Perspective on the Results

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This paper is an effort to put some of the things that we have found from the NASA study into perspective. I would like to start out by covering some issues that were not covered in detail in our discussions (Figure 1). One of the questions that we were originally asked was: is additional aircraft protection required? You should have noticed that air transport aircraft were included in the calculations of the risk profile, and, in fact, in the specific examples that were cited, you noted that the expected losses at the various airports were quite low. Independently, we have had Boeing, Lockheed, and Douglas analyzing each of their own aircraft, using fiber dissemination footprints that have been calculated for crash fires and explosions on an airport where quite high exposures have been predicted. We found, in the analysis of the aircraft systems, that the key issue that prevented aircraft from being considered perhaps totally invulnerable was the fact that occasionally aircraft avionic bay doors would be open. On those occasions, we found that the interior exposure was sufficient to fail one or two pieces of avionics equipment in a fleet of aircraft that were sitting on the ground where an aircraft accident had occurred. That fact suggests that some precautionary measures may be prudent. If you have an aircraft crash fire releasing carbon fibers on an airport it makes sense to close the doors on the aircraft and not allow interior exposure to carbon fibers.

We have also looked at fire-release strips as a possible cause of power interruptions. Our calculations show that only at a probability of one chance in a thousand will we be able to get power interruptions from the kind of composite strips that were generated at China Lake and Dugway Proving Ground tests. This kind of failure, incidently, is equivalent to the interruption that occurs when a squirrel shorts a powerline to ground.

The generation of composite strips and, in fact, the amount of carbon fiber debris that is actually found after a fire, suggests very clearly that carbon fiber debris should be cleaned up. Dr. Bell's paper, Reference 1, showed the mass balance distribution of carbon fiber from burned composites. The amount of debris or residue was quite large, in fact, many times the amount of free fiber that is released by the burn. Therefore, prudent practice would suggest that the aircraft owner go in and clean up the composite debris of an accident to prevent a secondary release of fibers. At this time it is the responsibility of an aircraft owner to clean up an accident so the extension of that requirement to include composite debris would be normal practice.

It should be pointed out that some unique carbon composites could be developed in the future. The term unique here applies to a carbon composite which has a release characteristic different from the average. Dr. Bell's paper described one composite with such a characteristic. It is possible that in the future, as additional carbon composite concepts are developed, other unique composites could turn up but we have also developed some test methods that are appropriate for evaluating the fiber release characteristics. We think that these methods will be used to analyze the potential release from new concepts.

As for the assumptions inherent in this study, Figure 2 lists those that we feel result in a conservative final answer. Our analysis assumptions have included one percent release for a crash fire and 3 and a half percent release for a crash explosion. This assumption was based on the amount of material that we had found to be released from specimen tests. Based on the data recently acquired from the outdoor tests, we see considerably less release than that. Therefore we feel that our estimate is quite conservative here.

In the case of the explosive release model that A. D. Little uses (Reference 2), the analysis is considered to be conservative, that is it gives excessive fiber concentrations because it is really a ground-level fiber release and not an explosive plume that is carried up in the developed fire plume.

Our analysis at this point ignores the filter effect on fiber length. Dr. Elber's paper (Reference 3), showed that not only did filtration reduce the number of fibers that entered into either cases or buildings, but that it also provided an effective shortening of the fiber length spectrum. This phenomenon has a strong effect on the failure rate, as shown by Mr. Taback's paper (Reference 4). Therefore the fibers that enter a filtered enclosure are not as damaging as the fibers exterior to that enclosure. Our analysis has not included that effect.

We have based our equipment vulnerabilities on tests done with 1970 technology avionics and electronics. And as we see the future, electronics, avionics, and computer design and packaging is aiming towards low power, well-protected circuitry. Some of the more recent aircraft designs are utilizing totally air-conditioned avionics bays, primarily to increase the effective reliability of avionics. This effect is not considered in our analysis.

