9

END-TO-END TESTING

Richard A. Pride
NASA Langley Research Center

With all the testing that has been done to determine vulnerability and failure of equipment, we still have not identified an occasion in which electrical or electronic equipment has failed because of carbon fibers released by the burning of composite parts in an aircraft-fuel fire. Therefore, the principal objective, figure 1, of the kinds of demonstration testing that I will discuss is to try to verify whether or not carbon fibers that are released by burning composite parts in an aircraft-fuel fire can produce failures in electrical equipment. A secondary objective is to experimentally validate the analytical models for some of the key elements in the risk analysis; source, dissemination, transfer function, and vulnerability of equipment.

The approach to this demonstration testing (figure 2) is two-fold; we are going to be conducting limited end-to-end tests at Dahlgren, Virginia, in the Naval Surface Weapons Center shock tube, and we are planning for some large outdoor burn tests at the Army's Dugway Proving Ground in Utah. There are certain qualifications for the large outdoor tests which will be discussed later. For now, I want to indicate that we do have these two types of tests in various stages of planning and development.

RISK ANALYSIS DEMONSTRATION TESTING

OBJECTIVES

- VERIFY WHETHER CARBON FIBERS RELEASED BY BURNING COMPOSITE MATERIAL PARTS IN A REAL AIRCRAFT-FUEL FIRE WILL PRODUCE FAILURES IN ELECTRICAL EQUIPMENT

- EXPERIMENTALLY VALIDATE ANALYTICAL MODELS FOR
    - SOURCE
    - DISSEMINATION
    - TRANSFER FUNCTION
    - VULNERABILITY OF EQUIPMENT

Figure 1

RISK ANALYSIS DEMONSTRATION TESTING

APPROACH

DAHLGREN NSWC - SHOCK-TUBE TESTS

ARMY DUGWAY PROVING GROUND - LARGE OUTDOOR BURN TESTS

Figure 2

Our objectives at Dahlgren (figure 3) are to verify the vulnerability of equipment to fire-released fibers and to identify some of the problems that would be associated with end-to-end tests that will be even more significant if we go outdoors. Our approach is to develop a burn and exposure facility in the shock tube for doing these end-to-end tests and then to subject typical vulnerable equipment to critical exposures of fire-released fibers along with the associated soot and smoke. When jet fuel is burned in open fires, a lot of smoke and soot is generated due to the fuel-rich type of combustion. The photograph from Vernon Bell's source paper of the outdoor pool fire at China Lake showed that it was certainly generating a lot of smoke. It was not clean burning by any means. Our smaller JP-1 fuel fires in the Dahlgren shock tube were also very smoky and sooty.

The Dahlgren shock-tube tests provide an opportunity to experimentally validate only a few of the elements of the risk analysis flow chart, figure 4, but these are probably the most important elements. For the source fire, we are using a controlled burning rate JP-1 commercial jet fuel. There is not much difference in combustion with JP-1, JP-4, or JP-5. We did try to make it realistic for the civil aviation situation by specifying JP-1. We are going to burn graphite composite parts from structural test programs at Langley. Combustion temperatures in the vicinity of those parts will be controlled from about 930 to 980°C

DAHLGREN NSWC - SHOCK TUBE TEST

OBJECTIVES

- VERIFY VULNERABILITY OF EQUIPMENT TO FIRE-RELEASED FIBERS
- IDENTIFY PROBLEMS ASSOCIATED WITH END-TO-END TESTS

APPROACH

- DEVELOP BURN-EXPOSURE FACILITY FOR END-TO-END TESTS
- SUBJECT VULNERABLE EQUIPMENT TO CRITICAL EXPOSURES OF FIRE-RELEASED FIBERS WITH ASSOCIATED SMOKE AND SOOT

