EFFECTS OF CARBON/GRAPHITE FIBER CONTAMINATION ON HIGH VOLTAGE ELECTRICAL INSULATION

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THE NATURE OF THE PROBLEM

The burning and/or explosion of carbon/graphite composites has been demonstrated to release large numbers of small, electrically conductive carbon/graphite fibers into the atmosphere. These fibers are propagated by air currents over large areas as they settle back down to the earth. The length spectrum, electrical conductivity and propagation characteristics have been characterized in detail by others. During the course of air propagation and settling, these conductive fibers come in contact with all structures located in the propagation path, including electrical power systems. The electrically conductive nature of these fibers caused concern over the potential effects of exposure to electrical power systems. To determine the degree of hazard posed, the U.S. Department of Energy, through its contractor, Westinghouse Electric Corporation, initiated a testing and evaluation program to quantify the effects of carbon/graphite exposure to high voltage electrical insulation and to power plant and substation control systems. This work was carried out in close cooperation with the NASA risk assessment program.

POWER SYSTEM COMPONENTS

The basic elements of a power system are shown, in simplified form, in Figure 1. These basic elements consist of:

1) Power plants
2) Bulk power substations
3) Transmission system
4) Transmission substations
5) Subtransmission system
6) Distribution substation
7) Distribution system
8) Utilization voltages

All of these components may be exposed to carbon/graphite fiber contamination. The areas of investigation are the vulnerability of high voltage insulation and the vulnerability of power plants and substation control systems. These areas encompass all of the eight enumerated power system components except utilization voltages. The vulnerability of utilization voltage installations and industrial plants is being evaluated by others.

The evaluation of high voltage insulation vulnerability to carbon/graphite fiber-induced failure required implementation of a laboratory testing program. A contamination test chamber was constructed, a fiber chopper was built and a high voltage power supply was assembled. Representative samples of distribution class (2400 Volts to 35 kV) and transmission class (over 35 kV) insulators were selected for testing.

CONTAMINATION SYSTEM

The contamination system includes the fiber chopper, dispersal chamber, air ducts and blower, and contamination chamber. A floor plan of this system is shown in Figure 2.

Fiber Chopper

The fiber chopper is a multi-knife roller type manufactured by Binks which was modified to cut the relatively light-weight carbon fiber and to operate at low speeds. Figure 3 shows a schematic of the chopper. This chopper has various multi-knife rollers to cut different lengths of fiber. During normal operation, a single end of fiber is fed off a 114-g (1/4-lb) roll into the chopper.

Dispersal Chamber

The dispersal chamber was designed to mix air with the chopped fibers and collect any clumps of fibers which may be generated by the chopper. A diagram of the dispersal chamber is shown in Figure 4. The dispersal chamber is constructed entirely of clear LEXAN sheeting material so its operation is clearly visible from the outside.

Contamination Chamber

The chamber provides dispersion and confinement of the fibers and maximum visibility of the test object. The layout of the chamber is shown in Figure 2. The chamber is constructed of .64-cm (.25-in) LEXAN sheeting coated with an anti-static compound and assembled with structural fiberglass and nylon fasteners. Structural members are external so the inside walls are smooth and clear of any projections to prevent any accumulation of fibers and to facilitate cleaning of the chamber. The dimensions of the chamber are 2.44 x 2.44 x 3.05 meters (8′ x 8′ x 10′).

Air Ducts and Suction Blower

The air ducts and suction blower transport the chopped fibers from the dispersal chamber into the contamination chamber. The suction blower also collects fibers during the contamination tests and during the clean-up of the chamber after a test. The air flow through the contamination chamber is controlled by an air by-pass at the suction blower. The location of the air ducts and suction blower are shown in Figure 2.

Lighting

Experiments were made with light positioning to obtain the best view of the test. The transparent chamber made changing light positioning simple. Finally, three 150 watt spotlights mounted in a triangle arrangement over the test object were found to allow good visual observation of the airborne fiber movements.

HIGH VOLTAGE POWER SUPPLY

IEEE Standard 4, "Standard Techniques for High Voltage Testing" recommends that a high voltage supply with an rms fault current of at least three to six amperes should be used for artificial contamination tests. Testing experience has shown that these fault current capabilities will result in five percent or less error in determining the disruptive discharge voltage. Therefore, the main design criterion selected for the high voltage supply was that it should produce at least 5 amperes of fault current at the lowest contemplated test voltage, 4 kV. There is no guarantee that the IEEE recommendations will apply directly to carbon fiber testing, but it is the best guideline available for contamination testing.

In order to minimize cost and delivery time, it was decided to design the high voltage supply using standard distribution transformers rather than ordering a custom built supply. In this particular design a distribution transformer can be energized from a 240 volt supply and the voltage stepped up to distribution class levels. A standard variable autotransformer can be used to adjust the test voltage by varying the voltage supplied to the low voltage side of the distribution transformer. It soon became apparent in pursuing this design that severe requirements are placed on the autotransformer if a single distribution transformer is chosen to supply test voltages from 4 kV up to approximately 30 kV. If a single distribution transformer was selected to supply 5 amps of fault current at 4 kV, then the fault current at 30 kV would be 37.5 amps. 37.5 amps of current supplied at 30 kV would subject the variable autotransformer to approximately 4,700 amps of current during an insulator flashover. The 4,700 amps of fault current is beyond the capability of readily available variable autotransformers. Considering the variable autotransformer limitations and distribution transformers which were readily available, it was decided to design the high voltage supply utilizing two different configurations. Figure 5 shows the configuration used for supplying test voltages from 4 kV to 15 kV and Figure 6 shows the supply configuration for producing test voltages from 15 kV to 30 kV.

By using the single distribution transformer scheme shown in Figure 5, fault currents of 5.6 amps and 21 amps were supplied at test voltages of 4 kV and 15 kV respectively.

In the scheme shown in Figure 6, three distribution transformers were placed in cascade to produce test voltages from 15 kV up to 30 kV. The fault currents available range from 4.5 amps at 15 kV to 9 amps at 30 kV. With this configuration the distribution transformer at ground potential steps the voltage up to 15 kV and energizes the transformers on the insulated platform. The transformers on the insulated platform then boost the test voltage by another 15 kV for a total of up to 30 kV on the test object. In later tests on transmission voltage class insulators two more distribution transformers were placed in cascade with the first three transformers to produce test voltages up to 45 kV line-to-ground.

Fiber Selected for Testing

Celanese GY-70 fiber was selected. It was used in all of the contamination tests. At high voltages the fiber resistivity becomes relatively insignificant. GY-70 was selected because of ease of chopping and its resistance to clumping after being chopped.

Fall Velocity Measurement

An improved method was developed for measurement of the mean fiber fall velocity during chamber operation. To measure fall velocity two sticky tapes were placed in the chamber, one covered and the other uncovered. The chopper was operated for 15 minutes. The chopper and blower were turned off and the second sticky tape uncovered allowing fiber in the air to settle on the sticky tape. If fibers from top to bottom of the chamber is assumed to be evenly distributed the number of fibers on the sticky tape uncovered at chopper shutdown corresponds to the fiber in a volume of air above it at the time of shutdown so concentration can be determined. The total 15 minute sticky tape count corresponds to the total amount of fiber chopped. Determination of velocity was made as follows:

E	=	Exposure
S_1	=	Fiber count on sticky tape uncovered at chopper shutdown
S_2	=	Fiber count on sticky tape left uncovered through the entire test
$\bar{C}$	=	Average concentration
V	=	Fiber velocity
vol	=	Volume above sticky tape
T	=	Total time chopper was run
C	=	Concentration

Then:

$$E = \frac{S_2}{V} = \bar{C} \times T \quad (1)$$

Solving for V:

$$V = \frac{S_2}{\bar{C} \times T} \quad (2)$$

but if it is assumed that average concentration is approximately the concentration at shutdown:

$$\bar{C} \cong C = \frac{S_1}{\text{vol}} \quad (3)$$

So,

$$V \cong \frac{S_2 \times \text{vol}}{S_1 \times T} \quad (4)$$

This method provides an alternate way of determining fiber fall velocity. Several tests were performed and the average velocity for 2 mm tests was determined to be 2 cm/sec.

CONTAMINATION TESTING

Several representative samples of distribution class insulation were selected for testing. These are enumerated in Table 1. The samples include pin insulators, line posts, station posts, transformer bushings, and suspension insulators. Rated voltages range from 5 kV to 34.5 kV. The samples selected cover the range of generic classes of distribution insulation present on modern power distribution systems throughout the United States.

Test Procedure

Each test was begun by mounting an insulator in the chamber and placing sticky tape near it. After the chamber door was sealed rated voltage was applied to the insulator and the charged ball detectors were activated. Then fiber material was injected into the chamber until flashover.

After flashover the fiber chopper was shut off, the fiber count from the charged balls and the time to flashover recorded, and the sticky tape removed and a count made.

Three parameters were monitored during tests; exposure, fiber length distribution, and concentration. These characteristics were monitored with sticky tapes and charged balls.

The sticky tape count is used to determine exposures up to 10^7 fiber-sec/m^3, but for greater exposures accurate counts cannot be made due to high fiber densities on the sticky tape. For these greater exposures the charged ball count was used. (The charged ball detection system, utilizing two differentially connected charged balls, is the same as that used by NASA and others in their testing programs and is shown in Figure 7.)

Fiber Lengths Selected for Contamination Testing

The fiber lengths selected for contamination testing were 2 mm nominal, 4.3 mm nominal, 9 mm nominal, and 10.8 mm nominal. In addition, combinations of fiber lengths were chopped simultaneously during selected tests. These combinations were 4.3 mm and 9 mm, and 9 mm and 10.8 mm. Each of these nominal lengths and combination of nominal lengths has a fiber length distribution associated with it and these are shown for the 2 mm, 4.3 mm, 9 mm, 10.8 mm, 4.3 mm plus 9 mm, and 9 mm plus 10.8 mm cases in Figures 8 through 13, respectively. Table 2 lists the significant parameters of these different length distributions. The actual fiber release spectrum for an accidental release as postulated by NASA is shown superimposed with the 2 mm fiber length spectrum in Figure 14. The fiber length spectrum for accidentally released fibers lies between that for 2 mm fibers and 4.3 mm fibers. However, the 4.3 mm fiber length distribution contains a far greater number of relatively long fibers than the fiber length distribution for accidentally released fibers. Hence the testing results for 2 mm fibers are, within testing accuracy, deemed the best overall representation of insulator performance under accidental release contamination. For the sake of conservation, an estimate of vulnerability between that for 2 mm and 4.3 mm fibers can be chosen for distribution class insulation vulnerability assessment. A wide range of fiber lengths and combinations of lengths was chosen to allow determination of the dynamic range and trends of insulator vulnerability to conducting fibers. This allows for a greater understanding of the contamination mechanics and resulting failure modes.

