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P-4618

MASTER

STUDY OF THE EFFECTS OF ACCIDENTALLY RELEASED CARBON/GRAPHITE FIBERS ON ELECTRIC POWER EQUIPMENT

PUBLISHED JANUARY 1981

~~SP-64~~

~~BR-201~~

SP-201

NTIS-25

PREPARED FOR:

U. S. DEPARTMENT OF ENERGY

ASSISTANT SECRETARY FOR

RESOURCE APPLICATIONS

OFFICE OF ELECTRIC ENERGY SYSTEMS

UNDER CONTRACT NO. DE-AC01-78 ET 29193

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**Study of the Effects of Accidentally Released
Carbon/Graphite Fibers on Electric Power Equipment**

**Program Final Report
June 5, 1978 — June 5, 1980**

Report Issued: June 5, 1980

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**This report discusses work performed under the U.S.
Department of Energy Sponsorship through the above contract.**

PROJECT DESCRIPTION: The objective of this project is to perform a study of the effects of accidentally-released carbon/graphite fibers on electric power equipment. Phase I of this project is to review existing data and ongoing projects and to assess the potential effects of accidental releases. Phase II of the project is to perform tests to quantify the effects of the fiber release.

ABSTRACT: The program to study the effect of accidentally released carbon fibers on electrical power equipment consisted of determining the vulnerability of system outage rates to carbon fiber contamination, and performing tests to quantitize the contamination required to cause flashover of external insulation.

Part One of this final report describes an assessment of the vulnerability of power systems to accidentally released fibers from a composite burn. The assessment describes the effect of carbon fibers on individual component failure rates and discusses the effect the change in component failure rates has on the power system reliability.

Part Two describes in detail testing performed to determine the vulnerability of external insulation to carbon fiber contamination. Testing consisted of airborne contamination tests on distribution insulators, limited tests on suspension insulators which are commonly used for transmission class voltages, and various tests to quantify the influence of fiber length, voltage stress, etc. on flashover characteristics.

The data obtained and analysis performed during this project show that the change of system reliability due to an accidental release from burned carbon fiber composite is negligible.

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PART I – VULNERABILITY OF POWER SYSTEMS TO CARBON/GRAPHITE FIBER INDUCED OUTAGE

Final Report – June 5, 1980

1. INTRODUCTION

A rapidly escalating usage of carbon/graphite fiber composites is predicted for aircraft, automobiles and other applications. This creates the possibility of accidentally releasing these fibers into the environment should the matrix material be burned during an aircraft crash or automobile collision. It has long been known that carbon/graphite fiber material is both electrically conductive and readily propagated in air currents. Various incidents of carbon fiber related electrical/electronic equipment failures have occurred in facilities that produce and/or fabricate carbon composite materials. This prompted a national investigation organized under a special President's Task Force chaired by the Office of Science and Technology Policy and coordinated by the National Aeronautics and Space Administration (NASA) into the likelihood of inducing failures in electrical/electronic apparatus in the industrial and civilian sectors by the accidental release of carbon/graphite fibers. The evaluation of electrical power systems was performed under auspices of the Department of Energy (DOE).

Data on present and expected future carbon fiber uses and consumption indicated that the greatest potential for accidental releases will be from aircraft crashes and fires. NASA has performed detailed studies on the types and amounts of fiber utilized in civil aircraft, the number and form of air crashes expected annually to 1990, the fiber air propagation characteristics and the fiber lengths, concentrations and exposures likely to be experienced over wide geographic areas in numerous air crash scenarios. NASA also coordinated the extensive testing of all manner of electrical and electronic components, air filters, mechanical apparatus, etc. by many organizations (except high voltage insulation which was tested by DOE). Test data from others provided the data base for the evaluation of power plant and substation controls. Data for the analysis of external insulation was gathered during tests described in Part II of this final report.

This report evaluates the ability of power systems to maintain normal operation when the surrounding environment is contaminated by accidentally released carbon fiber. Utilizing release scenarios postulated by the NASA program, this analysis assesses the vulnerability of power plant generating equipment, associated controls, instrumentation, auxiliary and support systems. It also discusses the likelihood and effect of failures of external high-voltage insulation on power system vulnerability to carbon fiber releases. The analysis includes transmission line, distribution line, and substation insulation.

2. SUMMARY

This portion of the project included analysis of the vulnerability of power plant and substation control systems to carbon/graphite fiber induced outages. It also included analysis of vulnerability of external insulation to carbon fibers. The control system vulnerability analysis was based on modeling power plant and substation control systems utilizing the concept of generic classes of equipment in generic power plants. Extensive use was made of vulnerability test data generated by others to evaluate power plant and substation control vulnerability. Data discussed in Part II of this final report were used in determining the vulnerability of power systems to carbon-fiber induced external insulation flashovers. Fiber exposure levels were determined from the accidental fiber release scenarios postulated by NASA. It is concluded that the accidental release of carbon/graphite fiber in the release scenarios postulated by NASA does not constitute a significant hazard to electrical power systems including power plant and substation control equipment and external high voltage insulation.

3. CONTROL VULNERABILITY ANALYSIS

The following types of power plants were included in the analysis:

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

Typical control systems for outdoor substations were also included in the analysis. The power plant and substation control, auxiliary, and support systems were evaluated to determine the probability of inducing a carbon fiber related malfunction of sufficient severity to shut down or curtail plant operation under the accidental release scenarios developed by NASA.

3.1 Analysis Methodology

The analysis methodology adopted utilizes the concept of generic power plants composed of generic classes of critical equipment. This is similar to the NASA methodology for evaluating the carbon fiber vulnerability of civil aircraft and industrial and manufacturing equipment.

During NASA investigations into the vulnerability of civil aircraft to carbon fiber contamination, it became apparent that detailed contamination testing of every item in every type of aircraft was not necessary. Similarly, it was not necessary to test every type of electrical/electronic equipment used in industry. This is because not all components are critical and only a few are likely to be both critical and highly vulnerable. In addition, sufficient similarities exist between the corresponding functional equipment in different industries (and aircraft) that the vulnerability of the equipment of one type can be assessed on the basis of knowledge of the vulnerability of a corresponding or similar piece of equipment. Thus the concept of "generic classes of equipment" and "generic classes of systems" arises.

The testing programs implemented by others indicated that certain types of electrical/electronic equipment, i.e., equipment with certain common features of construction, were nearly equivalent in vulnerability to carbon fiber contamination of the same type and length fibers regardless of the specific application of the equipment. Additionally, the carbon fiber transfer functions of similar types of equipment enclosures with similar ventilation characteristics were essentially equivalent. Therefore, given a knowledge of the equipment function and construction and a knowledge of the equipment enclosure, ventilation, etc. a reasonable estimation can be made of its vulnerability to carbon fiber contamination on the basis of test data for similar or related equipment.

This methodology was utilized in the vulnerability analysis of power plant and substation control systems. In the case of power plant and substation control systems it is not necessary to test every piece of equipment in every type of power plant to assess the vulnerability of the plants. By adopting this research methodology based on generic classes of equipment and developing generic classes of power plants and substations and generic classes of power

Figure 3.2-1 Spectrum of Fibers with Lengths Greater than 1 mm.

plant and substation control equipment, a reasonable assessment could be made on the likelihood of a carbon fiber related outage without detailed and expensive contamination testing of all manner of power plant and substation control and auxiliary equipment.

The vulnerability assessments performed in this manner possess sufficient accuracy to determine on a go/no go basis whether carbon fiber contamination is an insignificant problem or if a more detailed study is warranted.

3.2 Fiber Propagation and Release Scenarios

Airborne carbon fiber material that is of concern as a contaminant of power generating facilities and control systems is predominantly short fibers. The longer fibers, fiber clumps and composite ply strips released in the accident's fire plume generally settle out of the air rapidly, within one kilometer or so of the release point. A fiber length distribution for airborne fibers remote from the crash site was determined by NASA⁽¹⁾ and is shown in Figure 3.2-1. The lengths are exponentially distributed with a mean fiber length of approximately 2.5 mm. Less than five percent of the fibers will exceed 5 mm in length and less than one percent will exceed 10 mm.

Two accidental carbon fiber release scenarios were chosen for use in the controls vulnerability analysis. These release scenarios consisted of the average, or typical, release and a worst case release. Based on NASA calculations, the typical release resulted in an exposure of 10^3 fiber-seconds/meter³ to the outdoor power plant and substation environment. According to NASA, the release distribution is skew and 95% of all accidental releases will be less severe than 10^3 fiber-seconds/meter³. The worst case release resulted in an exposure of 10^4 fiber-seconds/meter³ to the power plant and substation environment. Releases resulting in exposures greater than this were not considered since NASA fiber propagation models have shown these exposures to be confined to extremely limited areas. Practically speaking, these areas are so small as to imply that the aircraft itself may have actually struck a power plant or substation, and hence contamination effects at these exposure levels are not considered. The result of this investigation is a point estimate of the probability of inducing a malfunction per plant-incident of exposure to carbon fiber contamination for each generic type of power plant and substation for each of the two release scenarios.

3.3 Generic Classes of Power Plants

During discussions with Gibbs & Hill, Inc. it was determined that buildings constructed for the purpose of containing power generating stations are relatively similar with regard to their air handling systems for plants utilizing the same fuel type. Similar air filtration specifications are utilized and the buildings are generally functionally layed out in a similar manner (i.e., control room, electrical areas, turbine generator hall, etc.). Because of these great similarities it was possible to select generic power plant structures for purposes of calculating carbon fiber transfer functions for each functional area of each type of plant. A carbon fiber transfer function for a plant area is defined as the ratio of carbon fiber exposure received inside the plant area divided by the exposure received outside the area. In this

(1) Vernon L. Bell, "Release of Carbon Fiber from Burning Composites", NASA Conference Publication 2119, *Assessment of Carbon Fiber Electrical Effects*, Hampton, VA, December 4-5, 1979, p.49.

case the exposure received outside the plant area is the exposure received by the outdoor environment. The outdoor exposure was determined by NASA fiber propagation models. It should be noted that this definition also applies to equipment enclosures. The plant air filtration system and electrical/electronic equipment enclosures, etc. reduce considerably the carbon fiber exposure to the volume contained therein.

Design details for typical plants representing the five types of power plants above were reviewed with Gibbs & Hill, Inc. These details were reviewed to assess the plants' propensity to admit carbon fibers from the outdoor air, expressed as the carbon fiber transfer function for each functional plant area. This was accomplished through analysis of the air filter specifications, analysis of the heating, ventilation and air conditioning system specifications, and analysis of the control room air supplies all considered in light of the plant's physical layout. It was determined early in the analysis that the carbon fiber transfer functions for corresponding functional areas of fossil-fueled power plants are essentially the same regardless of the plant fossil fuel type. This means the carbon fiber transfer functions are essentially equivalent for corresponding functional areas of coal-fired, gas-fired, and oil-fired power plants.

The building parameters of primary importance in determining these transfer functions are: building type, floor area, and volume of each functional area, air filter transfer function, and air flow rates through the heating, ventilation, and air conditioning systems. These building design parameters for the generic power plants and substations were obtained from Gibbs & Hill, Inc. Air filter transfer functions for the types of air filters usually used in power plants were obtained from NASA, who conducted a testing program to determine typical air filter carbon fiber transfer functions. It was discovered that the log of the carbon fiber transfer function of standard air filters was directly related to its ASHRAE dust spot efficiency rating. This is graphically shown in Figure 3.3-1.(2)

Because of the generic similarities between fossil-fueled power plants of the same fossil fuel type, the analysis is presented for generic nuclear power plants, generic fossil-fueled power plants, generic hydroelectric power plants, generic gas turbine power plants and generic substation control buildings (old and new). Old and new substation control buildings were considered separately since great differences frequently exist in the structure type as well as in the generic control equipment used. The building and structural data for these generic power plants and corresponding area transfer functions are summarized in Table 3.3-1. Column one itemizes the functional areas of nuclear, fossil fueled, hydroelectric and gas turbine power plants. Column two lists the types of air filters normally utilized, while column three presents the lower (or worst expected) dust spot efficiency rating of these filters. It should be pointed out that normally 60% or 85% dust spot rated filters are specified with a 40% dust spot prefilter, but in this analysis a 25% dust spot rating was used for conservatism. Column four presents the measured carbon fiber transfer function (worst expected) for this type of filter based on the test data average shown in Figure 3.3-1. Columns five and six present the area and volume, respectively, of each functional area of each

(2) John J. Paszek, Dudley D. Davis, James H. Patrick, "Carbon Fiber Transfer Functions Through Filters and Enclosures"; ARBRL-MR-02946, U.S. Army Ballistics Research Laboratory, 1980.