Figure 3

RISK ANALYSIS FLOW

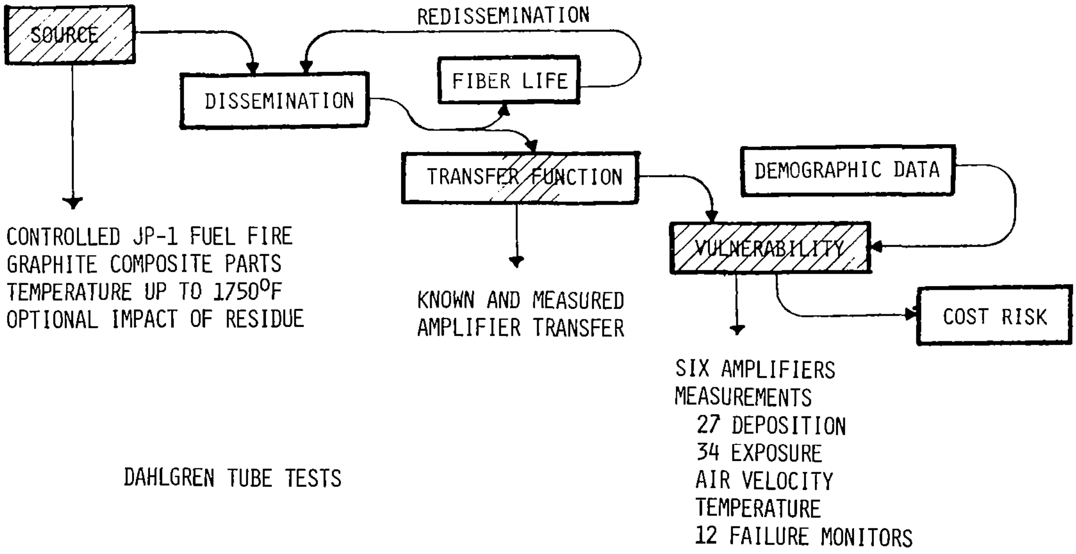

Figure 4

($1700-1800^{\circ}F$), and we will have a facility that has the option of agitating the residue after it has been burned, in order to study the difference in the amount of fibers that are released from just a burn compared to those released from an agitation towards the end of the burn. Because we are working inside a tube, we will not be getting much information about dissemination. We will not be able to measure plume parameters or downwind transport of the fibers in the sense that we can verify models that are developed for outdoor atmospheric dissemination. We will be disseminating fibers, but they will be constrained to stay within the walls of the shock tube at Dahlgren.

We will be getting some limited transfer function data, primarily the transfer function that is associated with the fibers being pulled inside the case of the fan-ventilated stereo amplifiers that we expect to be exposing for vulnerability at the target table in the shock tube. Our present plans are to expose a sample of six amplifiers. Failure characteristics have been established for these amplifiers based on chamber testing. They are reasonably low cost pieces of electronic equipment, and we think we understand pretty well the kinds of failure modes that are most apt to occur when they are exposed to carbon fibers. These amplifiers are representative of a class of generic circuit board equipment. They will allow us to determine failure rates when exposed to fire-released fibers for comparison with those rates that have been previously established for chamber-released fibers. In the shock-tube tests we will be measuring both deposition and exposure levels for fibers in the vicinity of the amplifier locations. We will be measuring air velocity, air temperature, and fire temperature, and we will have up to 12 failure monitors associated with the 6 amplifiers.

Figure 5 is an aerial photograph of the conical shock tube at Dahlgren which was built back in the mid-60's to study the effect on equipment of the pressure wave from a simulated atomic blast. The facility is approximately 0.8 km (a half-mile) long. It starts with four 16-inch naval gun barrels butted end-to-end, and expands to a 7.3-m (24-foot) diameter tube at the exit end. We are using approximately half the length, starting opposite the white building shown in figure 5, where we opened up the tube by taking out a couple of sections to provide an inlet. The fire pan for the simulated aircraft-fuel fire is located about 60 m (200 feet) from the inlet. The airborne effluent from the fire is pulled out through a filter system by a group of exhaust fans at the exit end of the tube. The filter system has been shown to filter out all the fibers and the heavier particles of soot, and essentially allow the discharge of only very-fine-particle soot and smoke into the atmosphere. We have monitored the particle content of the filtered smoke, and we have determined that the size of soot particles is less than 4 microns in diameter. We think our filtering system is very effective in taking out any particle sizes greater than 4 microns.

DAHLGREN NSWC - SHOCK TUBE

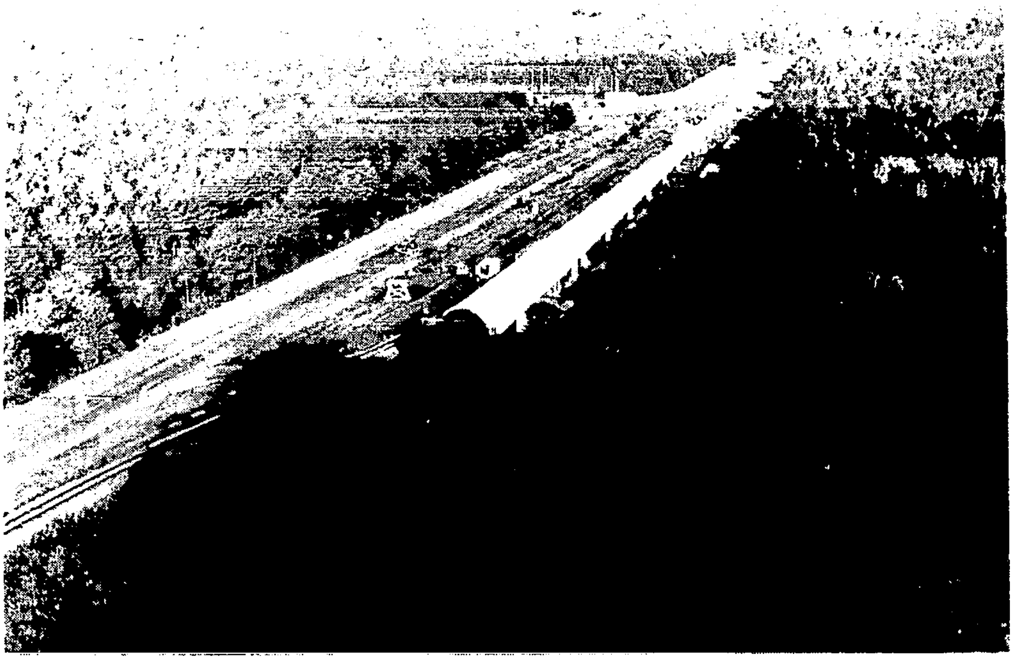

Figure 5

Figure 6 is a photograph of the inlet end of the tube. At this point, the cross section of the tube opened to the atmosphere is 3 m (10 feet) in diameter, which permits sufficient fresh air to be drawn in to feed the fire. The fire pan is shown in figure 7. We have two sizes of pan built up together, a 1.2-m (4 feet) square inner pan and a 2.4-m (8 feet) square outer pan, giving us the capability of building two different size fires, depending on the particular experiment requirements. Fuel is pumped at a controlled rate in through the bottom of the pan, which is kept flooded with water. Behind the fire pan is an array of tubing supporting a series of thermocouples that were used to survey and monitor flame temperature at locations downwind of the fire. Figure 8 is a photograph taken, from inside the tube, of one of the development fires. Modifications made since that time include a chimney around the fire pan to get the fire to stand more nearly vertical. With the addition of a chimney we have been able to provide a larger area in the flames in the 930-980°C (1700-1800°F) temperature range in which to mount the composite specimen for burning.