Effects of Weathering

Insulators installed outdoors on a utility distribution system have received a certain amount of weathering. These weathered insulators, though ideal for testing, are difficult to obtain in the numbers and variety necessary to this test program. Clean, new insulators are readily obtainable. In order for clean, new insulator samples to be tested in this program it was necessary to establish that their behavior under carbon/graphite fiber contamination does not differ significantly from that of weathered insulators. Samples of weathered 7.5 kV pin insulators were obtained from a local utility. Samples of new insulators of the same type were purchased from a supplier. Both groups were tested with 9 mm fibers and the results of the test series are shown in Figure 15. It can be seen that there is no statistical differences between the mean exposure to fail at 95 percent confidence level.

Hence, new insulators were used throughout the remainder of the test program as test samples with confidence that their behavior models that expected under field conditions.

TEST RESULTS

The data on exposure to flashover are presented in Table 4 for each test series performed. For uniformity and to facilitate comparisons all data were plotted on Weibull paper for analysis since this distribution provided the best fit. α_0 is the theoretical minimum exposure at which flashover is possible. It is a parameter necessary in making a Weibull curve fit. For these data an $\alpha_0 = 0$ was selected because we can be confident that 0 is a lower limit to flashover exposure and also most of the data fit best when $\alpha_0 = 0$. Each graph indicates the number of tests, the mean and standard deviation of the data, and α and β of the Weibull curve fit.

Confidence Intervals

Established techniques were used in placing confidence intervals about mean flashover exposure of an experiment. Because the data distribution is non-Gaussian, the technique utilized in placing confidence intervals about the mean is the Wilcoxon Signed-Ranks test. A description of this test may be found in the *National Bureau of Standards Handbook 91.*

For each confidence interval about the mean the Wilcoxon Signed-Ranks test is performed twice, once for the upper limit and once for the lower limit. In order to determine the confidence interval, the upper and lower limit must be assumed. After making the assumption, the Wilcoxon test is utilized. If a level of significance, $\alpha = .025$, is obtained then the limit has been found. If the desired level of significance is not obtained then a new assumed value of a limit must be chosen and the test performed again.

Another method of data evaluation discussed by Guttman and Wilkes in *Introductory Engineering Statistics* makes no assumption about the distribution of samples and places a probability of obtaining a flashover below the lowest observed exposure. This method states that the number of observations required so that the probability is δ that at least $1 - \alpha$ of the distribution will exceed the smallest observation of the sample is given by:

$$n = \frac{\log (1 - \delta)}{\log (1 - \alpha)} \qquad (5)$$

From this we can derive the statement that with δ confidence, there is no more than α probability of obtaining a flashover at an exposure below the least observed exposure of n tests or $\alpha = 1 - (1 - \delta)^{1/n}$. Table 3 shows the relationship between the number of tests and the probability of obtaining flashovers below the lowest observed exposure with confidence levels of 85%, 90%, and 95%. This table indicates that a large number of tests is required to establish the lower end of the flashover exposure curve for the confidence level listed. For example, 45 tests are required to establish 90% confidence that no more than 5% of an insulator type would flashover at an exposure less than the minimum observed exposure.

Table 4 summarizes data for all insulators tested. It shows the number of tests, the nominal fiber length of contaminating fibers, exposures, means and standard deviations, confidence limits about the mean exposures, minimum exposures, probability of obtaining an exposure less than the minimum, and the mean fiber concentrations during the experiment.

Short Fiber Tests

As discussed earlier the performance of distribution class insulation contaminated by short (2 mm) fibers is believed to be the most representative of what would be expected in an actual accidental fiber release. Studies have shown that most of the fibers at locations any distance away from the burn site would be short, averaging 2 mm to 2.5 mm. Figure 14 illustrated the fiber length distribution postulated by NASA for an accidental release superimposed on the 2 mm fiber length distribution used for the 2 mm tests in this report. The tests performed with 2 mm fibers indicate mean flashover exposures of approximately 10^8 fiber-sec/m^3 for distribution class insulation.

2 mm and 4.3 mm test data are found in Table 4. Only a limited quantity of 2 mm fiber test data are available because of the extended time required to complete each test.

Wet Tests

Wet insulation tests were conducted with 2 mm fibers to simulate actual fiber releases under heavy fog conditions. Insulator surfaces were wetted continuously during the tests by vapor condensing as it passed over the surfaces. The insulator was contaminated with airborne contamination. Wet surfaces were found to decrease the exposure required for flashover. There was great variability in the degree that wet testing lowered mean exposure to flashover. The 15-kV distribution post insulator test results showed only a slight decrease in exposure to flashover while the 7.5-kV pin insulator test results showed a great decrease in exposure to flashover. This can be seen in Table 4. Fibers show a greater tendency to stick to wet insulator surfaces than dry, lowering the exposure required to induce flashover. Also, the rising steam carries fibers up over the surface, contaminating lower surfaces which are normally shielded. The wet fibers tend to stick together in strings which align in the direction of the voltage gradients. This may also decrease flashover exposure. The wet tests give more consistent results than dry tests with less variability of data. For wet tests $\sigma/\mu \approx 25\%$ was obtained as compared to $\sigma/\mu \approx 50\%$ for dry tests. The severity of contamination of an insulator, wet from condensate, is usually greater than of one wet from pouring rain because running water over the insulator's surface would clean the insulator.

Long Fiber Tests

Test series with longer fibers had the advantage of being performed quickly since failures occur at much lower exposures. The data were also more consistent so these tests were better used to show trends in the data. The disadvantage is that in actual release situations very few long fibers are released, therefore long fiber tests are not representative of actual releases as predicted by NASA.

The usefulness of long fiber tests lies in application of trends discovered to predict data for more difficult tests such as short fiber or higher voltage tests. In many cases trends are indicated but not enough data exists to substantiate them. The next section discusses trends observed in the data.

ANALYSIS OF RESULTS

Test results were examined to determine the effects of fiber length, concentration, and voltage class on exposure to flashover of distribution class insulation. The effect of an accidental release on an actual power distribution system is reviewed.

The Effect of Fiber Length on Exposure to Flashover

Tests were performed on selected insulator specimens using several different fiber lengths. Mean exposure to flashover was determined at each length. Tests at several fiber lengths indicate an exponential relationship between mean fiber length ℓ and mean exposure to flashover E. E was found to be proportional to $e^{k\ell}$. The curves shown in Figure 16 indicate this trend in the data. The mean fiber length for tests with multiple fiber lengths also fits the exponential exposure curve as shown in the same figure.

The objective of the multiple fiber length tests was to determine the effect of irregular fiber length distributions on exposure to flashover. Test results indicate that even for unusual length distributions the mean fiber length can be used to obtain an approximation of flashover exposure.

Test time could be reduced if data from tests with long fibers could be extrapolated to the shorter fibers that would actually be released. As Figure 16 indicates, results of 9 mm and 10.8 mm test data could be used to indicate the results of 2 mm tests but the exposure to flashover predicted could be very inaccurate. For example, the results of actual tests on a 7.5 kV pin with 2 mm fibers indicate a mean flashover exposure of 2.8×10^8 but a flashover at over 10^{10} would have been predicted if only a line drawn through the 9 and 10.8 mm test data had been used.

To obtain a reasonably accurate prediction of short fiber flashover exposures, tests should be performed with at least three different longer fiber lengths such as 12, 8, and 4 mm.

The Effect of Fiber Concentration on Exposure to Flashover

The fiber concentration for the test series was somewhat controllable by varying the speed of the fiber chopper driving motor and by varying air flow through the dispersal chamber. Measured average concentrations vary as much as 3 to 1 during a given test series with test conditions unchanged. This is due to fiber clumping in the dispersal chamber, occasional chopper plugging, measurement inaccuracy, and the random nature of the phenomenon.

The concentration given for each test series in Table 4 represents the average over all the series test times. This average is determined by:

$$\text{Concentration} = \frac{\Sigma \text{ exposure}}{\Sigma \text{ test time}} \qquad (6)$$

Preliminary tests with long fibers indicate that lowering concentration levels tends to increase mean flashover exposures. This phenomenon was observed when accidental increases in concentration precipitated a flashover on several occasions. Although a limited number of tests indicate there is an effect, more tests are needed for quantification of this effect. Figures 17, 18, and 19 show the effect on test results of varying the concentration. Since concentrations expected in an accidental fiber release at any distance away from the release point are less than those used for testing, the test results of exposure to flashover may be conservative. Current predictions for an actual release indicate fiber concentrations of approximately 100 fibers per cubic meter may be expected.

The longer fiber length tests indicated a possible effect on concentration, but no pronounced concentration effect was observed during short fiber tests. Test concentrations for the short fiber tests were maintained at over 10^4 in an effort to shorten test times. No short fiber tests were made at lesser concentrations to determine the effect of concentration. All indications are that breakdown of test specimens is a fiber deposition related surface phenomenon even though concentrations are high. Although variations in flashover exposure with concentration were observed, no evidence of air breakdown was noted.

The Effect of Voltage Class on Exposure to Flashover

Tests on a given type of insulator indicate that mean exposure to flashover decreases as insulator rated voltage increases. The 9 and 10.8 mm data on pin cap insulators, transformer bushings, and distribution post insulators shown in Table 4 indicate this trend. This trend may not be applicable to station class insulation. It is hoped that future tests will clarify this trend.

Other Trends

Station insulation is designed with much larger creepage distances than is line insulation. As would be expected, station insulation is much more resistant to carbon fiber contamination. The exposure required to cause flashover for station insulation is so high that testing even with long fibers is very time consuming.

The mean exposure to flashover for insulators mounted vertically is lower than for the same insulators mounted horizontally in most cases. This trend is indicated in Table 4 by the data for 9 mm fiber lengths on the 15 kV distribution post and the 7.5 kV station post. The data on the 5 kV transformer bushing is not consistent with this trend. Since it is a spin top bushing different results are expected. For a spin top bushing the top electrode is enclosed and covered. There are holes in the sides around the high voltage electrode for wire entrance. When the 5 kV bushing is mounted vertically the fibers are better shielded from the more critical insulation near the high voltage conductor.

Another trend observed is that insulators with similar geometry have similar mean exposures to flashover as well as similar flashover probability distributions. For example, the 15 kV transformer bushing gives results very similar to the 15 kV distribution post. This is probably because insulator shapes and creepage distances are similar. The transformer bushing creepage is 28 cm while the distribution post creepage is 25 cm and the transformer bushing dry arcing distance is 17 cm while the distribution post dry arcing distance is 15 cm. There are 5 sheds on the transformer bushing and only 3 on the distribution post. The transformer bushing sheds are closer together which could offset the greater creepage distance since fibers are long enough to bridge some of the creepage distance.

