EVALUATION OF EQUIPMENT VULNERABILITY

AND POTENTIAL SHOCK HAZARDS

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Since the last report on this subject made on October 31, 1978, additional data has been collected on equipment which may be affected by graphite fibers released from aircraft accidents and on evaluating the significance of the shock hazard on consumer equipment. As outlined in Figure 1, this paper will describe the vulnerability tests, provide some illustrations of specific test results and discuss the parameters which affect vulnerability. The shock hazard for a hypothetical set of accidents will also be computed and evaluated. Figure 2 lists some of the conditions which bounded the parameters of the tests made in the Langley Research Center and Aberdeen Proving Ground test chambers. In general the tests were conducted with moderate graphitization fibers such as T-300, lengths were between 1 and 10 millimeters and with the equipment under test operating. Exposures were limited to values of 10^8 fiber seconds per meter^3, both for practical reasons of test duration, and because at this level very small national damage costs would be encountered. Limited tests were done with equipment either nonoperating or with simulated environments subsequent to fiber exposure, except for avionics equipment, in which expected flight environments were simulated.

Figures 3 and 4 list the results secured. Many pieces of equipment did not fail within the test limits under exposure to graphite fibers or when tested with a fiber simulator probe. The latter technique was used in devices wherein the number of electrical nodes were limited and could be easily sampled manually.

Some of the parameters which affect vulnerability are shown in the following figures. Figure 5 shows the effect of fiber length on two pieces of equipment. The power amplifier shows a consistent trend with length. In the range of average fire-emitted fiber lengths (2 to 4 mm) the exposure required for failure are

$$\bar{E} = 4 \times 10^6 \ (1/\ell)$$

This inverse trend with length is typical of equipment not protected with a case and/or filter. The ATC transponder has a nontypical response which is caused by the type of openings in the case. These are holes, approximately 3 mm in diameter. The transfer function for fibers through these openings varies inversely with fiber length for lengths equal to or larger than the holes so that there is a relative invulnerability to fibers longer than 3 mm. This size of opening is common in many types of avionics equipment as it provides adequate ventilation with sufficient electrical shielding.

Figure 6 illustrates the results secured with military specification type open terminal strips which are typical of those used in industrial 440V connections. Sustained arcs could only be secured under the conditions of three phase supply and with currents larger than 400 peak amperes. Equipment limitations were such that the maximum current was limited to 1500 amperes peak. It is believed that only sustained arcs provide a possibility of significant damage. The high levels of exposure required for these terminal strips, when coupled with the low transfer function which exists in most NEMA electrical enclosures, indicates that there is no serious industrial problem. When cooling air is forced through specific special case designs,each must be individually evaluated to determine whether a serious hazard exists. For the terminals shown the barrier strips insure that single fibers cannot individually bridge contacts. The alleviating effect of this will be covered later in this paper. In our experiments local damage to screwheads occurred and eventually fuses or breakers opened, and it is believed that similar experience would be encountered in any protected industrial circuit.

A number of representative results have been correlated in Figure 7. As was indicated by the previous listing, most consumer goods, 110V equipment and most avionics were found to be not vulnerable. The most vulnerable equipment, not reported herein, was equipment of 1950-1960 vintage, generally of high impedance and tested with high modulus fibers. At the time these tests were performed it was not known what the range of fire-emitted lengths would be. The test results which were secured over a range of fiber length, and which are typical of those used in the NASA risk analysis, are diagrammed in the remainder of the chart. There were no experimental points for any apparatus below the solid boundary line. The equation for this boundary is:

$$\bar{E} = 2 \times 10^7 \ (1/\ell)^2$$

This lower boundary is formed primarily by fan-cooled, nonfiltered equipment and by open terminal strips. For these there is no protection provided by the equipment case, or the forced airflow greatly enhances the number of fibers available to produce damage inside the case. All other failures are located to the right of this boundary. The demonstrated lower vulnerability is caused by case protection, the width of contact spacing, the invulnerability of specific types of circuitry or combinations of these factors. It should be emphasized that most of this testing was done with T-300 or equivalent fibers such as are now employed in aircraft construction. A partial tabulation of many of the tests is given in Table 1. Where no failures are shown the $\bar{E}$ values are the maximum values to which the equipment was subjected.

Fiber resistivity also potentially can affect equipment sensitivity. Figure 8 shows the result of probing the same amplifier with a fiber simulator which duplicates the contact resistance and burnout characteristics of a fiber. In the range of 3 to 7 mm contact gap lengths there were approximately 35 failure nodes with T-300, and about one tenth that number with DE-114. DE-114 is an experimental fiber produced primarily for its high resistivity. The actual average exposures to failure are shown on Figure 9. There is somewhat over one order of magnitude change in vulnerability shown in the tests done with fiber on the test amplifier in the test chamber. This agrees well with the results secured by the probe. Two other pieces of equipment were also tested with fibers of differing resistivity. No probe testing was done on these more complicated circuits; however, the effect of resistivity is clearly shown. The relative slopes are greatly dependent on the separations of nodes and on the specific fiber resistivity. The large variation in the vulnerability of the color TV and transponder was not expected for the less than 3:1 ratio of resistances of the fiber types. Insufficient work has been done to be able to predict the slope of the vulnerability curve against fiber resistance for various classes of equipment.

In order to determine whether fire-released fibers would affect equipment in a manner similar to those used for chamber testing a series of tests was run at the Naval Surface Weapons Center, Dahlgren, Virginia. These tests will be discussed in detail in a later talk. Figure 10 diagrams the results of these tests. Six amplifiers were exposed to soot alone, as a control, to determine whether failures would occur, or affect the vulnerability of the equipment. Two amplifiers failed, one during soot exposure and one subsequently. A detailed examination of the failed equipment could not determine whether the cause was soot or not. The remaining four amplifiers were evaluated in the Aberdeen test chamber. The average exposure to failure was 0.8×10^6 for these tests. The change, if any, from the average exposure determined previously with 3 mm fibers, 2×10^6, is considered insignificant and is probably caused by normal statistical spread.

In a repeat test wherein graphite composite was burned at Dahlgren six amplifiers were again exposed. All of the amplifiers failed subsequent to an exposure of 5×10^6. At this exposure (measured by an electrical grid which detected 2 mm and longer fibers) it would be predicted that 6 failures would occur as shown on Figure 11. It may be concluded that the fire-released fibers have at least the same damage potential as the fibers used for chamber testing. Figure 12 further substantiates this point. Resistivity measurements were made of fibers released from fires at Dahlgren and during full-scale fire tests made at Dugway. This was accomplished with a wire-grid instrument wherein the voltage-current characteristics of each fiber that intersected the grid was determined. A continuous measurement was made of each fiber until fiber burnout occurred. The resistivity, when compared to the average resistance of virgin cut fiber, is essentially unchanged. Other data presented at this meeting indicates that measured diameters of fibers are smaller than pre-fire diameter. The data shows that there is a high correlation between fire-induced diameter reduction and small fiber length so that the wire grid would not detect most of the fibers of smaller diameters and short lengths. The long high-resistance tail on the distribution plot indicates that a small number of decreased diameter fibers may have been encountered.

Figure 13 outlines the test flow for commercial avionics. In this test series it was important to ascertain whether the flight environment subsequent to graphite fiber exposure could introduce failures by redistribution of trapped fibers. Each device was subjected to an exploratory vulnerability test to determine if detailed testing was warranted. Three exposures to $\overline{E} = 3 \times 10^7$, without intermediate cleaning, and with simulated environment after each exposure were used. If the equipment did not fail, testing was terminated as the exposure to 9×10^7 was sufficient indication of invulnerability. If a failure occurred at any fiber length, four tests were run as indicated with no cleaning between the tests which were made at increasing levels of exposure. The results of this sequence are shown on Figure 14. It is interesting to note that for this equipment, tested under simulated landing shocks and 100 db of white acoustic noise, that five of the fifteen failures occurred during simulated environment. The average exposures to failure for this equipment as used in the NASA risk analysis included the effect of environment as demonstrated in these tests.

A limited number of tests, not reported herein, attempted to simulate the post-exposure experience of turning ground-based equipment on and off, and of moving the equipment. In no case were failures encountered subsequent to the fiber exposure period in the test chamber.