The combustion products and fibers from the burned composite are pulled through the tube approximately 210 m (700 feet) to the location of the target table, figure 9. This is a table that is about 5 m (16 feet) wide and 9 m (30 feet) long. The vulnerable electronic equipment will be exposed on this table and connected

SHOCK-TUBE INLET

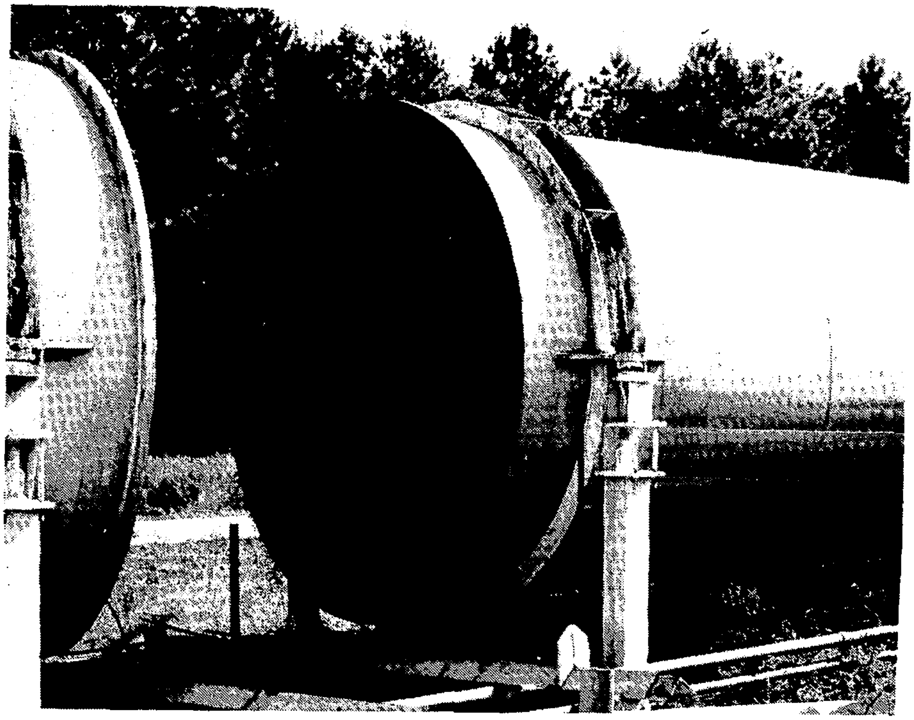

Figure 6

SHOCK-TUBE FIRE PAN

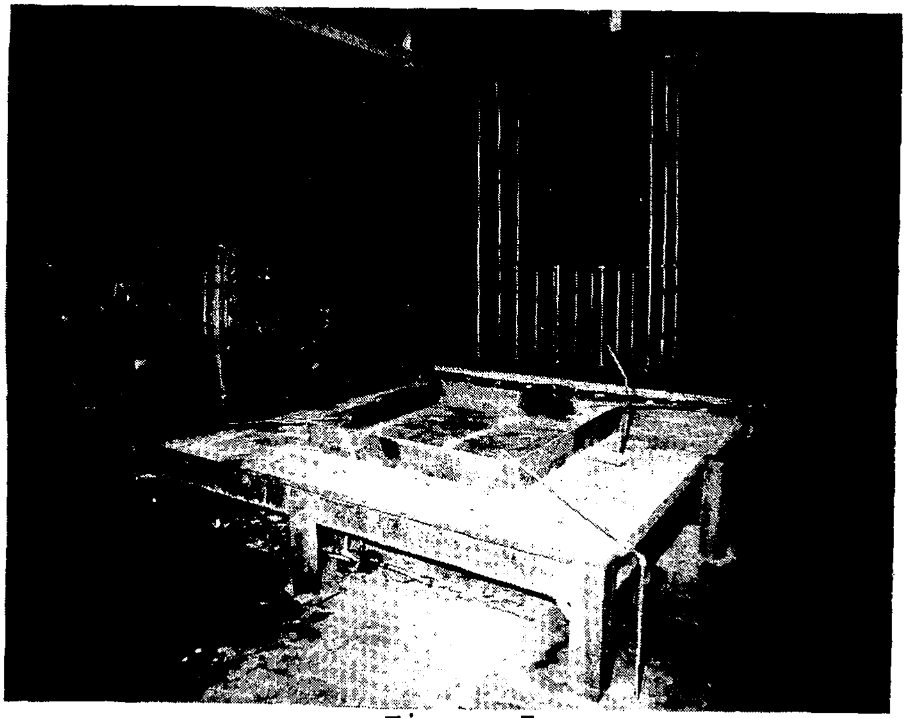

Figure 7

DEVELOPMENT FIRE IN SHOCK TUBE

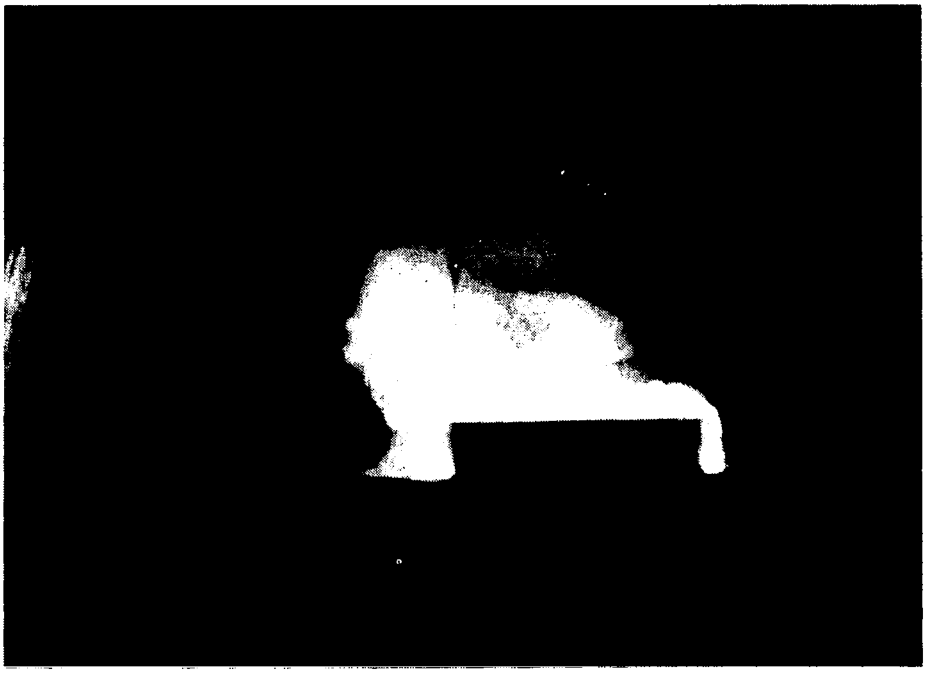

Figure 8

SHOCK-TUBE TARGET TABLE

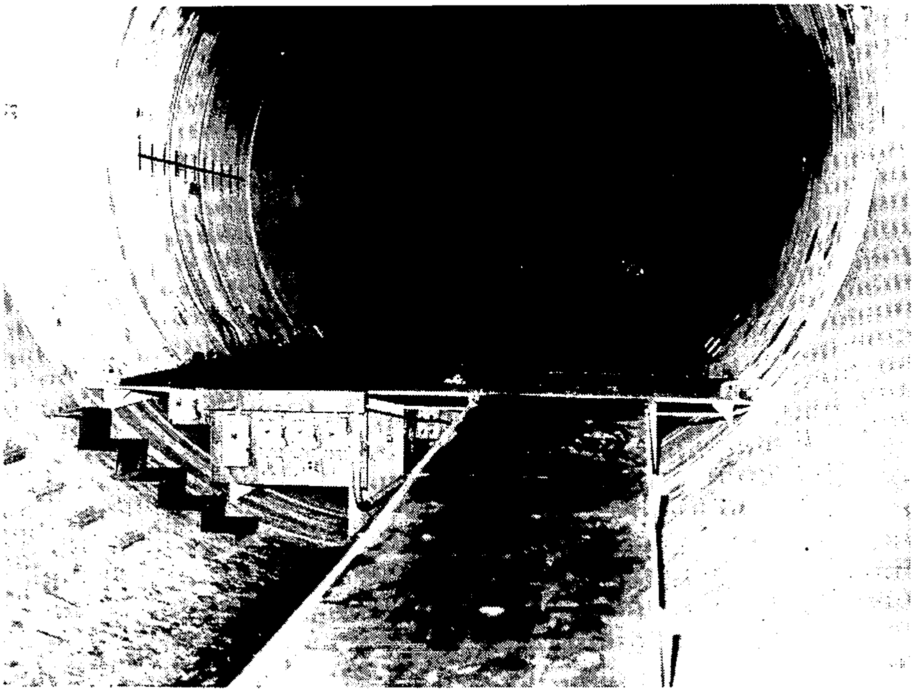

Figure 9

to the electrical switch boxes shown. There are some wires standing up from the surface of the table. Those wires hold the sticky cylinders that we use to measure the fiber exposure. A propeller anemometer is also on the table to measure local air velocity. This particular view is looking up the tube towards the location of the fire pan. The opening that can be seen at the end is where the section of the tube was removed for the inlet. Note that there is an indication of deposition of soot on the upper portions of the tube wall. There appears to be a fair amount of stratification in the airflow coming down the tube. The bulk of the soot tends to be near the top, but there is an ample deposition of soot all over the table and on the floor of the tunnel in that location.