The equipment failure model over-predicts the failure rate for multi-fiber sensitive equipment. Test data described by Mr. Taback (Reference 4) shows the multi-fiber effect on equipment failure rates. There is a lot of equipment that we know requires multiple fiber contacts to initiate failure. In fact, anytime the electrical contact spacing exceeds the fiber length, shorting can occur only when two or more fibers bridge the space. From a practical sense, for this analysis, we don't think it is practical to try to even identify the multi-fiber sensitive equipment.

A final item on this list of conservative assumptions is that the analysis is made assuming that no precautions are taken against a known carbon fiber accident. Earlier, I pointed out that aircraft avionics can be effectively protected, when a crash fire occurs in an airport, by simply closing the avionics bay doors to prevent penetration by carbon fibers. Also, Mr. Taback (Reference 4) pointed out that in the worst case, the range of a scanning beam M.L.S. landing aid would be effectively reduced by 45% if an approaching aircraft was flown directly down the center of a fire released carbon fiber plume. Obviously, even present operating rules would not allow a second aircraft to approach an airport directly over a burning aircraft where the crash cause was undetermined and could have been related to the operating condition of the landing aid. These examples of prudent precautions will obviously be expanded if cost effective measures are found suitable even with the current level of projected risk.

There are limitations in the analysis (Figure 3). One is that the data sample is small. We have only about 250 specimen burns in which to quantify the fiber release data. In addition, we have five outdoor tests in the most recent Dugway Proving Ground experiments that quantify the carbon fiber release. It is a small sample of data upon which to base our analysis. In addition, the total variety of equipment that we have examined for fiber vulnerability, either in the chamber here at Langley, at the Army Ballistic Research Laboratory, or in the work that has been done by the Department of Commerce Bureau of Standards, consists only of about 150 pieces of equipment. We have had to have quantified the vulnerability of all of the equipment considered nationally from a very limited number of tests. We are aware of and have considered other data in our analysis which is not available to the public.

One limitation that is important to recognize is that the structural concepts tested are considered typical of carbon composites of the future. Basically we have made the assumption that the structural concepts that we have available to us today are those which are going to be used in composite applications on aircraft built in the future.

We have not considered redissemination for the reasons that Dr. Elber (Reference 3) presented in his paper. In addition, a test in a clean wall and floor room showed that even a fan recirculating fibers increased exposure only about a factor of two. Both results indicate redissemination should not be a significant problem.

We believe that an accident clean up should include the accident debris, and as an assumed prudent measure, that would be a limitation of this analysis.

It should be pointed out that this analysis is limited to accidental release from civil aircraft and to damage done to residential, public, utility, commercial and industrial installations. What has been left out? The answer is very simple, what has been left out is the potential risk from military aircraft crashes and the potential damage to military sites. That is the subject of Department of Defense analyses.

It is appropriate to review the key findings of this study (Figure 4). We know that the release of fibers does require agitation of the composite residue. We see, from the evidence that we have, that a substantial portion of the carbon fiber is oxidized away. We see, from our specimen tests, that about one percent of the available fiber is released, but in our outdoor tests, we found only about 0.13 percent released or about a factor of eight conservative from our assumptions in our risk calculations. One final point is that most released single fibers are very short. This point should be amplified because we have had some specific examples of released fibers where the averages are longer than what we used in our analysis. A look at the sensitivity of the risk estimates to the average fiber length is appropirate. If we normalize the risk at the 3 mm length used in the risk calculations, we can study the effect of fiber length on the risk. In our large scale tests in the Dahlgren shock tube, we found a mean fiber length of 2 millimeters. Now perhaps that is because of the extreme agitation of operating on the composite material with the rotisserie. However, in the outdoor tests we found a mean fiber length, in the worst case, of about 5 millimeters. Now, what is the effect of the mean fiber length on the mean exposure level for failure? Israel Taback (Reference 4) pointed out several possibilities. One possibility is that E bar is proportional to one over the length. Another possibility is that E bar is proportional to one over the length cubed. Figure 5 shows the effect of these two variations in the mean exposure to failure on the normalized risk assuming all equipment follows either one law or the other. The notation indicates the lengths obtained from the large scale tests. It is appropriate to point out that at least we have bracketed the large scale test data. The actual value of the risk could vary at the most, as a result of fiber length, by a factor of 2. Considering the fiber release characteristics as a whole, including percentage released as well as length, it would appear that we over-estimated the potential damage by somewhere between a factor of 4 and a factor of 8.

