF THE CARBON FIBER CLOUD
3. FOR A GIVEN FACILITY CATEGORY, ALL FACILITIES ARE EQUAL IN SIZE, EQUIPMENT INVENTORY, AND FINANCIAL CHARACTERISTICS
4. FAILURES OCCUR IMMEDIATELY AFTER EXPOSURE, WITH INDEPENDENCE AMONG UNITS OF EQUIPMENT
5. SECOND-ORDER IMPACTS OF EQUIPMENT FAILURE ARE NOT INCLUDED IN ECONOMIC LOSS (e.g. interruption of telephone service)

Figure 26

The second assumption is that atmospheric conditions remain constant during the dispersion of the carbon fiber cloud. However, a cloud traveling 50 miles at a speed of about 2 miles per hour can take a day or so and, obviously, the atmospheric conditions are going to change. Therefore, this assumption will clearly not hold in practice. Nonetheless, since all the different atmospheric conditions will occur with the appropriate frequencies, simulation over a large number of accidents should yield a risk profile that gives a good indication of the potential economic losses.

The third assumption is that, for a given facility category, all facilities are identical in the sense that they have the same revenue, the same size of operation, and the same types of equipment in the plant. In reality we know that there is a wide range of facilities; in his presentation, Mr. Ansel Butterfield demonstrated some of the variation that can occur. However, we assumed an average type of facility for the purpose of calculating economic loss. The fourth assumption is that failures occur immediately after an accident and that the failure of different units is independent. Although Mr. Israel Taback discussed the issue of possible post-exposure vulnerability, we assumed that, if electronic equipment is vulnerable, then the failure will occur immediately after the accident. The independence assumption means that we don't take into account the locations of units within a facility. If the units are located close to one another, then their failures may somehow be correlated. The fifth assumption, which is an important one, concerns the types of losses considered in this analysis. We considered only that we called primary losses, namely those that were a direct outcome of the incident, resulting either in equipment repair costs or in business interruption costs. We did not consider the potential secondary impacts, such as the losses incurred by the interruption of telephone service to a community. In the case of an airport, for example, we did not consider the potential costs of clean-up or decontamination following a carbon fiber exposure. We looked only at the costs of potential failures that would occur.

Figure 27 gives the actual risk profile that was derived. The axis on the left shows the annual probability of losses exceeding a certain amount. The axis at the bottom shows the total losses in dollars. This curve is the risk profile for a single year for the nation as a whole. This means that, in 1993, there is an 80% chance that we will experience losses in excess of 10,000 dollars. Further, moving down the curve about every ten years we would expect to incur a loss of a million dollars or more. Following the curve to the right-hand end, we learn that once about every thousand years, one would expect losses of the order of ten million dollars or more. We also extrapolated the curve further and are in the process of sharpening estimates, so that we can examine the possibility of higher losses at the very low tail end of the risk profile. There may, in fact, be probabilities of the order of 10^{-4} of losses exceeding 20 or 30 million dollars.