Figure 10 is a picture of the filtering system. In the background is a framework which supported an initial attempt at building a filter wall which consisted of fiberglass furnace filters. They were very effective in taking out particles of soot and fibers; however, they became clogged in about three minutes of operating time, stopping the airflow and choking the fire upstream. We are looking for operational times on the order of 20 minutes on a particular burn. In the foreground is the current filter system which is basically a fire-fighting type water-spray fogging nozzle. A fire hose is connected to the inclined supply pipe supported on the scaffold. The nozzle is at the upper end. This nozzle emits an effective fog of fine par-

SHOCK-TUBE FILTERING SYSTEM

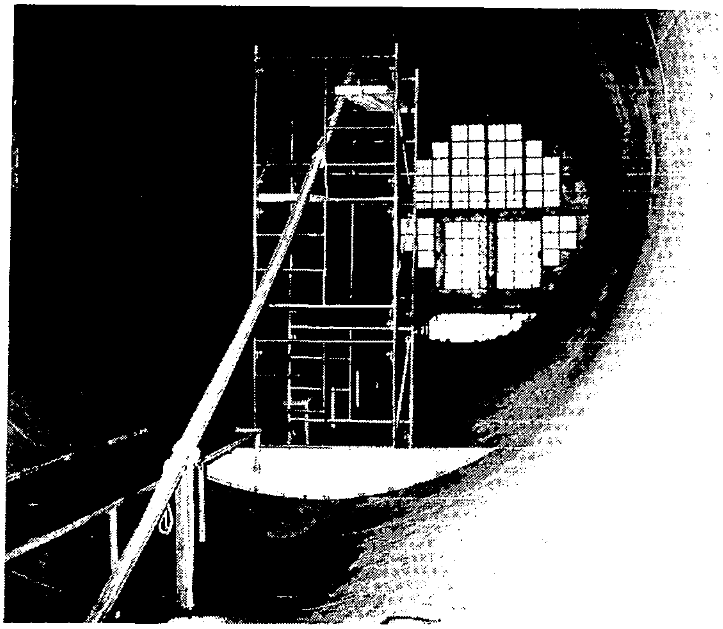

Figure 10

ticle water which washes fibers and soot particles greater than 4 microns in diameter out of the airstream. We think it also washes out a considerable number of particles under 4 microns, but it does not capture all of them. The washed out fibers, soot, and water collect on the floor of the tube and then are filtered between a series of baffles shown in figure 11. We have a skimming system which allows the water to run under these baffles in a controlled manner and retains the soot and fibers that are floating on the surface. The water drains through a hole in the floor of the shock tube. We have been monitoring the output of particles and fiber by deposition on sticky cylinders in the exhaust end of the tunnel. The filtering system has been working very effectively.

Figure 12 is a photograph of the exhaust end of the shock tube. Six exhaust fans were installed in the bulkhead in the end of the tube. Access to instrumentation is through a steel door which is closed and locked prior to testing. The six exhaust fans have variable speed control, providing a wide range of airflow ranging from essentially zero up to a maximum of about 3400 cubic meters per minute (120 000 cubic feet per minute). Typically we are operating at about 1130 cubic meters per minute (40 000 cubic feet a minute) which gives us an average velocity over the target table of about 0.5 m/sec (1.2 miles per hour).