FILTER DATA COMPARISON

Figure 3.3-1 FILTER EFFICIENCY ASHRAE DUST SPOT RATING

TABLE 3.3-1 Summary of Filter Transfer Functions

(1)	(2)	(3)	(4)	(5)	(6)	(8)		(9)	(10)
Location	Type	Filter	Transfer Function	Area m ²	Vol. m ³	AIR FLOW RATES		Area Transfer Function	Area Exposure Typical/Worst Case
		Dust Spot Rating				Intake	Air Circ.		
						Q m ³ /Sec	Q _{AC} m ³ /Sec		
A. NUCLEAR PLANTS									
1. Control Room									
A. Open	Roll	25%	3x10 ⁻³	1419	8637	1.92/1.44	17.24/12.95	3.25x10 ⁻⁴ /2.70x10 ⁻⁴	.27/3.5
B. Closed	HEPA	99.8	10 ⁻⁶	1419	8637		19.19/14.39	0	0
2. Diesel Area	Mesh	0	0.27	495	7561	42		0.218	218/2180
3. Unc. Access Area	Roll	25%	8x10 ⁻³	3149	68252	379		6.86x10 ⁻³	7/69
4. Safeguards	Roll	25%	8x10 ⁻³	764	18068	75.26/50.19		6.64x10 ⁻³ /6.13x10 ⁻³	6/6
5. Fuel Handling	Roll	25%	8x10 ⁻³	1215	37949	158/105		6.93x10 ⁻³ /6.44x10 ⁻³	6/69
6. Controlled Access	Roll	25%	8x10 ⁻³	3747	76465	318/212		6.47x10 ⁻³ /5.91x10 ⁻³	6/65
7. Electrical Bldg.	Roll	25%	8x10 ⁻³	874	21325	88.8/59.2		6.68x10 ⁻³ /6.17x10 ⁻³	6/67
8. Containment	Roll	25%	8x10 ⁻³	950	99122	413/275		7.64x10 ⁻³ /7.47x10 ⁻³	7/76
9. Turbine Gen.	Mesh	0	0.27	3907	129595	719		0.244	244/2440
B. FOSSIL-FUELED									
1. Control Room									
2. Electrical Areas	Roll	25%	8x10 ⁻³	641	11724	2.60/1.95	23.4/17.58	5.38x10 ⁻⁴ /4.84x10 ⁻⁴	.5/5
3. Turbine Gen.	Roll	25%	8x10 ⁻³	576	18436	76.81/51.21		6.97x10 ⁻³ /6.53x10 ⁻³	7/70
4. Boiler Area - Indoor	Mesh	0	0.27	2604	86377	479		7.21x10 ⁻³	7/72
Outdoor	Mesh	0	0.27	1371	97819	543		7.61x10 ⁻³	8/76
	—	—	—	—	—	—	—	—	1000/10000
C. UNDERGROUND									
HYDRO	Roll	25%	8x10 ⁻³	5576	101954	56.6	226	1.154x10 ⁻³	1.2/12
D. GAS TURBINE									
GENERATOR	Fiber-Glass	25%	8x10 ⁻³	641 (2 Units)	11724	1.95	17.58	5.38x10 ⁻⁴	.5/5
E. SUBSTATION NEW									
CONTROL BLDG.	Fiber-Glass	25%	8x10 ⁻³	176	615	.17	1.025	9x10 ⁻⁵	.09/.9
OLD	Mesh	0	.27	176	615	.17	2.057	8x10 ⁻³	8/80

generic type of plant. Air flow rates through each area for intake air and recirculated air are given in columns seven and eight, respectively. With assistance from NASA, a carbon fiber area transfer function was calculated for each functional area of each type plant and these appear in column nine.⁽³⁾ In most cases, two values were calculated to place a lower and upper bound on the relatively conservative assumptions already made. It can be seen that, with the exception of the mesh filtered and unfiltered areas, the area transfer functions are on the order of 10^{-3} to 10^{-4} .

This means that the ratio of the carbon fiber exposure inside these areas to that outdoors in the natural environment is 10^{-3} to 10^{-4} . Very few fibers are able to enter the plant and substation buildings. In the unfiltered areas with low air circulation such as the diesel area in a nuclear plant, the transfer function is 0.218. Similarly, the transfer function for the turbine generator area of a nuclear plant is 0.244. This could also be expected in unfiltered fossil-fueled plant turbine generator areas. Fortunately, those areas with the highest (worst) carbon fiber transfer functions, receiving the highest carbon fiber exposure, also contain the least sensitive or most invulnerable equipment.

Column ten contains the estimated average and worst case carbon fiber exposures likely to be experienced in each plant functional area based on the NASA postulated average and worst case accidental release scenarios described previously.

3.4 Generic Classes of Equipment

Power plant control and auxiliary equipment as well as substation control equipment is functionally a set of electrical, electronic and mechanical equipment assembled in such a manner so as to carry out the control and operation of power generating facilities and substations. Each necessary control and operation function, or system, requires a subset of this equipment. Proper functioning of all equipment systems is necessary for proper control of power plant and substations. In the case of redundant equipment, at least the minimum required number of sets or units must be functioning properly to control the plant or substation without a partial or total curtailment of operation. This can be visualized as the group of minimum necessary systems or functions which must not experience malfunction if the plant or substation is to operate normally. These are the critical functions of the system. Each of these functions is composed of many types of equipment located in different parts of the power plant. In the case of substation controls, some components are indoors and others are outdoors. These individual equipment items can be reduced to simpler terms by defining their individual components. It is then apparent that these components can be classed generically in terms of their function and described in this manner for estimating vulnerability to carbon fiber induced failure.

For example, the boiler controls consist of equipment located in the control room (composed of computers, control switches, terminal strips, readouts, etc.) equipment in the plant electrical area (low voltage switchgear, high voltage metal clad switchgear, transformers, uninterruptible power supplies, batteries, etc.) and equipment on the boiler (gas burners and

(3) Israel Taback, "Transfer Functions", NASA Conference Publication 2074, *Carbon Fiber Risk Analysis*, November 1979, p.99-107.

controls). These component systems can be further reduced to: 1) solid state electronics, digital and analog, for the control computers, 2) low voltage circuit breakers, transformers and insulators, high voltage insulators and low voltage control relays, terminal strips and switches for the equipment in the electrical area, and 3) enclosed electronics and electromechanical equipment for the boiler mounted equipment. While carbon fiber contamination testing data is not available on each system (such as medium voltage switchgear or automatic boiler controls), it is generally available for the individual components of these systems (such as digital computers, analog electronic circuits on printed circuit cards and high voltage insulators).

Under the NASA program, all manner of electronic, electrical and electromechanical equipment was tested by others in carbon fiber contamination test chambers to determine vulnerability to carbon fiber contamination.⁽⁴⁾ However, high voltage insulation was tested by DOE. The equipment tested in all the NASA and DOE programs included:

• digital computers	• high voltage insulators
• VHF transceivers	• consumer appliances
• television sets	• small gasoline-driven generators
• electric motors	• electronic connectors
• terminal strips (power)	• elevator motors
• terminal strips (electronic)	• terminal blocks (480 V)
• telephone equipment (relays)	• power panels
• control relays	• switches and outlets (120 V)
• analog electronics	• aviation electronics

The results of these tests were utilized to estimate, on a generic basis, the vulnerability of power plant and substation control and auxiliary equipment.

Normally this test data is presented as an exponential probability distribution of exposures to fail of a given test item. This model is generally regarded as conservative for carbon fiber contamination testing. The probability of a device failing for an exposure up to amount E fiber-seconds/meter³ with a measured mean exposure to fail of $\bar{E}$ fiber-seconds/meter³ is given by Equation 1.

$$P_f = 1 - \exp(-E/\bar{E}) \quad (1)$$

$\bar{E}$, the mean exposure to fail, is determined from the contamination tests for each device.

It should also be noted that the electrical/electronic portions of virtually all power plant and substation control and auxiliary equipment are mounted in some type of enclosure. This can be in a panel, in an instrument rack or in some type of general-purpose or dust tight, or rain tight, or weatherproof or even explosion-proof enclosure. These enclosures will act to exclude airborne carbon fibers from the equipment contained within the enclosure. The effect-

(4) Israel Taback, "Evaluation of Equipment Vulnerability and Potential Shock Hazards", NASA Conference Publication 2119, *Assessment of Carbon Fiber Electrical Effects*, December 4-5, 1979, p.73-99.

tiveness will be a function of the enclosure design. Thus, enclosures also have transfer functions that must be considered when assessing the vulnerability of the system or equipment contained therein. Some of the electrical and electronic equipment tested by others was also in some type of enclosure when tested and other equipment was not. This also had to be considered when estimating the mean exposures to fail, E's, of equipment on a generic basis.

The volume of test data produced by all these testing programs was so large that it is not practical to reproduce it here. The individual reports covering the appropriate classes of equipment should be consulted if it is desired to obtain greater detail of the test procedures or test results. The appropriate data is summarized in this report relative to estimating the vulnerability of power plant and substation control equipment on a generic basis.

3.4.1 Generic Equipment Types in Power Plants and Substations

Discussions were held with Gibbs & Hill, Inc. and design drawings were reviewed for typical power plants. From this information, lists were compiled on the generic types of equipment present in the different functional areas of each generic type of power plant; nuclear, fossil-fueled, hydroelectric and gas turbine-generator and for typical old and new substation control buildings. This equipment is itemized in Table 3.4-1 for generic nuclear power plants; in Table 3.4-2 for generic fossil fueled power plants; and in Table 3.4-3 for generic old and new substation control buildings. Generic gas turbine-generator and hydroelectric plant control rooms are generally equivalent to a fossil fueled plant control room. The generator areas of gas turbine and hydroelectric plants are generally not vulnerable to carbon fiber induced outages owing to enclosure of all critical equipment. The electrical area of a gas turbine plant is similarly rendered invulnerable. The electrical area of a hydroelectric plant generally contains only metal clad switchgear and some control equipment, also normally in metal enclosures. The degree of protection provided by the foregoing, in addition to the high mean exposures required to fail the components contained, can be considered to render the generator and electrical areas of gas turbine and hydroelectric plants virtually invulnerable. It should be noted that designs for hydroelectric power stations vary greatly, i.e., they are site specific, but this does not appear to greatly affect their estimated vulnerability to carbon fiber induced outages since the equipment utilized is similar.

Power substations also contain some outdoor control equipment. This is generally mounted in weatherproof enclosures located on the major controlled device (such as circuit breaker close/trip equipment or transformer tap changers). The weatherproof nature of these enclosures as well as the wiring methods employed, normally metal conduit, serve to make these control devices and circuits invulnerable to carbon fiber contamination.

3.5 Probability of a Plant Outage

Existing carbon fiber test data on generically similar types of equipment, or on related equipment when available, were assembled and used in light of vulnerability testing experience and engineering judgment to assess the vulnerability of the individual generic critical components as previously discussed. Each of the generic power plants and generic substations was then evaluated for overall vulnerability in light of the expected accidental carbon fiber release scenarios postulated by NASA. This analysis considered both the typical and worst case release scenarios involving exponentially distributed fiber lengths with a mean

TABLE 3.4-1

NUCLEAR GENERATING STATIONS

**Types of Electrical Equipment in the Functional Locations
Within a Typical Installation**

NUCLEAR POWER CONTROL ROOM AND ADJACENT AREAS

Indicating Panel Lights
Protective Relays (Mech. and Solid State)
Chart Recorders
Strip Recorders
Control Switches
Terminal Strips
Instrument Transducers
Panel Meters
Microwave Equipment
Telemetry Equipment
Solid State Equipment in Panels (Analog)
Solid State Equipment in Panels (Digital)
Nuclear (Radiation) Instrumentation
Digital Readouts
Digital Computers
Mechanical Relays
Small Electronic Switches
Cathode Ray Tubes and Equipment
Computer Terminals (Video) (Can be Part of Control)
Emergency Shutdown System (Two Systems)

Note: This equipment is in rack panels, usually unfiltered and usually without cooling fans.

TABLE 3.4-1 (Cont.)

DIESEL AREA

Diesel Generators
Generator Automatic Starter
Generator High Voltage Switchgear
Generator Auxiliaries

UNCONTROLLED ACCESS AREA

(Contains Equip. for Normal Plant Operation)

Batteries and Chargers
Low Voltage Switchgear
Medium Voltage Switchgear
Dry Type Step Down Transformers (Low Voltage)
Dry Type Step Down Transformers (Medium Voltage)
Unit Substations (Dry Type)
Analog Electronic Control
Digital Electronic Control
Low Voltage Motor Controllers and Motors
Medium Voltage Motor Controllers and Motors plus Auxiliaries

SAFEGUARDS AREA

(Emergency Equip.)

