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AS ASSESSMENT OF POWER SYSTEM VULNERABILITY TO RELEASE OF CARBON FIBERS DURING COMMERCIAL AVIATION ACCIDENTS

GERALD R. LAROCQUE

ARTHUR D. LITTLE, INC.
CAMBRIDGE, MA. 02140

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Langley Research Center
Hampton, Virginia 23665

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PREFACE

This work was conducted by Mr. Gerald R. Larocque under the direction of Dr. Ashok S. Kalelkar. The contributions of Drs. John J. Bzura, Donald Rosenfield, Joseph Fiksel, and Ms. Caren Woodruff are acknowledged. Also acknowledged is the assistance of the Transmission and Distribution Division of Boston Edison, Inc.

1. INTRODUCTION

The high strength and low weight characteristics of carbon fiber composite materials make them extremely attractive for the fabrication of aircraft structural components. A potential hazard has been identified, however, due to the possible release of fibers resulting from an aviation accident which involves fire and/or explosion. Following such a release, the fibers may propagate downwind for considerable distances. The electrically conductive nature of these fibers presents a potential hazard to electrical devices which may be encountered and which is enhanced by the tendency of the fibers to align with strong electric fields. NASA has been engaged in a comprehensive risk analysis program directed at the hazards associated with potential widespread use of such materials in commercial aviation.

One of the possible hazards is the potential for significant electric power outages due to fiber interactions with electric power systems. Such outages are most likely to be associated with medium voltage distribution networks, since the very high voltages associated with long distance power transmission are likely to burn away the carbon fibers without adverse effects. This report addresses the power system problem in some detail and develops risk estimates based on the release and dissemination properties of carbon fibers and the structural properties of electrical distribution systems. The estimates are conservative but are independent of detailed network properties which may vary from location to location. Such conservative estimates bound the risk presented to power distribution, and since the estimated risks are negligible in comparison to normal outage rates, more detailed analysis and system-specific calculations are not warranted.

The principal sources of data used in this analysis are experimental insulator failure studies performed by Westinghouse, Inc., discussions with the Transmission and Distribution Division of Boston Edison, Inc., and estimates detailed in the Arthur D. Little, Inc., Phase I and Phase II reports to NASA.

2. ELECTRIC POWER DISTRIBUTION SYSTEMS

2.1 BACKGROUND

An electric power distribution system is the portion of an electric power system which provides the connection between consumers and a bulk power source such as a transmission line termination. Its functions are to provide reliable service to consumers and to perform the required voltage reduction from the higher voltage levels used for long-distance transmission. Historically, individual systems have evolved in response to changing electric power demands. There are, consequently, significant variations among utilities with regard to specific design practices. Even within a particular utility network, there may be variations in circuit design to accommodate the load requirements of a specific area. However, since all utilities seek the common objectives of minimum voltage variations, minimum service interruptions, reasonable cost, and flexibility to adapt to future power demand, certain general design practices have emerged which characterize a large fraction of existing power distribution circuits. This chapter discusses these practices and presents a specific distribution system in order to provide the details required in the analysis of the potential for carbon fiber induced power outages. The emphasis is on the identification of general properties characteristic of distribution systems rather than details of any specific system. In this way, the risk estimate furnishes a meaningful indication of the overall risk to electric power distribution.

2.2 GENERAL DESIGN CONFIGURATION OF DISTRIBUTION SYSTEMS

In general, an electric power distribution system can be divided into five components; subtransmission circuits, distribution substations, primary feeders, secondary circuits and consumer service connections. Figure 2.1 is a schematic representation of a typical power distribution system and indicates each of these components.

The bulk power source is typically a high-voltage (115 kV or greater) transmission line providing the connection to distant power generation facilities. Subtransmission circuits are commonly operated at approximately

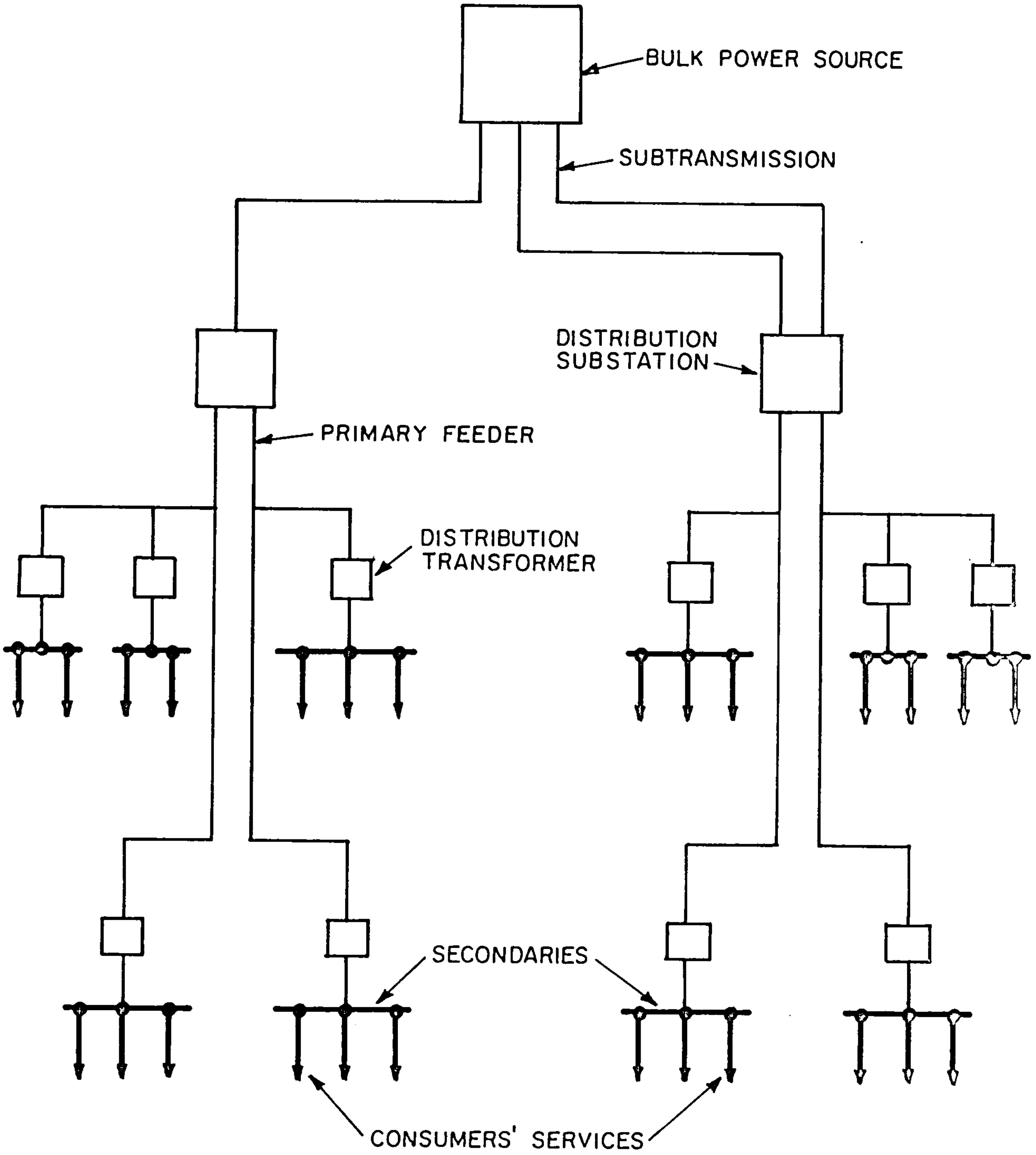


FIGURE 2.1. TYPICAL DISTRIBUTION SYSTEM SHOWING COMPONENT PARTS.