DRAIN BAFFLES IN SHOCK TUBE

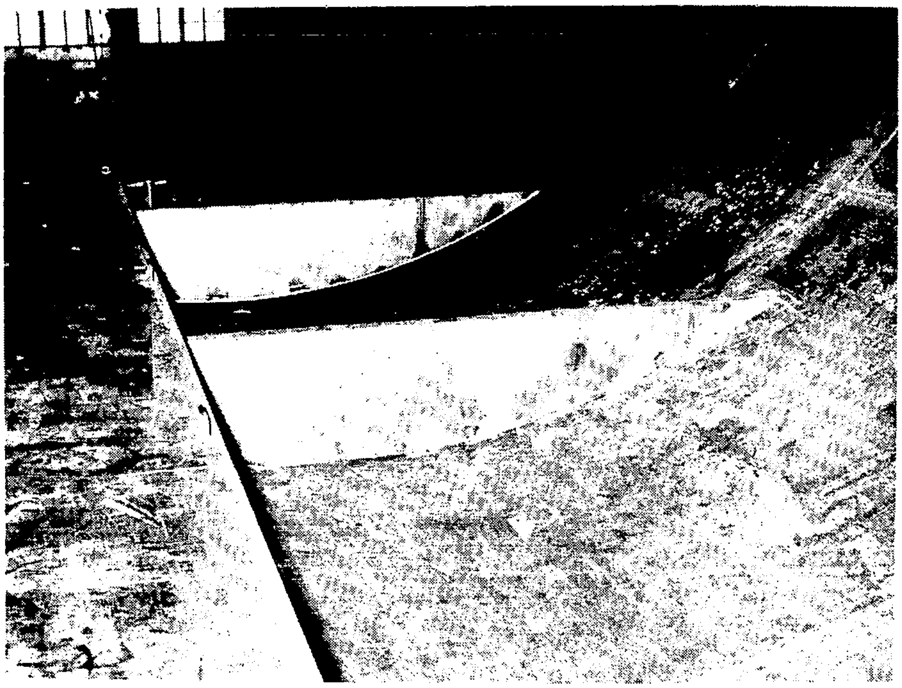

Figure 11

SHOCK-TUBE EXHAUST

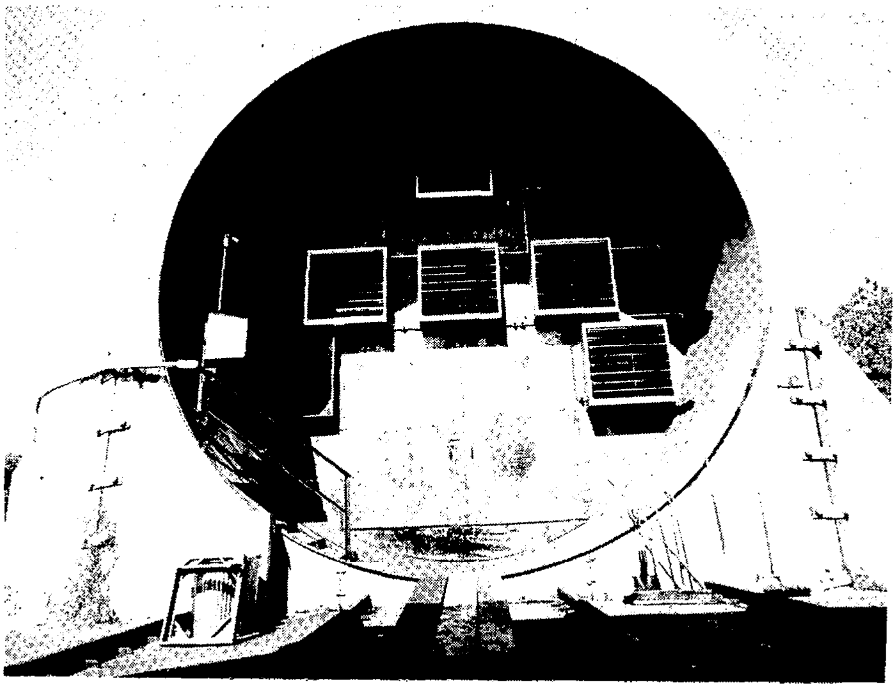

Figure 12

One of the first graphite composite samples that was burned in the shock-tube fire was monitored for fiber release with sticky cylinders at the target table. Sticky cylinders are made by rolling a 50-mm (2 inch) square piece of sticky paper into a cylinder with the sticky surface on the outside and mounting it on a wire with the cylinder axis perpendicular to the airflow. Figure 13 is an enlarged photograph of a portion of one of the sticky cylinders after exposure and after cutting it open to flatten it. This part of the sticky cylinder shows a cluster of about six fibers ranging in length from 3 to 15 mm. Those six fibers on that particular sticky cylinder represent an exposure of about 10^4 fiber-seconds/cubic meter for a 20 minute fuel burn. That is not enough for the levels that are needed to generally produce electrical failures, but considering that it was our first attempt at burning composite in that facility, we were quite encouraged.

Figure 14 is a photograph of a circuit board out of an amplifier that failed in chamber testing. It represented an electrical short caused by a fiber getting across a critical element in the amplifier, which then caused both the transistor and a resistor to burn out. There is a lot of smoke, oil, and soot associated with the burn out, which created a failure in that particular case and is an indication of the kinds of failures that can occur on this type of equipment in chamber testing. I should say that, in connection with our preparation