If we review the key findings in the area of vulnerability of equipment, (Figure 6), we find that the damage done by released fibers is not as severe as once thought. The reason is that equipment vulnerability is lower for the currently acceptable structural fibers than for the very highly graphitic fibers once considered. If highly graphitic fibers (possessing modulus at elasticity two times that obtainable with current structural fibers) are found acceptable in the future, the base vulnerability level would have to be reevaluated. We find from our test data that vulnerability of domestic and industrial electronics and avionics is very low. The vulnerability of industrial electronics and avionics is low primarily because they are conformly coated and well protected. In addition our industrial power arc studies show that power vulnerability is low and unlikely to cause damage when properly fused. We have found that 110 volt motors and home appliances can not be hurt by carbon fibers.

Our present assessment of the risk, using current estimates of the carbon fiber release from civil aircraft and conservative vulnerability data, indicated that the expected annual cost is insignificant (Figure 7). A comparison of the results from the A. D. Little and the ORI studies (Figure 8) shows quite reasonable agreement. While the details of the risk profiles are slightly different, the expected annual cost for air transport for either is under $500. Adding the expected dollar loss from crash fires of carbon composite general aviation aircraft adds about 50% to the mean cost. Compared with the mean cost of the aircraft accidents the expected annual cost is an insignificant number. The FAA study of 1966-1975 aircraft accident costs (Reference 5) showed that the costs of air transport aircraft accidents range from less than a million dollars to nearly fifty million dollars (non-fire accidents are included). The mean cost of those accidents where the aircraft sustained at least substantial damage ranged from 5 million dollars for small jet aircraft to in excess of 10 million dollars for large jet aircraft. Therefore, considering the annual number of aircraft crashes, the $500 annual potential damage from released carbon fiber must be compared with annual aircraft crash costs of nearly 100 million dollars (based on 1974 dollars). Considering that comparison,the worst case, low probability event is basically a low cost event. Figure 8 shows that there is only about one chance in 2000 of exceeding $150,000 damage annually. Our studies show that there is no need for additional protection of civil aircraft avionics, and the potential shock hazard is insignificant, hence risk to life should not be a consideration in carbon fiber applications.

In conclusion, we have some work to do (Figure 9). We have completed the planned work on the agreed to schedule. We will publish this conference proceedings, complete and publish the analysis of our large scale outdoor tests, and complete our final NASA summary report. NASA efforts in the carbon fiber hazard area will be completed when all NASA studies are published.

References

1. Bell, Vernon L.: Release of Carbon Fibers From Burning Composites. Assessment of Carbon Fiber Electrical Effects. NASA CP-2119, 1980 (Paper 3 of this compilation).

2. Fiksel, J.; Rosenfield, D.; and Kalelkar, A.: Assessment of Risk Due to the Use of Carbon Fiber Composites in Commercial and General Aviation. Assessment of Carbon Fiber Electrical Effects. NASA CP-2119, 1980 (Paper 9 of this compilation).

3. Elber, Wolf: Dissemination, Resuspension, and Filtration of Carbon Fibers. Assessment of Carbon Fiber Electrical Effects. NASA CP-2119, 1980 (Paper 4 of this compilation).

4. Taback, Israel: Evaluation of Equipment Vulnerability and Potential Shock Hazards. Assessment of Carbon Fiber Electrical Effects. NASA CP-2119, 1980 (Paper 5 of this compilation).

5. Fallon, William L.: Cost Analysis of Aircraft Accidents. Proceedings of the 31st Annual International Air Safety Seminar, Flight Safety Foundation, Inc., Nov. 1978, pp. 72-82.

ADDITIONAL AIRCRAFT PROTECTION IS NOT REQUIRED

PRECAUTIONARY MEASURES ARE PRUDENT

FIRE RELEASED STRIPS HAVE LOW PROBABILITY OF CAUSING DAMAGE

CARBON FIBER DEBRIS SHOULD BE CLEANED UP

UNIQUE CARBON COMPOSITES COULD BE DEVELOPED IN THE FUTURE

TEST METHODS ARE DEVELOPED FOR FIBER RELEASE EVALUATION

Figure 1.- Issues not covered in detail.