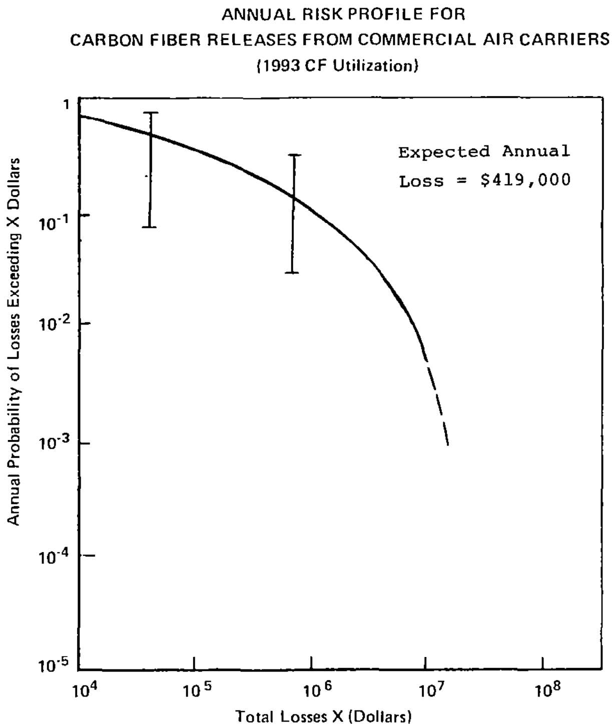


Figure 27

Although the curve in figure 27 is an economic loss profile, it is possible to develop a risk profile showing the potential fatalities due to shock hazards using a very similar procedure. The entire methodology that I've described is applicable to that case, except that, instead of looking at failures of equipment, we would simply look at the probability of a shock hazard for each facility that is examined in the exposed area.

The confidence bounds shown on the profile in figure 27 are estimates and we are currently sharpening these estimates. Although the profile was calculated with 1993 carbon fiber utilization figures, it reflects the 1972 census figures and is expressed in 1977 dollars, so it's a hybrid risk profile. It shows us what the risk would be in 1977 assuming that the number of facilities has remained relatively constant and assuming that airplanes today were carrying the kind of fibers that they would in 1993.

We feel that this risk profile is conservative, in the sense that it tends to overestimate the risks rather than underestimate the risks. There are several reasons for this. One is that in most of our release assumptions, we attempted to be on the conservative side. Another is that the building transfer functions used were in every case at the maximum or high end of the range. On the other hand, although it's a conservative risk profile, secondary losses are not included. It is conceivable that there would be additional losses due to some types of impacts, such as telephone or airport service interruption, which have not yet been quantified, and these inclusions might tend to move the risk profile slightly to the right.

Now, in order to compare our results against risks which have been estimated for other types of disasters or accidents, let's compare against the curves which Dr. Karen Credeur showed previously. These curves, shown in figure 28, are taken from the Reactor Safety Study, the Wash 1400 report. Shown are the curves corresponding to natural events, man-caused events, and nuclear power plants. These curves have different meanings than the risk profile that I showed you a moment ago; they are national annual loss frequencies. They don't show losses to the US as a whole in a given year; instead they show how frequently accidents occur involving various levels of loss. The axis on the left gives the frequency of incidents per year involving dollar damages greater than a certain amount, X. For example, $10,000 is the lowest level of loss shown and, since a log scale is used, the plot says that we will have approximately two carbon-fiber related accidents per year involving losses of more than $10,000. As you move down the curve, you find that the frequency of accidents involving losses of greater than a million dollars is

COMPARISON OF RISK PROFILES

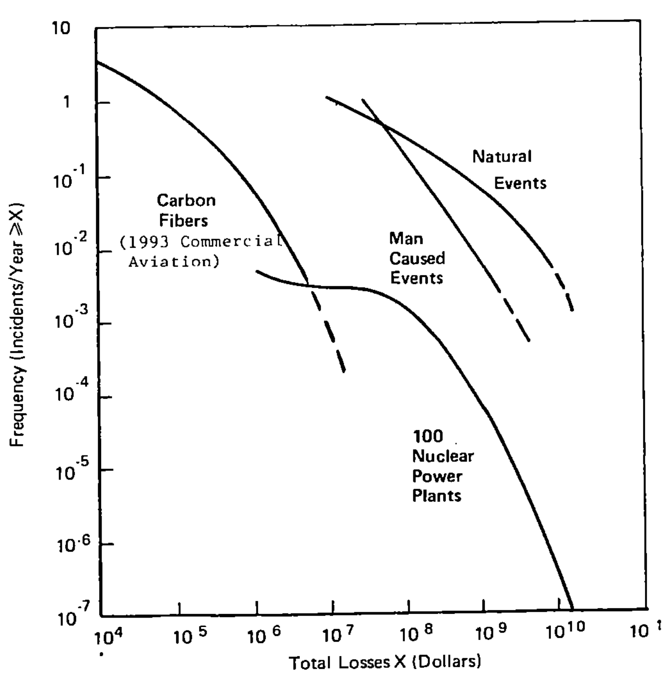


Figure 28

only one in a hundred. In other words, there's a one hundredth chance of an incident each year involving a loss greater than a million dollars.