Radiation Detectors
Electrical Switchgear – Medium Voltage
Electrical Switchgear – Low Voltage
Electrically Operated Water Valves
Electrically Operated Steam Valves
Dry Type Step Down Transformers – Medium Voltage
Dry Type Step Down Transformers – Low Voltage
Protective Relays – Mechanical and Solid State
Solid State Control Systems in Panels (Sensors)
Pressure Transducers/Transmitters (Sealed)
Temperature Transducers/Transmitters (Sealed)
Cables Terminated on Strips (Enclosed)
Unit Substations (Dry Type)
Flow Transmitters (Sealed)
Pumps (ECCS) and Auxiliaries
Valves (ECCS)
Radwaste (ECCS)

TABLE 3.4-1 (Cont.)

FUEL HANDLING AREA

Lighting Panels
Radiation Detectors
Electrically Operated Water Valves (Spray System)

CONTROLLED ACCESS AREA

Electrically Controlled Water Valves
Electrically Controlled Steam Valves
Pressure Transmitters (Sealed)
Temperature Transmitters (Sealed)
Radiation Detectors (Sealed)
Flow Transmitters (Sealed)

ELECTRICAL BUILDING

(Safety Related Gear)

Batteries and Chargers (125 VDC)
Lighting Panels
Uninterruptible Power Supplies (5-25 KVA Solid State)
Low Voltage Switchgear
Medium Voltage Switchgear
Low Voltage Motor Starters
Medium Voltage Motor Starters
Protective Relays
Chart and Strip Recorders
Control Switches
Panel Meters
Indicating Lights
Radiation Monitors
Volt, Amp, Watt, Var, PF Transducers
Air Compressors

TABLE 3.4-1 (Cont.)

CONTAINMENT AREA

(Equipment Enclosed and Sealed Normally)

Reactor Coolant Pumps
Pump Motor Auxiliaries (lube oil, etc.)
Temperature Transmitters
Pressure Transmitters
Flow Transmitters
Electrically Actuated Water Valves
Electrically Actuated Steam Valves
Radiation Monitors (Air)
Emergency Shutdown System Components
Leak Detectors (Pump Motor)
Control Rod Drive Equipment
Leads From Internal Reactor Instrumentation
External Temperature and Air Pressure Monitors
Reactor

TURBINE-GENERATOR BUILDING

Turbine-Generator
Exciter
Isolated Phase Bus
Steam Valves and Controls (Throttle Valve and Governor Valves)
Pressure Transmitters
Temperature Transmitters
Vibration Detectors
Radiation Detectors
Enclosed Terminal Strips (Thermocouple Leads, etc.)
HVAC Fans, Starters, and Controls
Condensate Pump(s)
Condenser Vacuum Pump(s)
Condenser Cooling Water Pump(s)
Tachometer Generator
Speed Governor (Transmitter)

TABLE 3.4-2

FOSSIL FUELED GENERATION STATIONS

**Types of Electrical Equipment in the
Functional Locations Within a Typical Installation**

FOSSIL PLANT CONTROL ROOM

Indicating Panel Lights
Protective Relays (Mech. and Solid State)
Chart Recorders
Strip Recorders
Control Switches
Terminal Strips
Uninterruptible Power Supplies
Instrument Transducers
Panel Meters
Microwave Equipment
Telemetry Equipment
Solid State Equipment in Panels
(Analog Control and Instrumentation)
Solid State Equipment in Panels
(Digital Control and Instrumentation)
Digital Readouts
Digital Computers
Mechanical Relays
Small Electronic Switches
Cathode Ray Tubes and Equipment
Computer Terminals (Vidco)

TABLE 3.4-2 (Cont.)

COMMON AREA

(Electrical Equipment) Same for Coal, Oil and Gas Fired

Low Voltage Step Down Transformers (Dry Type)	
Medium Voltage Step Down Transformers (Dry Type)	
Unit Substations (Dry Type)	
Medium Voltage Motor Starters	— Panel Mounted with Associated Relays, Transducers Control Switches, etc.
Low Voltage Motor Starters	
Medium Voltage Switchgear	
Low Voltage Switchgear	
Batteries and Chargers	
Uninterruptible Power Supply (May also be in Control Room)	
Control Switches	
Panel Lights	
Solid State Motor Controls	
Mechanical Relays	
Protective Relays	
Electrically Actuated Steam Valves	
Electrically Actuated Water Valves	
Low Voltage Bus Duct	

TURBINE-GENERATOR AREA

(Same for Coal Fired, Oil Fired, Gas Fired)

Turbine-Generator
 Steam Valves and Controls (Throttle Valve and Governor Valve)
 Exciter
 Isolated Phase Bus
 Pressure Transmitters
 Temperature Transmitters
 Vibration Detectors
 Terminal Strips in Boxes (Thermocouple Leads, etc.)
 HVAC Fans, Starters and Controls
 Condensate Pump(s)
 Condenser Vacuum Pump(s)
 Condenser Cooling Water Pumps
 Tachometer Generator
 Speed Governor
 May be some Low and Medium Voltage Switchgear

TABLE 3.4-2 (Cont.)

OUTDOOR EQUIPMENT

(Same for Coal, Oil, Gas and Nuclear)

Cooling Tower Fans, Motors and Controls
Medium Voltage Switchgear
Low Voltage Switchgear
Medium Voltage Motor Starters
Low Voltage Motor Starters
Water Pumps (River or Lake Water Cooling) and Controls
(Several Hundred or Thousand Horsepower)
Motors and Auxiliaries

TABLE 3.4-3

OUTDOOR SUBSTATIONS

**Types of Electrical Equipment
In a Typical Installation**

NEW INSTALLATIONS

Instrument Transducers
Panel Meters and Indicating Lights
Telemetry Equipment
Analog Solid State Equipment in Panels
Digital Control and Monitoring Equipment
Lighting Panels
Batteries and Chargers
Protective Relays
Chart Recorders
Control Switches
Microwave Equipment
Terminal Strips

OLD INSTALLATIONS

Terminal Strips
Lighting Panels
Batteries and Chargers
Protective Relays
Chart Recorders
Control Switches
Instrument Transducers
Panel Meters and Indicating Lights
Telemetry Equipment

length of 2.5 mm. For some cases, test data was utilized from tests involving 2 mm or 3 mm fibers. Approximations were made to correct for length differences if longer lengths were involved.

An exponential probability distribution was utilized to estimate all probabilities of carbon fiber induced outages calculated herein. This is generally regarded as a conservative assumption. Only single contingency failures are considered in this analysis except for the reliability of the emergency diesel generators at a nuclear power plant where two simultaneous failures were deemed necessary to be critical. It became apparent as the analysis proceeded that in every functional area of each type of plant there was one critical device (class of generic components) that was much more sensitive, or vulnerable, to carbon fiber contamination than the other critical devices present. Usually the most sensitive critical device was at least one order of magnitude more sensitive in terms of its estimated mean exposure to fail, $\bar{E}$. Thus, the reliability calculation for each area is dominated by its most sensitive component and can be reasonably represented by that component's reliability. When the overall plant or substation vulnerability was estimated, there are usually one or two sensitive functional areas that dominate that calculation also.

Table 3.5-1, Column 2, shows the most sensitive critical component in each functional area of each type of plant listed in Column 1. Overall, it can be seen that analog and digital electronic controls are the most vulnerable, i.e., have the lowest mean exposure to fail. Using an exponential probability model and the previously calculated typical and worst case carbon fiber exposures in each functional area from Column 10 of Table 3.3-1, the probability of inducing a critical failure in each area of each type of plant and substation was calculated for typical and worst case release scenarios. These are shown in Column 3 of Table 3.5-1. The overall probability of inducing a plant outage for each type of power plant and substation was then calculated and is shown in Column 4 of Table 3.5-1. These figures are point estimates of the probability of an induced failure per plant-exposure incident. It can be seen from Table 3.5-1 that the probability of inducing a power plant or substation outage is on the order of 10^{-5} to 10^{-7} per plant exposure incident for the worst case and average release scenarios, respectively. This implies that if a power plant or substation was exposed once a year to a worst case release for every year of its estimated thirty-year life, only between 1×10^{-5} to .024 total failures could be expected over the entire thirty years! Consider the actual situation where only between 2 and 3.8 releases are expected annually nationwide where 95% of these releases will produce a maximum exposure of 10^3 fiber-seconds/meter³ and only over a limited area; then the expected number of plant outages is on the order of 2.8×10^{-5} to 1.2×10^{-7} per year.

Figure 3.5-1 shows the operating reliability statistics for power plants in the United States between 1967 and 1976, based on the Edison Electric Institute's Equipment Availability Report.⁽⁵⁾ These graphs show the operating availability and forced outage rates for coal-fired and nuclear plants from 1967 to 1976. It can be seen that forced outages from causes

(5) "Report on Equipment Availability for the 10-year Period, 1967 through 1976", EEI Publication Number 77-64, Edison Electric Institute, New York - December 1977.

Figure 3.5-1 Comparison of Fossil Coal-Fired* Units 400 MW and Above to
All Nuclear Units

UNIT YEAR AVERAGES

1967 - 1976

—— FOSSIL

---- NUCLEAR

* COAL PRIMARY FUEL

** NORMALIZED TO MAXIMUM DEPENDABLE CAPACITY AND
BASED ON TOTAL HOURS IN FULL YEAR PERIOD

TABLE 3.5-1 Estimated Probabilities of Plant Outages

(1) Location	(2) E of Most Sensitive Component	(3) Probability of Failure in Each Area Typical/Worst Case	(4) Overall Probability of Plant Outage Typical/Worst Case
A. NUCLEAR PLANTS			
1. Control Room			
A. Open	2.8×10^6 Digital Equip.	$9.6 \times 10^{-8} / 1.3 \times 10^{-6}$	$7.5 \times 10^{-6} / 8.1 \times 10^{-5}$
B. Closed	2.8×10^6 Digital Equip.	0 0	
2. Diesel Area	1.0×10^7 Diesel Elec. Sys.	$4.8 \times 10^{-10} / 4.8 \times 10^{-8}$	
3. Unc. Access Area	2.8×10^6 PC Boards	$2.5 \times 10^{-6} / 2.5 \times 10^{-5}$	
4. Safeguards	2.8×10^6 PC Boards	$2.1 \times 10^{-6} / 2.4 \times 10^{-5}$	
5. Fuel Handling	3.1×10^7 Relays & Cont.	$1.9 \times 10^{-7} / 2.2 \times 10^{-6}$	
6. Controlled Access	2.8×10^6 PC Bds./Digital	$2.1 \times 10^{-6} / 2.3 \times 10^{-5}$	
7. Electrical Bldg.	3.1×10^7 Elec. Cont./Swgr.	$1.9 \times 10^{-7} / 2.2 \times 10^{-6}$	
8. Containment	1.0×10^8 Pwr. Pnls. (Enclosed)	$7.0 \times 10^{-8} / 7.6 \times 10^{-7}$	
9. Turbine Gen.	1.0×10^9 Swgr./Elec. Pnls.	$2.4 \times 10^{-7} / 2.4 \times 10^{-6}$	
B. FOSSIL-FUELED			
1. Control Room	2.8×10^6 Digital Equip.	$1.8 \times 10^{-7} / 1.8 \times 10^{-6}$	$3.4 \times 10^{-6} / 3.4 \times 10^{-5}$
2. Electrical Areas	2.8×10^6 Electronic Cont.	$2.5 \times 10^{-6} / 2.5 \times 10^{-5}$	
3. Turbine Gen.	1.0×10^9 Elec. Swgr. & Cont.	$7.0 \times 10^{-9} / 7.2 \times 10^{-8}$	
4. Boiler Area —	Indoor 3.1×10^7 Controls	$2.6 \times 10^{-7} / 2.5 \times 10^{-5}$	
	Outdoor Not Vulnerable	Not Vulnerable	
C. UNDERGROUND HYDRO			
	2.8×10^6 Digital Equip.	$4.3 \times 10^{-7} / 4.3 \times 10^{-6}$	$4.3 \times 10^{-7} / 4.3 \times 10^{-6}$
D. GAS TURBINE GEN.			
	2.8×10^6 Digital Equip.	$1.8 \times 10^{-7} / 1.8 \times 10^{-6}$	$1.8 \times 10^{-7} / 1.8 \times 10^{-6}$
E. SUBSTATION CONTROL			
BLDG.	NEW		
	2.8×10^6 Digital Equip.	$3.2 \times 10^{-8} / 3.2 \times 10^{-7}$	$3.2 \times 10^{-8} / 3.2 \times 10^{-7}$
	OLD		
	3.1×10^7 Relays & Cont.	$2.6 \times 10^{-7} / 2.6 \times 10^{-6}$	$2.6 \times 10^{-7} / 2.6 \times 10^{-6}$

unrelated to carbon fiber contamination put coal-fired and nuclear plants out of operation nearly 15 percent of the time. When scheduled maintenance and other planned outages are included, these power plants are only available, i.e. operational, 70 to 80 percent of the time on an annual basis. With these plants normally out of service 20 to 30 percent of the time, the incremental increase in outage rates attributable to carbon/graphite contamination pales to insignificance. Incremental increases in outage rates on the order of 10^{-5} to 10^{-7} as predicted in this analysis will be indistinguishable from the non-fiber related outages currently being experienced.