EFFECTS OF CARBON FIBER CONTAMINATION ON POWER DISTRIBUTION SYSTEMS

Portions of the actual power distribution systems surrounding selected major airports are being evaluated by NASA to determine the degree of hazard posed by a worst-case accidental fiber release. Technical information on the types and number of insulators in the areas immediately surrounding the selected airports was obtained by NASA from the electric utility companies serving these areas. This information was used in conjunction with the Waltz Mill chamber test data on distribution class insulation to evaluate the vulnerability of the power distribution systems. The vulnerability calculations were performed by NASA in conjunction with the development of the computerized risk models.

The carbon fiber exposures predicted by the NASA fiber release models indicate a worst case of about 10^5 fiber-seconds/m^3 with the vast majority of releases less than 10^3 fiber-seconds/m^3. The areas of maximum exposure involved in these worst case scenarios are on the order of one square kilometer. These areas of high exposure are small and the worst case exposures are 3 to 5 orders of magnitude below the mean exposure required to fail distribution class insulation with 2 mm fibers. The probability of inducing extensive insulation failures was shown to be negligible. The outage incidence due to accidental carbon fiber releases is insignificant when compared to the current distribution system outage rates normally experienced by these electric utilities due to such occurrences as lightning, tree contact, vehicular damage, etc. The NASA calculations were performed to verify this. Results of these calculations were presented earlier.(1)

SLURRY DEVELOPMENT

The purpose of the slurry development and the efforts to discover trends relating voltage to flashover exposure is to allow testing of transmission class insulation without the use of an airborne contamination test chamber. The objective is to develop a technique for performing these tests "synthetically". Work was performed on the development of a slurry testing technique to supplant airborne fiber testing in a contamination chamber. It was found that:

1. Shorter fibers do not clump as easily in the slurry. The question remaining is whether 2 or 4.3 mm fiber is better for testing.

2. Resistance measurements do not work in determining how many fibers are in the slurry.

3. A binder or thickening agent is needed in the slurry to keep fibers on the insulator surface. A wetting agent alone was utilized and too many fibers slid off the surface.

Two things are required for a slurry to be useful. First, a requirement of a useful slurry is a method of correlating results to make them meaningful in the case of an actual airborne contamination problem. Results can be correlated by using a standard slurry which flashes near the operating voltage of an insulator and then comparing other insulators by determining the voltage at which they flash. Another way of correlating results is always testing at rated voltage and varying slurry fiber density to obtain flashover at the rated voltage.

Varying the voltage is more useful because it is more easily and quickly done. The greatest value of a slurry is in allowing relative comparisons between insulators. It is doubtful that direct correlation could be made between slurry and airborne contamination in all circumstances.

A second requirement is a method of measuring fiber density in the slurry. One possible solution to this problem is to measure the fibers put into the slurry by weight. Otherwise, expensive particle counters set up to count particles in a suspension could be utilized. To verify the applicability of determining fiber density by fiber weight measurements, work needs to be performed to determine if water evaporation or insulator dipping would cause appreciable changes in slurry fiber density.

The slurry can be used either dry or wet. The following points should be considered when deciding whether it is better wet or dry. The wet slurry allows more rapid testing and less delay because there is no wait for insulators to dry. However, results are not so reproducible if insulators are tested wet because they need to be handled to be mounted. Also, the uneven drying caused by leakage currents heating the surface during testing could change flashover characteristics.

The dried slurry binds fibers so no change in orientation occurs during testing. When the dry slurry was tried some of the fibers on the insulator surfaces jumped out of the binder and off the surface. A dried slurry would allow multiple dipping which would be convenient for increasing fiber deposition on the insulator surfaces.

To enable correlation of deposition on insulators at flashover to slurry depositions, qualitative deposition measurements were made. This was done for the airborne tests by sticking transparent tape on contaminated insulator surfaces and using it to lift the fibers. The tape was preserved by placing it on white paper. The fiber does not deposit evenly over insulator surfaces. For short fiber tests upper surfaces have fibers piled up before lower surfaces are contaminated enough to cause flashover.

Further development of slurry techniques will enable an investigation of binders to be used for the slurry. One is Metylan wallpaper paste. The other is Cab-o-Sil, a pyrogenic silica. Preliminary testing was done using a Metylan slurry. Best results were obtained with approximately 13 grams of Metylan per liter of water. Flashover of a 7.5 kV pin insulator occurred near rated voltage when the insulator was dipped, allowed to dry, dipped again in a solution with 1.4 gms of fiber per liter of solution, and allowed to dry again. A selection of fiber length, binder, and the test method will be made as future work.

Work to be Performed in the Future

- Continue slurry development and evaluation of transmission class insulation vulnerability.
- The power supply will be uprated to 40 kV line-to-ground.
- Investigate power supply requirements for DC testing.
- Data analysis will be continued and tests made to better establish observed trends.
- Limited testing will be performed with air flow across insulator surfaces to examine the effects of wind on flashover characteristics.

VULNERABILITY OF NUCLEAR, FOSSIL, AND HYDRO GENERATING PLANTS TO CARBON/GRAPHITE FIBER INDUCED OUTAGES

This study evaluated the ability of power generating stations to maintain normal power generation when the surrounding environment is contaminated by an accidental carbon fiber release. Loss of non-essential equipment is not considered critical since loss of the plant does not result. The vulnerability assessment included only the power plant generating equipment and its associated controls, instrumentation, and auxiliary and support systems. It specifically excludes exposed outdoor high voltage substations, but includes the substation's controls. The outdoor substation high voltage equipment is being evaluated separately using insulation failure data determined under Phase II of this project.

This study includes the following types of power plants:

- Nuclear power plants
- Coal fired power plants
- Oil and gas fired power plants
- Hydroelectric power plants
- Gas turbine-generators.

Investigative Methodology

During NASA investigations into the vulnerability of civil aircraft to carbon fiber release it became apparent that detailed testing of every item in the aircraft was not necessary. This was because not all components are critical and only a certain few are likely to be both critical and highly vulnerable. The analysis procedure involves identifying the critical systems and selecting items from these systems for tests based on an engineering evaluation of vulnerability using test data on generically similar or related components. It has been demonstrated that reasonably accurate estimates of carbon fiber vulnerability can be made for items on which test data on generically similar items is available. These generic classes of equipment include such things as TTL logic on PC boards-coated/uncoated, terminal strips – .64-cm (1/4-in) spacing, cabinets with top and bottom louvers – natural circulation, etc. This approach has been adopted for estimating the vulnerability of the control systems in power plants and substations.

The investigation of power plants and substation vulnerability proceeded along the following lines:

1. Detailed discussions were held with Gibbs & Hill, Inc. to obtain the design details of nuclear and fossil fired power plants. The designs of typical plants were reviewed for vulnerability to fiber penetration regarding outside air entrance points, air filtering, plant internal heating, ventillation and air conditioning, and control room air supplies. Using this information, along with transfer function test results for commercial air filters, carbon/graphite fiber transfer functions were determined with assistance from NASA for the numerous functional areas of each type of power plant. This permits an evaluation of expected fiber exposures to equipment in these areas.

2. From these design drawings of typical power plants, and from power equipment manufacturer's technical literature lists have been compiled of the generic types of equipment in the different functional areas in the power plants under consideration.

3. These lists were refined to identify only the critical functions and equipment in each type of power plant.

4. Existing test data on generically similar types of equipment, or on related equipment if available, has been assembled. This is used in light of vulnerability testing experience and engineering judgement based on the generic classes of components present to assess the vulnerability of the individual critical components.

5. Each type of power plant was then evaluated in light of expected release scenarios to determine its vulnerability to carbon fiber releases.

6. The vulnerability analysis of substation controls proceeded along similar lines with typical substation control layouts, building details, air filter data, and technical information on equipment having been obtained. The vulnerability analysis relative to critical components also proceeded in a similar manner.

STATUS AND RESULTS OF INVESTIGATION

During the course of the investigation it became apparent that the area transfer functions for fossil fired plants were essentially the same for corresponding plant areas regardless of the plant fuel type. In other words the functional area transfer functions are equivalent for corresponding areas of coal fired, gas fired, and oil fired power plants. The area transfer functions calculated for these plant types are applied to all the generic fossil fuel-fired power plants considered in the analysis.

It also became apparent that the control equipment located in these plants is generically equivalent regardless of the type of plant. For example, a control computer can be expected to have the same vulnerability to carbon/graphite fibers regardless of the type of plant it is located in. This same principle applies to other typical power plant and substation control equipment.

Table 5 itemizes the functional areas for the generic power plants and substations under consideration. It also shows:

- The type of air filter typically utilized for air filtration in each functional plant area.
- ASHRAE dust spot efficiency for the filters above (conservative) and filter transfer function.
- Volume and floor area for each functional area in each plant (typical).
- Air infiltration and circulation rates.
- The calculated area carbon/graphite fiber transfer function for each area.
- The expected range for typical and worst case carbon/graphite exposures to equipment located inside each area.
- The assessed or estimated mean exposure to fail for the most sensitive component in each area.

It can be seen from Table 5 that the mean exposure required to fail the most sensitive critical component in each area is several orders of magnitude greater than the worst exposure it is expected to ever receive. The probability of inducing a failure in a component under these conditions is extremely small. The equation below is used to calculate the probability of component failure, P_f, due to carbon/graphite fiber contamination.

$$P_f = 1 - e^{-\frac{E}{\bar{E}}} \qquad (7)$$

It can be seen that this probability of failure, for the expected exposures, is on the order of 10^{-5} to 10^{-7} during any given exposure incident. However, these components generally have an inherently much higher probability of failure in any given year of normal service due to malfunctions other than those likely to be induced by carbon/graphite exposures. These "routine" malfunctions during normal service, and the resulting outage of the particular item involved, are generally compensated for through redundancy of this critical equipment at the time of plant design and construction. In addition, most automatic control systems, besides redundancy, may allow for a manual mode of operation in the event of unit failure. Through this redundancy of design and the extremely low probability of a carbon/graphite fiber induced failure, it is concluded that accidental releases of carbon/graphite fibers do not pose any unusual hazard to power plant and substation control systems.