69 kV and deliver power to the distribution substations. These circuits may be single lines as shown on the left side of Figure 2.1, or may be multiple connections as illustrated on the right. The latter configuration is employed where higher reliability is required. It should be noted, however, that the increase in reliability may be reduced with respect to carbon fiber hazard since the lines would often occupy the same right of way and, therefore, may be subject to similar exposure levels.

At the distribution substation, the voltage is further reduced to the level selected for general distribution throughout the load area. Although there is significant variation in the selected voltage, most utilities use voltages in the 4 to 33 kV range. The substation consists of one or more transformer banks, switching equipment, and voltage regulation equipment. For purposes of this analysis, the only significant features are the voltage reduction and the presence of a reclosing circuit breaker which disconnects the entire load area when a fault is experienced along a primary feeder.

The primary feeders run from the distribution station through the approximate geographical center of the load area. Usually, the only fault protection for these lines is the main breaker at the substation. Thus, an insulator failure along a primary circuit will cause an outage affecting the entire load area. At suitable locations, lines branch off from the primary feeder (generally following side streets) which are protected by fuses. This helps to improve the system reliability since a fault on one of these "laterals" will not operate the circuit breaker at the station. It will, however, produce a localized outage of longer duration since it is necessary for personnel to replace the blown fuse.

Distribution transformers are located at regular intervals along the primary feeders and laterals to provide the final reduction of voltage to the level required for household connections. Typically, a distribution transformer services approximately ten homes. Finally, the secondary circuits provide direct connections from the distribution transformers to the individual consumers.

This type of distribution system is referred to as a radial system and is by far the most commonly used system in predominantly residential neighborhoods. Its widespread use is attributable to its simple configuration which minimizes the required switchgear and, hence, lowers its cost. Its principal disadvantage is the relatively high potential for power interruption due to the lack of redundant circuits. Consequently, it is used primarily for residential loads whereas alternative distribution systems would be used for specific loads (such as industrial operations) where continuity of service is more critical. The risk analysis, however, will be based on a radial system both because it is the most commonly used system and because it provides a conservative estimate of the general reliability of a distribution system.

2.3 DESCRIPTION OF A SPECIFIC DISTRIBUTION SYSTEM

With the advice of the transmission and distribution department of Boston Edison, circuit number 533-H2, serving parts of Bedford and Lexington, MA, has been selected as a representative suburban distribution system. This system reflects the design practices currently followed by Boston Edison and is felt to be representative of many suburban distribution systems. A suburban system was selected for analysis because it represents the most vulnerable type of system. This is the case because power distribution in an urban area is generally underground, and therefore, quite secure against carbon fiber exposure. Rural systems are also less vulnerable because they have wider spacing between poles and hence have fewer insulators. Additionally, a power failure in the rural area will generally impact fewer customers than in a populated suburban area. The analysis of a suburban system is, therefore, felt to represent the largest risk presented to power distribution.

The principal mechanism for power failure due to carbon fiber exposure is a ground fault due to insulator flashover. Consequently, the most important system properties for purposes of this analysis are the number and types of insulators, their spatial distribution and the probable consequences of their failure.

In general, the consequences of an insulator failure are strongly dependent on its location within the system. However, the present risk assessment is directed at distribution in general and not specifically at Bedford, MA. It is, therefore, desirable to find a conservative approximation to reduce dependence on specific properties of the Bedford system. An important observation in this regard is that the distribution network is composed of a number of "circuits" or groups of insulators protected by a single device. Such circuits often serve side streets or small neighborhoods and the failure of one or more insulators within the circuit implies a power outage for all customers served by the circuit. Since individual circuits are spatially localized and since a cloud of carbon fibers encloses a contiguous set of insulators, the probability of multiple insulator failures within a single circuit is high in comparison to the probability of multiple failures within several circuits. Multiple failure in several circuits, of course, involves a much higher consequence. It follows, therefore, that an assumption that the exposed insulators are randomly located within the distribution system is conservative since it increases the probability of exposing insulators from several different circuits relative to the probability of exposing them from the same circuit. Such an assumption is important to assure the general validity of the risk estimate since it removes from the calculation dependence on the specific geographic locations of individual circuits, thus making the calculation less sensitive to the arrangement of any particular town. To perform a risk calculation based on this assumption, it is only necessary to know the number of protective devices, the fraction of the total insulators associated with each device and the number of customers whose power is interrupted by activation of the protective device. This information is summarized in Table 2.2 and is used for the calculations in Chapter 3.

Clearly, an assumption of uniform insulator spacing is conservative if the highest insulator density observed in the system is used to represent the entire area. Based on examination of system maps and a visit to the area, the region of the highest insulator density was located and the number of insulators per unit area estimated based on the observation that each pole supports 3 pin type 15 kV porcelain insulators. The result of this is that the number of insulators per unit area is approximately 1.04×10^{-3} ins/m^2.

TABLE 2.2

PROPERTIES OF BOSTON EDISON CIRCUIT 533-H2 REQUIRED FOR RISK ESTIMATES

Total number of insulators = 1200

Total number of fuses = 11

Total area of the Bedford, MA system = .6 sq mi = 1.6×10^6 m^2

Area of the densest population = 2.87×10^5 m^2

Number of poles in the densest area = 100

Number of insulators in the densest area = 300

Number of insulators in the densest area that will operate the station breaker = 60

Fraction of the insulators in the densest area that will operate the station breaker = 0.2

Fraction of the insulators in the densest area that will operate a fuse = 0.8

Average number of insulators per unit area (assuming highest density)

$$= \frac{300 \text{ insulators}}{2.87 \times 10^5 \text{ m}^2} = 1.04 \times 10^{-3} \text{ ins/m}^2$$

This examination of the Bedford distribution system has estimated only macroscopic properties of the system and has ignored detailed properties such as geometric configuration and fault clearing by the substation breaker. However, the simplifying assumptions which have been made result in overestimation of the potential for power outages due to carbon fibers and, as discussed in Chapter 3, still result in negligible additional risk of power outage.

2.4 OUTAGE HISTORY

In order to provide a basis for assessing the significance of the estimated outage rates due to carbon fiber exposure, a limited amount of data regarding the system outage history from normal causes has to be obtained. This information is summarized in Table 2.3 and will be referred to in the next chapter. In general, there are at least six outages per year on this circuit and a total of at least 1000 customers are affected annually.

TABLE 2.3

PARTIAL OUTAGE HISTORY FOR BOSTON EDISON CIRCUIT NUMBER 533-H2

Date	Duration (hrs)	Number of Customers Affected
4/24/79	0.88	20
6/19/79	1.34	120
7/17/79	3.03	90
7/27/79	0.85	90
1/10/78	1.95	240
1/11/78	0.83	120
3/14/78	2.16	885
6/14/78	1.41	90
7/25/78	1.35	400
8/14/78	1.31	240
8/28/78	2.01	3
8/29/78	0.76	240
11/27/78	0.96	2,400
9/12/77	0.93	120
10/19/77	1.00	65
11/09/77	1.20	10
11/27/77	1.01	665
12/06/77	3.75	2,400
12/13/77	0.53	2,400

Source: Private Communication, Boston Edison, Inc.