Table 3.5-2 summarizes in detail the power plant availability for fossil, nuclear, gas turbine, jet engine, diesel, hydro and pumped storage generating units. All outages — forced outages, maintenance outages and planned outages — account for as much as 20 to 30 percent of generating unit time. It can be seen from Table 3.5-2 that the average duration of these outages can vary from a few days to several weeks depending on the plant type. The effort required for repair and/or scheduled work is generally several hundred to several thousand man-hours for non-fiber related causes.

On the remote chance a carbon fiber release should cause a plant outage, repair will frequently be limited to cleaning fibers out of the affected equipment with a vacuum cleaner — a relatively simple process. Highly destructive failure modes, though they may occur, generally have a lower likelihood of occurrence.

It is concluded that the accidental release of carbon/graphite fibers in the release scenarios postulated by NASA does not constitute a significant hazard to power plant and substation control equipment.

TABLE 3.5-2 Summary of Power Plant Availability, 1967 - 1976 (5)

<u>UNIT YEAR AVERAGES (HOURS)</u>										
Designation of Units	Equivalent Availability %	Equivalent Forced Outage Rate %	Forced Outages*		Mean Time Between Full Forced Outages	Scheduled Outage Rate %	Scheduled Outages			
			Outage Hours	Manhours			Outage Hours	Maintenance Outage Manhours	Planned Outage Hours	Planned Outage Manhours
Fossil	82.17	8.31	436.31	2965.44	1057.86	10.38	252.56	2255.05	646.62	7418.14
Nuclear	67.26	17.82	689.96	5010.91	841.59	16.91	330.72	8794.81	1058.62	16986.81
Gas Turbine	86.13	37.17	596.43	690.97	818.56	6.48	274.91	444.33	262.62	299.36
Jet Engine	84.68	51.64	678.52	946.12	799.52	5.46	259.60	671.17	198.81	411.77
Diesel	94.31	33.96	334.31	36.63	1071.68	1.12	60.37	46.66	35.51	15.89
Hydro	95.42	1.64	96.56	74.07	3370.06	3.41	67.42	118.07	231.24	541.98
Pumped Storage	86.52	14.43	383.30	146.58	1037.71	8.90	286.06	475.50	464.50	1088.77
Miscellaneous	79.19	9.03	404.07	3648.20	1278.88	13.79	136.58	4452.00	833.69	6682.80
Total			471.75	2101.59			230.16	1629.87	434.97	4984.54

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* Equivalent figures normalized to maximum dependable capacity and based on total hours in full year period.

4. EXTERNAL INSULATION VULNERABILITY ANALYSIS

The study of the vulnerability of power transmission and distribution insulation to carbon fiber contamination was divided into three sections based on the primary uses of external insulation. The three primary areas where external insulation is used are; a) transmission lines, b) distribution lines, and c) substations. This analysis discusses only accidental releases such as would result from burning a carbon fiber composite. Airborne fibers released from burned composites are short and widely dispersed. The fiber length used for an accidental release was based on data appearing in NASA reports showing that the mean fiber length released would be about 2.5 mm. Maximum exposures used for this analysis are also based on NASA data which show that exposures for 95% of all accidental releases are less than 10^3 fiber-sec/m³ while 5% may go as high as 10^4 . Additionally, NASA data shows that the areas covered by these extremely large exposures would be very small. This analysis utilizes the conservative exponential model for calculating flashover probabilities. Waltz Mill tests discussed in Part II indicate that a Weibull distribution provides a better curve fit for probability of failure. However, this analysis uses an exponential model for the sake of conservatism.

4.1 Transmission Lines

The vulnerability of transmission line external insulation to flashover due to carbon fiber contamination is tempered by standard design practice for transmission systems. Most transmission systems are designed with sufficient redundancy that a line can go out of service and power still be provided to customers. Since transmission lines are generally geographically dispersed, a carbon fiber release typically would only contaminate a few kilometers on a single line. Therefore, loss of service to customers would not be likely to result from such a carbon fiber-caused flashover.

To further reduce the likelihood of a power outage, transmission lines are frequently equipped with high speed reclosers. This means that lines are designed so that an insulator flashover causes the line to be momentarily de-energized. As soon as the arc extinguishes a reclosing relay automatically re-energizes the line. Tests performed at Waltz Mill indicated that in most cases the insulation strength of the line is restored after arc extinction when carbon fiber induced the flashover. Therefore, the line would probably re-energize successfully and no service interruption would result. In summary, if a flashover did occur on a transmission line, customer power outages would be extremely unlikely.

The probability of an insulator flashover is small even when it is exposed to carbon fibers. Suppose a large release occurred because of an airplane crash near a transmission line. If the crash occurred within a few hundred meters of the line it is quite possible that debris hit the line and removed it from service. This analysis only considers a crash occurring in close proximity to the line but far enough away so debris would not be likely to hit the line. If it occurred more than a few hundred meters from the line an exposure to carbon fiber as high as 10^3 fiber-sec/m³ is unlikely. Waltz Mill tests indicate that the transmission line insulation average exposure to flashover is over 10^8 fiber-sec/m³.

A transmission line typically has about 3 towers/kilometer, each tower typically has six insulator strings. Three kilometers of line would be an extreme length to receive an exposure

as high as 10^3 fiber-sec/m³. In such a case, 54 insulators would be exposed. Using a conservative model for the probability of one or more insulator systems flashing over:

$$P = 1 - \exp(-10^3/10^8 \times 54) = 0.00054$$

The probability of a carbon fiber caused outage is small in comparison to non-fiber related outage rates. Transmission lines typically experience .02 failures/km/year,⁽⁶⁾ so for three kilometers of line .06 failures would be typical. If a carbon fiber release occurred near a line each year and every flashover caused an outage, it would only increase the outage probability for a 3 km section by $(.00054/.06) \times 100 = .9\%$. Since the remainder of line would not be exposed, the increase in probability of flashover over the entire length of line is much smaller. For a 50 km line, 50 x .02 or 1 failure is typically expected each year from non-fiber related causes. So even in the unlikely instance that a release occurred near a line each year, that the release exposure was 10^3 fiber-sec/m³, and that each flashover caused an outage, a 50-km line's failure probability only increases by:

$$(.00054/1) \times 100 = .05\%$$

The accidental release of carbon fiber from a burned composite causes essentially no problem to transmission lines because of the low flashover probability and the minimal consequences of a flashover if one should occur.

4.2 Distribution Lines

Distribution lines are more susceptible to carbon fiber contamination than transmission lines. This is a result of several factors. First, there are more distribution insulators in a given area than transmission insulators. Second, although most distribution lines are equipped with automatic reclosers, some are fused so an insulator flashover is more likely to cause temporary interruption of power to a limited number of customers. Also, more extended failures would be expected from fault overload conditions on equipment and conductor burndown due to the failure of, or misapplication of, protective devices (fuses, relays, etc.).

Visualize a distribution system as a constant insulator density over an entire suburb. Data for Table 4.2-1 is taken from NASA Conference Publication 2119 — Assessment of Carbon Fiber Electrical Effects. The table shows test results giving typical exposures for various distances downwind from a carbon fiber release resulting from a burned composite.

(6) G. A. Nunan, "A Simplified Procedure for Reliability Evaluation of Electric Transmission and Distribution Systems", p. 49 of *Proceedings of the Fourth Reliability Engineering Conference for the Electric Power Industry*, July 16-17, 1977.

TABLE 4.2-1

a Meters Downwind	b Greatest Exposure Measured (fiber-sec/m ³)	c Area* (m ²)	d b x c	e Size Comparable to
200	4000	10500	4.2 x 10 ⁷	Football Field
1000	1000	251000	2.5 x 10 ⁸	Block
2200	300	1010000	3.0 x 10 ⁸	
3800	243	2510000	6.1 x 10 ⁸	Development
5500	330	4140000	1.4 x 10 ⁹	Suburb
10200	533	19300000	1.0 x 10 ¹⁰	
19200	200	69272118	1.4 x 10 ¹⁰	City

* Represents the area exposed to the exposure given. Area was computed using an ellipsoid 1/3 as wide as long with the length given by Column a.

As the table shows, the product of exposure and area is much greater for very large areas. For a probability of a failure over a large area composed of smaller areas at various exposures, the exponential model for flashover probability yields:

$$P = 1 - \exp(-E_1/\bar{E})^{A_1 C} \exp(-E_2/\bar{E})^{A_2 C} \exp(-E_3/\bar{E})^{A_3 C} \dots$$

rewritten:

$$P = 1 - \exp[-C/\bar{E}(E_1 A_1 + E_2 A_2 + E_3 A_3 \dots)]$$

Where:

P	probability of a flashover
$\bar{E}$	mean flashover exposure for a single insulator
E_n	exposure over a given area
A_n	area exposed
C	insulator density

By the exponential model the exposure-area products in column d add; because the product is so much smaller for smaller areas at higher exposures, the impact of smaller areas on the total probability of flashover is negligible. An area larger than a suburb would not have continuing high insulator densities nor would it be exposed to continued high exposure so the greatest possible impact of a release on distribution systems would probably be on an area the size of a suburb (20 sq. km). For that area the extreme exposure expected is about 500 f-sec/m³ as predicted by NASA simulations.

To determine the probability of an insulator flashover, an average insulator density is needed to determine the number of insulators exposed. The total number exposed is the insulator density times total area considered. A number was developed for insulator density by assuming a suburb in which every house was on a 1/4-acre lot. Each set of 4 houses was assumed to have one pole with 4 insulators associated with it. Using these numbers, insulator

density was determined to be 900/km². If we assume 900 insulators/km², the total number of insulators exposed in 20 km² would be 18,000. For distribution insulators, mean flashover exposure was determined experimentally to be 10⁸ fiber-sec/m³. The probability of one or more insulator flashovers is:

$$P = 1 - \exp(-500/10^8 \times 18000) = 0.086$$

This means that if a carbon fiber release covering this 20 km² area occurred every year for twelve years, one insulator would be expected to flashover somewhere in this system. A typical failure rate due to non-fiber related causes, for distribution systems is .26 failures/km/yr.⁽⁷⁾ There would be 4 insulators/.06 km of line if every four houses, each on a 1/4-acre lot, had 4 insulators. Then, (0.26 x 0.6/4) x 100 = 0.4 failures/100 insulators/year. Since there are 18000 insulators in the example suburb, 0.4 x 18000/100 = 70 insulator failures are experienced each year. Seventy flashovers would normally occur in the suburb during a year so the carbon fiber exposure would be expected to increase the insulator failure rate by 0.086/70 x 100 = .1% if the suburb were exposed every year.

As with transmission lines, distribution lines are configured such that line failures cause minimal power interruptions. In fact, reclosers are frequently installed and operate to reclose a line after a fault. Carbon fiber contaminated distribution insulators can normally be re-energized after a flashover so customer outage is unlikely to occur. Although carbon fibers are more likely to cause an outage for a distribution system than a transmission system, the increase in outage rate even if the suburb were exposed every year is so small as to be imperceptible from existing distribution system outage rates. Hence, it is negligible.

4.3 Substations

An accidental carbon fiber release would have its greatest impact if the release occurred near a substation because of the greater consequences of insulator flashover and higher insulator densities. Greater insulator flashover consequences result from the critical nature of substation equipment relative to system reliability. Some substation buswork and lines do not automatically reclose, therefore if certain insulators flashed over an outage could occur. An outage in a substation could cause temporary loss of service to a large number of customers. A flashover would probably not cause damage to equipment since relays would operate circuit breakers, or fuses would blow to clear the fault.

If a release occurred near enough to a substation to cause an exposure of 10⁴ or greater, it is quite possible that the aircraft or flying debris hit the substation or caused failure of incoming lines. Therefore, this analysis will consider a maximum exposure of 10³ fiber-sec/m³ and use the exponential probability distribution as was used for transmission and distribution lines. Substation insulation normally has a much greater mean exposure to flashover than distribution insulation as determined from the test data to be discussed later in this report. This analysis will use a mean flashover exposure of 10⁸ fiber-sec/m³ although actual numbers are closer to 10⁹.

(7) Ibid.