TABLE 1.- INSULATOR DESCRIPTION AND MANUFACTURER

DESCRIPTION	MANUFACTURER	TYPE NUMBER
7.5 kV Pin	Ohio Brass Company	9953
15 kV Pin	Ohio Brass Company	37715
5 kV Transformer Bushing	Westinghouse Transformer Plant	773C902C02
15 kV Transformer Bushing	Westinghouse Transformer Plant	772C078G03
34.5 kV Transformer Bushing	Westinghouse Transformer Plant	772C078G13
7.5 kV Suspension Insulator	NGK – Locke	16583
7.5 kV Station Post	Lapp	73631-70
10 kV Suspension Insulator	Lapp	8200-70
34.5 kV Station Post	Lapp	73634-70
15 kV Distribution Post Insulator	Lapp	4415-70
15 kV Horizontal Distribution Post	Lapp	74115-70
34.5 kV Distribution Post	Lapp	9435-70

TABLE 2.- FIBER LENGTH

Nominal Length	μ (Mean) mm	u (Mode) mm	σ (Standard Deviation) mm
2	2.06	2.06	.67
4.3	4.3	4.1	.51
4.3 + 9	5.0	4.0	2.1
9	9.0	8.6	.74
9 + 10.8	9.2	9.8	1.4
10.8	10.8	11.8	2.7

TABLE 3.- PERCENT OF INSULATORS (α) THAT WILL FAIL AT AN EXPOSURE OF LESS THAN MINIMUM SAMPLE

Number of Tests	Confidence Level (δ)		
	85%	90%	95%
1	85%	90%	95%
2	61%	68%	78%
3	47%	54%	63%
4	38%	44%	53%
5	32%	37%	45%
6	27%	32%	39%
7	24%	28%	35%
8	21%	25%	31%
9	19%	23%	28%
10	17%	21%	26%
11	16%	19%	24%
12	15%	17%	22%
13	14%	16%	21%
14	13%	15%	19%
15	12%	14%	18%
16	11%	13%	17%
17	11%	13%	16%
18	10%	12%	15%
19	10%	11%	15%
20	9%	11%	14%
21	9%	10%	13%
22	8%	10%	13%
23	8%	10%	12%
24	8%	9%	12%
25	7%	9%	11%
26	7%	8%	11%
27	7%	8%	11%
28	7%	8%	10%
29	6%	8%	10%

TABLE 4.- COMPILATION OF RESULTS OF TESTS ON INSULATOR SPECIMENS

Insulator	n	Fiber Length mm	Exposure μ	Exposure σ	Confidence Interval About Mean 95%	Minimum Exposure	P<min*	Concentration Mean
7.5 kV Pin	4	2.0	2.8×10^8	1.3×10^8		1.4×10^8	44%	1.6×10^4
7.5 kV Pin (Wet)	7	2.0	5.8×10^7	2.0×10^7	$3.4 \times 10^7 < \mu < 7.4 \times 10^7$	4.8×10^7	28%	1.5×10^4
15 kV C-Neck D. Post Vert	2	2.0	7.3×10^7	3.0×10^7		5.2×10^7	68%	1.6×10^4
15 kV C-Neck D. Post (Wet)	10	2.0	6.2×10^7	1.0×10^7		4.7×10^7	21%	1.6×10^4
34.5 kV D. Post Vert	5	2.0	1.8×10^8	$.9 \times 10^8$		1.53×10^8	37%	1.8×10^4
7.5 kV Pin	46	4.3	4.1×10^7	4.0×10^7	$2.6 \times 10^7 < \mu < 5.7 \times 10^7$	2.8×10^7	5%	1.3×10^4
7.5 kV Stat. Post Vert	1	4.3	$>4.0 \times 10^8$					1.5×10^4**
7.5 kV Stat. Post Hor.	1	4.3	4.0×10^8					2.1×10^4
7.5 kV Pin	15	4.3 + 9	1.7×10^7	7.6×10^6	$1.3 \times 10^7 < \mu < 2.3 \times 10^7$	3.0×10^6	14%	8.3×10^3
15 kV C-Neck D. Post Vert	26	4.3 + 9	2.9×10^6	2.6×10^6	$2.0 \times 10^6 < \mu < 3.0 \times 10^6$	8.7×10^5	8%	6.7×10^3
7.5 kV Pin	52	9.0	4.8×10^6	2.9×10^6	$3.7 \times 10^6 < \mu < 5.3 \times 10^7$	1.6×10^6	6%	5.0×10^3
15 kV Pin Cap	14	9.0	2.1×10^6	5.9×10^5		1.3×10^6	15%	2.5×10^3
7.5 kV Stat. Post Vert	10	9.0	1.2×10^7	1.2×10^7	$4.3 \times 10^6 < \mu < 2.47 \times 10^7$	1.6×10^6	21%	4.3×10^3
7.5 kV Stat. Post Hor.	5	9.0	3.4×10^7	2.3×10^7		1.2×10^7	37%	6.9×10^3
34.5 kV Stat. Post Vert.	9	9.0	4.9×10^7	4.7×10^7		1.3×10^6	23%	12.2×10^3
5 kV Fostoria Insulator	4	9.0	8.4×10^6	6.6×10^6		2.9×10^6	44%	2.0×10^3
5 kV Trans. Bushing Vert.	5	9.0	3.8×10^6	7.9×10^5		7.5×10^6	37%	1.2×10^3
5 kV Trans. Bushing Hor.	6	9.0	2.3×10^6	7.1×10^5		1.3×10^6	32%	1.0×10^3

TABLE 4.- Concluded

Insulator	n	Fiber Length mm	Exposure μ	Exposure σ	Confidence Interval About Mean 95%	Minimum Exposure	P<min*	Concentration Mean
15 kV Trans. Bushing Vert.	16	9.0	1.0×10^6	3.3×10^5		6.0×10^5	13%	1.3×10^3
15 kV C-Neck D. Post Vert.	15	9.0	1.2×10^6	4.0×10^5	$9.0 \times 10^5 < \mu < 1.4 \times 10^6$	5.6×10^5	14%	1.2×10^3
15 kV C-Neck D. Post Hor.	15	9.0	1.8×10^6	6.0×10^5		5.6×10^5	14%	1.6×10^3
34.5 kV D. Post Vert.	18	9.0	9.5×10^5	6.4×10^5	$5.1 \times 10^5 < \mu < 1.3 \times 10^6$	3.0×10^5	12%	9.2×10^2
7.5 kV Suspension Vert.	13	9.0	7.9×10^6	4.8×10^6		2.7×10^6	16%	2.9×10^3
7.5 kV Pin	17	9.0+10.8	5.0×10^6	3.2×10^6	$3.3 \times 10^6 < \mu < 6.5 \times 10^6$	2.3×10^6	13%	4.5×10^3
34.5 kV D. Post Vert.	15	9.0+10.8	8.0×10^5	2.8×10^5	$6.4 \times 10^5 < \mu < 9.8 \times 10^5$	3.0×10^5	14%	1.1×10^3
7.5 kV Pin	15	10.8	6.5×10^5	2.4×10^5	$5.1 \times 10^5 < \mu < 7.8 \times 10^5$	2.6×10^5	14%	8.6×10^2
7.5 kV Stat. Post Vert.	20	10.8	4.5×10^6	4.3×10^6	$2.35 \times 10^6 < \mu < 4.7 \times 10^6$	1.2×10^6	11%	4.6×10^3
15 kV C-Neck Dist. Post Vert.	15	10.8	5.2×10^5	3.18×10^5	$3.5 \times 10^5 < \mu < 6.2 \times 10^5$	2.4×10^5	14%	6.3×10^2
34.5 kV Dist. Post	16	10.8	2.2×10^5	1.2×10^5	$1.5 \times 10^5 < \mu < 2.7 \times 10^5$	1.5×10^5	13%	5.2×10^2

* *Likelihood of a flashover to occur at an exposure of less than the minimum observed exposure, with 90% confidence.*

** *This insulator flashed only after given exposure and twice rated voltage.*

TABLE 5.- SUMMARY OF TRANSFER FUNCTION DATA, POWER GENERATION LOCATIONS

LOCATION	FILTER TYPE	FILTER DS/RATE	FILTER TF	AREA m^2	VOLUME m^3	AIR FLOW RATES Q_i m^3/sec	AIR FLOW RATES Q_{AC} m^3/sec	AREA TRANSFER FUNCTION	AREA EXPOSURE TYPICAL/WORST CASE	$\bar{E}$ OF MOST SENSITIVE COMPONENT
A. NUCLEAR PLANTS										
1. Control Room										
A. Open	Roll	25%	$8x10^{-3}$	1419	8637	1.92/1.44	17.24/12.95	$3.45x10^{-4}/2.70x10^{-4}$	.27/3.5	10^6 Digital Equip.
B. Closed	HEPA	99.8	10-6	1419	8637		19.19/14.39	0	0	10^6 Digital Equip.
2. Diesel Area	Mesh	0	0.27	495	7561	42		0.218	218/2180	10^7 Diesel Elec. Sys.
3. Unc. Access Area	Roll	25%	$8x10^{-3}$	3149	68252	379		$6.86x10^{-3}$	7/69	10^6 PC Boards
4. Safeguards	Roll	25%	$8x10^{-3}$	764	18068	75.26/50.19		$6.64x10^{-3}/6.13x10^{-3}$	6/66	10^6 PC Boards
5. Fuel Handling	Roll	25%	$8x10^{-3}$	1215	37949	158/105		$6.93x10^{-3}/6.44x10^{-3}$	6/69	10^7 Relays & Cont.
6. Controlled Access	Roll	25%	$8x10^{-3}$	3747	76465	318/212		$6.47x10^{-3}/5.91x10^{-3}$	6/65	10^6 PC Bds./Digital
7. Electrical Bldg.	Roll	25%	$8x10^{-3}$	874	21325	88.8/59.2		$6.68x10^{-3}/6.17x10^{-3}$	6/67	10^7 Elec. Cont./Swgr.
8. Containment	Roll	25%	$8x10^{-3}$	950	99122	413/275		$7.64x10^{-3}/7.48x10^{-3}$	7/76	10^8 Pwr. Pnls. (Enclosed)
9. Turbine Gen.	Mesh	0	0.27	3907	129595	719		0.244	244/2440	10^8 Swgr./Elec. Pnls.
B. FOSSILE FUELED										
1. Control Room	Roll	25%	$8x10^{-3}$	641	11724	2.60/1.95	23.4/17.58	$5.38x10^{-4}/4.84x10^{-4}$	.5/5	10^6 Digital Equip.
2. Electrical Areas	Roll	25%	$8x10^{-3}$	576	18436	76.81/51.21		$6.97x10^{-3}/6.53x10^{-3}$	7/70	$10^6/10^7$ Electronic Cont.
3. Turbine Gen.	Mesh	0	0.27	2604	86377	479		$7.21x10^{-3}$	7/72	10^7 Elec. Swgr. & Cont.
4. Boiler Area	Mesh	0	0.27	1371	97819	543		$7.61x10^{-3}$	8/76	$10^7/10^9$ Controls
C. UNDERGROUND HYDRO	Roll	25%	$8x10^{-3}$	5576	101954	56.6	226	$1.154x10^{-3}$	1.2/12	10^6 Digital Equip.