3. ESTIMATES OF RISK TO ELECTRIC POWER DISTRIBUTION SYSTEMS

3.1 BACKGROUND

The previous chapter has provided descriptions of power distribution systems, the spatial distribution of insulators within the system, and the typical consequences of an insulator failure. To produce estimates of the risk of power failure, it remains to combine these results with data regarding insulator failure probabilities and estimates of carbon fiber exposure levels.

Throughout this analysis, a number of conservative assumptions have been used to ensure that the resulting estimates will be relatively independent of specific properties of any particular distribution system. Some of the key assumptions are summarized below:

- The aircraft crash occurs at or near an airport in the immediate vicinity of a suburban neighborhood.
- A maximum carbon fiber release occurs and weather conditions distribute the fiber in a way that causes the highest possible outage probability (uniform exposure distribution).
- Insulator failures occur at random locations throughout the system rather than in a particular region (higher probability of multiple circuit failures, see Section 2.3).
- Insulators are uniformly distributed over the suburban area at the highest density (number per unit area) observed anywhere in the system.

These assumptions result in a conservative estimate (i.e., an overestimate) of the risk.

3.2 DISCUSSION OF WESTINGHOUSE DATA ON INSULATOR FAILURE

In order to determine the risks associated with the release of carbon fibers, Westinghouse has conducted an experimental program to investigate the failure probability due to flashover of wet and dry 7.5 kV, 15 kV, and 35.4 kV insulators exposed to airborne carbon fibers.

These results were based on laboratory tests of seven 7.5 kV pin insulators and ten 15 kV C neck distribution post insulators. The insulators were exposed to 2 mm carbon fibers at concentrations of 1.5×10^4 fibers/m^3 and 1.6×10^4 fibers/m^3, respectively. Assuming that insulator failure probability depends only on fiber exposure, the percentage of insulators failed as a function of exposure was recorded.

Figures 3.1 and 3.2 show the percentage of insulators failed as a function of carbon fiber exposure level for 7.5 kV and 15 kV insulators respectively. Since these plots are on Weibull paper and are approximately linear, we concluded that, over the range of testing, the insulator failure probabilities are well represented by a two parameter cumulative Weibull distribution with the parameters as indicated on each plot. Table 3.1 summarizes these values of the Weibull parameters and the functional form is provided by Equation 3.1.

$$P_F(E) = 1 - e^{-\left(\frac{E}{\alpha}\right)^{\beta}} \qquad (3.1)$$

where:

E = specified carbon fiber exposure level

$P_F(E)$ = probability of insulator failure before reaching exposure E

α, β = Weibull parameters (see Table 3.1).

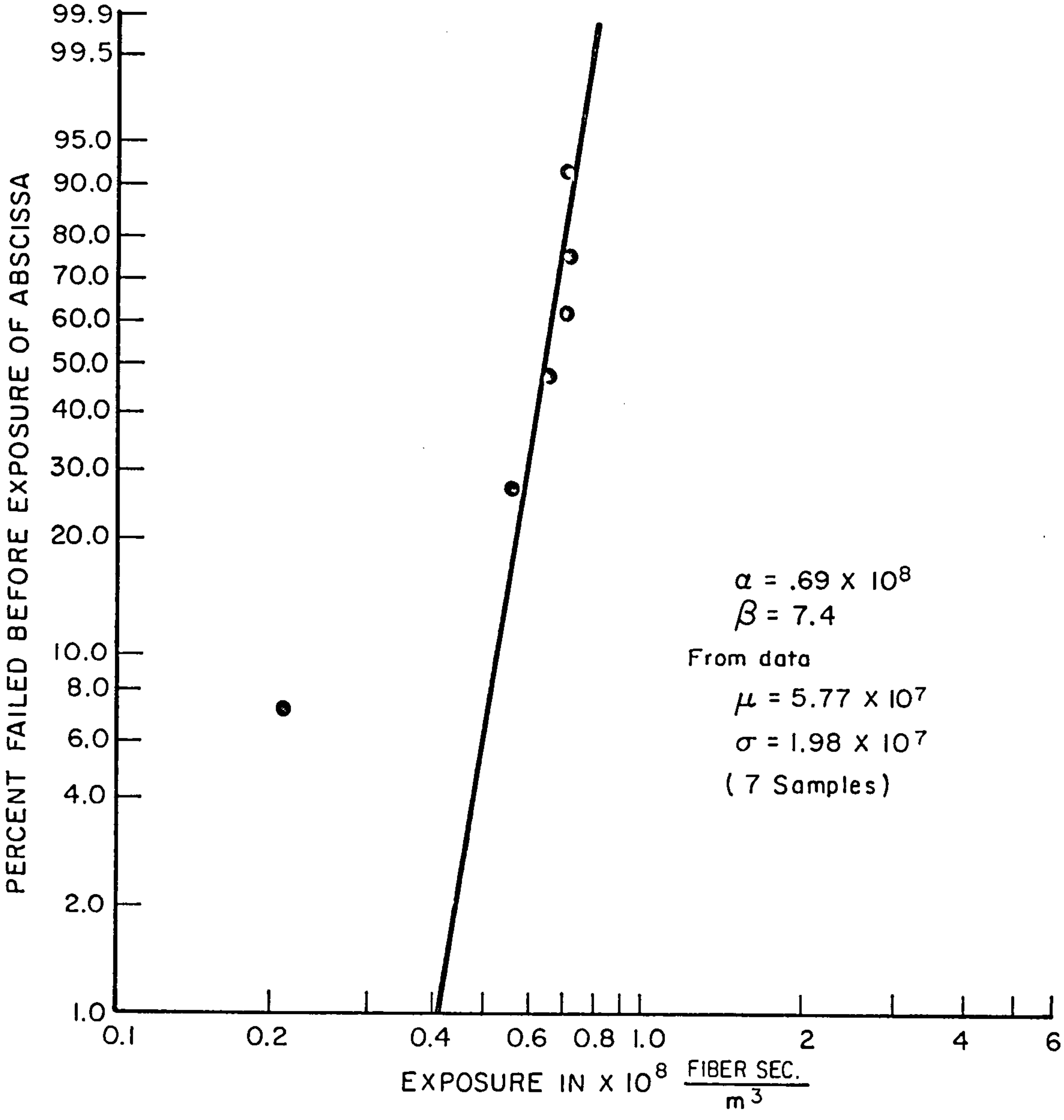


FIGURE 3.1 EXPOSURE TO FLASHOVER FOR WET 7.5kV PIN INSULATOR, 2mm FIBER.