ANALYSIS ASSUMPTIONS 1% FIRE, 3 1/2% EXPLOSIVE RELEASE

EXPLOSIVE RELEASE MODEL GIVES EXCESSIVE FIBER EXPOSURES

ANALYSIS IGNORES FILTER EFFECT ON FIBER LENGTH

EQUIPMENT VULNERABILITIES BASED ON 1970'S TECHNOLOGY

MODEL OVERPREDICTS FAILURE RATES FOR MULTI-FIBER SENSITIVE EQUIPMENT

NO PRECAUTIONS TAKEN AGAINST KNOWN CF ACCIDENT

Figure 2.- Conservative assumptions.

THE DATA SAMPLE IS SMALL

STRUCTURAL CONCEPTS TESTED ARE TYPICAL OF THE FUTURE

REDISSEMINATION IS NOT CONSIDERED

ACCIDENT CLEAN UP INCLUDES COMPOSITE DEBRIS

ANALYSIS LIMITED TO:

- ACCIDENTAL RELEASE FROM CIVIL AIRCRAFT
- DAMAGE TO RESIDENTAL AND PUBLIC, UTILITY, COMMERCIAL AND INDUSTRIAL INSTALLATIONS

Figure 3.- Limitations in analysis.

- REQUIRES AGITATION OF RESIDUE
- SUBSTANTIAL PROPORTIONS ARE OXIDIZED AWAY
- 1% OR LESS RELEASED AS SINGLE FIBERS IN SPECIMEN TESTS
- 0.13% OR LESS RELEASED IN LARGE-SCALE OUTDOOR BURNS
- MOST RELEASED SINGLE FIBERS ARE VERY SHORT

Figure 4.- Key findings in carbon fiber risk analysis. Release of fibers by fire.

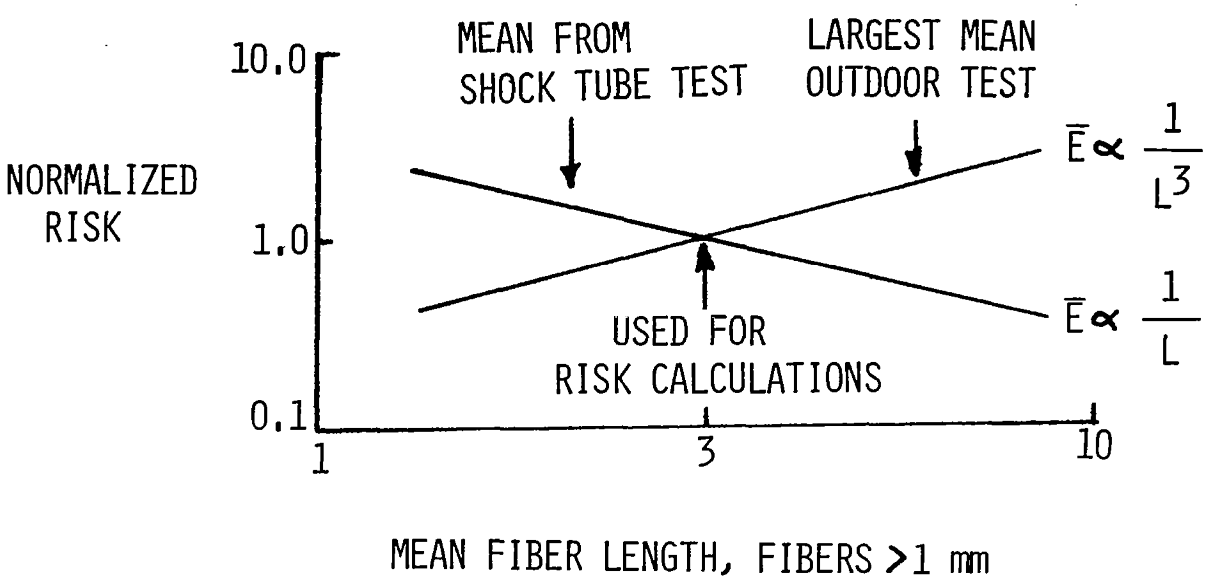

Figure 5.- Sensitivity of risk calculation to average released fiber length.