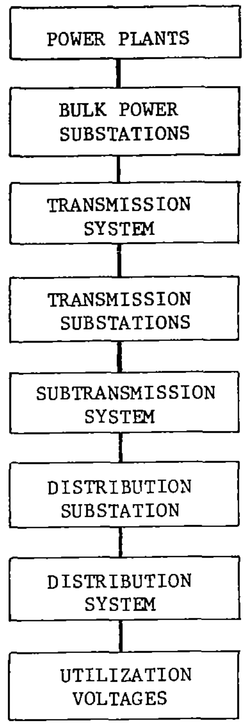


Figure 1.- Basic elements of a power system.

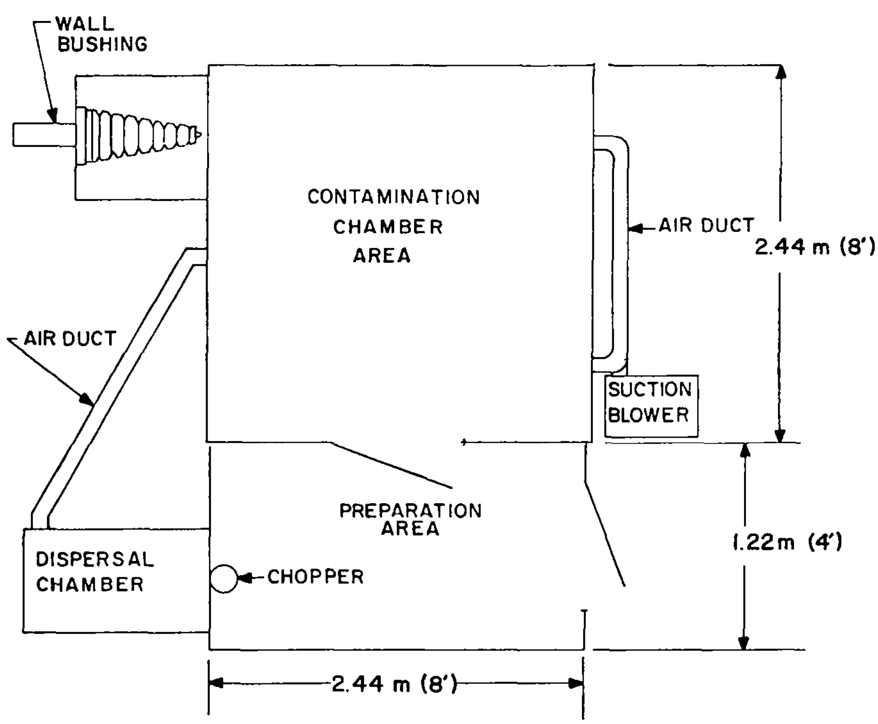


Figure 2.- Contamination system floor plan.

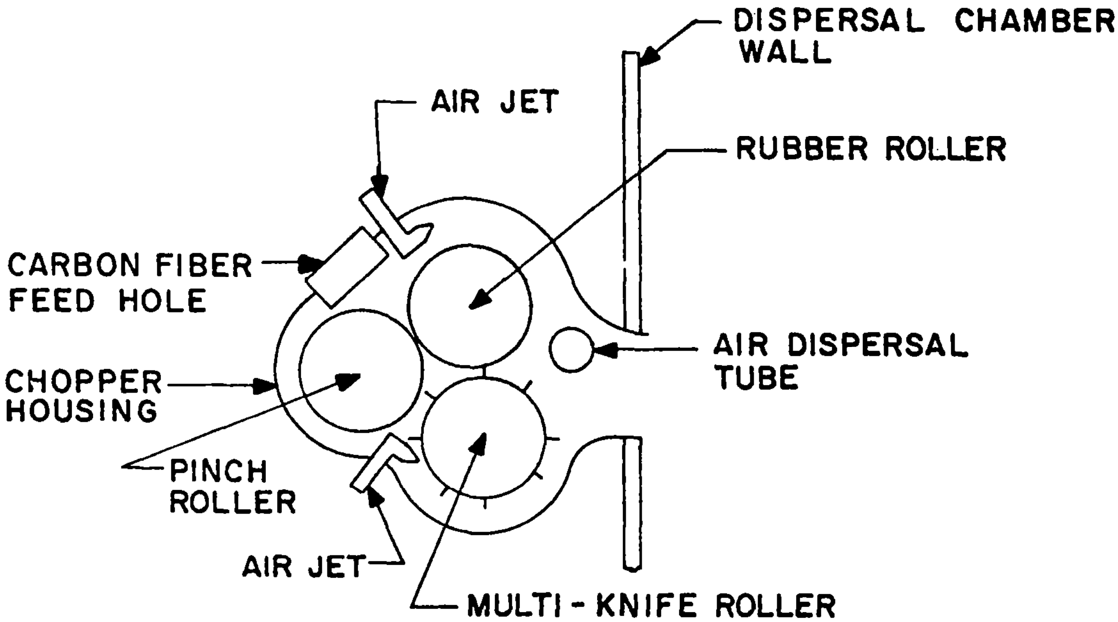


Figure 3.- Multi-knife carbon fiber chopper.

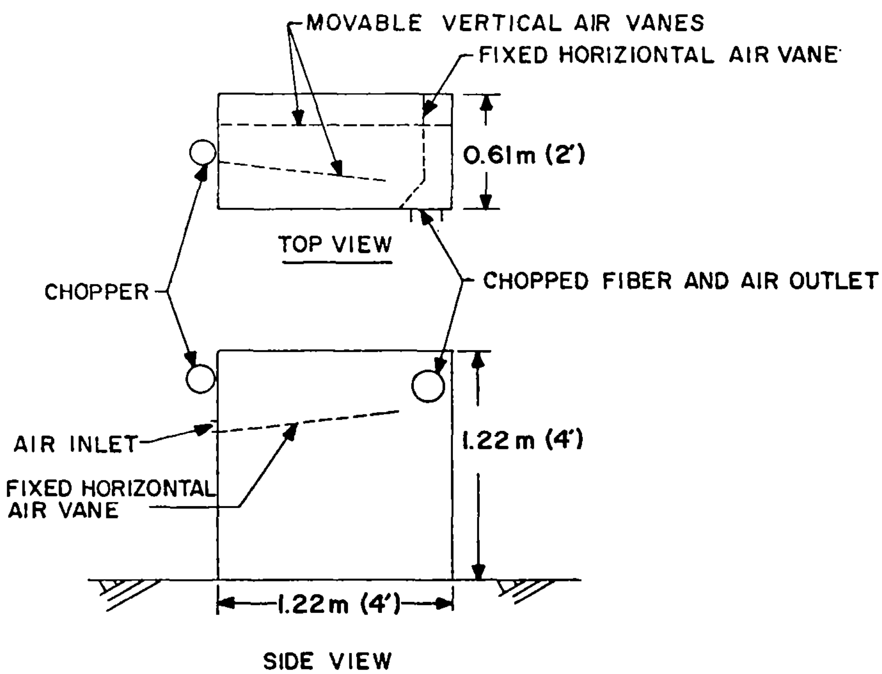


Figure 4.- Dispersal chamber.

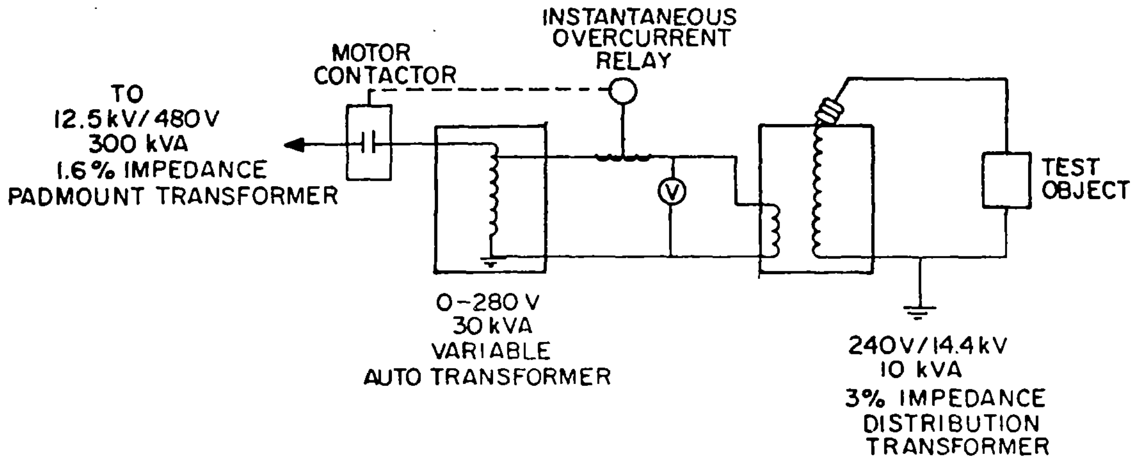


Figure 5.- High voltage supply for 4 kV to 15 kV.

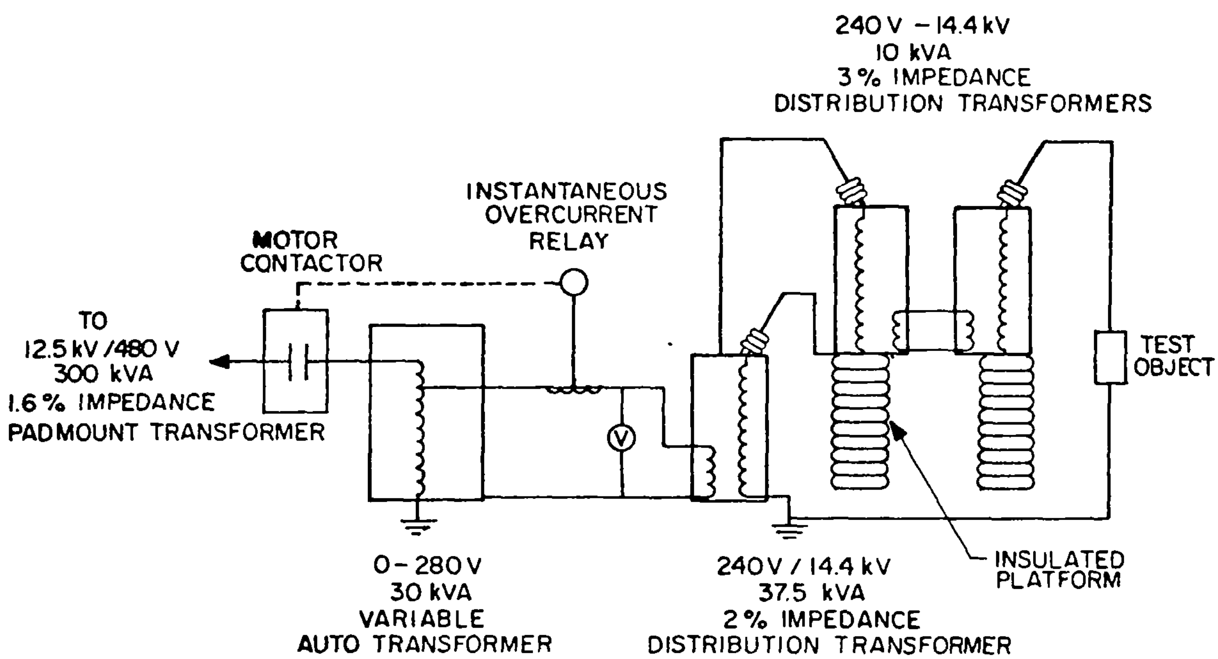


Figure 6.- High voltage supply for 15 kV to 30 kV.