One other facet of aviation risk was investigated analytically to determine if a sufficient hazard exists to require some precautionary action. The effect of a graphite fiber cloud on existing and proposed terminal landing aids was evaluated. Figure 15 outlines the results secured on the 300 MHz glide slope equipment now in use and on the planned 5 GHz microwave landing systems (MLS) scanning antenna systems which will be deployed as per present FAA planning. There is no effect of concern on the glide slope equipment as attenuation effects are negligible, nor is there any problem with differential attentuation of the beams from the two antennas used in this system. For the MLS there is appreciable attenuation of the beam only in the very conservative case of the beam traveling through the entire length of the fire-ejected plume into the aircraft antenna. Even in this worst case the specified capability for the system insures that the range is not below 17 kilometers, which is still adequate. If the signal strength is below acceptable limits in the aircraft for any cause the pilot is warned by a display flag and will disregard the display until signal strength is adequate. It is most probable that during normal controlled operations the aircraft would be diverted or delayed if the fire plume really occupied the direct landing environment of the airport.

The ground based equipment which generates the ILS and MLS signals is well protected, both by air-conditioned building enclosures and by specific filtering of cooling air entering the equipment racks so that there is no concern with interfering with the ground based equipment.

The shock hazard potential of graphite fibers has been investigated for a large number of consumer electrical items. A detailed report on method and results will be presented tomorrow by the National Bureau of Standards. Data extracted from their report is presented herein in order to approximately evaluate the magnitude of the danger nationally. Figure 16 lists all of the items considered a potential hazard by the NBS and subsequently tested in the BRL test chambers. Six items were tested. The toaster, because of the number in use, and the highest vulnerability to case shorts was selected for detailed testing. It is believed that there is no appreciable national risk compared to the toaster from the other five items. Figure 17 presents the results of the tests made on 6 toasters over a fiber length range of 1 to 12 mm. While the absolute values are different for each unit, the curve shapes are all similar and follow a characteristic inverse E vs length relationship. For the smaller length fibers such as may be released from a fire the equation

$$\bar{E} = 5 \times 10^8 \ (1/\ell)^3$$

provides a good fit to all of the data.

To provide a sample computation for the national risk the shorting probability versus exposure relationship must be ascertained. Figure 18 shows these relationships for toaster #6 for each of three fiber lengths. While the 3 mm and 10 mm experimental points follow an exponential failure curve, as would be expected when bridging can be accomplished by a single fiber, the experimental points for the 7 mm fibers are an indication that multiple fibers are required to produce a short. Similar results were secured for other lengths in other toasters, particularly for the shorter fiber lengths. The use of simple exponential failure laws for these cases will overestimate the risk for low exposures. It is difficult to evaluate the magnitude of the overestimate without taking large numbers of data points to better define the damage curves at low exposures. Because of this, and because the computation will always produce conservative answers the exponential failure law has been applied throughout the risk analysis and will be used for the shock hazard approximation.

In order to integrate the effects of a fiber spectrum so that equipment vulnerability in a fire can be evaluated it is necessary to summate the damage potential for all lengths. Figures 19 and 20 indicate the two methods by which this can be accomplished. In the detailed stepwise integration method it is necessary to find the exposure at each length and divide by the $\bar{E}$, the average E for damage for that length. An overall summation across the length spectrum then provides an expression for the probability of damage; for a normalized quantity of fibers

$$P_D = 1 - e^{-\int_0^\infty \frac{F(\ell)d\ell}{\bar{E}}}$$

If the length spectrum and damage relationships can be expressed as simple exponentials or power laws it is possible to derive analytic expressions for the overall integrals as shown in Figure 20. Dr. W. Elber has derived closed form relationships which express these integrals for various exponents of the damage curve and for various values of the average fiber length, ℓ_a. For the case shown where E is proportional to $(1/\ell)^2$ he has shown that an equivalent E can be used which is the E that occurs at $\sqrt{2}\ \ell_a$. For the case where $\bar{E}$ varies as $(1/\ell)^3$ the equivalent E occurs at $\ell = 1.8\ \ell_a$. This relationship is used in this paper and has been used to simplify the national risk analyses which will be presented in later papers. For most of the fire data to date average fiber lengths have been about 2 millimeters, so that computations presented herein will be based upon the E values which have been secured with 3 mm test fibers. An increase of average length to 3 mm would increase the E estimate by a factor of three, and the overall risk estimate by a factor of two (because of the smaller number of fibers per unit mass release).

The sample computation is shown in Figure 21. The assumptions are that 1000 kilograms of fiber are involved in each of 5 fire related accidents per year, that 1% of the mass is released and could enter homes having average transfer-functions of .01. The population and toaster density, 330 per square kilometer is typical of a densely populated city and all of the fibers are assumed to land in that area. The results of tests performed on six toasters, reported in detail in CR 159147 show that the E for 3 mm fibers for the average toaster is 2×10^7 fiber seconds/meter^3. The tests also indicated that, in only 16 of 25 tests did the voltage to the case exceed 60 volts. In addition, when the toaster was energized, in only 3 of 25 tests was the fiber retained long enough to allow a measurement of current carrying capability. In these measurements the maximum current carried was 10 milliamps. When this data is substituted in the equation shown, the computed probability of a potential hazard is 0.38/year. This is not a large hazard (Figure 22) and is probably excessively conservative in that it ignores the multi-fiber failure relationship, and the statistics connected with the distribution of user resistance to ground. Finally the currents which were maintained below 10 milliamps could produce shock sensations and secondary injury but could not themselves be more than an annoyance.

The last figure (Figure 23) outlines the conclusions drawn from the data presented. The data collected and analyzed has been used in the NASA National Risk Analysis which will be presented in a following paper. While the data is restricted to T-300 or similar fibers it is believed that structural materials would have similar properties. Extensions of these data to other fibers having different resistances or fall rates is not warranted.

The characteristics of fire-released fibers have been measured, both by direct measurement in fire plumes and indirectly by exposing equipment to a fire plume. The damage potential to electrical equipment does not change materially because of the fire.

The failure rates for avionics equipment are influenced by post exposure environmental conditions. These effects have been taken into account in the national risk estimate.

There is a negligible shock hazard in a small number of home appliances. The national risk is small and can in no case result in a hazard to life with the test fibers used.

A final word about repairs. In almost all cases failures were cleared by simple vacuuming of the equipment. Where damage to components occurred it was not caused by the limited energy-dissipation characteristics of the fiber, but rather by upsetting a control circuit, or in the case of three phase arcs, by initiating an energy release almost independent of the fiber characteristics. For other than 3 phase industrial equipment, where downtime costs may predominate, the major cost encountered would be those costs associated with examining and cleaning rather than replacing components in the equipment.

TABLE 1.- SUMMARY OF VULNERABILITY TESTING FOR ELECTRICAL EQUIPMENT

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\overline{E}$	# of TESTS	REMARKS
Power Supply	LaRC	Thornell 300	8.0	1.0×10^8	1	No Failures
Wall Socket	LaRC	Thornell 300	3	3.0×10^8	4	
			7	8.0×10^7	4	
			16	4.0×10^8	4	
Quick Disconnect Terminals	RADC	GY 70	3	$.6 \times 10^7$	6	0.635 cm (0.25 in.) Spacing
			7	$.3 \times 10^6$		
			12	$.2 \times 10^6$		
			3	$.2 \times 10^9$		1.905 cm (0.75 in.) Spacing
			7	$.2 \times 10^7$	6	
			12	$.5 \times 10^6$		
			3	$.4 \times 10^9$		1.27 cm (0.5 in.) Spacing
			7	$.1 \times 10^8$		
			12	$.1 \times 10^7$	6	
Gen'l Aviation Type Distance Measuring Transponder (DME)	BRL	AS	1	5.7×10^8	2	No Failures
			3.5	5.4×10^7	3	No Failures
			7	6.7×10^7	2	No Failures
Amplifier, Audio Power, 410	BRL	Thornell 300	2.5	2.5×10^6	4	
			7.5	5.0×10^5	4	
			14.5	3.0×10^4	4	
Calculator/Printer	BRL	AS	20	3.9×10^7	1	No Failure
		Thornell 300	1.3	5.9×10^8	4	No Failure
		Thornell 300	2.1	3.5×10^8	2	No Failure
			8.0	3.2×10^7	4	No Failure
			20	3.3×10^7	2	No Failure