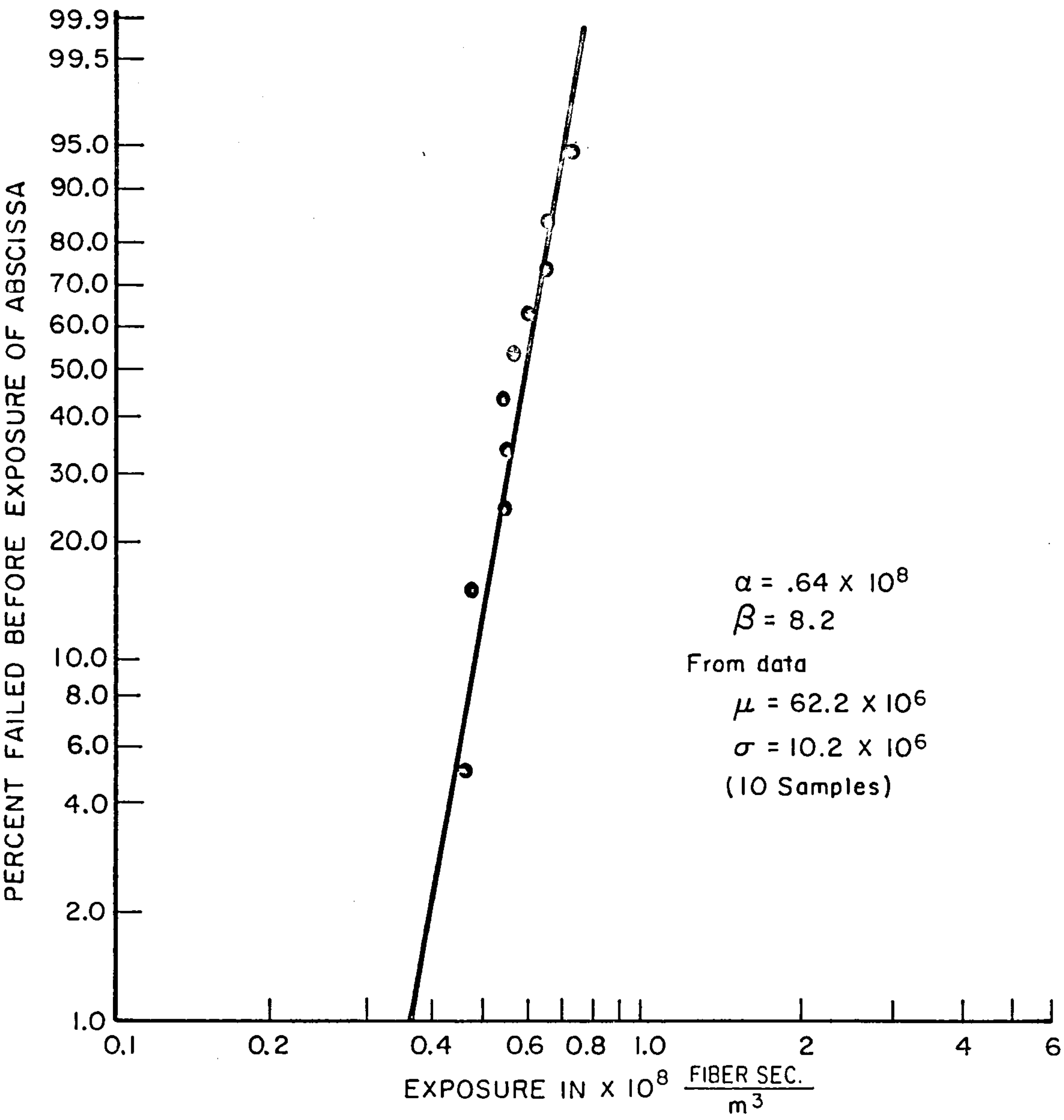


FIGURE 3.2 EXPOSURE TO FLASHOVER FOR WET 15kV DISTRIBUTION POST, 2mm FILTERS.

TABLE 3.1

SUMMARY OF WEIBULL PARAMETERS

INSULATOR	α	β
7.5 kV	0.69×10^8	7.4
15 kV	0.64×10^8	8.2

The straight lines in Figures 3.1 and 3.2 are the plots of this expression with the specified parameters. The experimental data show a Weibull behavior for exposure levels as small as 4×10^7 fiber-sec/m^3. For lower exposures, however, the assumption of a Weibull distribution may overestimate the failure probability. For instance, it may be that, at lower exposures, the relatively few fibers will burn without any adverse consequences to the insulator thus preventing any failures below some threshold exposure. In the absence of specific experimental results for these lower exposures, we assumed that the insulator failure probabilities due to carbon fiber exposure can be characterized by a Weibull distribution throughout the range of interest.

For exposures much below 1×10^7 fiber-sec/m^3 the insulator failure probabilities are negligible, generally less than 10^{-15}. Consequently, this exposure will be taken as a lower bound in the subsequent calculations.

3.3 ESTIMATED CARBON FIBER EXPOSURE LEVELS

The detailed estimation of carbon fiber exposure contours, in general, depends not only on the amount of carbon fibers released but also on the specific atmospheric conditions. Detailed modelling of such factors is clearly beyond the scope of this study, so it is necessary to rely on existing results and conservative approximations to obtain reasonable bounds on the expected risk. The Arthur D. Little Phase I and II studies on the risks associated with the use of carbon fiber composites in commercial aviation provide results of numerical modelling for a limited number of release scenarios. Some of the results on typical contours are presented in Tables 3.2 and 3.3 In general, exposures of 10^7 or greater occurred infrequently and covered only a small area, and were not estimated for these studies.

Table 3.2

REPRESENTATIVE RESULTS FOR CARBON FIBER RELEASE IN FIRE-EXPLOSIVE MODE

Type of Atmosphere	Wind Velo City (M/S)	Mass Rel eased (KG)	Height of Source (M)	Nearest point of contour, NEAR, (M); Farthest downwind travel distance, FAR(M); Maximum width, WMAX, (M); and area within contour, AREA, (M^2); for different exposure values.															
				1.0E6 FS/M^3				1.0E5 FS/M^3				1.0E4 FS/M^3				1.0E3 FS/M^3			
				NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA	NEAR	FAR	WMAX	AREA
4	4	50	0	50	950	118	8.34E4	50	3350	369	9.58E5	50	11000	1115	9.59E6	50	34000	3098	8.26E7
4	4	50	10	100	1200	137	1.19E5	100	4300	455	1.50E6	50	14100	1394	1.54E7	50	43100	3828	1.29E8
4	4	50	20	200	1200	124	9.77E4	150	4600	477	1.67E6	150	15300	1494	1.78E7	100	46650	4102	1.50E8
4	4	100	0	50	1400	167	1.77E5	50	4850	518	1.95E6	50	15600	1538	1.88E7	50	46900	4135	1.52E8
4	4	100	10	100	1750	199	2.58E5	50	6150	642	3.08E6	50	20000	1915	3.00E7	50	59100	5090	2.36E8
4	4	100	20	150	1850	196	2.61E5	150	6650	681	3.48E6	100	21650	2052	3.47E7	100	63800	5449	2.73E8
4	4	500	0	50	3350	369	9.58E5	50	11000	1115	9.59E6	50	34000	3098	8.26E7	50	95900	7863	5.92E8
4	4	500	10	100	4300	455	1.50E6	50	14100	1394	1.54E7	50	43100	3828	1.29E6	50	118600	9558	8.90E8
4	4	500	20	150	4600	477	1.67E6	150	15300	1494	1.78E7	100	46650	4102	1.50E8	100	127400	10198	1.02E9

Source: A. D. Little, Inc. Phase I Report

Table 3.3

SAMPLE RESULTS FROM PLUME RISE AND FIBER DEPOSITION MODEL

Explanation of Variables:

IATM: Atmospheric Stability (Pasquill Type)
U10: Wind Speed at Height of 10 Meters (M/S)
HM: Mixing Depth (M)
XSTAR: Downwind Distance at which Plume Reaches Max Height (M)
CFKGS: Total KGS of Carbon Fibers Released (KG)
HP: Plume Rise Height (M)

VS: Deposition Velocity of Fibers (M/S) = 0.032
DOTMF: Fuel Burning Rate (KG/S) = 33.3
TIMEB: Total Time of Burning (S) = 600
DIAM: Diameter of the Pool (M) = 60
TA: Temperature of Atmosphere (K) = 288
TLAPSE: Temperature Lapse Rate in the Atmosphere = 0.03

Nearest point of contour, NEAR, (M); Farthest downwind travel distance, FAR, (M); Maximum width, WMAX, (M); and area within contour, AREA, (M^2); for different exposure values.