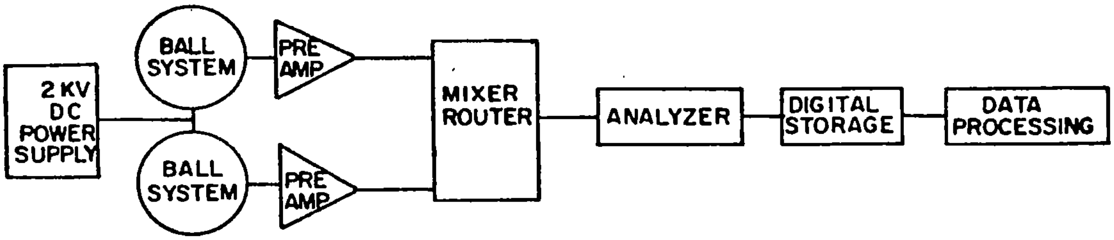


Figure 7.- Fiber counting instrumentation.

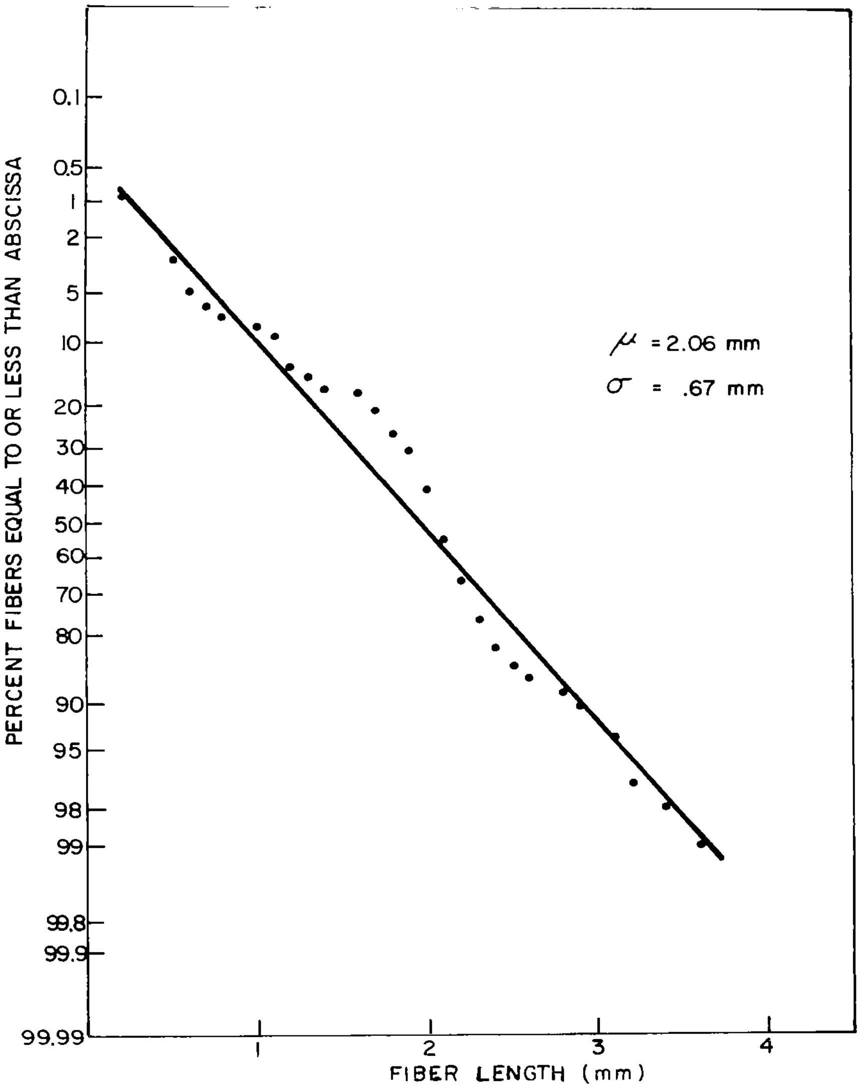


Figure 8.- The 2 mm fiber length distribution plotted on normal probability paper.

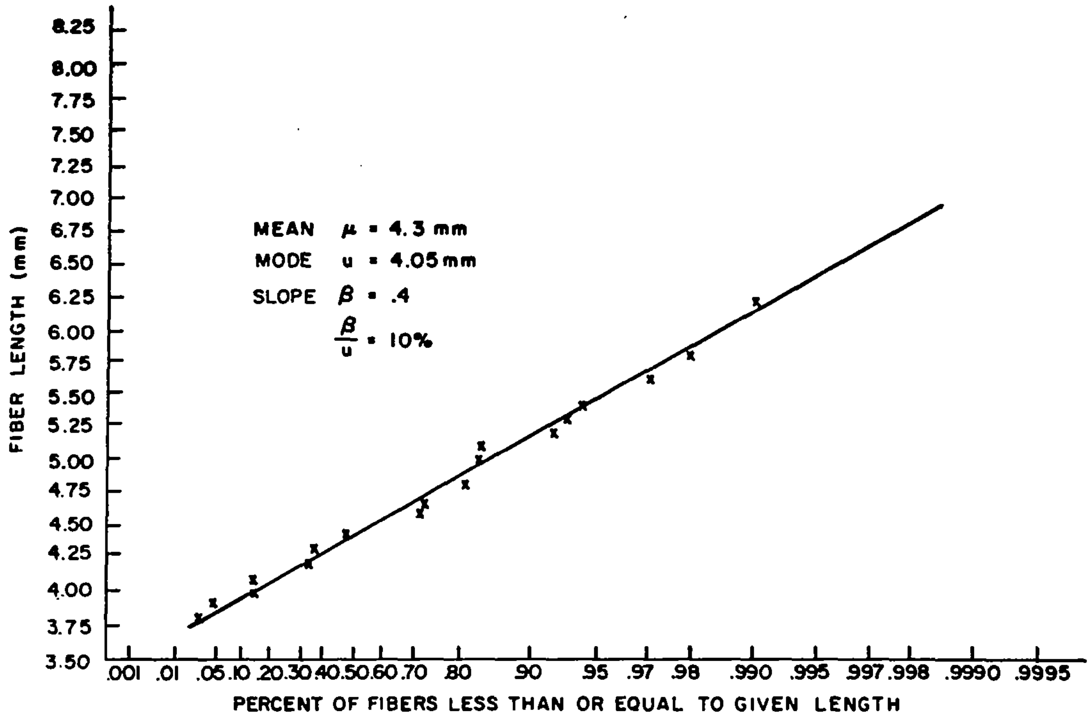


Figure 9.- 4.3 mm fiber length distribution.

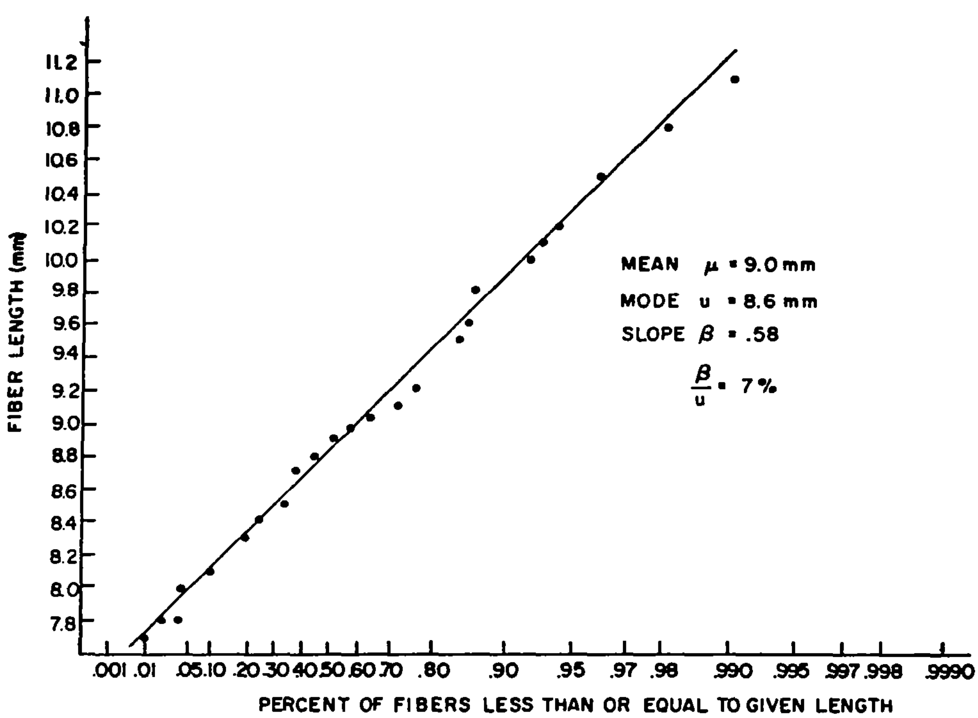


Figure 10.- 9 mm fiber length distribution.