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	E	# of TESTS	REMARKS
Computer, MOS Open Circuit Board	BRL	Thornell 300 Thornell 300	1.3 1.3 4 4	1.5×10^7 5.0×10^7 7.4×10^7 1.2×10^6	2 3 2 2	No Failure No Failure No Failure No Failure
Computer	BRL	HMS	1 1 1.7 3.5 4.7 7.8 8	8.9×10^6 1.0×10^8 Est. 1.6×10^6 2.9×10^7 5.6×10^5 3.3×10^5 5.0×10^6 Est.	9 3 7 1 5 10 10	No Failure, Off Mode Off Mode Off Mode
Dishwasher	BRL	HMS	3.5 7.5 10	1.0×10^8 6.0×10^7 4.5×10^7	3 3 2	No Failure, Off Mode No Failure, Off Mode No Failure, Off Mode
Dryer, Clothes	BRL	HMS	3.5 7.5 10	6.0×10^7 6.5×10^7 3.0×10^7	3 10 5	No Failure, Off Mode No Failure, Off Mode No Failure, Off Mode
Heater, 1500 Watt Electric	BRL	HMS	3.5 7.5 10	1.0×10^8 6.0×10^7 4.5×10^7	7 10 9	No Failure, Off Mode No Failure, Off Mode No Failure, Off Mode
Iron, Hand	BRL	HMS	3.5 7.5 10	6.0×10^7 6.5×10^7 3.0×10^7	3 9 6	No Failure, Off Mode No Failure, Off Mode No Failure, Off Mode
Food Mixer, Hand #1	BRL	HMS	3 7.5 10	1.0×10^8 6.0×10^7 4.5×10^7	3 3 4	No Failure, Off Mode No Failure, Off Mode No Failure, Off Mode

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\overline{E}$	# of TESTS	REMARKS
Food Mixer, Hand #2	BRL	HMS	3	6.0×10^7	4	No Failure, Off Mode
			7.5	6.6×10^7	4	No Failure, Off Mode
			10	3.0×10^7	2	No Failure, Off Mode
Microwave Oven #1	BRL	Thornell 300	1	8.1×10^7	2	No Failure, Off (Clock On)
			4	5.0×10^6 Est.*	2	No Failure, On & Off
			4	3.5×10^7	3	Off, (Clock On)
			4	6.0×10^6	1	On, Low Power
			10	6.6×10^6	1	Low Power
Microwave Oven #2	BRL	HMS	3.5	1.0×10^8	4	No Failure, Off Mode
			7.5	6.0×10^7	5	No Failure, Off Mode
			10	4.5×10^7	2	No Failure, Off Mode
Radio, Clock	BRL	HMS	2.5	2.0×10^8	4	No Failure, FM
			2.5	3.2×10^8	6	No Failure, Off Mode
			7.5	4.0×10^7	3	No Failure, FM
			7.5	1.1×10^8	4	No Failure, Off Mode
			15	1.1×10^8	4	No Failure, Off Mode
Radio, Portable	BRL	Thornell 300	2.5	1.9×10^8	3	No Failure, FM
			7.5	1.1×10^8	3	No Failure, FM
			7.5	6.4×10^7	2	No Failure, Off Mode
			15	7.5×10^7	3	No Failure, FM
Radio Receiver, AM-FM	BRL	Thornell 300	2.5	2.0×10^8	3	No Failure, FM
			7.5	1.9×10^8	5	FM
			15	5.7×10^7	3	No Failure, FM

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\overline{E}$	# of TESTS	REMARKS
Tape Recorder, Portable	BRL	Thornell 300	2.5	1.3×10^8	2	No Failure, Record to Off
		Thornell 300	2.5	1.5×10^8	2	No Failure, Record to Off
		Thornell 300	7.5	2.0×10^8	4	No Failure, Record to Off
		Thornell 300	7.5	8.3×10^7	2	No Failure, Off Mode
		Thornell 300	14.5	1.2×10^8	4	No Failure, Record to Off
Tape Recorder, AC or Portable	BRL	Thornell 300	2.5	7.5×10^7	3	No Failure, Record to Off
			7.5	1.1×10^8	3	No Failure, Record to Off
			15	1.9×10^8	3	No Failure, Record to Off
Cash Register	BRL	Thornell 300	2.5	1.1×10^8	2	No Failure. On Memory
			7.5	1.4×10^8	4	No Failure. ON
			7.5	3.7×10^7	2	No Failure. Overnite Standby
			15	6.3×10^7	2	No Failure. ON
			15	3.8×10^7	2	No Failure. On Memory
Stereo System	BRL	Thornell 300 unsz	2.5	2.2×10^8	3	No Failure. On, FM Stereo
			7.5	2.2×10^8	5	No Failure. On, FM Stereo
			15	5.7×10^7	3	No Failure. On, FM Stereo
Telecopier	BRL	Thornell 300 H_2O sz	2.5	1.1×10^8	3	No Failure, Off Mode
			7.5	4.0×10^7	3	No Failure, Off Mode
			14.5	6.8×10^7	2	No Failure, Off Mode

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\bar{E}$	# of TESTS	REMARKS
Television, B&W 16"	BRL	HMS	3.5	4.3×10^{6}	1	No Failure
			3.5	5.9×10^{7}	1	No Failure, Off Mode
			7	9.6×10^{7}	3	No Failure,
			7	1.8×10^{7}	1	No Failure, Off Mode
			7	4.2×10^{7}	1	No Failure, Back Cover Removed
Television, B&W 19"	BRL	Thornell 300	1	2.3×10^{8}	3	No Failure, Off Mode
			2.5	4.8×10^{7}	3	
			2.5	1.4×10^{8}	2	No Failure, Off Mode
			7.5	1.1×10^{7}	4	
			7.5	1.1×10^{8}	3	No Failure, Off Mode
			16	6.8×10^{7}	2	No Failure
Television, Color 19"	BRL	AS	20	6.6×10^{7}	2	
		HMS	8	6.7×10^{6}	5	
		Thornell 300	8	4.7×10^{7}	4	
		Thornell 300	20	3.9×10^{5}	1	No Failure
		Thornell 300	1.3	5.9×10^{8}	1	
		Thornell 300	2.1	3.5×10^{8}	2	No Failure
		Thornell 300	8	8.0×10^{6}	4	
		Thornell 300	7.5	1.2×10^{7}	5	Back Cover Removed
Television, Color 25"	BRL	Thornell 300	2.5	1.1×10^{8}	2	
			7.5	1.2×10^{8}	4	No Failure
			7.5	6.1×10^{7}	2	No Failure, Off Mode
			15	2.5×10^{7}	4	
Terminal, Telephone	BRL	Thornell 300	1.3	8.0×10^{6}	3	Frequent Recall by Keying
			4	1.7×10^{7}	2	Frequent Recall by Keying

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\bar{E}$	# of TESTS	REMARKS
Terminal, Video	BRL	Thornell 300	1 4 4 10	8.1×10^7 5.1×10^7 4.3×10^7 6.6×10^6	2 4 2 1	Writing & Scrolling Writing & Scrolling Off Mode Writing and Scrolling All 4-No Failure
Thermostat, (Millivolt)	BRL	HMS	7 7	5.7×10^7 1.2×10^7	3 1	No Failure, Open No Failure, Open No Cover
Thermostat, 24 VAC	BRL	HMS	7 7	5.7×10^7 1.2×10^7	3 1	No Failure, Open 24 VAC Applied No Failure, Open 24 VAC Applied, No Cover
Thermostat, 110 VAC	BRL	HMS	7	6.9×10^7	4	No Failure, Open 110 VAC Applied
Toaster-Oven #1	BRL	HMS	3.5 7.5 10	1.0×10^8 6.0×10^7 4.5×10^7	3 6 9	No Failure, Off Mode No Failure, Off Mode No Failure, Off Mode
Toaster-Oven #2	BRL	HMS	3.5 7.5 10	6.0×10^7 6.6×10^7 3.1×10^7	3 6 2	No Failure, Off Mode No Failure, Off Mode No Failure, Off Mode
Vacuum, Upright	BRL	HMS	3.5 7.5 10	1.0×10^8 6.0×10^7 4.5×10^7	3 3 2	No Failure, Off Mode No Failure, Off Mode No Failure, Off Mode