	1.0E6 FS/M^3					1.0E5 FS/M^3					1.0E4 FS/M^3					1.0E3 FS/M^3				
	NEAR	FAR	WMAX	AREA	WMAX occurs at X =	NEAR	FAR	WMAX	AREA	WMAX occurs at X =	NEAR	FAR	WMAX	AREA	WMAX occurs at X =	NEAR	FAR	WMAX	AREA	WMAX occurs at X =
IATM=4 U10=4 HM=1500 XSTAR=300 CFKGS=100 HP=403	0	0	0	0	0	0	0	0	0	0	0	0	0.	0	0	8300	87300	11048	6.86E8	75300
IATM=4 U10=4 HM=1500 XSTAR=300 CFKGS=500 HP=403	0	0	0	0	0	0	0	0	0	0	10300	83300	8080	4.63E8	74300	6300	94300	16107	1.11E9	77300
IATM=6 U10=2 HM=1100 XSTAR=150 CFKGS=100 HP=508	0	0	0	0	0	50150	52150	676	1.06E6	51150	37150	58150	5069	8.36E7	52150	31150	61150	7181	1.69E8	53150
IATM=6 U10=2 HM=1100 XSTAR=150 CFKGS=500 HP=508	0	0	0	0	0	39150	57150	4247	6.00E7	53150	33150	60150	6608	1.40E8	52150	28150	63150	8363	2.30E8	53150

SOURCE: Arthur D. Little, Inc., Phase I Report

As pointed out in the previous section, however, insulator failure probabilities due to carbon fibers are negligible for exposures of 10^6 fiber-sec/m^3 or less. It was necessary, therefore, to develop an approximation of the contour areas for the higher but less probable exposure levels.

Since a power outage occurs whenever at least one insulator fails, a conservative estimate of outage probability will be obtained by choosing a fiber exposure distribution which maximizes the probability of observing at least one insulator failure. This requires evaluation of the combined effects of the variation in failure probability with exposure level and the variation in the area of the exposure contours. Under the assumption of uniform insulator spacing and Weibull distributed failure probabilities, the maximum outage probability will occur when the fibers are uniformly distributed to produce a region of constant exposure. Consequently, although this type of fiber dispersion is extremely unlikely in nature, the risk of power outage can be bounded by examining, as a function of exposure level, the largest regions which can receive uniform exposures of specified levels subsequent to a carbon fiber release. Figure 3.3 illustrates the geometry of this exposure scenario.

Under these conditions, if the fibers settle at a velocity v_s and N fibers are released, it follows that the ambient concentration, χ, is given by:

$$\chi = \frac{N}{Ah} \qquad (3.2)$$

where h = height of fiber cloud

A = area exposed

Further, during a time $t = h/v_s$, all of the released fiber will settle onto the ground. Thus, since exposure is the time integral of concentration, the carbon fiber exposure experienced at any point in the area A is given by:

$$E = \chi t = \frac{N}{Ah} \bullet \frac{h}{v_s} = \frac{N}{Av_s} \qquad (3.3)$$

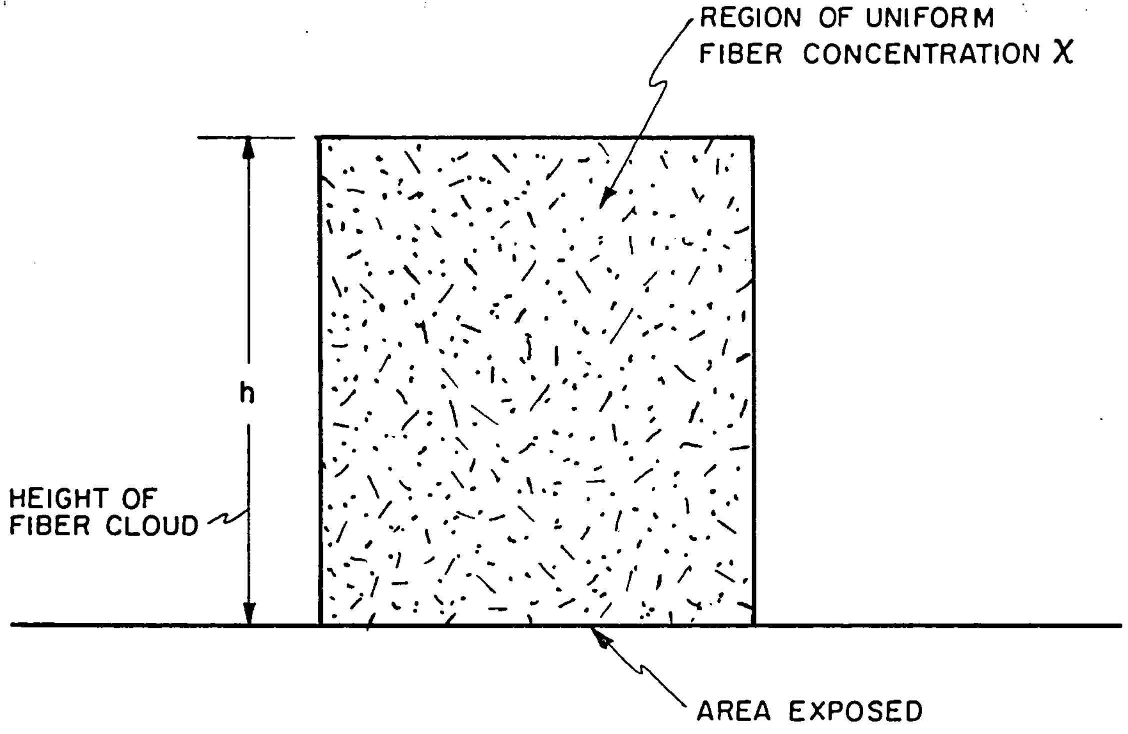


FIGURE 3.3 GEOMETRY OF ASSUMED FIBER RELEASE.

Alternatively, for the release of N fibers, the maximum area which can experience exposure E is given by:

$$A = \frac{N}{v_s E} \tag{3.4}$$

This relation is used in the following analysis to provide upper bounds on the risk to electric power distribution. The calculation has the advantage of being independent of location-specific weather conditions.

Based on ADL's Phase I and Phase II Studies, we assumed the settling velocity for carbon fibers to be 0.032 m/sec and the number of fibers released to be 5 x 10^9 fibers/kg of released fiber mass. The minimum exposure to produce a significant insulator failure probability is of the order of 10^7 fiber-sec/m^3 and the data from the Phase I contouring indicate that even exposures of 10^6 fiber-sec/m^3 are highly unlikely in the absence of explosive agitation (see for example, Table 3.3). Consequently, <u>the following analysis considers only a combined fire and explosion accident</u>. In this case, the mass of released fiber will be taken as 2.5% of the mass of carbon fiber on the aircraft based on NASA's experimentally derived upper-bound estimates of carbon fiber release in combined fire and explosion accidents.