An estimate of the number of insulators in a substation is obtained by determining the number of bays. A typical bay has 30 insulators. A large substation may have up to 8 bays so $8 \times 30 = 240$ insulators. A more typical substation with 3 bays would have 90 insulators. For a large substation the probability of flashover of one or more insulators is given by the equation:

$$P = 1. - \exp (- 10^3 / 10^8 \times 240.) = 0.0024$$

For a normal substation:

$$P = 1. - \exp (- 10^5 / 10^8 \times 90) = 0.0009$$

This means that if a substation were exposed once a year for 1111 years, one insulator or bus support would be expected to flashover.

A typical substation suffers 0.6 accidental interruptions due to all non fiber related causes each year. Typically, substation bus work suffers .005 faults/year. This means that if a large substation was exposed to a carbon fiber incident each year, the substation buswork fault frequency would increase by $(.0009/.005) \times 100 = 18\%$. Even if every flashover caused a customer outage, the probability of an outage would increase by only $0.0009/.6 \times 100 = 0.15\%$. However, the standard design practice for power systems minimizes the effect of faults of the buswork so the actual outage probability increase would be less. Detailed analysis would require that calculations be performed for all non carbon fiber caused faults and then be performed again adding the fault probability due to carbon fibers. By this methodology the system's sensitivity to carbon fiber release could be determined. Even for an accidental fiber release near a substation the additional faults caused by carbon fiber are only a small percentage of the normally expected outages.

4.4 Summary

For the three classifications of external insulation, transmission lines, distribution lines and substations, the impact of carbon fibers on component failure has been shown to be negligible. Also, since power systems are designed in such a way that a component failure normally does not cause a customer outage, the expected impact of carbon fiber on the system performance is less than the impact on the component. Hence, accidentally released carbon fibers pose no significant hazard to external insulation.

5. CONCLUSION

The findings of this study indicate that an accidental release of carbon/graphite fibers poses no hazard to electric power generating plants, substation control systems, or to transmission, distribution, and substation insulation. Even the conservative assumptions utilized in this study indicate that the impact of carbon fiber releases, as postulated by NASA, is so small as to be insignificant to power systems' performance.

PART II – TESTS ON EXTERNAL HIGH VOLTAGE INSULATION

Final Report – June 5, 1980

1. INTRODUCTION

The objective of the work described in this report was to determine the effect of airborne carbon fiber contamination on power systems. Part I has discussed the vulnerability of power systems to carbon fiber. It uses results from NASA tests as well as results of tests discussed here, in Part II, of this report.

The investigation was prompted by two factors. First, the use of carbon fiber composites in aircraft, automobiles and equipment where its strength and weight characteristics are utilized. Second, several incidents during which fiber releases caused insulator flashovers. Flashovers have occurred in and near fiber manufacturing plants after incineration of long carbon fiber strands. The analysis in this report, however, discusses the effect of shorter carbon fibers which result from the accidental fiber release conditions postulated by NASA. Tests were directed toward the fiber released from burned composite material (resulting from an aircraft or automobile accident) which is generally short.

This part of the final report on the DOE program, Part II, discusses the tests performed on external insulation to determine flashover exposure levels. Test facilities and methodology are presented. Results of tests are discussed and recommendations made. The tests indicate that a mean flashover exposure of 10^8 fiber-sec/m³ is reasonable, in fact conservative, for transmission, distribution and station insulation.

2. SUMMARY

This final report presents a compilation of the results of tests performed to determine the effect on external insulation of airborne carbon fiber contamination such as that released by burning carbon fiber composite. The report discusses the test equipment and detailed test procedures including safety precautions, test set-up and clean-up procedures.

The objective of these tests was to determine fiber exposure for insulator flashover. Since tests simulating actual accidental release conditions were time consuming, most tests were performed using long fibers at high concentrations. To extrapolate these test results to accidental release conditions, tests were performed to determine the appropriate trends.

Detailed test results are also presented including mean flashover exposure and probability distributions for the insulators tested. Results of special tests are discussed and recommendations are made for future tests which may be performed if additional data is desired.

3. FACILITIES AND EQUIPMENT

The following sections describe the facilities and equipment utilized in contamination testing. Tests were performed at the Waltz Mill, Pennsylvania facility in a building previously used to perform carbon fiber contamination testing for the U.S. Air Force. Specific equipment used in testing is described in the following sections.

3.1 Contamination Chamber

The chamber provides dispersion and confinement of the fibers and maximum visibility of the test object. The configuration of the chamber is shown in Figures 3.1-1 and 3.1-2.

3.1.1 Chamber Description

Field plots indicated that voltage stress in the immediate area of insulators on a typical distribution system at 34.5 kV line-to-line would not be significantly influenced by a chamber that is 1.5 meters on a side. Sketches of field plots are shown in Figures 3.1.1-1 through 3.1.1-2. The plots show that, along the insulator (approximately 0.5 meters down from the conductor), the stresses are greater for the distribution line model than the chamber model. This means that the chamber walls were adequately spaced to allow accurate duplication of electric fields in the chamber. Further field plots indicated that as ground planes representing other structures in the system were included in the vicinity of the test piece, electric fields in the chamber were similar to those near a distribution line.

Since the chamber was used to test insulation up to 34.5 kV ac and up to 50 kV dc, the chamber was designed for a maximum test voltage of approximately 60 kV peak line-to-ground. The resulting design is 2.44 x 2.44 x 2.44 meters on a side (8' x 8' x 8'). The chamber was located over a sump pit in the test facility to permit easy washing.

3.1.2 Chamber Composition

The chamber is constructed of .64 cm thick Lexan sheeting coated with an anti-static compound and assembled with structural fiberglass and nylon fasteners to prevent interference with electric fields. Structural members are external so that the inside walls are smooth and clear of any projections to prevent accumulation of fibers and to facilitate cleaning of the chamber. The dimensions of the chamber (including personnel access/entrance area) are 2.44 x 2.44 x 3.05 meters (8' x 8' x 10').

3.1.3 Selection of Wall Bushing

The high voltage conductor was brought into the chamber through a 69 kV apparatus bushing which was installed recessed in the chamber wall. The sizing of the bushing was chosen to prevent undesired flashovers along the bushing under the test voltage and contamination conditions. The bushing was sized with more creepage than any expected test piece. The bushing was recessed into the chamber wall to shield it from direct contamination.

Figure 3.1-1 Contamination System Floor Plan

Figure 3.1-2 Contamination Chamber Configuration

Figure 3.1.1-1 Distribution Line Model

Figure 3.1.1-2 Chamber Model

3.2 Air Handling System

The contamination chamber air circulation system was carefully designed to permit even distribution of carbon fiber during testing. Another consideration was containment of carbon fiber within the test area. The following sections describe the air blower and dispersal chamber.

3.2.1 Dispersal Chamber

The dispersal chamber was designed to mix air with the chopped fibers and collect any clumps of fiber which were generated by the chopper. A diagram of the dispersal chamber is shown in Figure 3.2.1-1. The dispersal chamber is constructed entirely of transparent Lexan sheeting material so its operation is clearly visible.

3.2.2 Air Ducts and Suction Blower

The air ducts and suction blower transport the chopped fibers from the dispersal chamber into the contamination chamber and approximate a vertical fiber fall onto the test object. The suction blower causes a net flow of air into the chamber when the chamber access door is opened to prevent fibers from escaping from the enclosed test system. It also disperses the fibers during a test run. The suction blower is also used to collect fibers during the clean-up of the chamber after a test. The air flow through the contamination chamber is controlled with an air by-pass at the suction blower. Air is drawn through the upper ducts during tests and the lower duct for chamber clean up. During tests air drawn across the top of the chamber distributes fiber throughout the chamber with little horizontal travel of the fibers. When cleaning up, fiber is picked up through a hose connected to the lower duct. The location of the air ducts and suction blower are shown in Figure 3.1-1 and 3.1-2.

3.2.3 Fiber Dispersal

Initial tests were made to determine fiber dispersal in the test chamber and experiments were made with baffles to obtain an even distribution of fibers over the test area and to obtain a vertical fall with the fibers.

Fiber distribution was determined qualitatively by visual inspection of white paper placed on the test table and quantitatively by counting fibers on sticky tapes placed at various locations. The test procedure included cleaning the chamber, placing sticky tapes on the test table, positioning baffles, and running a known length of fiber through the chopper. Fiber distribution was then determined and other baffle arrangements selected based on previous tests.

Trial runs were performed using several baffle arrangements near the contamination chamber air inlet. The use of no baffle produced a high concentration directly in front of the air inlet. A 'V' shaped baffle mounted in front of the inlet on a shelf produced high concentrations at both sides of the chamber. A flat baffle 8 cm in front of the inlet produced an even fiber distribution and also knocked fiber clumps down at the inlet side of the chamber. A flat baffle placed 2 cm from the inlet produced a very even fiber distribution, but generated excessive turbulence in the chamber.

Figure 3.2.1-1 Dispersal Chamber

Another baffle arrangement investigated was to hinge the flat shelf below the inlet and angle it to direct the fibers up and out. A 'U' shaped baffle directly in front of the inlet spread the air out to give an even fiber distribution. This baffle arrangement seemed to give better efficiency, but it allowed more of the clumps to fall into the test area in the chamber.

Good fiber distribution was obtained using a vertical flat baffle placed 10 cm in front of the air inlet on a level shelf. This configuration was used for most of the tests.

3.3 Power Supply

The power supply designed for this study permitted testing to a maximum of 45 kV_{1-g} (78 kV_{1-l}). The description of its design and the capabilities of the supply are discussed in the following sections.

3.3.1 AC Power Supply

The decision to design a low impedance power supply was precipitated by initial test results with a 35 kV, 5 kVA high impedance test transformer. These test results indicated that a considerable portion of the test voltage was dropped across the transformer leakage impedance during intermittent arcing. The voltage drop prevented a total flashover on the test insulator.

To comply with recommended test procedures for artificial contamination tests, it was decided that a high voltage supply with a lower impedance should be used for the carbon fiber tests. 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 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 apply directly to carbon fiber testing, but it is the only available guideline, and, at the conclusion of this program, it is thought to be adequate.

In order to minimize cost and delivery time, a high voltage supply using standard distribution transformers was designed rather than ordering a custom-built high-current supply. In this particular design a distribution transformer was energized from a 240-volt supply and the voltage stepped up to distribution class levels. A standard variable autotransformer was used to adjust the test voltage by varying the voltage applied 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, the high voltage supply was designed utilizing three different configurations of single and cascaded connections. Figure 3.3.1-1 shows the configuration which was used for supplying test voltages from 4 kV to 15 kV, Figure 3.3.1-2 shows the supply configuration for producing test voltages from 15 kV to 30 kV and Figure 3.3.1-3 shows the configuration which was used to supply test voltages above 30 kV.

Figure 3.3.1-1 High Voltage Supply for 4 kV to 15 kV

Figure 3.3.1-2 High Voltage Supply for 15 kV to 30 kV

Figure 3.3.1-3 High Voltage Supply for 30 kV to 45 kV

By using the single distribution transformer scheme shown in Figure 3.3.1-1, calculations showed that currents of 5.6 amps and 21 amps would be supplied at test voltages of 4 kV and 15 kV respectively.

In the scheme shown in Figure 3.3.1-2, three distribution transformers were placed in cascade to produce test voltages from 15 kV up to 30 kV. The fault currents available ranged 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 the scheme shown in Figure 3.3.1-3, five distribution transformers were placed in cascade to produce test voltages from 30 kV to 45 kV. The fault currents available were calculated to range from 4.7 amps at 30 kV to 7 amps at 45 kV. As was explained for the 30-kV power supply, the additional two transformers on insulated platforms boost the test voltage from 30 kV to 45 kV on the test object.

The low impedance power supply was installed and tested. A series of voltage oscillograms were obtained using a digital memory oscilloscope. These oscillograms verified that power supply tripouts were a result of total insulator breakdown. There was some initial concern that the tripout relay might be set at too low of a sensitivity and that some tripouts might be a result of a partial insulator breakdown. There was also concern that the voltage drop may be so large that the arc might extinguish rather than cause a complete breakdown as was experienced with a high impedance supply. However, measurements verify that the sensitivity was accurate and that the voltage supply current was sufficient such that the arc does not extinguish due to voltage drop in the supply.

Figures 3.3.1-4 and 3.3.1-5 are typical of the test voltage immediately preceding a tripout of the power supply. These waveforms are from measurements on the single and double cascade supplies. To verify the validity of tests performed using the triple cascade AC power supply, measurements were performed to determine voltage and current waveforms during flashover. Waveforms confirmed calculations showing that fault currents were adequate to maintain flashover until the fault was cleared. Fault current for the triple cascade supply at the lowest voltage for which it is used, 30 kV, was measured to be about 8 amps RMS. Four to five amp is considered adequate fault current for contamination testing. Figure 3.3.1-7 shows that voltage and current waveforms were similar to those for the single and double cascade supply. It is evidenced from these oscillograms that the tripouts occurred after at least one full cycle of power follow current. It may be observed from these oscillograms that there is a minor amount of arcing across the insulator before the test voltage collapses into the classical steady state arc voltage. After approximately 1.5 cycles of arc voltage the fault current is cleared by a magnetic contactor on the primary of the power supply.