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\overline{E}$	# of TESTS	REMARKS
Valve, Gas, (Millivolt)	BRL	HMS	7	6.9×10^7	4	No Failure, Closed
Valve, Gas (24 VAC)	BRL	HMS	7	6.9×10^7	4	No Failure, Closed
Transponder, General Aviation	BRL	AS	3.5 7.0 15.0	$.96 \times 10^8$ 1.0×10^8 2.4×10^8	12 12 12	Three Failures Two Failures One Failure
ASR-3 Transmitter Cabinet	BRL	HMS	7.5 10.0 7.5	9.3×10^7 1.5×10^7 3.02×10^6	4 1 5	No Failure with Filter No Failure with Filter 5 Failures, without Filters
ASR-3 Receiver Cabinet	BRL	HMS	7.5 7.5	5.04×10^7 7.8×10^5	8 8	4 Failures, with Filters 8 Failures, without Filters

TABLE 1.- Concluded

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\bar{E}$	# of TESTS	REMARKS
ATC Transponder*	LaRC	Thornell 300	1 3 10	5.5×10^7 3.7×10^6 1.6×10^7	5 5 5	3 Failures 5 Failures 5 Failures
VHF Transceiver*	LaRC	Thornell 300	1 3 10	9×10^7 3×10^7 9×10^7	1 4 1	No Failures No Failures No Failures
ILS Receiver*	LaRC	Thornell 300	1 3 10	9×10^7 9×10^7 9×10^7	1 1 1	No Failures No Failures No Failures
D.M.E.*	LaRC	Thornell 300	1 3 10	9×10^7 3×10^7 9×10^7	1 4 1	No Failures No Failures No Failures
Flight Director*	LaRC	Thornell 300	1 3 10	9×10^7 3×10^7 6×10^7	1 4 4	No Failures 3 Failures 2 Failures

* Tests included exposure to simulated flight environments

- VULNERABILITY
- FACTORS AFFECTING VULNERABILITY
- SHOCK HAZARD EVALUATION
- CONCLUSIONS

Figure 1.- Vulnerability of equipment and shock hazards.

TEST CONDITIONS

A) T-300 OR EQUIVALENT FIBERS

B) LENGTHS FROM 1 TO 10 MILLIMETERS

C) LOW-TURBULENCE ROOM OR SIMULATED VENTILATION

D) EQUIPMENT OPERATING

E) MAXIMUM TEST EXPOSURES = 10^8

F) FOR AVIONICS ONLY - POST EXPOSURE ENVIRONMENTAL SIMULATION

Figure 2.- Equipment vulnerability and shock hazards.

WITH NO FAILURES

- TELECOMMUNICATOR
- BLACK & WHITE TELEVISION
- ASR 3
- CALCULATOR
- CALCULATOR & PRINTER
- TAPE RECORDER
- ELECTRIC MOTORS (6) 110 V.
- THERMOSTATS (2)
- CASH REGISTERS
- PORTABLE HEATER
- AM/FM RADIO
- HOME MUSIC SYSTEM
- CLOCK RADIO
- 10 BAND RADIO
- CAR RADIO
- TOASTERS
- ILS RECEIVER
- DME
- SMOKE ALARMS
- IRONS
- TOASTER OVEN
- FOOD MIXER

WITH FAILURES

- MISC. EQUIPMENT,
  - -HIGH MODULUS FIBERS
  - -RESTRICTED LENGTHS
- COMPUTER
- COLOR TELEVISION
- DIGITAL VOLTMETER
- ATC TRANSPONDER
- VHF TRANSCEIVER
- FLIGHT DIRECTOR
- CONNECTOR BLOCKS
- QUICK DISCONNECTS
- RELAYS
- GENERIC CIRCUITS
- POWER AMPLIFIER
- MICROWAVE OVEN

Figure 3.- Equipment tested in chamber.

WITH NO SIGNIFICANT FAILURES

- REFRIGERATORS
- FREEZERS
- RANGES
- DISHWASHERS
- CLOTHES WASHER
- CLOTHES DRYER
- VACUUM CLEANERS
- IRONS
- FRY PANS
- BED COVERS
- COFFEE MAKERS
- PERCOLATORS
- FOOD MIXERS
- CAN OPENERS
- PORTABLE HEATERS

WITH FAILURES

NONE

Figure 4.- Appliances tested with fiber simulator.

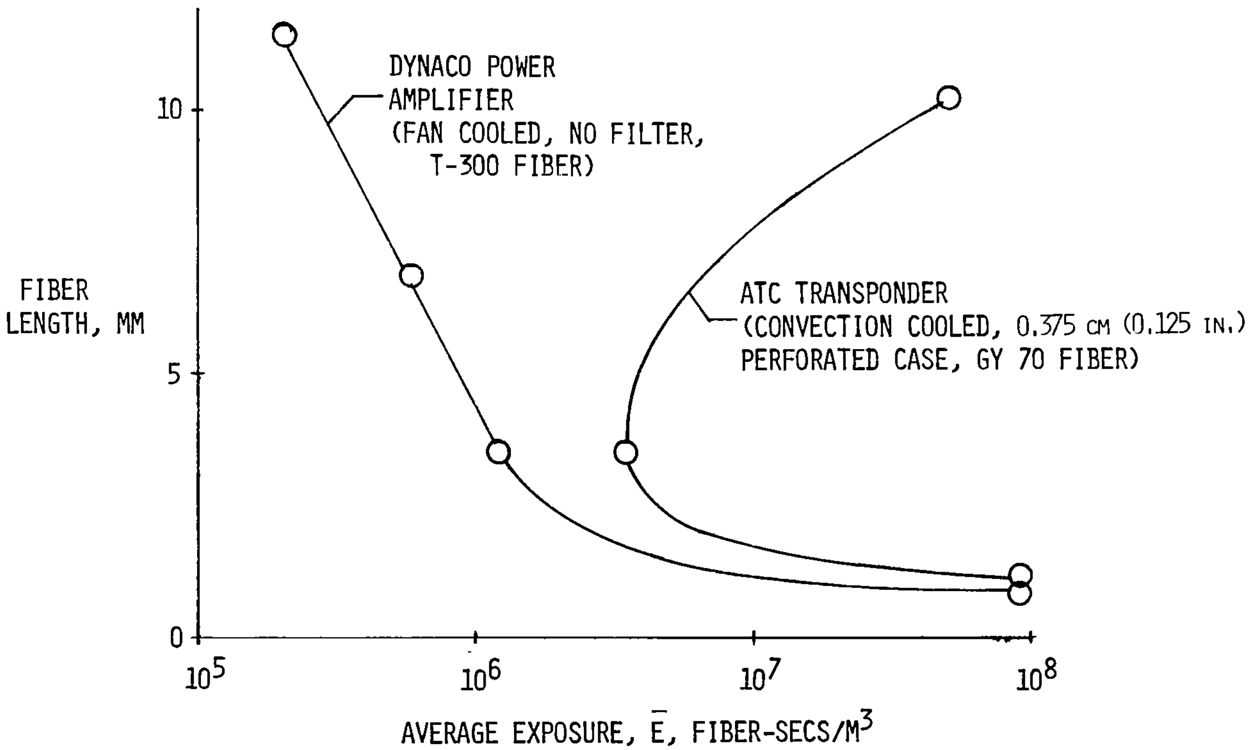
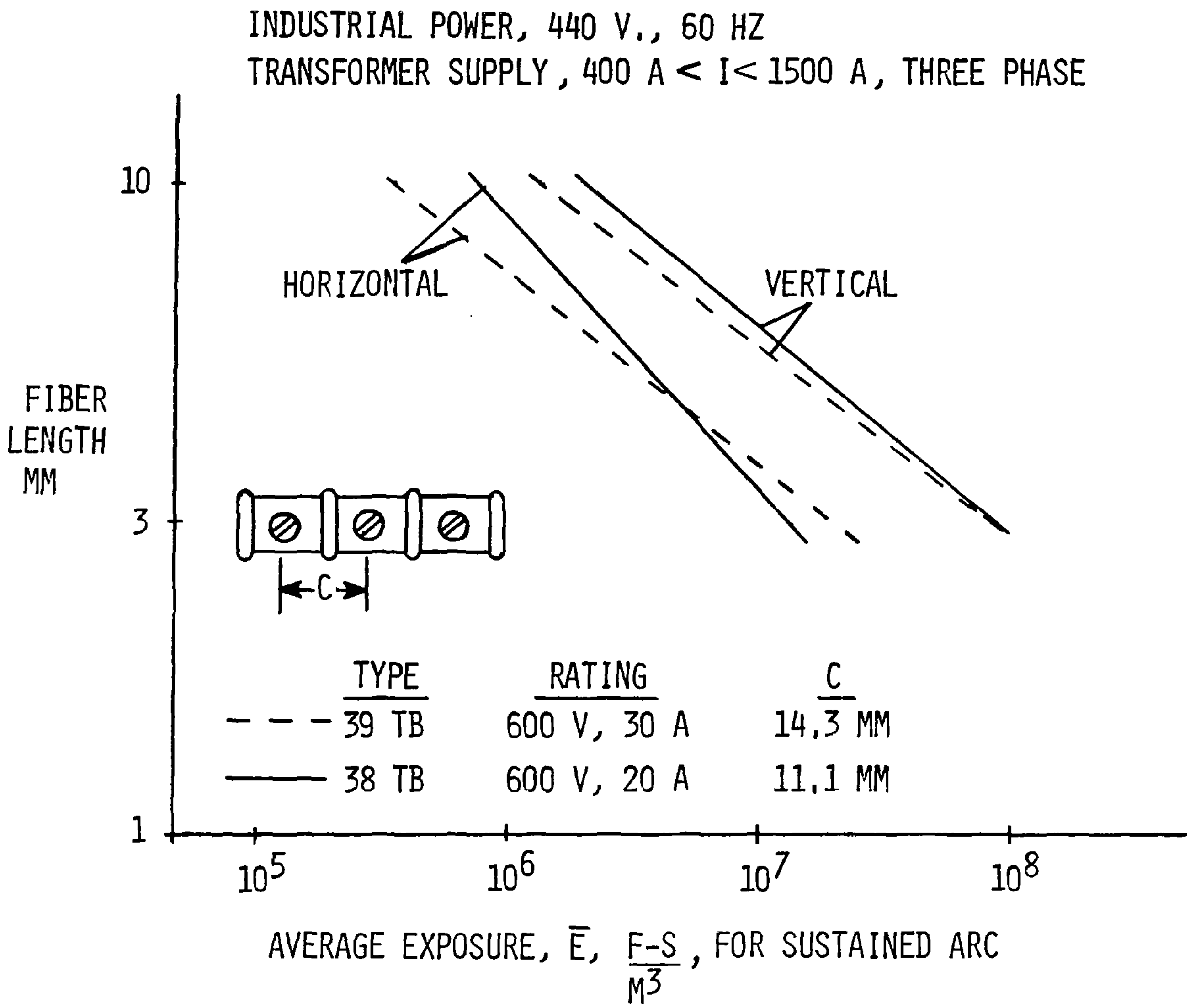