It is also important to consider that in general, wind conditions are not such as to transport the released fiber in the direction of the power distribution system. Further, the cloud will generally travel some distance before reaching the network, permitting some fraction of the fiber to settle onto the ground before reaching the distribution system. In order to accommodate the first factor, the distribution system has been assumed to be located at the edge of a 1 mi^2 airport and the probability of the cloud being transported towards the system is taken as the angular fraction subtended by the distribution system. This implies a probability of 0.15 that the cloud will move towards the system. As the fiber cloud is being transported downwind toward the distribution system, many fibers will settle onto the ground. This process may be modeled by adjusting N in the above relation to represent the number of fibers which are still airborne upon reaching the distribution system. Standard relations for calculating this depletion are available in the literature (see Slade, 1978) and under the assumption that the cloud travels at least one mile before reaching the system, it follows that 60% of the released fiber will have settled onto the ground. In the following calculations, N is reduced by a factor of 0.6 to account for this settling.

3.4 RISK ANALYSIS

Based on the NASA/Westinghouse experimental work, estimates of insulator failure probabilities as a function of carbon fiber exposure have been developed. As described in Section 3.1, these probabilities are characterized by a two-parameter cumulative Weibull distribution.

Under the assumption that the Weibull distribution holds over the entire exposure range, it is recalled that the insulator failure probability may be approximately expressed as follows:

$$P_F(E) = 1 - e^{-\left(\frac{E}{\alpha}\right)^{\beta}} \qquad (3.5)$$

Where:

$P_F(E)$ = probability of insulator failure before exposure of level E
E = specified exposure level
α, β = Weibull parameters from Table 3.1

If the failure of each insulator exposed to a cloud of carbon fibers is considered as a statistically independent event, the number of insulators failing as the result of exposure of I insulators to a cloud of carbon fiber may be considered as the result of I trials of a binomial experiment with probability $P_F(E)$.

In order to estimate the number of insulators exposed, the contour estimates developed in Section 3.2 are used along with an estimate of the number of insulators enclosed in the exposed areas based on analysis of the Bedford, MA power distribution system. To conservatively estimate the risk, the largest density of insulators found in the system was used to represent the entire area. This density was found to be 1.04×10^{-3} insulators/m^2. Assuming this uniform density of insulators and the results of Section 3.2, the number of insulators subjected to a given exposure level may be written as:

$$I = \frac{F_{RE} (5 \times 10^9) DM}{v_s E} \qquad (3.6)$$

where:

E = specified exposure level (fiber-sec/m^3)
I = maximum number of insulators exposed at this level
D = maximum number of insulators per square meter
v_s = carbon fiber setting velocity (0.032 m/s)
M = mass of carbon fiber on board aircraft
F_{RE} = fraction of mass released as single fibers during a fire and explosion accident

In applying this expression, it must be noted that I must be integer valued since it represents the number of insulators contained within the cloud. The amounts of carbon fiber mass on board aircraft were classified according to the possible maximum integer values of I.

In order to form an overall risk estimate for a specified exposure level, it remains to attach probabilities to various numbers of insulator failures using the above results along with accident probabilities and parameters from the ADL Phase II report. These probabilities are summarized in Table 3.4 and the estimated 1993 carbon fiber distribution within the aircraft fleet is presented in Table 3.5. Using the above values, the annual probability of experiencing x insulator failures due to carbon fiber exposure level E is given by:

$$P(x) = P_A \cdot N_{OP} \cdot P_D \cdot P_{CF} \cdot P_E \cdot P_m \cdot \sum_{I=1}^{I_{max}} \sum_{i=1}^{3} F_i \left[f_i(M_{I+1}) - f_i(M_I) \right] \cdot \binom{n}{x} P_F{}^{x}(E) \left[1 - P_F(E)\right]^{n-x} \qquad (3.9)$$

where:

$f_i(M)$ = the fraction of aircraft in size class i having less than or equal to M kg of carbon fibers on board (Table 3.5).

I_{max} = the largest number of insulators that can be exposed (corresponding to largest mass of carbon fiber in any aircraft).

M_I = aircraft carbon fiber mass required to expose at most I insulators.

P_m = probability of fiber cloud being blown toward the distribution system (0.15).

Although this expression appears complex due to the large number of variables, it simply expresses the probability of experiencing x insulator failures as the product of the probability of an accident involving an aircraft carrying a particular mass of carbon fiber with the probability of x failures conditioned on the resulting fiber release and summed over all possible masses of carbon fiber.

TABLE 3.4

ASSUMED PROBABILITIES AND PARAMETERS FOR HAZARD CALCULATION

Description	Assumed Value	Symbol
Accident probability per aircraft operation	5×10^{-7}	P_A
Annual aircraft operations at Logan International Airport	3×10^5	N_{OP}
Probability of total destruction during a crash	0.7	P_D
Probability of combined fire and explosion subsequent to crash	0.05	P_E
Probability that an aircraft operation at Logan Airport involves an aircraft carrying carbon fiber	0.63	P_{CF}
Fraction of Logan Airport flight operations involving large aircraft	0.485	F_1
Fraction of Logan Airport flight operations involving medium aircraft	0.415	F_2
Fraction of Logan Airport flight operations involving small aircraft	0.10	F_3
Fraction of carbon fiber mass that is released during a fire and explosion accident	0.025	F_{RE}

TABLE 3.5

ASSUMED DISTRIBUTION OF CARBON FIBER ON BOARD AIRCRAFT

Small Aircraft		Medium Aircraft		Large Aircraft	
Percentage	Mass (kg)	Percentage	Mass (kg)	Percentage	Mass (kg)
0	0	0	0	0	0
4	11.4	4	216.0	5	286.0
8	55.0	16	330.0	38	1283.0
54	139.0	24	351.0	44	2022.0
100	183.0	26	567.0	50	3044.0
		50	1492.0	63	4643.0
		100	3794.0	80	5179.0
				99	6083.0
				100	15652.0

Source: Private Communication with Principal Airframe Manufacturers.

To assess the importance of these probabilities, criteria such as outage severity and frequency of occurrence should be taken into account. As discussed in Chapter 2, the impact of a particular insulator failure can vary significantly with its location within the system. For the present analysis, however, it is undesirable to introduce specific geometric features into the calculation. In order to generalize the calculation, it has been conservatively assumed that the insulator failures occur randomly throughout the system (see section 2.3).

In order to evaluate the anticipated consequence of insulator failures, some analysis of the distribution system is required. The details of this analysis are described in Chapter 2 and are not repeated here, but the basic result is that for an insulator selected at random, its failure will imply failure of the entire system with probability 0.2, affecting 2400 customers,and that at most 11 other circuits, each affecting approximately 10 homes, will fail with probability 0.07. Assuming random selection of insulators, it follows that the expected consequence of x insulator failures is expressed by:

$$C = (2400)[1 - 0.8^{x}] + (0.8)^{x} \cdot 10 \cdot \sum_{n=1}^{\min(11,x)} n \binom{x}{n} (0.07)^{n} (0.93)^{x-n} \quad (3.10)$$

In order to account for these estimates of consequence, the annual probability of experiencing x failures was multiplied by the expected consequence of x failures and summed to produce an annual expected number of customers affected.