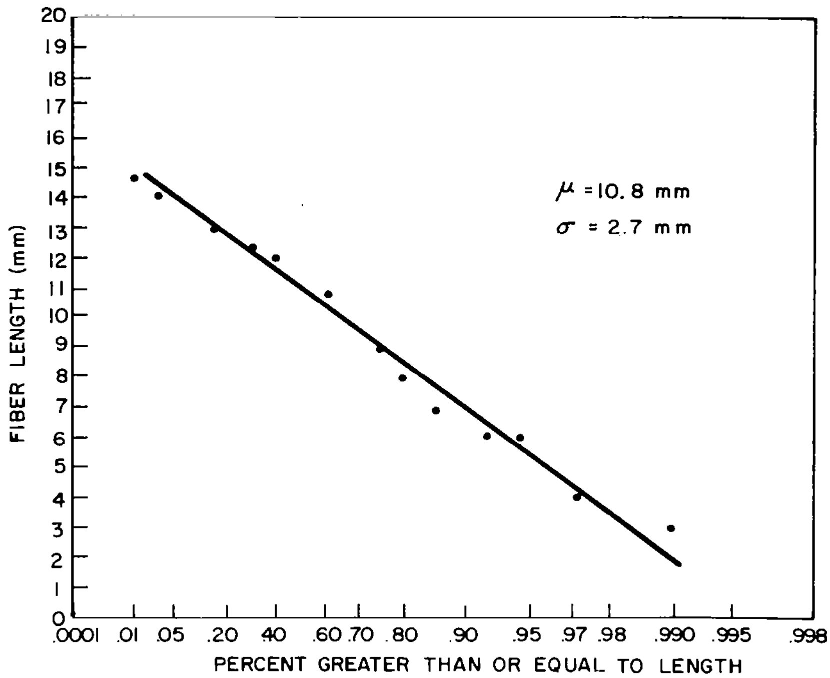


Figure 11.- The fiber length spectrum for 10.8 mm fibers plotted on extreme value paper.

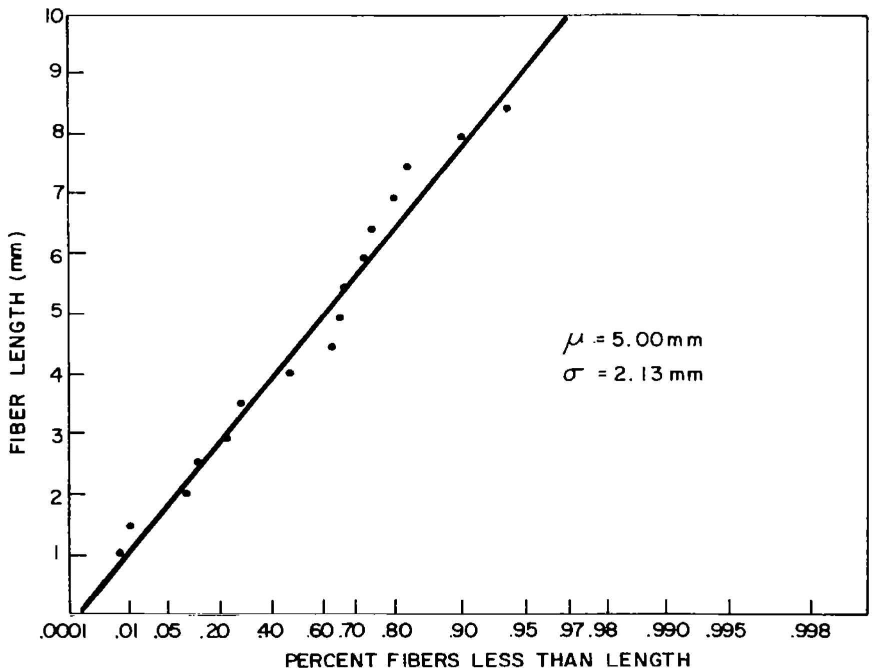


Figure 12.- The fiber length spectrum for 4.3 and 9 mm fibers combined, plotted on extreme value paper.

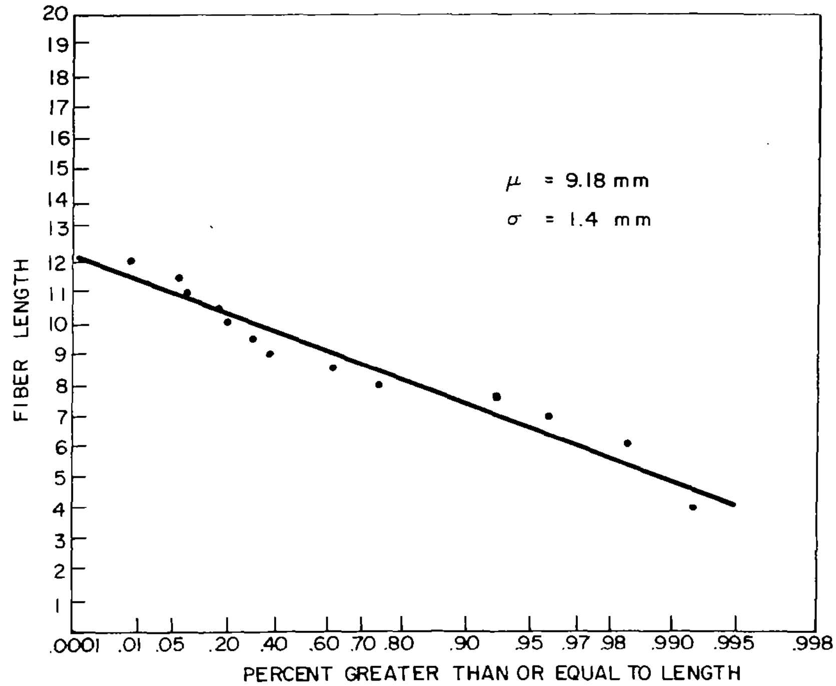


Figure 13.- The fiber length spectrum for 9 and 10.8 mm fibers combined, plotted on extreme value paper.

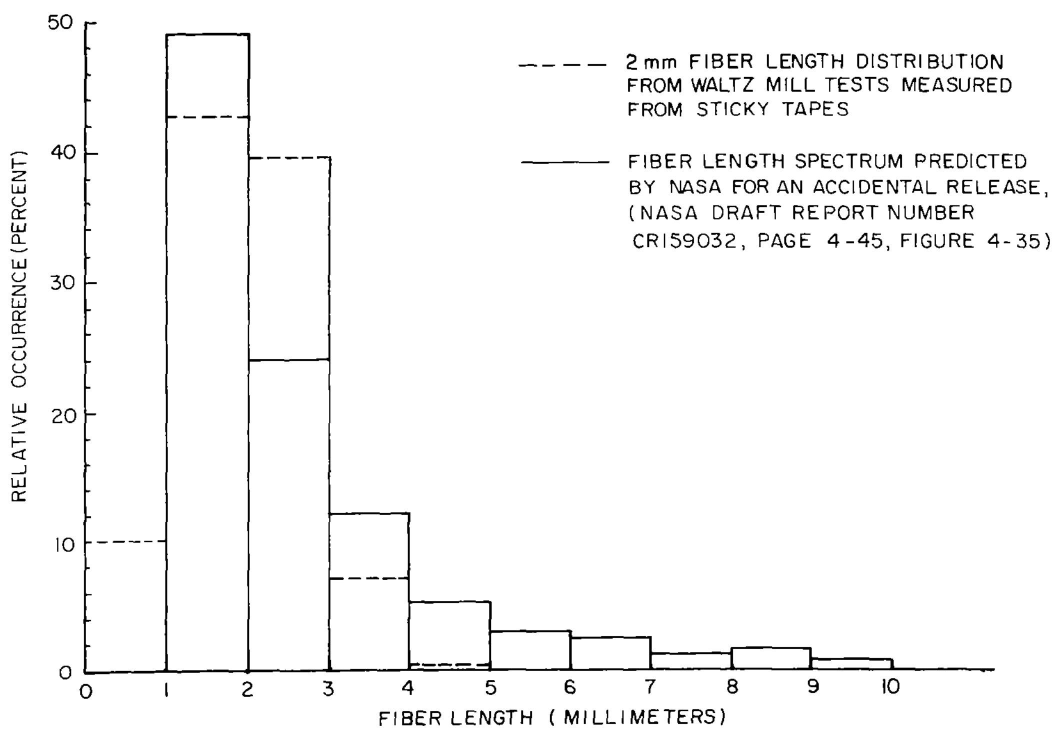


Figure 14.- Comparison of 2 mm fiber length distribution with the expected length distribution of an actual release.

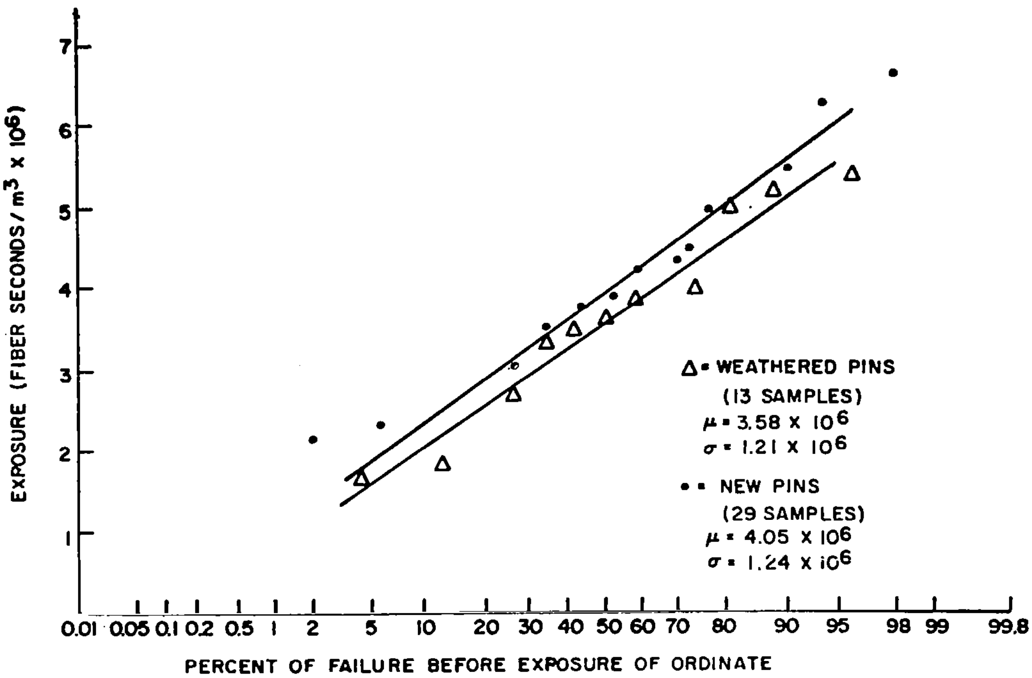


Figure 15.- Exposure to flashover for weathered versus non-weathered 7.5 kV pin insulators with 9 mm fibers.