Figure 5.- Fiber length effect on equipment vulnerability.



NO SUSTAINED ARCS WITH SINGLE PHASE, TRANSFORMER SUPPLY, 440V, 60HZ

Figure 6.- Exposures for sustained arcs.

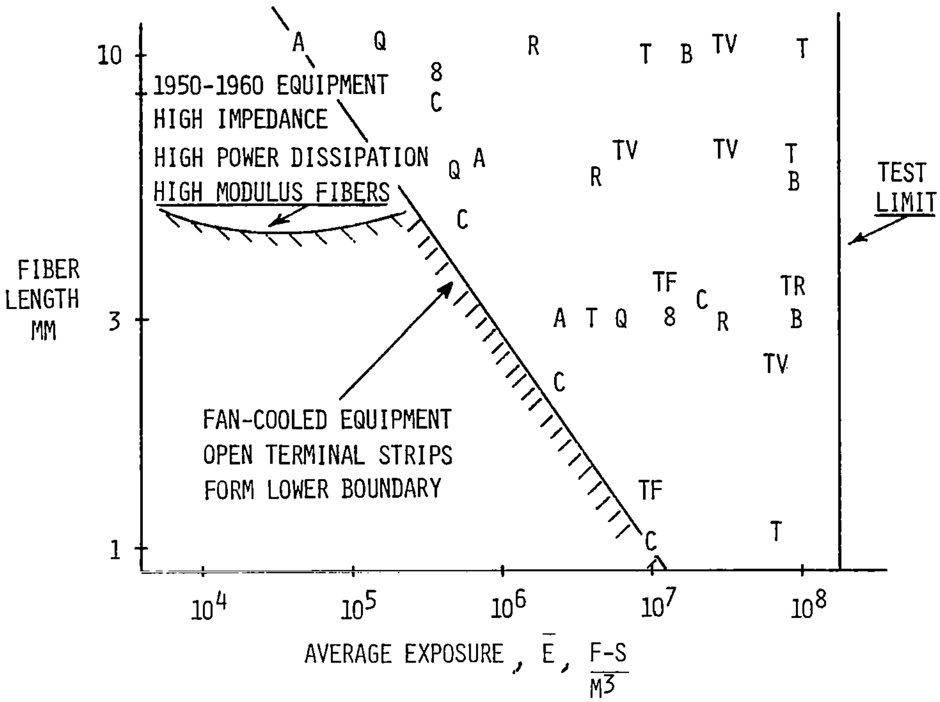


Figure 7.- Correlation of vulnerability with fiber length.

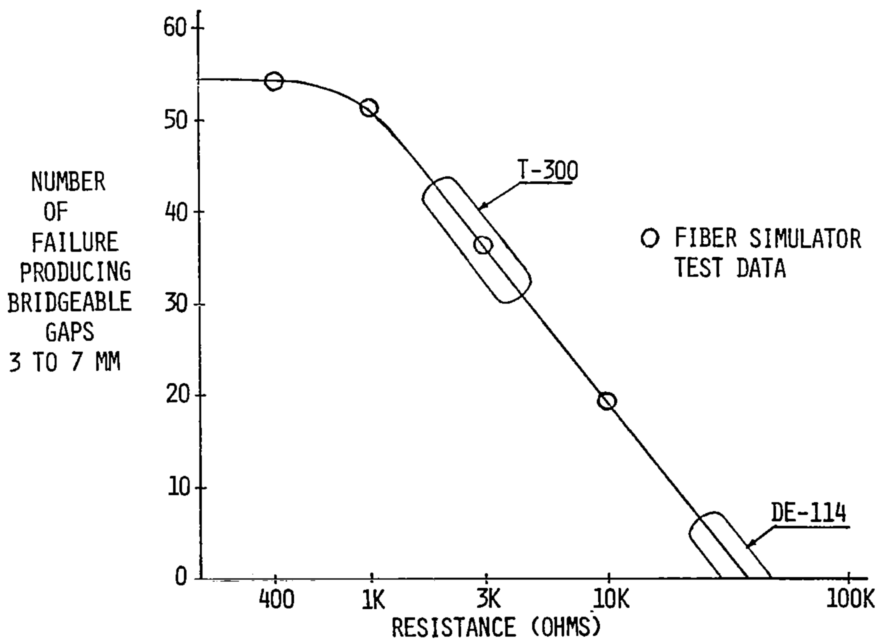


Figure 8.- Effect of fiber resistivity on Dynaco power amplifier.