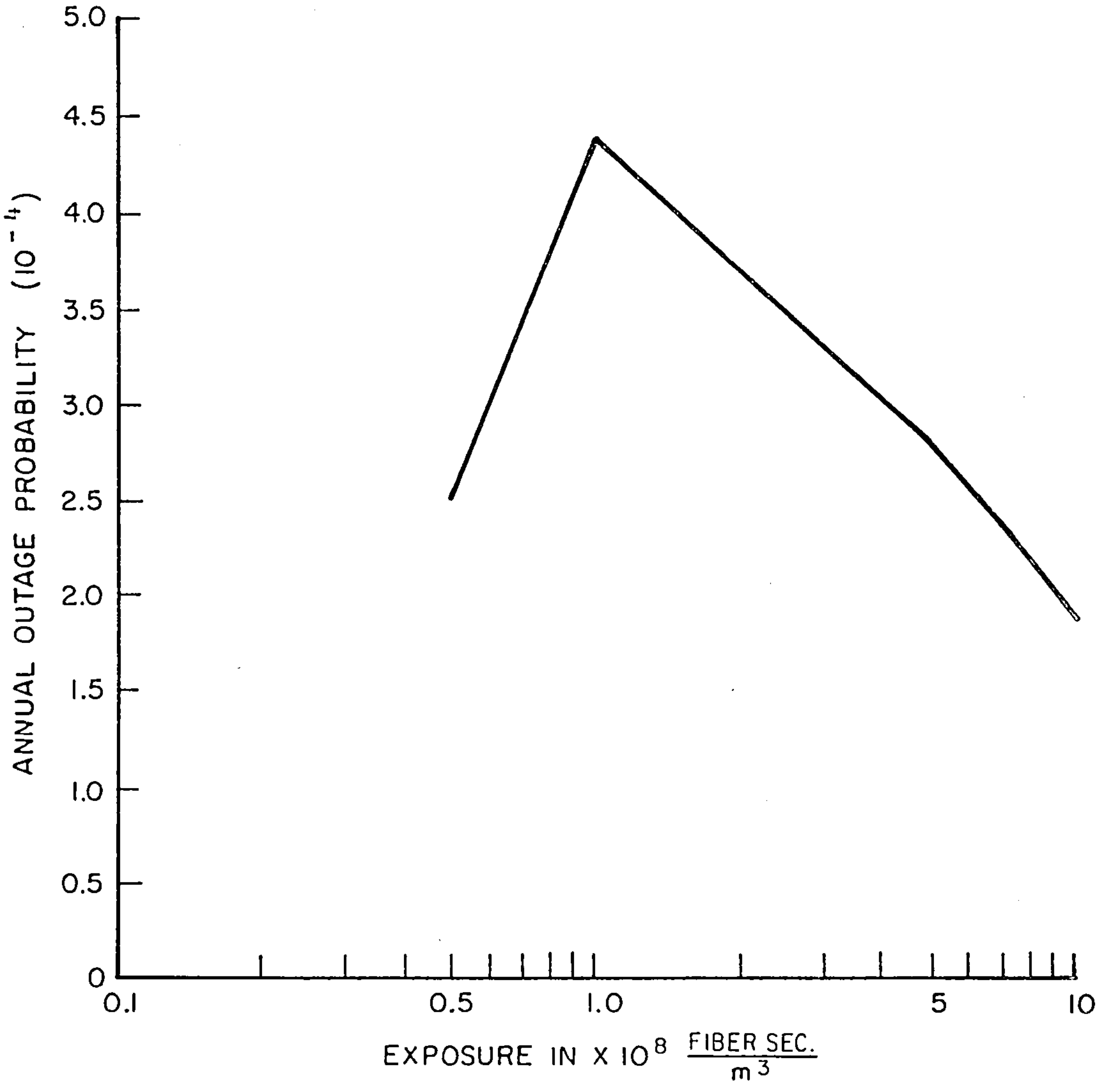
Due to the amount of computation required to evaluate these expressions, a simple computer program was written to perform this calculation. Table 3.6 summarizes the resulting annual outage probabilities, meantime to failure and expected number of customers affected for each of several exposure levels. Figure 3.5 shows the annual outage probability

TABLE 3.6

ESTIMATED RISKS DUE TO CARBON FIBER EXPOSURE OF 15 kV PIN INSULATORS

Exposure Level (Fs/m^3)	Annual Outage Probability	Annual Expected Number of Customers Affected	Mean Time Between Outages (yrs)	Average Number of Customers Affected per Outage
5×10^{7}	2.5×10^{-4}	0.22	4,000	880
5×10^{8}	4.4×10^{-4}	0.75	2,300	1,700
5×10^{8}	2.8×10^{-4}	0.25	3,600	890
7.5×10^{8}	2.3×10^{-4}	0.16	4,300	690
1×10^{9}	1.9×10^{-4}	0.11	5,300	580

FIGURE 3.5 - ANNUAL OUTAGE PROBABILITY VERSES EXPOSURE LEVEL FOR 15kV POWER SYSTEM



plotted as a function of exposure level and displays a clear peak in the vicinity of 1 x 10^8 fiber-sec/m^3.

This peaking phenomenon represents the competing effects of contour size and exposure level. Since high exposure levels generally imply small exposure areas, the number of insulators exposed decreases for higher exposure levels tending to decrease the probability of a power outage. On the other hand, failure probability decreases rapidly with decreasing exposure so that low exposure levels are also unlikely to produce power outages. The combination of these effects produces an exposure level which causes the highest system failure probability.

It is then conservative to approximate the annual risk by the results for an exposure of 1 x 10^8 fiber-sec/m^3. At this level, the analysis shows a mean time between outages of approximately 2300 years and an average of 0.7 persons affected annually. (That is, once every 2300 years, .7 x 2300 or 1600 people are affected.) The system outage history, however, indicates that typically there are annually at least 6 outages affecting a total of about 1000 people. The expected time between outages thus increases by .007% (6 to 6.0004 per year) due to carbon fiber, and the expected annual number of customers losing power increases by .07% (1000 to 1000.7). It is thus apparent that even based on conservative assumptions, there is negligible additional risk of power outage associated with commercial aviation applications of carbon fiber composites.