Although most visible arcing resulted in a total breakdown of the insulator, several intermittent arcs were observed during insulator tests. Figure 3.3.1-6 is a voltage oscillogram obtained during one of the intermittent arcs that did not result in a power supply tripout. In this situation it is hypothesized that some of the fibers involved in the partial breakdown are blown out of the arc path before sufficient ionization occurs to result in a lasting breakdown.

Figure 3.3.1-4 Oscilloscope of Insulator Test Voltage During Carbon Fiber Breakdown.

Figure 3.3.1-5 Oscilloscope of Insulator Test Voltage During Carbon Fiber Breakdown.

Figure 3.3.1-6 Oscilloscope of Insulator Test Voltage During Intermittent Arcing.

3.3.2 DC Power Supply

A DC supply was constructed as shown in Figure 3.3.2-1. The core of the supply is a high voltage rectifier assembled as shown in Figure 3.3.2-3. The rectifier is rated at 100 kV PIV, 50 amp peak surge current for 1/2 cycle, and 15 amp surge current for 10 cycles. The rectifiers have controlled avalanche junctions to eliminate the need for grading resistors and capacitors.

Fault current and filtering measurements were made for the DC supply. Fault currents, though of short duration, were very large, about 50 amp peak as shown in Figure 3.3.2-2. Ripple was 1 percent as shown in Figure 3.3.2-4. This low level of ripple was a result of the small load on the power supply relative to the large capacitance of the filter.

3.4 Carbon Fiber Cutter

Three types of cutters were considered. They are:

- 1) Rotary knife with catnip-like type feed (Manufactured by Foster and Allen). This is similar to the solenoid operated knife above.
- 2) Multi-knife roller with a pinch roll feed operated in tandem (Manufactured by Binks).
- 3) The third type of cutter, shown schematically in Figure 3.4-1, was the least expensive and easiest to control. It was also better suited for cutting relatively short lengths of carbon fiber (2 - 10 inches) than the roller type. The Binks chopper was modified to cut lightweight carbon fiber, on low speeds, with a pinch roll feed needed some modifications. It was the most cost and time effective.

The Binks chopper was modified to cut lightweight carbon fiber, on low speeds, and have interchangeable multi-knife rollers to cut different lengths of fiber. During normal operation a single end of fiber is fed off a 1/4-pound roll into the chopper.

caused by action in the chopper to help eliminate jamming and clumping of fibers. This was added to the cutter to inject air at 50 PSI into the fiber chopper. This fault voltage/current corresponding 60 cycle waveform

3.5 Fiber Characteristics

Carbon fiber lengths, concentrations, and exposures selected for use in the test chamber have been determined from an analysis of available laboratory and field test data and from discussions with the agencies performing these tests.

The field tests at China Lake, as reported in Report No. TRW-78.2.78.4370, provided the major data for these tests. The chamber tests on power distribution insulators at Ballistic Research Laboratories, as reported in Report No. ARBRL-TR-02032, aided in determining a maximum limit on test carbon fiber concentration and exposure.

Figure 3.3.1-7 Triple Cascade Supply Fault Measurements

3.3.2 DC Power Supply

A DC supply was constructed as shown in Figure 3.3.2-1. The core of the supply is a high voltage rectifier assembled as shown in Figure 3.3.2-3. The rectifier is rated at 100 kV PRV, 50 amp peak surge current for 1/2 cycle, and 15 amp surge current for 10 cycles. The rectifiers have controlled avalanche junctions to eliminate the need for grading resistors and capacitors.

Fault current and filtering measurements were made for the DC supply. Fault currents, though of short duration, were very large, about 30 amp peak as shown in Figure 3.3.2-2. Ripple was .1 percent as shown in Figure 3.3.2-4. This low level of ripple was a result of the small load on the power supply relative to the large capacitance of the filter.

3.4 Carbon Fiber Cutter

Three types of cutters were considered. These are:

- 1) Solenoid operated knife with pinch roll feed. (Developed by the Rome Air Development Center.)
- 2) Rotary knife with a caterpillar type feed. (Manufactured by Foster and Allen.) This is similar to the solenoid operated knife above.
- 3) Multi-knife roller with a pinch roll feed operated in tandem. (Manufactured by Binks.)

The third type of cutter, shown schematically in Figure 3.4-1, was the least expensive and easiest to control. It was also better suited for cutting relatively short lengths of carbon fiber (2 - 20 mm) quickly and accurately. While the Binks version of the multi-knife roller with a pinch roll feed needed some modifications, it was the most cost and time effective. The Binks chopper was modified to cut light-weight carbon fiber, operate at low speeds, and have interchangeable multi-knife rollers to cut different lengths of fiber. During normal operation a single end of fiber is fed off a 1/4-pound roll into the chopper.

Air supply lines are added to the cutter to inject air at 50 PSI into the fiber chopper. This causes a cleaning action in the chopper to help eliminate jamming and clumping of fibers.

3.5 Fiber Characteristics

Carbon fiber lengths, concentrations, and exposures selected for use in the test chamber have been determined from an analysis of available laboratory and field test data and from discussions with the agencies performing these tests.

The field tests at China Lake, as reported in Report No. TRW-78.2 78.4370, provided the major data for selection of a range of fiber lengths and concentrations for use. The chamber tests on power distribution insulators at Ballistic Research Laboratories, as reported in Report No. ARBRL-TR-02032, aided in determining a maximum limit on test carbon fiber concentration and exposure.

Figure 3.3.2-1 DC Power Supply

Figure 3.3.2-2 DC Power Supply Fault Current

Figure 3.3.2-3 Rectifier Design for DC Testing

WITH $2.9 \mu F$ FILTER

WITHOUT FILTER, ONLY
8 pF OF EQUIPMENT
CAPACITANCE

WITHOUT RECTIFIER, SAME
VOLTAGE SETTING

Figure 3.3.2-4 DC Filter Measurements

Figure 3.4-1 Multi-Knife Carbon Fiber Chopper

Most fiber released in burning carbon fiber composites are short (approximately 2 mm). Chamber tests were performed to evaluate the effect of short fibers on external insulation. Fiber propagation models have indicated that small fibers may be propagated as far as 100 kilometers from the release point.

Fiber diameters are reduced somewhat by oxidation in high temperature fires. Tests at China Lake indicated a reduction in pretest mean fiber diameters from typically 7 micrometers to 5 or 6 micrometers after the tests. Electrical conductivity tests by BRL on burned fibers shows that they remain electrically conductive and the degree of electrical hazard at high voltages is not reduced due to any differences in conductivity.

The fiber type and manufacturer does not appear to be important since, relative to the insulation system, all fibers are conductive. The diameter of each fiber should not affect the results, providing the diameter is of the same magnitude (approximately 10 micrometers). Therefore, testing was performed using Celanese GY-70 material mainly because of the ease of use in injection systems and in generating single fibers.

3.6 Fiber Deposition Measurements

At the beginning of the study it was felt that a knowledge of fiber deposition on the insulator surface would be useful in the development of a slurry. Initial deposition tests were performed on 7.5 kV pin insulators. The deposition test method involved removing the contaminated insulator from the pin and tie wire. The insulator was then washed in a plastic bag using acetone. The acetone was filtered and the filter was dried. An attempt to weigh the fibers failed due to the small weight of the fibers. Later an attempt was made to measure fiber deposition by counting fibers on the filter paper through a magnifying lens. To obtain an even distribution on the filter paper, a flat filter was used. This attempt also failed due to clumps of fiber on the filter paper.

The most successful method of deposition measurement was the partial removal of fibers from insulator. Fiber deposition was measured using transparent tape which was stretched along the insulator surface from top to bottom after contamination and used to lift fibers from the surface. The tape was then placed on white paper to preserve the deposition. Fibers were counted using a magnifying glass, then fiber density was determined through either averaging over the whole tape or separation by location, whether on upper or lower insulator surfaces.

3.7 Exposure Monitoring

Since all available data representing the amount of fiber released in an accident is measured in units defined as exposure, methods of determining exposure to flashover were required. Exposure is determined by counting fiber deposition on a horizontal surface and dividing by fiber fall velocity. Other methods of determining exposure are calibrated using this technique. Several methods of measuring exposure were used.

3.7.1 Fiber Feet

Two methods of measuring exposure used the fiber feed into the chamber as a monitor. One method required the use of a digital counter which incremented each time the fiber spool

completed a revolution. Another method assumed a constant feed rate with time. By monitoring the number of turns of the spool or the time fiber was injected, the total number of fibers chopped could be calculated. Thus, exposure could be calculated by determining the efficiency of the system in dispersing fiber. The accuracy of this method was highly dependent upon the consistency of the fiber dispersal mechanism efficiency. Chamber efficiency was determined in conjunction with other tests. The total length of fiber fed through the chopper was recorded and sticky tape counts performed. Computations were then made to determine exposure obtained for a given length of fiber fed into the chamber.

3.7.2 Sticky Tape

One successful method of measuring exposure involved the use of a sticky tape. This sticky tape consists of a sheet of clear acetate with a 1 cm grid on it. The sticky tape is coated with "Filter Coat" oil and placed in the airborne contamination test chamber near the insulator prior to a test. The fibers that fall on the sheet stick in the oil. After the test is completed the sticky tape is removed from the chamber and placed in an overhead projector. The projected fibers are manually counted.

To determine exposure from a sticky tape count, the count in fibers per square meter is divided by the fall velocity of the fibers past the insulator. For our purposes, the air was considered to be still and the fiber velocity was taken to be the fall velocity which was tested and determined to be 3 cm/sec for the Celanese GY-70 fibers in agreement with Rome Air Development Center (RADC) test results. The fall velocity did not show any large dependency on fiber length so 3 cm/sec was used for all tests.

The positioning of the sticky tape was determined after dispersal tests were made. Dispersal tests were discussed in the section on the air handling system. Much of the data available on fiber releases was standardized by sticky tape monitoring and sticky tapes proved to be the most dependable. Therefore, sticky tape counts were used to provide exposure data through most of the test program.

3.7.3 Charged Balls

The charged ball technique of counting fibers was selected because it was accepted by most people working in carbon fiber test programs. The charged ball technique would facilitate comparison with data obtained from Aberdeen Proving Ground. The charged ball was used both to determine concentrations of fibers during contamination and total exposure levels.

Figure 3.7.3-1 is a block diagram of the charged ball counting system. A 3-kV, 6 mA power supply was selected for charging the balls to allow flexibility in selecting voltage levels and to give ample current for 2 balls.

Figure 3.7.3-1 Fiber Counting Instrumentation

The ball system consists of a charged ball with a 2.2 M Ω resistor connection to the 3-kV power supply and a capacitor connection to a unity gain operational amplifier. The system operates through the charging of the fibers as they touch the ball which causes a current pulse through the resistor and a voltage pulse output. The capacitor and resistor components shape the pulses for acceptance by the counting instrumentation.

The pre-amps, mixer router, and analyzer are all standard nuclear counting instrumentation. The counting instrumentation is capable of either pulse height analysis or multichannel scaling. It was anticipated that the pulse height analysis would give data that could be used to obtain fiber size distribution and the multichannel scaling option could be used to measure concentration levels. A Tracor Northern Model 1706 system was selected based on discussions with personnel familiar with this equipment. The system includes a mixer router that allows the use of 2 sets of balls (4 total balls) in the chamber to aid in determining the distribution of carbon fibers across the chamber area.

The system digital output is suitable for a 20 mA current loop teletype output. An ASR 33 teletype was selected to give hard copy and paper tape of the output.

The charged balls required calibration to obtain exposure and a fiber length spectrum. Sticky tapes were used as an exposure standard for their calibration. The following method was used to determine the constant relating exposure to ball count. Charged balls were placed at the opposite side of the chamber from the test object to minimize interference from the high voltage conductor. The ball detector and insulator locations were standardized since change in location affected the calibration. Fiber distribution in the chamber was assumed to be constant from test to test. The ball counts were compared to the exposure measured by sticky tapes for 23 trials. A frequency distribution for the constant relating the two was determined and plotted on normal probability paper in Figure 3.7.3-2. The abscissa shows the percent of the 23 tests for which the constant determined was less than the constant of the ordinate. The ordinate is the constant which, multiplied by the charged ball count, yields the exposure. That is:

$$E = C \times N$$

Where:

E is exposure

C is the constant

N is the charged ball count.