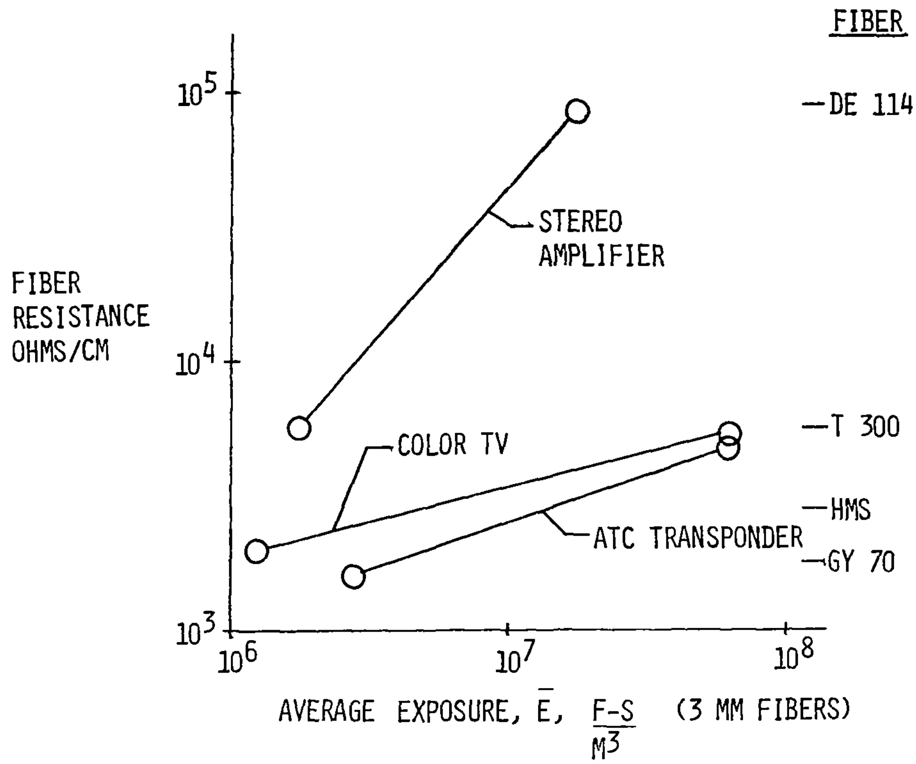


Figure 9.- Fiber resistance effect on equipment vulnerability.

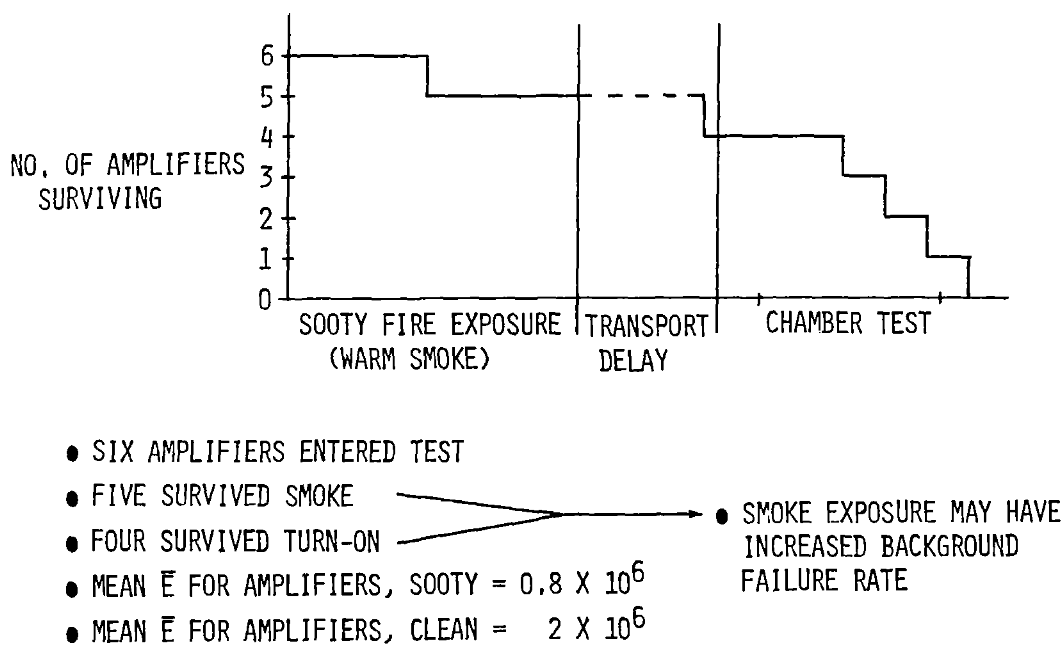


Figure 10.- Effect of soot exposure on Dynaco amplifiers.

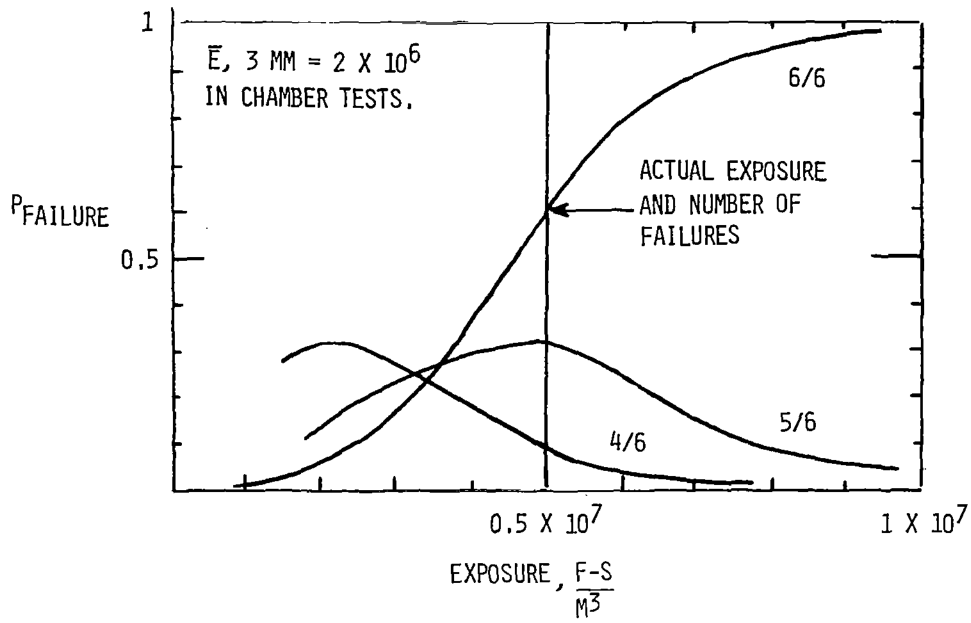


Figure 11.- Vulnerability of amplifiers to fire-released fiber.

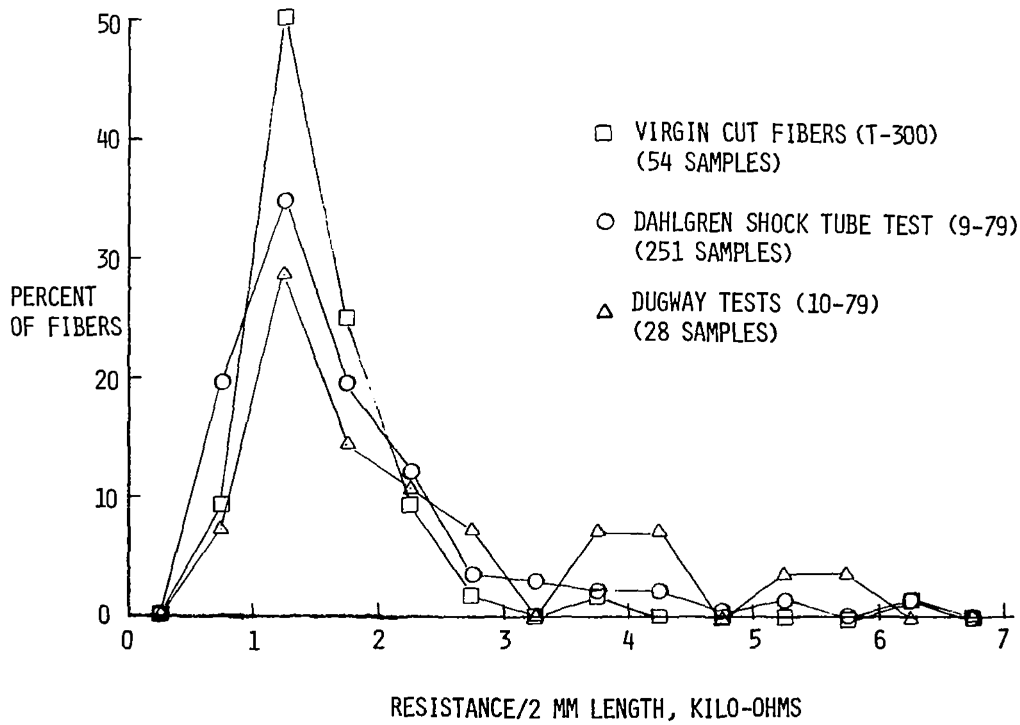


Figure 12.- Fire-released fiber resistivity.