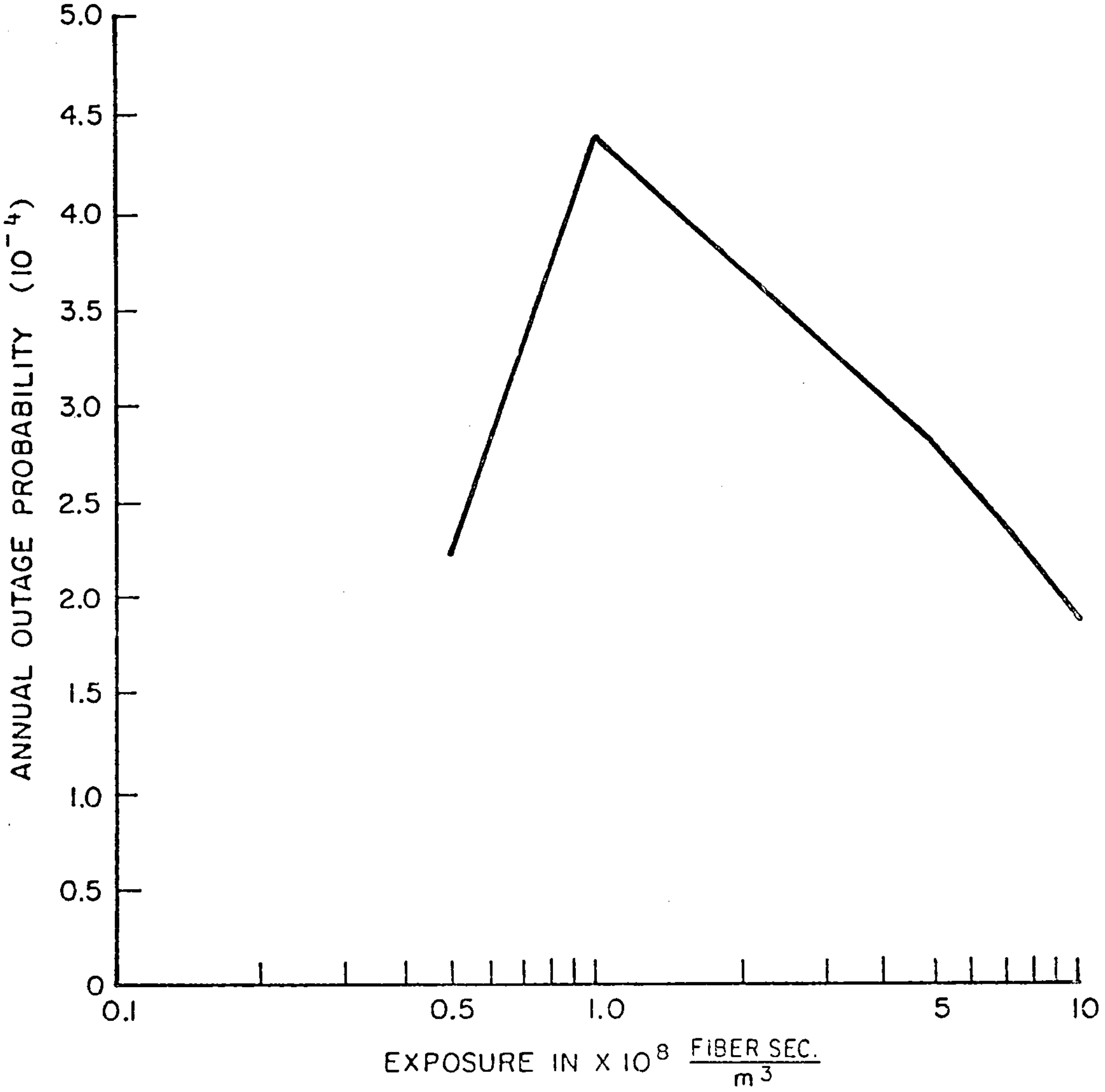
At the voltages used for power distribution, the pole spacing and hence the number of insulators is determined primarily by house spacing and not from structural considerations. Thus, the number of insulators per unit area will be essentially independent of system voltage and the risks presented to a lower voltage (7.5 kV) system may be approximated by performing the above calculation using the Weibull parameters for the 7.5 kV insulators. The results of the calculation are shown in Table 3.7 and Figure 3.6. This approach somewhat overestimates the consequences of an outage, however, since a lower voltage system is likely to serve fewer customers. The risks presented are, however, still inconsequential compared to the prevailing rates of power outage.

TABLE 3.7

ESTIMATED RISKS DUE TO CARBON FIBER EXPOSURE OF 7.5 kV INSULATORS

Exposure Level (Fs/m^3)	Annual Outage Probability	Annual Expected Number of Customers Affected	Mean Time Between Outages (yrs)	Average Number of Customers Affected per Outage
5×10^7	2.2×10^{-4}	0.17	4,500	770
1×10^8	4.4×10^{-4}	0.75	2,300	1,700
5×10^8	2.8×10^{-4}	0.25	3,600	890
7.5×10^8	2.3×10^{-4}	0.16	4,300	690
1×10^9	1.9×10^{-4}	0.11	5,300	580

FIGURE 3.6 - ANNUAL OUTAGE PROBABILITY VERSES EXPOSURE LEVEL FOR 7.5kV POWER SYSTEM



3.5 SUMMARY AND CONCLUSIONS

The foregoing analysis has utilized a number of conservative approximations in order to bound the risk of power outages due to carbon fiber exposure. The objective of these approximations has been not only to simplify the computational efforts but also to extend the general applicability of the results by reducing the dependence on detailed properties of specific distribution systems. When required, however, specific system properties have been estimated based on a circuit selected with the advice of Boston Edison as being representative of current design practices in suburban power distribution.

Despite the conservative nature of the calculations, the above analysis has predicted that in the worst scenario, the annual outage probability will be 4×10^{-4} with an expected annual consequence of 0.7 customers experiencing power failure. This implies a mean time between carbon fiber induced outages of approximately 2300 years. Examination of historical outage data for the circuit considered shows, however, that there are generally at least 6 power outages per year and at least 1000 people are affected. In fact, considerably higher outage rates are not at all uncommon. For example, Table 2.3 shows that there have been 3 failures of the entire circuit (2400 customers) during the past three years alone. In comparison to these data, the estimated outage rates due to carbon fiber are negligible. It is interesting to note, however, that the expected consequence of a carbon fiber induced outage is relatively large compared to its outage rate. This reflects the fact that much of the system is protected by the combination of a main system circuit breaker and a series of lightning arrestors. The lightning arrestors provide considerable protection against complete system failure resulting from natural causes but do not provide protection against carbon fibers. Thus, carbon fiber outages are comparatively likely to result in complete failure of the distribution system. Even this, however, does not appear to be cause for concern because of the very long (2300 years) expected time between outages.

The estimates developed above are believed to be quite representative of the overall risks presented to electric power distribution by the use of carbon fiber composites in commercial aviation. The justification for this statement lies both in the fact that the calculations are fairly independent of specific system properties and that the system selected for analysis was chosen to reflect standard design practice. It is felt, therefore, that the above analysis is sufficient to conclude that the use of carbon fiber composites in commercial aviation poses a very small risk to electric power distribution.

3.6 SUMMARY OF UNCERTAINTIES

It should be noted that the risk estimates are subject to uncertainty from a number of different sources. Some of the principal uncertainties are described below.

- Carbon fiber usage - the carbon fiber usage levels represent projected 1993 levels based on information obtained from the principal airframe manufacturers. It is possible that actual usage will deviate from the assumed levels.
- Number of fibers by weight - this report assumes there are 5×10^9 single fibers per kilogram of carbon fiber available for release based on previous NASA estimates. Although this number may be much greater, this study also includes the conservative assumption that all carbon fiber composite mass is exposed to the fire. This assumption compensates for the possibility of release of larger numbers of fibers per unit mass.
- Fraction of carbon fiber released - Recent test results suggest that the 2.5% figure used in the analysis is conservative.
- System vulnerability - vulnerability estimates were developed for a particular power distribution system. Although there are design variations among power systems, the network chosen reflects standard design practice and the vulnerability estimates were based on conservative assumptions.

In general, although there are a number of sources of uncertainty in the assumed data, the analysis has followed a conservative approach and still resulted in very small risks. It is felt that the inherent conservatism of the analysis more than compensates for the possible uncertainties.

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16. Abstract

The vulnerability of a power distribution system in Bedford and Lexington, Massachusetts to power outages as a result of exposure to carbon fibers released in a commercial aviation accident in 1993 was examined. Possible crash scenarios at Logan Airport based on current operational data and estimated carbon fiber usage levels were used to predict exposure levels and occurrence probabilities. The analysis predicts a mean time between carbon fiber induced power outages of 2300 years with an expected annual consequence of 0.7 persons losing power. In comparison to historical outage data for the system, this represents a 0.007% increase in outage rate and 0.07% increase in consequence.

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