GRAPHITE FIBERS DEPOSITED FROM FIRST COMPOSITE SPECIMEN BURNED IN JET FUEL FIRE AT DAHLGREN

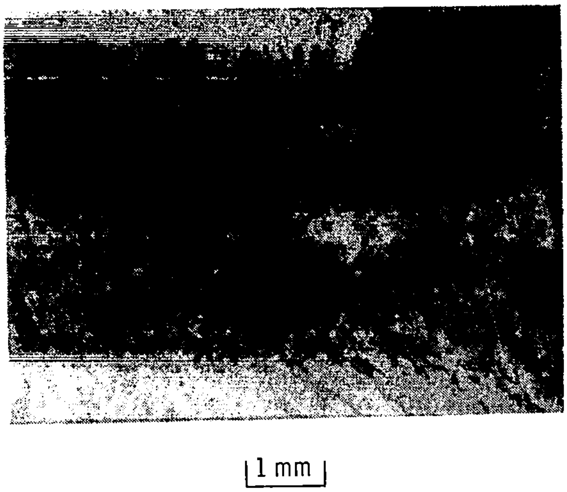

Figure 13

AMPLIFIER CIRCUIT BOARD FAILURE

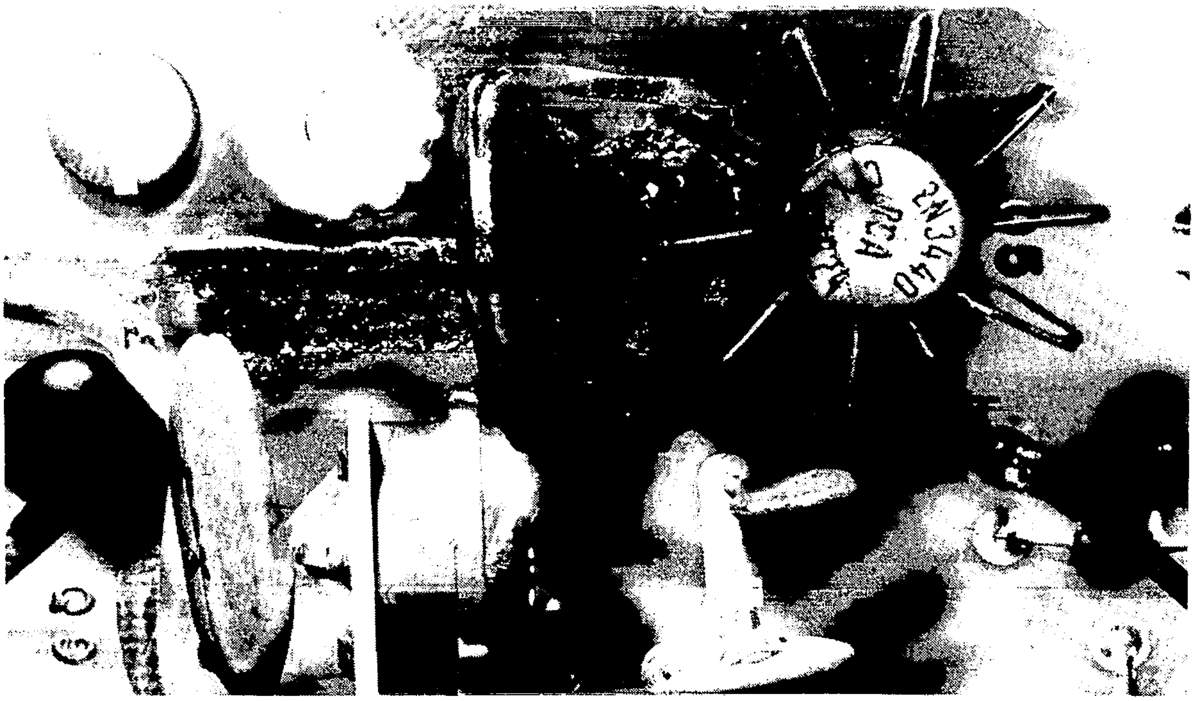

Figure 14

for testing in the shock tube, we have exposed these amplifiers without fibers in the tube for periods up to an hour to determine if smoke and soot would cause a failure. There was no indication of failure.

The typical failure curve that has been obtained on these stereo amplifiers in the chamber testing is shown in figure 15. For this equipment, 27 tests produced 27 failures with a mean exposure for the failures of 8.48 × 10^5 fiber-seconds/cubic meter. These were tests at various fiber lengths, ranging from 3 to 14 millimeters. The indications from those early sticky cylinders exposed in the shock tube are that the fibers we have seen so far range in length from less than 1 mm to about 15 mm. But again this is preliminary data. Future effort will be directed towards increasing the number of released fibers to achieve exposure levels comparable with chamber tests.

The second part of the two-fold approach to demonstration testing would be to go to Dugway Proving Ground for outdoor, end-to-end tests, figure 16. Dugway is not the only place in the United States where this type of test might be conducted; however, it does provide a location which appears to be quite satisfactory for doing large outdoor burns of graphite composites for the purpose of verifying the kinds of risk analysis elements that are