The constant relating exposure to charged ball count varied greatly and the exposures obtained by this method were sometimes contaminated by noise.

A major source of noise in the ball detector instrumentation was the close proximity of the high voltage source. Two things were done to minimize the effects of noise generated by the high voltage source on the measuring system. First, the balls were shielded by surrounding them with grounded metal cylinders. Second, outputs of two balls were connected to a differential amplifier and the gains were adjusted so that the noise from the balls cancelled. The shield and differential amplifier were based on similar techniques used by Bionetics, Ballistic Research Laboratories, and others. The gain adjustment optimal for cancellation of noise resulted in two different gains for the fiber pulses. This caused difficulty in obtaining fiber length distributions on the charged ball system because the same length fiber would be shown at different magnitudes depending on which ball it hit. To

Figure 3.7.3-2 Constant Relating Charged Ball Count to Exposure for 4.3 mm Tests

eliminate this problem the balls were configured so that the instrumentation acknowledged the counts from only one ball at a given fiber length. The counts from the other ball at that fiber length were rejected. Ball counts were erroneous due to noise problems even though care was taken in arranging and shielding the balls and the leads. Not all variations in measured exposures were due to noise problems. Some variability in results is due to the random nature of carbon fiber behavior.

After several months of data analysis and recalibration the reliability and validity of this counting technique was very much in question. Inconsistent fiber counts resulted primarily because of noise caused by the high voltage test probe. Noise from the probe caused random counts to appear on the multichannel analyzer. Attempts to correlate charged ball fiber counts to sticky tape counts failed as is evidenced by the large standard deviation in the constant relating charged ball count to sticky tape count as is shown in Figure 3.7.3-2. The charged balls were not used for exposure determination because of their inaccuracy.

4. TEST PROCEDURES

Contamination tests were performed on selected distribution class insulation to determine exposure required to cause a flashover. The test procedures and safety precautions are discussed in the following sections.

4.1 Safety and Health Precautions

The normal safety precautions were taken for dealing with high voltage. Special effort was made to eliminate the possibility of chamber entrance while the test conductor was energized. A door switch was placed on the chamber which tripped the power supply when opened and would not allow it to be energized. Also, before anyone entered the chamber a current near the supply a grounding strip was placed across the test conductor. The power supply was surrounded by a grounded wire mesh cage. A red light was on whenever a safety switch which allowed the supply to be energized was on. Finally, the supply was not energized unless two persons were present.

The safety precautions used in handling the carbon fibers were those recommended by the Celanese Company. Air filters, goggles and coveralls were worn when entering the chamber. Upon leaving, the coveralls were vacuumed and left in the preparation chamber.

Since the air handling system was a closed system, fiber was contained to the contamination and preparation chambers. A very small amount of fiber escaped as personnel left the chamber area even though clothing was vacuumed. Used fiber was collected in plastic bags and placed in 55-gal. drums which were disposed of as landfill.

4.2 Set-Up and Clean-Up Procedures

A procedure was standardized for setting-up each test in order to maintain a consistent approach.

4.2.1 Insulator Mounting

Figure 4.2.1-1 shows the mounting of a 7.5 kV pin cap for contamination testing. In the background there are cylinders containing the charged balls and in front of these charged balls is the sticky tape. Figure 4.2.1-2 shows the mounting of a 34.5 kV station post. The energized conductor is wired to the top of the insulator while the insulator pin is solidly grounded. Figure 4.2.1-3 shows the mounting for a 34.5 kV distribution post. Figure 4.2.1-4 shows an example of a 15 kV distribution post mounted horizontally. Figures 4.2.1-5 and 4.2.1-6 show the mountings for a 15 kV transformer bushing and three 7.5-kV suspension insulators respectively. In all cases except the suspension insulator the high voltage conductor was applied to the top of the insulator. In the case of the suspension insulator, the ground cable was attached to the top of the string and the energized conductor to the bottom as in Figure 4.2.1-6.

Figure 4.2.1-1 Mounting of 7.5 kV Pin Insulator
in Test Chamber

Figure 4.2.1-2
Mounting of 34.5 kV
Station Post in Test
Chamber

Figure 4.2.1-3 Typical Mounting for 34.5 kV
Distribution Post

Figure 4.2.1-4 Typical Horizontal Mounting for 15 kV
Distribution Post

Figure 4.2.1-5 Mounting for 10 kV Transformer Bushing

Figure 4.2.1 6 Mounting for Three 7.5 kV Suspension Insulators

4.2.2 Insulator and Chamber Preparation

Before starting a test the contamination chamber was vacuumed, the insulator cleaned with acetone or alcohol, and a new sticky tape placed near it. When fiber lengths were changed from longer to smaller lengths, the chamber was washed to help eliminate the possibility of longer fibers contaminating the insulator. When changing fiber length from smaller to longer, the chamber was operated for approximately 30 minutes to reduce the number of residual, shorter fiber lengths in the dispersal chamber. The chamber was not washed in this case because of the decreasing effect on flashover that smaller fibers have in comparison to longer ones.

4.2.3 Test Conditions

Relevant test conditions were recorded to facilitate finding a relationship between test conditions and flashover exposure. Among the recorded conditions were fiber feed rate, chamber vacuum, chamber temperature, room temperature, humidity, barometric pressure and elapsed time. Only fiber feed rate and chamber vacuum were readily controllable.

Fiber feed rate was chosen to maintain a reasonable test time. If flashover occurred too quickly (1 - 5 min.) the concentration fiber feed rate was decreased. If flashover did not occur for a long period of time, then chopper speed was increased. Chamber vacuum was maintained constant throughout all tests in an effort to standardize chopper efficiency and fiber dispersal.

4.3 Start-Up Procedure

Each test began 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. 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, the sticky tape removed and a count made.

5. TEST RESULTS

This section discusses the results of tests performed using the procedures discussed previously. The section includes three subsections. The first presents trends discovered during the tests and compiles recommended flashover exposures to be used in calculating failure probability for transmission, distribution, and substation insulation. The second is a detailed presentation of airborne fiber test results to determine exposure to flashover on distribution insulators and the third discusses some special tests performed which, although not directly relevant to determining flashover exposure, contributed greatly to understanding of the contamination mechanism.

The test results described in the following sections were obtained under artificial conditions and do not necessarily represent accidental release conditions.

5.1 Factors Affecting Flashover

This section presents trends discovered during tests and provides data interpretation that was used to determine recommended exposures. Extensive testing indicated that an exposure of 1×10^8 fiber-seconds/m³ could cause insulation breakdown for distribution, transmission, or substation insulation. The mean flashover exposure of distribution class insulation is not likely to be less than 10^8 fiber-seconds/m³. Transmission and station insulation tend to require higher flashover exposures than distribution class insulation. The exposure level of 1×10^8 fiber-seconds/m³ is a conservative exposure level for transmission and station insulation.

During testing several trends were observed relating carbon fiber flashover exposure to various parameters. Parameters affecting flashover exposure were: fiber length, fiber concentration, voltage stress, and deposition.

5.1.1 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 and mean flashover exposure E . E was found to be proportional to e^k . The curves shown in Figure 5.1.1-1 indicate this trend in the data even for tests made using two fiber lengths simultaneously. The mean fiber length fits the exponential exposure to flashover curve.

5.1.2 The Effect of Concentration on Exposure to Flashover

Concentration is a measure of fiber density in the air measured in units of fibers/m³. Tests with long fibers indicate that lowering concentration levels tends to increase mean flashover exposure. This phenomenon was observed on several occasions when accidental increases in concentration precipitated a flashover.

Deposition data verifies the effect of concentration on exposure to flashover. Tests were performed using 7.5 kV station posts and 15 kV distribution posts in which deposition was measured and compared to exposure at various average concentrations. As concentration

Figure 5.1.1-1 Trend Relating Flashover Exposure to Mean Fiber Length Plotted on Semi Log Paper.

increases the deposition per exposure increases. Low linear correlation of the data indicates that the exact nature of the correlation is not clear. Figure 5.1.2-1 shows available data. The effect of concentration on deposition was smaller for the 7.5-kV station post because it had less voltage stress across it. Since flashover deposition is constant and deposition per exposure is greater at higher concentrations, flashover exposure decreases at higher concentrations. Additional data supporting this trend is found in Figures 5.1.2-2, 5.1.2-3, and 5.1.2-4 which show the effect of varying the concentration on flashover exposure. Since concentrations expected in an accidental fiber release at any distance away from the release point are less than those used for testing, the exposure to flashover test results are conservative. Current predictions for an actual release indicate that less than 100 fibers per cubic meter may be expected, so flashover exposures determined during this test program are conservative.

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 represents the average over all the series test time. This average is determined by:

$$\text{Concentration} = \frac{\Sigma \text{ exposure}}{\Sigma \text{ test time}}$$

The longer fiber length tests indicated a possible effect of concentration, but no pronounced effect of concentration 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 breakdown phenomenon even though concentrations are high. Although variations in flashover exposure with concentration were observed, no evidence of air breakdown was noted.

5.1.3 The Effect of Voltage Stress on Flashover Exposure

Test results indicated that as voltage stress increases flashover exposure decreases. This observation was verified using several approaches. One approach uses the observation, as will be discussed in Section 5.1.4, that deposition at flashover is constant. A number of tests were performed on an insulator using varied voltages. As shown in Figure 5.1.3-1, increasing voltage stress caused greater deposition per exposure so the insulator flashed over at lower exposures.

Another comparison was made by determining deposition for energized and unenergized insulators placed in the chamber simultaneously to receive identical exposures. As Table 5.1.3-1 shows, deposition is 2 to 3 times greater on the energized insulator for the lightly stressed station posts and 5 to 6 times greater on the energized insulator for the more highly stressed distribution posts.

Figure 5.1.2-1 Concentration Versus Deposition Rate for Insulators Tested at Rated Voltage

Figure 5.1.2-2 Exposure to Flashover for 7.5 kV Pin, Combined 4.3 and 9 mm Fibers, Concentration.

Figure 5.1.2-3 Exposure to Flashover for 15 kV Distribution Post, Combined 4.3 and 9 mm Fibers, Concentration.

Figure 5.1.2-4 Exposure to Flashover for Vertical 7.5 kV Station Post, 10.8 mm Fibers, Concentration.

Figure 5.1.3-1 Voltage Stress Versus Deposition Rate

Table 5.1.3-1

Mean Total Depositions for Energized and Unenergized Insulation at Different Stress and Concentration

	Energized Fibers/cm ² $\mu (\sigma)$	Unenergized Fibers/cm ² $\mu (\sigma)$
7.5 kV Station Post at 4.3 kV and 1400 f/m ³	5.5 (2.7)	2.9 (0.8)
7.5 kV Station Post at 4.3 kV and 3067 f/m ³	4.8 (2.4)	2.4 (0.3)
7.5 kV Station Post at 4.3 kV and 6167 f/m ³	6.3 (2.2)	3.1 (0.9)
7.5 kV Station Post at 4.3 kV and 7000 f/m ³	7.3 (2.8)	3.3 (1.3)
15 kV Station Post at 6.45 kV and 1550 f/m ³	6.5 (1.9)	1.0 (0.6)
15 kV Station Post at 8.66 kV and 1550 f/m ³	5.1 (0.9)	1.1 (0.4)
15 kV Station Post at 10.8 kV and 1550 f/m ³	4.8 (0.5)	1.7 (0.7)
15 kV Station Post at 12.9 kV and 1550 f/m ³	2.4	0.5
15 kV Station Post at 17.32 kV and 1550 f/m ³	3.4 (.6)	0.4 (0.2)
15 kV Station Post at 8.6 kV and 4300 f/m ³	3.7 (1.0)	1.1 (0.2)
15 kV Station Post at 8.6 kV and 7000 f/m ³	4.8 (.9)	0.9 (0.2)
20 cm glass disc at 3.5 kV and 690 f/m ³ *	3.7 (.75)	1.5 (.45)
40 cm glass disc at 7.5 kV and 960 f/m ³ *	1.2 (.14)	1.3 (.50)
20 cm glass disc at 3.5 kV and 780 f/m ³ **	6.3	3.6
20 cm glass disc at 7.0 kV and 1280 f/m ³ **	5.3	3.9

* Glass Disc placed on metal sheet.

** Glass disc suspended in air.

A direct correlation between measured deposition and measured sticky tape count could not be found because of the wide variations in sticky tape counts. Similarly, a correlation could not be made between sticky tape count and time of exposure to cause flashover. Because of the above stated reasons, and the fact that sticky tape counts fluctuated vastly, it would be incorrect to draw specific trends or conclusions from the sticky tape data provided in Figure 5.1.4-2.