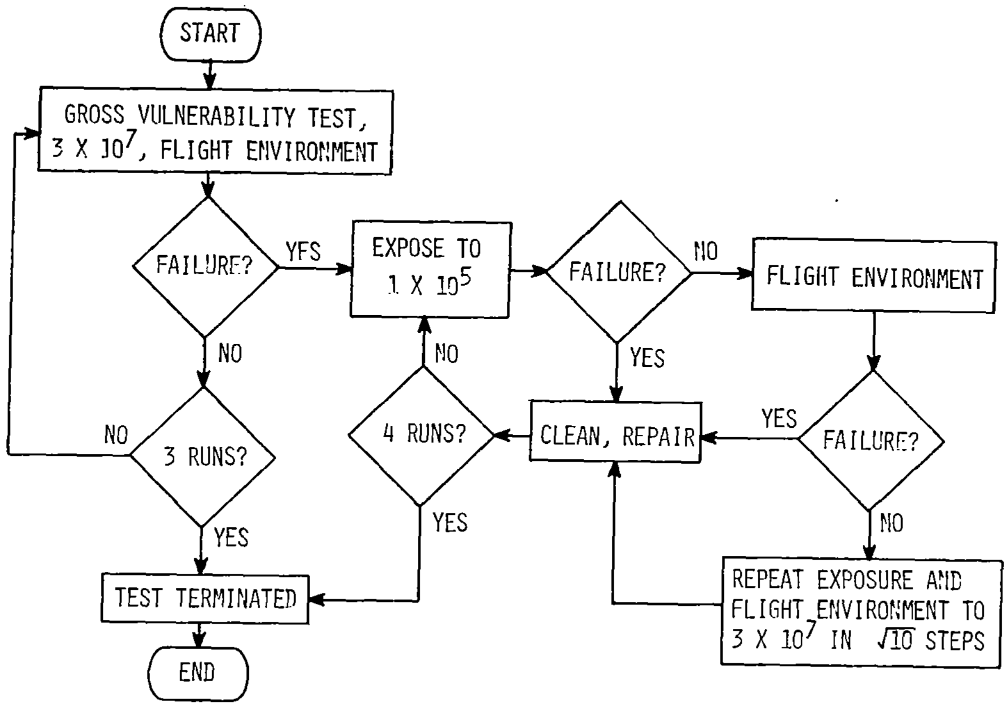


Figure 13.- Test method for avionics.

ITEM	FIBER LENGTH	FAILED EXPLORATORY TEST	EVALUATION TESTS: WITH NO FAILURE	FAILED DURING EXPOSURE	FAILED POST EXPOSURE
ILS RECEIVER	1	NO			
	3	NO			
	10	NO			
ATC TRANSPONDER	1	YES	2	2	-
	3	YES	-	3	1
	10	YES	-	4	-
DME	1	NO			
	3	YES	4	-	-
	10	NO			
FLIGHT DIRECTOR	1	NO			
	3	YES	1	1	2
	10	YES	2	-	2
VHF TRANSCEIVER	1	NO			
	3	YES	4	-	-
	10	NO			
			13	10	5

Figure 14.- Vulnerability of avionic equipment.

ASSUMPTIONS:

- 1000 KG FIRE
- 0.01 RELEASE, 3 MM FIBERS
- PLUME CROSS-SECTION - 100M X 100M
- BEAM INTERCEPTS TOTAL LENGTH OF PLUME

EFFECTS:

SYSTEM	FREQUENCY	ATTENUATION	EFFECT
I.L.S. (GLIDE-SLOPE)	330 MHZ	0.05 DB	NEGLIGIBLE
M.L.S. (SCANNING BEAM)	5 GHZ	5 DB	45% RANGE DECREASE (MIN. SPEC. RANGE = 37 KM)

Figure 15.- Graphite fiber effects on landing aids.

		FIBER LENGTH, MM		
		3	7	10
TOASTER	(6)	2×10^7	2×10^6	8×10^5
TOASTER OVEN	(2)	NONE	5×10^7	2×10^7
FOOD MIXER	(2)	7×10^7	NONE	3×10^7
HEATER		2×10^7	8×10^6	6×10^6
IRON		NONE	1×10^7	6×10^6
MICROWAVE OVEN		1×10^8	3×10^7	5×10^7

TOASTER IS THE GREATEST RISK
BECAUSE OF NUMBER IN USE AND VULNERABILITY

Figure 16.- Average exposures required to produce short to case.

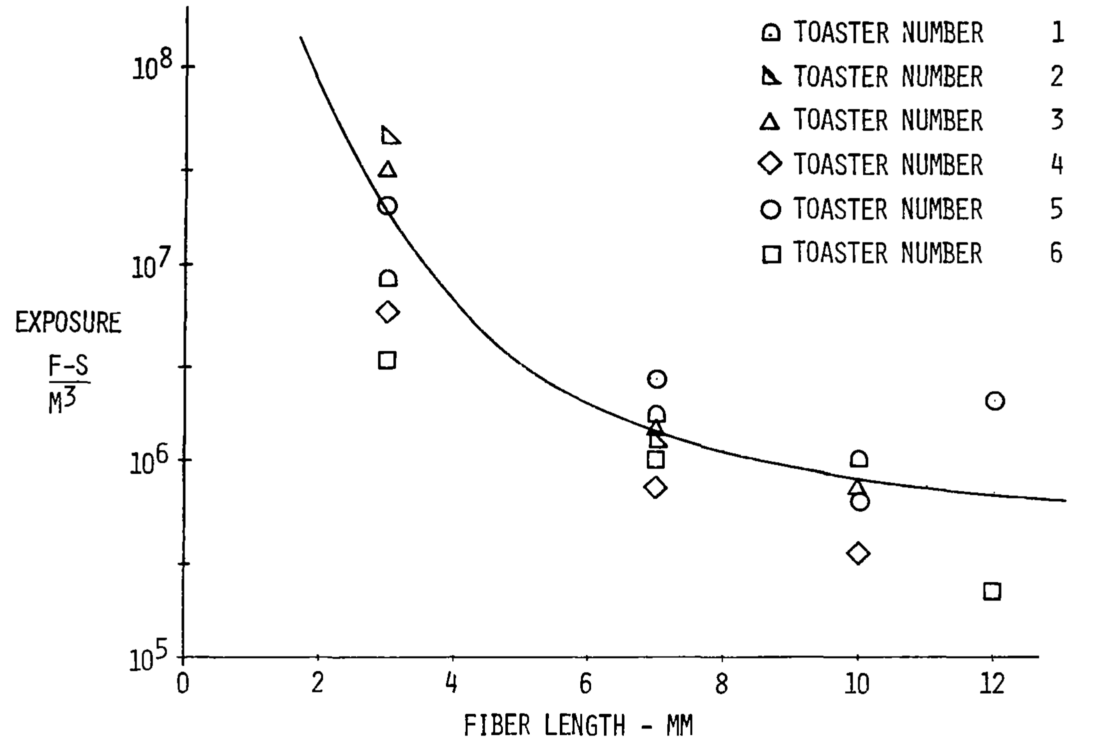


Figure 17.- Average exposure required for short to case of six toasters.