If you compare the CF curve against the other curves shown in figure 28, you find that it falls well to the left of those curves, indicating that at the same level of frequency the potential losses due to aircraft accident carbon fiber releases are significantly lower. For example, at the 10^{-2} level, in other words, the one accident in a hundred, the estimated damages from carbon fiber are a million or more, but, in the case of the man-caused or natural events, they are considerably more, on the order of $1 billion. The same is true of the Reactor Safety Study curve for a hundred nuclear power plants. Although there isn't much overlap between the ranges of these two curves, where there is some overlap we again see that for an equivalent low frequency of occurrence, the damage cost is higher for nuclear power plants. For example, for the one accident in a thousand, the damage from carbon fibers is about ten million dollars, whereas an accident involving a nuclear power plant would have damage in excess of a billion dollars.

Figure 29 gives the areas of future effort which will improve the risk estimates that I've shown. These estimates must be considered preliminary due to some of the assumptions that have been

AREAS OF FUTURE EFFORT

1. REFINEMENT OF RELEASE AND DISPERSION ANALYSIS

2. DETAILED ECONOMIC ANALYSIS FOR SPECIFIC BUSINESS CATEGORIES

3. PROJECTING IMPACTS OF GROWTH IN ELECTRONICS INDUSTRY

4. DETERMINATION OF CONFIDENCE BOUNDS FOR RISK PROFILE

5. PERFORM ANALYSIS OF WORST CASE SCENARIO

6. DETAILED ANALYSIS OF ECONOMIC IMPACTS AT AIRPORTS

Figure 29

made. However, there are a number of areas that will assist us in refining the estimates. Note that the expected annual loss on the risk profile is $419,000 for the nation as a whole due to any accidents that might release carbon fibers. The standard deviation of that risk profile is $785,000. This large deviation shows a fairly wide variation, and, for this reason, we need a risk profile to examine the possible range of damage that might result.

In the areas of possible future effort, the refinement of the release and dispersion analysis is important, particularly with respect to the release conditions at the time of the accident. In addition, the economic analysis for business categories could be improved by examining specific industries more carefully and by looking at the variation within industries. The impacts of growth in the electronic industry should be accounted for so that we can have a better feeling for what the potentially vulnerable equipment will look like in 1993.

The confidence bound shown on the risk profile can be improved through sensitivity analysis and we're currently in the process of doing that. The sensitivity analysis examines the effect of the uncertainty in each of the variables which enter into the risk profile calculation. We are also in the process of analyzing the worst case scenario. It is possible that there are extremely costly accidents with extremely small probabilities, but which are still realistic and might occur. We will identify the potential worst case which may, in fact, exceed the current value that we estimate for the maximum loss due to any one accident, which is about 10 million dollars. In fact, we may identify accidents which potentially could cause a greater loss, perhaps 20 million dollars or more. Finally, the economic analysis at the airports needs to be improved. In particular, the cost of prevention and decontamination, and the question of the potential failure of airplanes after exposure are still open issues. That concludes our presentation.

QUESTIONS

Question: Question related to (1) differences in the ORI and A. D. Little risk analysis and (2) the sensitivity of the estimates to the amount of fiber released.