- LOW FOR CURRENT STRUCTURAL FIBERS
- HIGHER FOR HIGHLY GRAPHITIC FIBERS
- VERY LOW FOR DOMESTIC, INDUSTRIAL ELECTRONIC AND AVIONICS
- LOW FOR POWER SYSTEMS
- ZERO FOR 110-VOLT MOTORS AND HOME APPLIANCES

Figure 6.- Key findings in carbon fiber risk analysis. Vulnerability of equipment.

- THE USE OF CONSERVATIVE ESTIMATES OF ACCIDENTAL CF RELEASE FROM CIVIL AIRCRAFT AND CONSERVATIVE VULNERABILITY DATA INDICATES THAT:
  - THE "EXPECTED ANNUAL COST" IS INSIGNIFICANT
  - THE WORST CASE, LOW PROBABILITY EVENT IS A LOW COST EVENT
  - NO ADDITIONAL PROTECTION OF CIVIL AIRCRAFT AVIONICS IS REQUIRED
  - THE POTENTIAL SHOCK HAZARD IS INSIGNIFICANT - HENCE RISK OF LIFE IS NOT A FACTOR

Figure 7.- Key findings in carbon fiber risk analysis. Present assessment of risk.

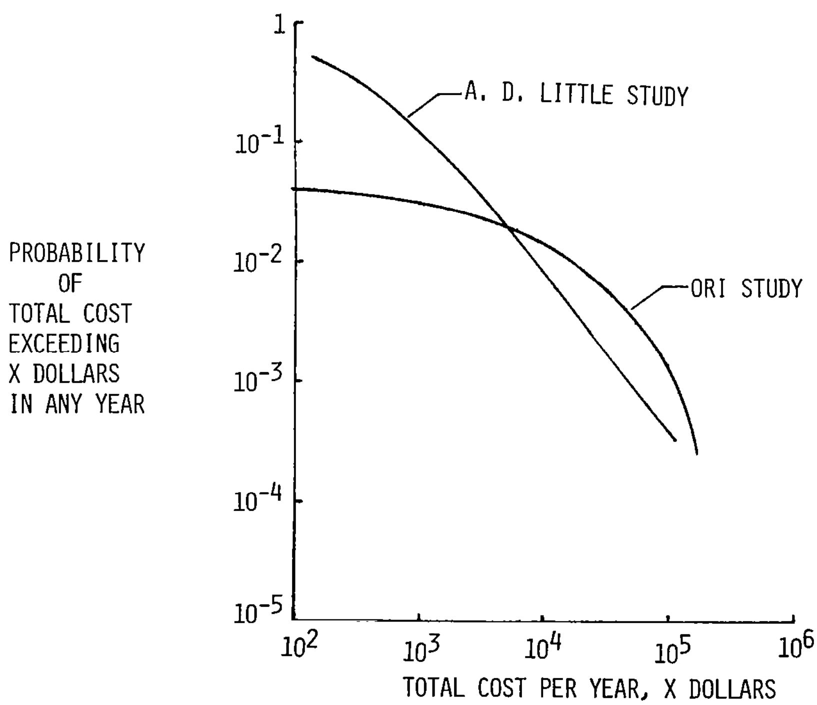

Figure 8.- National annual risk profile. Carbon fiber released from commercial air carrier accidents. (1993 CF usage.)

- REMAINING WORK

  PUBLISH CONFERENCE PROCEEDINGS

  FINAL ANALYSIS OF LARGE-SCALE OUTDOOR TESTS

  FINAL NASA REPORT ON PUBLIC RISK DUE TO ACCIDENTALLY RELEASED CF FROM CIVIL AIRCRAFT

- NASA EFFORT WILL BE COMPLETE UPON PUBLICATION OF ALL TEST AND STUDY RESULTS

Figure 9.- Conclusion of carbon fiber risk assessment.