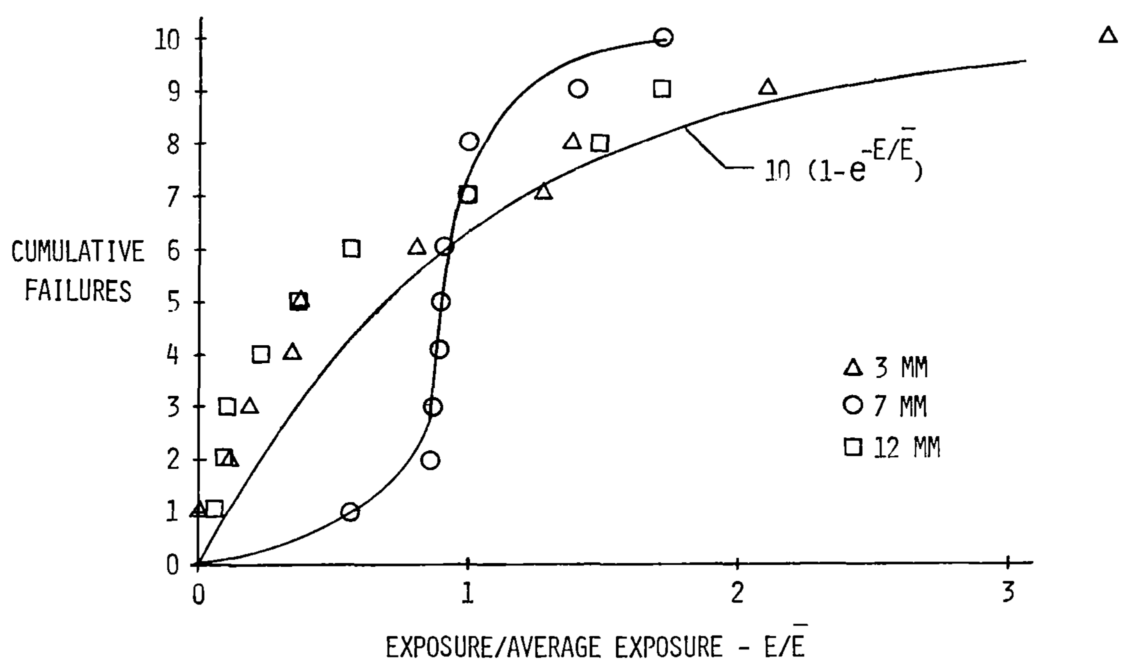


Figure 18.- Cumulative failure versus exposure toaster no. 6.

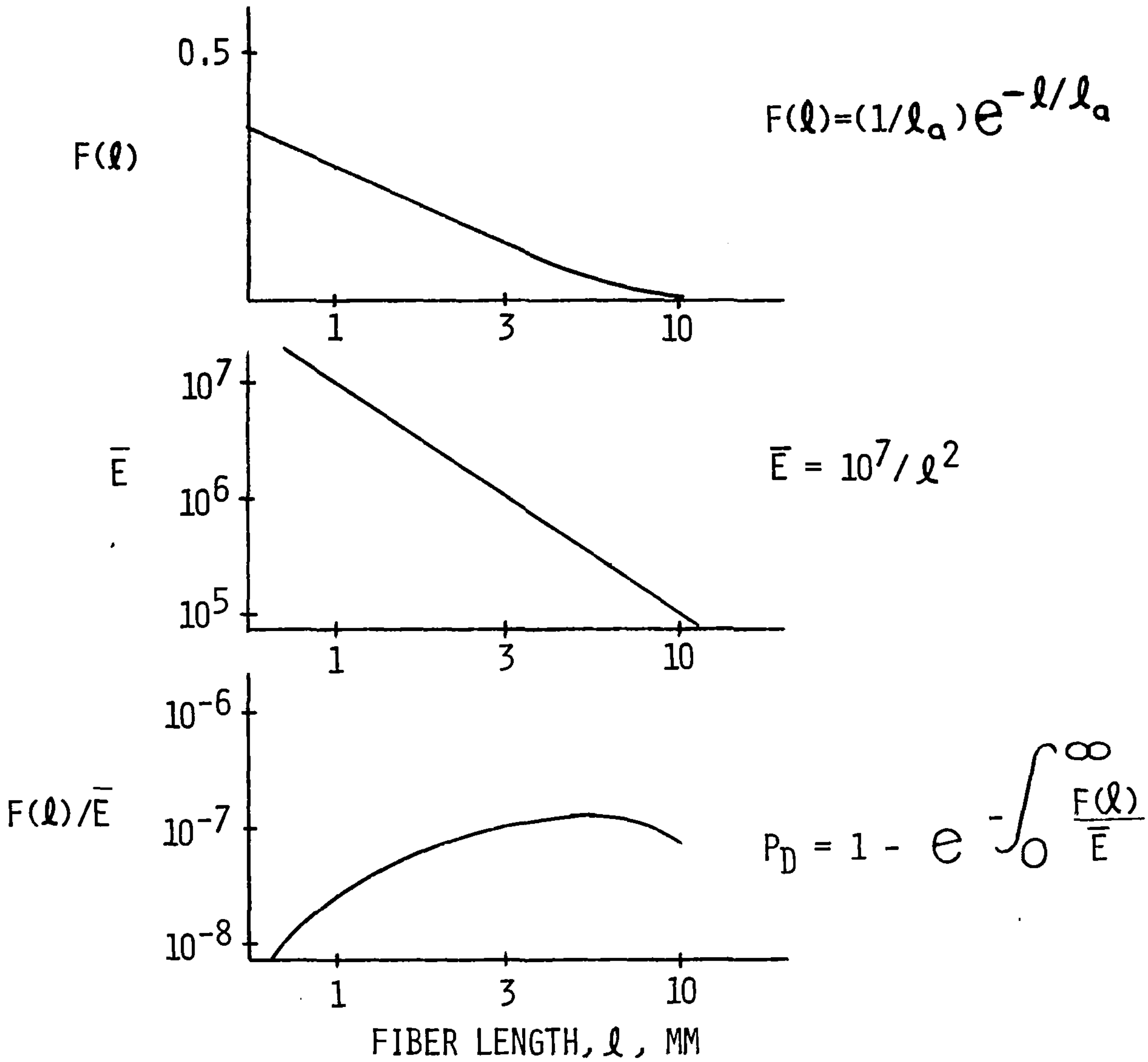


Figure 19.- Fiber length spectrum evaluation, detail integration.

1) ALL FIBERS OF LENGTH ℓ_a

2) EQUIVALENT EFFECTIVE $\bar{\bar{E}}$;
$\bar{\bar{E}}$ AT $\ell = \sqrt{2}$ TIMES AVERAGE LENGTH

3) $P_D = 1 - e^{E_{\ell_a}/\bar{\bar{E}}}$

Figure 20.- Fiber length spectrum evaluation, analytical.

ASSUMPTIONS
- 1000 KG IN EACH OF 5 ACCIDENTS/YEAR
- .01 FIRE RELEASE RATE
- 330 TOASTERS/KM^2
- TRANSFER FUNCTION, .01

EXPERIMENTAL RESULTS
- $\bar{E} = 2 \times 10^7$, 3 MM FIBERS
- VOLTAGE > 60 V IN 16 OF 25 TESTS
- FIBER RETENTION IN 3 OF 25 TESTS
- $I_{MAX} \leq$ 10 MA

$$P_{\substack{POTENTIAL\\SHOCK}} = \left[\frac{N}{U_S}\right]\left[\frac{T.F.}{\bar{E}}\right]\left[\frac{TOASTERS}{AREA}\right]\left[P_V > 60\right]\left[P_R\right]$$

$$P_{\substack{POTENTIAL\\SHOCK}} = 0.38/YEAR$$

Figure 21.- Potential for shock from toaster.

NOT A LARGE HAZARD, ESTIMATE IS CONSERVATIVE:

- MULTI-FIBER FAILURE STATISTICS
- DISTRIBUTION OF USER RESISTANCE TO GROUND
- CURRENT CAPABILITY IS NOT LETHAL

Figure 22.- Shock hazard evaluation.

1. A DATA BASE HAS BEEN COLLECTED FOR USE IN RISK ANALYSIS ON THE VULNERABILITY OF ELECTRONIC, ELECTRICAL AND AVIONIC EQUIPMENT TO T-300 FIBERS.

2. FIRE-RELEASE EXPERIMENTS HAVE SHOWN THAT FIBER RESISTIVITY IS UNCHANGED AND DAMAGE POTENTIAL IS APPROXIMATELY THAT OF VIRGIN FIBER.

3. POST EXPOSURE AVIONICS VULNERABILITY HAS BEEN INVESTIGATED AND WILL BE USED IN THE RISK ANALYSIS.

4. THERE IS A NEGLIGIBLE SHOCK HAZARD FOR A SMALL NUMBER OF HOME APPLIANCES. THE HAZARD WILL BE OVER-ESTIMATED BY USING SINGLE FIBER DAMAGE MODELS.

Figure 23.- Conclusions.