Response: With respect to the differences between our estimates, there is some uncertainty, and different methods were used. We feel that our estimate is an accurate reflection of a conservative risk profile. There are confidence bounds on our estimate and I think it's possible that the results shown by the other organization will fall within those confidence bounds. With respect to the second question, the purpose of the sensitivity analysis is to identify the possible variations in risks that might be due to uncertainty in the variables of interest, for example, the percentage of fibers released. This is still a question, and it is being investigated. We are attempting to see what the effect would be on a risk profile of varying the inputs. You can assume a 20% fiber release or you can assume a 1% release; the question is: What is the impact upon the total risk? As Dr. Kalelkar mentioned earlier, even with substantial uncertainty bounds, the risk profile still allows you to say something about the risks. It still may allow decisions by the appropriate decision makers regarding the risks.

Comment: . . . the risk analysis says the problem falls somewhere between no problem and a major problem.

Response: I don't think we ever said that there was a major problem. We're showing that with some probability you could do a million dollars worth of damage. As to whether that's a problem that we should be concerned about or not, we haven't judged.

Response by Israel Taback: I thought the point of the comment was that one of the computations indicated no problem, and the other one did indicate somewhat of a problem. Actually, I'm surprised that the two answers are so close. If you take the ORI Washington statistics and multiply by the ratio of operations in the nation to those in Washington, and then multiply by 10, the difference between 1985 and 1993, the expected values per year come out to be about the same as the ADL number.

Question: Which of the variables which enter into the risks has the greatest effect upon the risks?

Response: We are currently investigating that in a sensitivity analysis and in our final report we will try to indicate which of the variables has the greatest impact. It's a little early to say at this point, but you got some indications from what was shown. For example, the transfer functions vary over 3 to 4 orders of magnitude. As we've indicated, we've always used the highest transfer function in the spirit of trying to be conservative, and get an overestimate initially rather then an underestimate. So that is one area which can influence it. The other is that economic analysis was done in a relatively straightforward manner and requires substantial additional work. The actual losses that might be encountered could be quite different.

We have done some sensitivity analyses on the transfer function, and it turns out that if you go down to the minimum of the range, the expected value of the risk is diminished by about 80%.

Question: I realize for purpose of the analysis that it is necessary to assume as you did, (1) all failures occur immediately, and (2) you can't start out by trying to assess the cost of the secondary failure downstream, such as the cost of being without telephone service or computer service. Yet it seems to me a very real possibility that several hours after the accident or even a day after the accident the redistribution is a very significant problem. You may have a small immediate cost of 10,000 dollars whereas the secondary down the line costs might be millions. Is somebody pursuing that type of analysis to see how severe those problems can be?

Response: Yes, we intend to give that additional thought. We just haven't had a chance to do it all yet. We are pursuing that.

Question: On your third curve from the last, that showed the possible dollar value of each incident, you showed a rather large spread from each of the points. I notice you took the zero as your starting point and for your first spread you went very near the top of the spread and for the second spread you were at the middle. If you had redrawn that curve so you would cross those spreads towards the center of both you would come out more with a straight line so that the future accidents could have amounted to somewhat higher levels of money, instead of one times ten to the sixth perhaps closer to ten to the seventh or eighth. I was just curious why you chose to draw more a downward pointing curve rather than more of a straight line?

Response: Well, there are two parts to that answer. If you're talking about the risk profile itself, you realize that on the left-hand side, it can never go above one. So, there is a constraining factor there. Then, as Dr. Karen Credeur pointed out, there is a different amount of conservatism applied to different portions of the curve. So sometimes we might have an estimate that could err larger in the upside risk if you will, than in the downside risk, and sometimes the other way around. They don't have to be centrally located in respect to their actual value as shown. It is properly adjusted for that and the curve you saw was our best estimate of the risk.

Question: Question related to the effect of the size of the carbon fibers.

Response: In actuality, fiber size makes some difference in the amount of damage that can occur, the way they disperse, and so on. In this analysis, we assumed that they were between 7 and 10 millimeters long.

Another open area which I guess we neglected to mention is the fact that we were dealing really with dispersion of single fibers. It was pointed out in previous presentations that you can have lint or clumps; this has not been looked at.