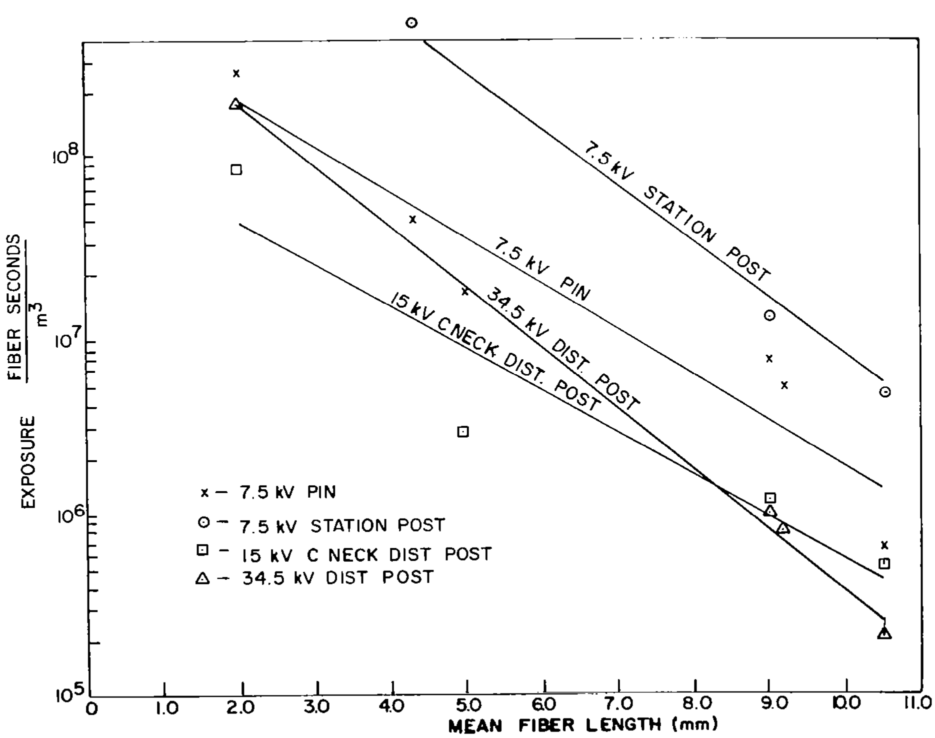


Figure 16.- Trend relating flashover exposure to mean fiber length plotted on semilog paper.

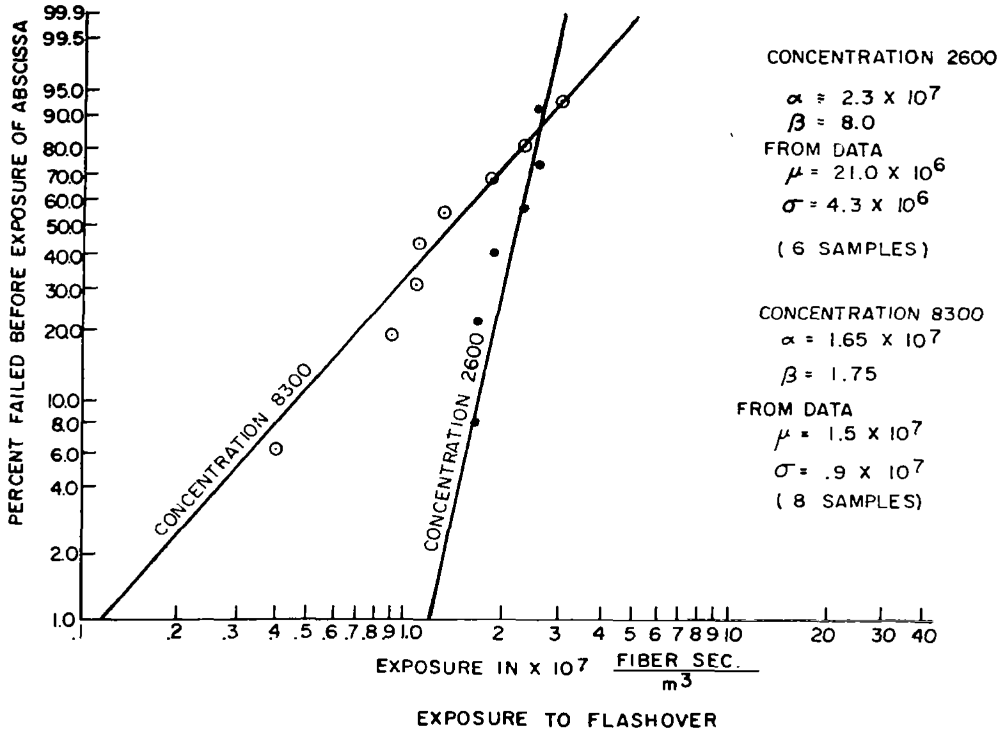


Figure 17.- Exposure to flashover for 7.5 kV pin, combined 4.3 and 9 mm fibers, concentration.

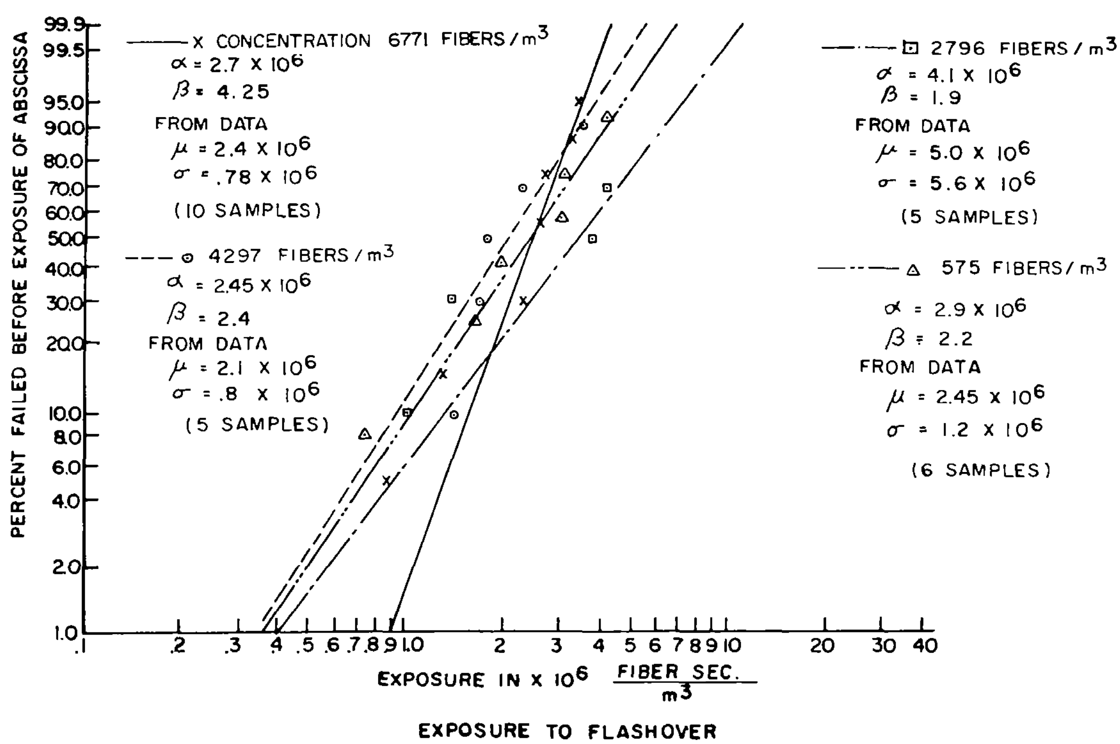
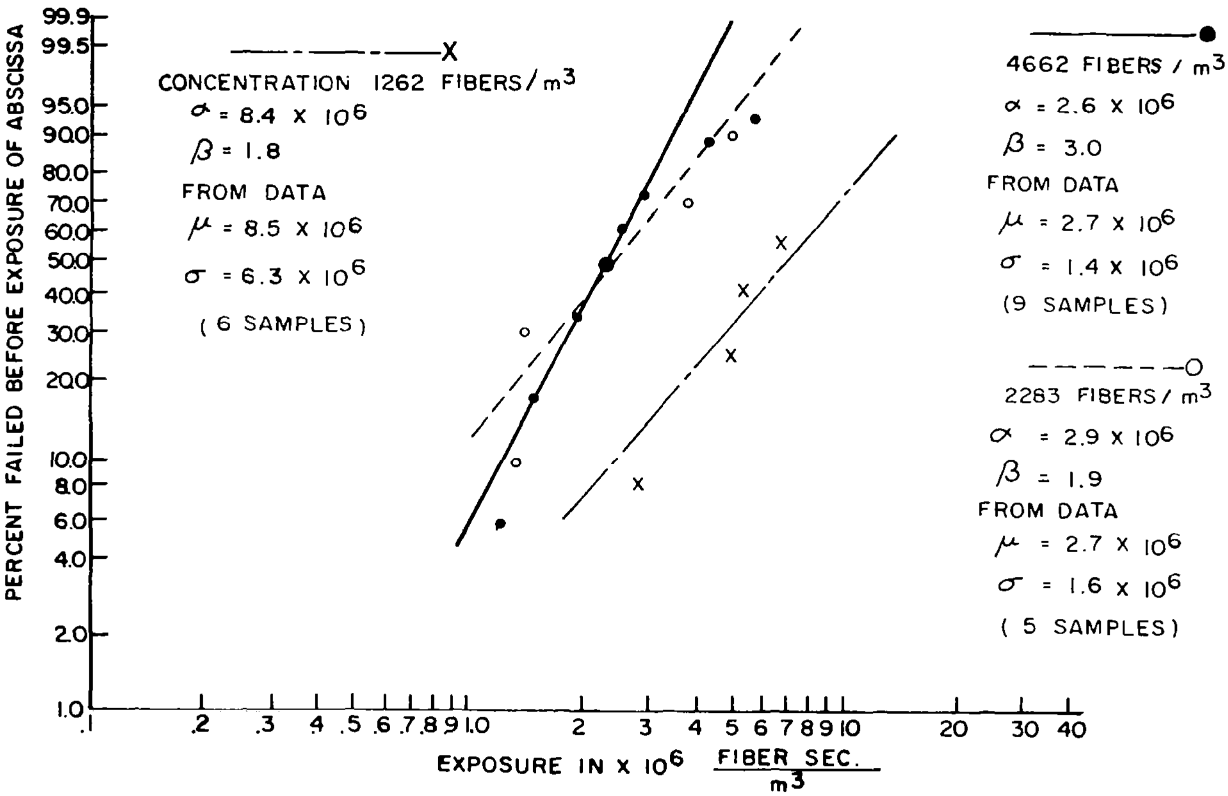


Figure 18.- Exposure to flashover for 15 kV distribution post, combined 4.3 and 9 mm fibers, concentration.



EXPOSURE TO FLASHOVER

Figure 19.- Exposure to flashover for vertical 7.5 kV station post, 10.8 mm fibers concentration.