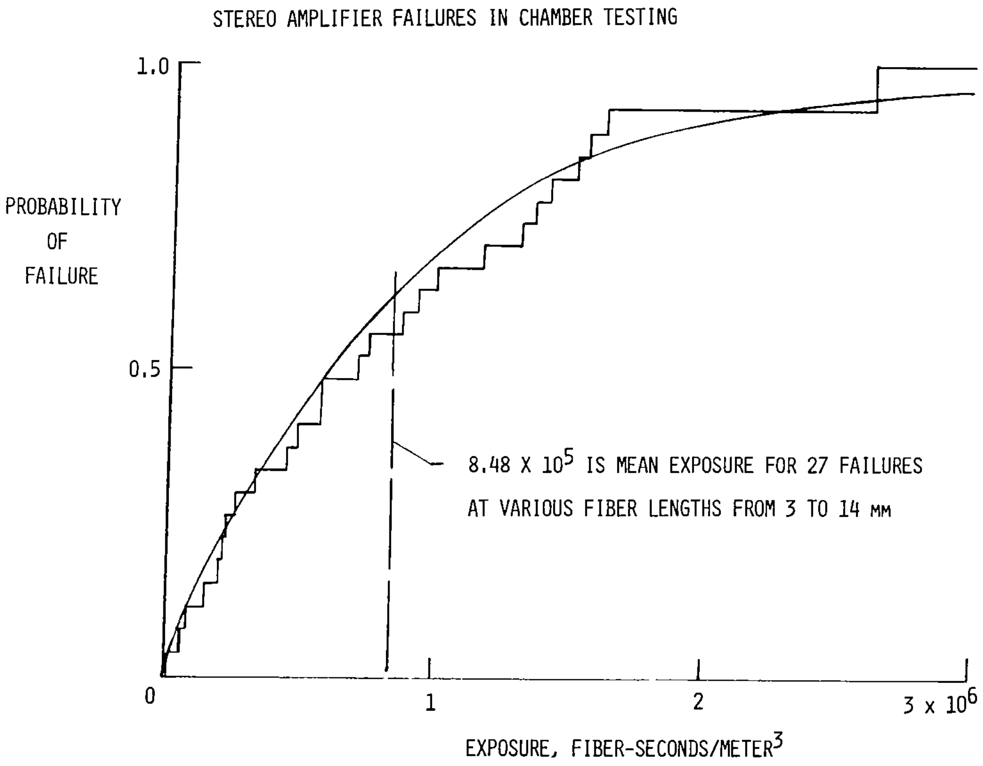

Figure 15

DUGWAY PROVING GROUND END-TO-END TESTS

OBJECTIVE

LARGE OUTDOOR BURN FOR VERIFICATION OF RISK ANALYSIS ELEMENTS

APPROACH

USE ACCIDENT EXPERIENCE TO DEVELOP CREDIBLE FIRE SCENARIOS

USE TEST EXPERIENCE AND RISK ANALYSIS TO SELECT EXPOSED ELECTRICAL EQUIPMENT

PREPARE PRE-TEST PREDICTIONS OF: FIBER RELEASE
FIBER DISPERSION AND PENETRATION
PROBABLE EQUIPMENT FAILURES

MEASURE ALL VARIABLES KNOWN TO INFLUENCE FINAL RESULTS

COMPARE PRE-TEST PREDICTIONS WITH TEST RESULTS

MANDATORY PREREQUISITES

ESTABLISHED CONFIDENCE IN: FIRE PLUME PREDICTIONS
FIBER RELEASE PREDICTIONS
MODELS FOR FIBER DISSEMINATION

CONCERNS: IF WIDESPREAD DISSEMINATION FOOTPRINTS - TEST MAY BE IMPRACTICAL

Figure 16

shown in figure 17. In this case if we go outdoors, we not only have the capability of verifying source but we can also verify outdoor dissemination. We can verify in a more effective manner a number of transfer functions and the vulnerability of suitable electrical equipment. Our approach is to use the accident experience that is being generated by the three commercial airplane manufacturers, using their data to select a creditable scenario for a fire for the source of fiber release. We will use our test experience in the risk analysis program to select the appropriate kinds of electrical equipment to be exposed. We want to be able to prepare pretest predictions for the amount of fibers to be released, their dispersion and penetration, and the probable equipment failures that will result from a test of that sort. We need to have the capability of measuring all the variables that are known to influence the final results. That is one of the reasons Dugway is considered to be a favorable location. In their past experience with airborne release of a number of chemical agents for the army, they have built up a very comprehensive network of meteorological stations, so they have a knowledge of the weather conditions over the entire range at the time of release as well as before and after release. We will be able then to modify our pretest predictions with the weather conditions actually present.

RISK ANALYSIS FLOW

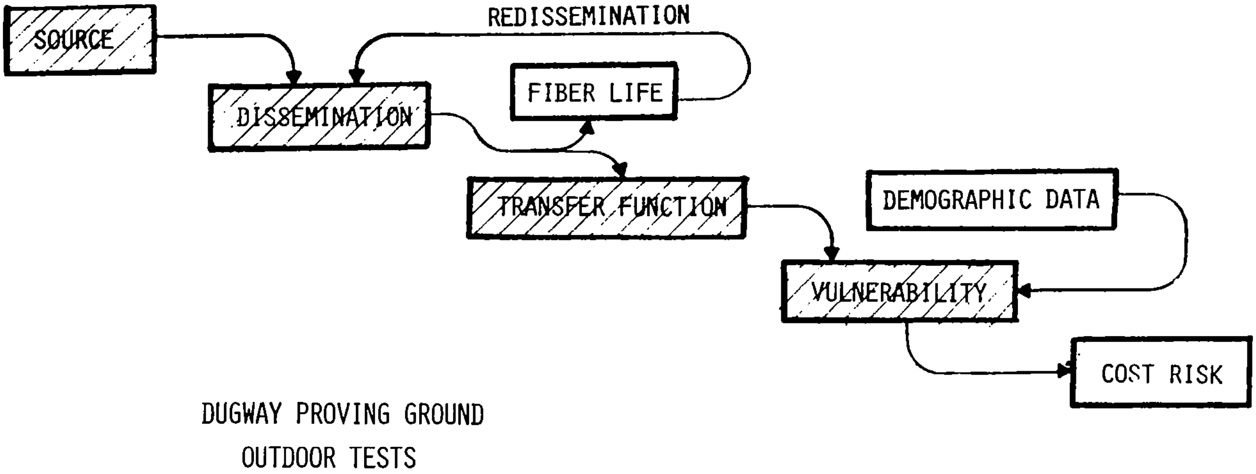

Figure 17

We do have a couple of mandatory prerequisites to conducting the end-to-end test. We need to have already established confidence in our fire plume predictions, in the fiber release predictions, and in the models for fiber dissemination. Until we have a good level of confidence established, it is probably futile to go outdoors and start burning composites. Our chances of finding fibers, knowing where they are going, and catching them again would be quite uncertain. One concern is that if we get a widespread dissemination footprint, the available fibers are scattered over such a large area that the whole test may become impractical to perform from the experimental point of view. That is not to say that the problem is not there; it just becomes very difficult to try to track down the results.

Question:

What is the rationale for burning fiber first and then exploding it? Isn't this kind of the reverse of what it should be?

Answer:

The impact, or explode, and then burn seems to be the general scenario for commercial aircraft accidents. We do not have the final answers in from the aircraft manufacturers, but the preliminary indications are that for most of the commercial aircraft accidents the plane crashes and burns. Then, if there is an impact, it will be a low-order type impact. It will not be an explosion. A major impact like a crash occurs before the fire and really does not have anything to do with disseminating carbon fibers. The crash would scatter parts of the airplane around, but the fibers can not be scattered until after they have been released from the composite by burning out the matrix. You have to have a fire to burn the matrix out before the impact or explosion is going to have a significant effect on scattering fiber. Most of the civil accidents that have been investigated do not have the kind of explosion that occurs after the fire has burned out the epoxy matrix. I am sure there are going to be a number of exceptions to the above crash and burn situation, but I think, for civil aircraft, you generally do not have the burn and then explode situation.