A third method of verifying the trend relating voltage stress to flashover exposure utilized data compiled from the airborne contamination tests. Calculations were performed to determine if exposure to flashover could be correlated to voltage stress on insulator surfaces. The data for all insulators tested with 9 mm fibers is plotted in Figures 5.1.3-2 and 5.1.3-3. These figures show the effect of voltage stress on 9 mm fiber flashover exposure. Voltage stress is shown as a function of strike distance in Figure 5.1.3-2 and as a function of creepage distance in Figure 5.1.3-3. As the graphs show, there is a slight trend for flashover exposure to increase as the insulator stress decreases. When only data for similarly stressed post type insulators were plotted no trend could be observed because of the narrow range in voltage stress of the data. The data for distribution post insulators is plotted in Figure 5.1.3-4. All insulators fail with 9 mm fiber contamination at exposures between 10^6 and 10^8 fiber-sec/m³.

5.1.4 Deposition at Flashover

Tests were performed on a simple cylindrical porcelain configuration to determine the effect of insulator height on flashover exposure. An 80 cm high cylinder of porcelain was used; Figure 5.1.4-1 shows the setup. Tests were performed by placing a band of metal tape at the top and bottom of the smooth cylindrical portion and tying one of the tape electrodes to ground and the other to the energized conductor. Tests were performed with the bottom metal band identically placed for every test, and moving the top band to obtain desired separation. All tests were performed using a voltage stress of 394 V/cm. Figure 5.4.1-2 summarizes test results. Depositions at flashover were similar for various voltages and strike distances as long as the voltage stress was the same.

Further data indicating the consistency of deposition data at flashover and the inconsistency of sticky tape data is found in Table 5.1.4-1. This table presents the mean and standard deviation of the deposition and sticky tape counts in fibers per square centimeter at flashover. There is much more consistency in the deposition measurements than the sticky tape measurements. This is indicated by the much smaller ratios of standard deviation to mean. Flashover exposures have varied so much for some test series that standard deviations are close to the same magnitude as the mean. Flashover exposure as usually defined is essentially deposition on a horizontal surface outside of field effect regions. The fact that flashover depositions are fairly consistent shows that flashover is a function of deposition on insulator surfaces.

Deposition is a function, not only of exposure, but also of concentration, electric field strength, and insulator geometry. Sections 5.1.2 and 5.1.3 indicate that deposition per exposure increases with increasing fiber concentration and electric field strength. Insulator geometry also effects deposition per exposure as indicated by experiments with various glass discs as discussed in Section 5.3.7.

Figure 5.1.3-2 9 mm Airborne Exposure Vs. Test Voltage/Dry Arc Distance

Figure 5.1.3-3 9 mm Airborne Flashover Exposure Vs. Test Voltage/Creepage

Figure 5.1.3-4 Exposure to Flashover (9 mm Fibers) for Post Geometry Insulation
Plotted Versus the Test Voltage/Creep and Test Voltage/Strike Ratios

* I IS INSULATOR STRIKE DISTANCE.

Figure 5.1.4-1 Porcelain Cylinder Test Arrangement

Figure 5.1.4-2 Porcelain Cylinder Test Results

TABLE 5.1.4-1
Correlation of Deposition and Sticky Tape Data at Flashover

Insulator Description	Test kV line-to-ground	Concentration f/m ³	Deposition f/cm ²			Sticky Tape f/cm ²		
			μ	σ	σ/μ	μ	σ	σ/μ
15 kV Dist. Post	6.5 kV	1550	5.2			5.7		
15 kV Dist. Post	8.7 kV	1550	5.6	.86	.15	6.8	1.3	.19
15 kV Dist. Post	10.8 kV	1550	4.8	.46	.10	5.6	3.8	.68
15 kV Dist. Post	12.9 kV	1550	3.3			3.9		
15 kV Dist. Post	17.3 kV	1550	3.3	.51	.15	1.5	1.1	.73
15 kV Dist. Post	8.7 kV	4300	3.8	.92	.24	6.4	2.2	.34
15 kV Dist. Post	8.7 kV	7000	4.8	.93	.19	5.1	1.3	.25
2.5 cm Cylinder	1.0 kV	2670	7.8	1.46	.19	10.9	4.97	.46
7.6 cm Cylinder	3.0 kV	2240	5.4	1.28	.24	18.8	4.52	.24
12.7 cm Cylinder	5.0 kV	2430	4.5	.69	.15	9.1	2.55	.28
17.8 cm Cylinder	7.0 kV	1500	4.6	.64	.14	6.3	5.72	.91
22.9 cm Cylinder	9.0 kV	3470	6.5	1.21	.19	7.3	5.01	.69
27.9 cm Cylinder	11.0 kV	7800	4.4	1.4	.31	12.8	11.1	.87
43.1 cm Cylinder	17.0 kV	7600	4.6	.53	.11	21.7	9.6	.44
53.3 cm Cylinder	21.0 kV	2900	5.1	.67	.13	34.8	15.7	.45
63.5 cm Cylinder	25.0 kV	4400	4.8	.61	.13	27.8	8.5	.30
78.7 cm Cylinder	31.0 kV	2800	4.4	1.0	.23	17.0	3.9	.23
8.9 cm Glass Disc	3.5 kV	700	3.47	.81	.23	1.5	.45	.30
19.1 cm Glass Disc	7.5 kV	970	3.03	.37	.12	1.3	.50	.40

TABLE 5.1.4-2
Typical Line Post Insulation

a Usual Line Voltage (kV)	b Leakage Distance (cm)	*c Voltage Stress (a x .64) x 1000/b [V/cm]	d BIL (kV)	e Dry Arc (cm)
25	35.6	(449.4)	130	16.5
35	55.9	(400.7)	180	24.1
45	73.7	(390.8)	210	31.2
55	101.6	(346.5)	255	36.8
66	114.3	(369.6)	290	43.9
88	134.6	(418.4)	330	49.0
138	208.3	(424.0)	525	92.2
138	254.0	(347.7)	610	107.4
138	279.4	(316.1)	695	122.7
138	330.2	(267.5)	780	137.9
230	350.5	(420.0)	860	149.9
230	391.2	(376.3)	945	165.1
230	424.2	(347.0)	1025	180.3
230	424.2	(347.0)	1025	162.6
230	538.5	(273.4)	1105	185.4
230	584.2	(252.0)	1185	200.7
345	609.6	(362.2)	1610	261.6

* Typically the maximum line to ground voltage across an insulator is the usual line to line voltage x .64.

TABLE 5.1.4-3
Typical Station Post Insulation

a Usual Line Voltage (kV)	b Leakage Distance (cm)	*c Voltage Stress (a x .64)/b x 1000 [V/cm]	d BIL (kV)	e Dry Arc (cm)
7.5	26.7	(179.8)	95	15.2
15	39.4	(243.7)	110	18.5
23	61.0	(241.3)	150	26.7
34.5	94.0	(254.9)	200	36.8
46	109.2	(269.6)	250	43.2
69	182.9	(241.4)	350	66.0
115	251.5	(292.6)	550	99.1
138	294.6	(299.8)	650	114.3
161	335.3	(307.3)	750	129.5
230	419.1	(351.2)	900	162.6
230	502.9	(292.7)	1050	193.0
345	586.7	(376.3)	1300	228.6
345	670.6	(329.3)	1470	259.1
500	774.7	(413.1)	1550	274.3
500	914.4	(350.0)	1800	325.1
765	1097.3	(446.2)	2050	388.6
765	1280.2	(382.4)	2425	454.7

TABLE 5.1.4-4
Typical Suspension Insulator Insulation

a Usual Line Voltage (kV)	b No. Of Insulators	c (.64 x a)/b (Average kV/Insulator)	d Voltage Stress (c x 1000)/29.2 [V/cm]	c BIL (kV)
69	min 4	11.0	378.1	430
	usual 6	7.4	252.1	600
	max 8	5.5	189.0	760
115	min 6	12.3	420.1	600
	usual 8	9.2	315.1	760
	max 10	7.4	252.1	930
138	min 8	11.0	378.1	760
	usual 10	8.8	302.5	930
	max 12	7.4	252.1	1100
161	min 9	11.5	306.8	850
	usual 11	9.4	251.1	1020
	max 14	7.4	197.3	1270
230	min 12	12.3	420.1	1100
	usual 16	9.2	315.1	1440
	max 20	7.4	252.1	1780
287.5	min 16	11.5	393.8	1440
	usual 18	10.2	350.1	1610
	max 22	8.4	286.4	1950
345	min 15	14.7	504.1	1360
	usual 18	12.3	420.1	1610
	max 23	9.6	328.8	2030
500	min 23	13.9	476.5	2030
	usual 24	13.3	456.6	2110
	max 30	10.7	365.3	2590

For Each Suspension Insulator — Leakage 29.2 cm, Dry Arc 19.7 cm.

TABLE 5.1.4-5
Typical Apparatus Bushing Insulation

a Usual Line Voltage (kV)	b Leakage Distance (cm)	c Voltage Stress (a x .64) x 1000/b [V/cm]	d BIL (kV)
Outdoor Apparatus Bushings (IEEE No. 21)			
15	27.9	344.1	110
23	43.2	340.7	150
34.5	67.3	328.1	200
46	88.9	331.2	250
69	123.2	358.4	350
92	167.6	351.1	450
115	200.7	366.7	550
138	233.7	377.9	650
161	289.6	355.8	750
180	342.9	336.0	825
196	342.9	365.8	900
230	431.8	340.9	1050
287.5	520.7	353.4	1300
Condenser Bushings			
15	43.2	222.2	110
23	67.3	218.7	150
34.5	88.9	248.4	200
Standard Apparatus Bushing			
92	167.6	351.3	450
115	200.7	366.7	550
138	233.7	377.9	650
161	289.6	355.8	750
180	342.9	336.0	825
196	342.9	365.8	900

TABLE 5.1.4-6
Station Arrester Insulation

a Usual Line Voltage (kV)	b Arrester Rating (kV)	*c Leakage Distance (cm)	d (a x .64)x 1000/c [V/cm]	e BIL (kV)
5	4.5	32.8	97.6	75
8.7	9	48.3	115.3	95
15	15	55.9	171.7	110
23	21	98.3	149.7	150
34.5	30	122.4	180.4	200
34.5	36	150.1	147.1	200
34.5	39	170.2	129.7	250
46	45	181.1	162.2	250
46	48	196.6	149.7	250
69	60	170.9	258.4	350
69	72	202.9	217.6	350
115	108	303.3	242.7	550
138	120	372.1	237.4	550
138	132	409.4	215.7	650
161	144	442.5	232.9	650
230	180	570.0	258.2	825
230	192	609.6	241.5	900
345	240	744.2	296.7	1050
345	264	818.9	269.6	1300
345	288	884.9	249.5	1300
345	312	948.9	232.7	1300
500	396	1263.9	253.2	1980
500	420	1319.5	242.5	2100
500	468	1464.3	218.5	2350

5.1.5 Recommended Mean Flashover Exposures

Most tests were performed with a fiber length greater than 2 mm because of the extremely long test times required for flashover with 2 mm fibers. Most tests were also performed on distribution insulation because distribution voltages are more easily obtained and shorter test times required. Because only limited tests could be performed simulating actual release conditions, steps were taken to determine reasonable mean flashover exposures to use in determining vulnerability of external insulation.

Mean flashover exposure for station insulation is much higher than for distribution insulation. Since mean flashover exposure for station posts is an order of magnitude above that of distribution posts with 9 mm long fibers, the 2 mm exposure to flashover is also an order of magnitude greater. Therefore, 10^8 fiber-sec/m³ is a conservative number to use for flashover exposure of station insulation.

Several approaches were taken to determine the flashover exposure of transmission class insulation. As was discussed in Section 5.1.3, increasing voltage stress causes a decrease in flashover voltage. To extrapolate test data to higher (transmission class) voltages, tables were prepared showing typical stresses on various insulators. Tables 5.1.4-2 through 5.1.4-6 show that stresses are similar for various voltage classes. The most critical insulators are line posts and apparatus bushings. Flashover exposures at distribution voltages for the most critical insulation with 9 mm fibers are about 10^6 fiber-sec/m³, so similar exposures are expected at transmission class voltages.

Tests were performed on a simple cylindrical porcelain configuration to determine the effect of insulator height on flashover exposure. A simple geometry was used in an attempt to provide a basis for comparison between different voltage classes. By using identical voltage stress and diameter and varying only the insulator height and voltage the effect of insulator skirts could be eliminated so there were fewer differences between different insulator heights. An 80 cm high cylinder of porcelain was used; Figure 5.1.4-1 shows the setup. Tests were performed by placing a band of metal tape at the top and bottom of the smooth cylindrical portion and tying the tape electrodes to ground and the energized conductors. Tests were performed with the bottom metal band identically placed for every test, and moving the top band to obtain desired electrode separation. All tests were performed using a voltage stress of 394 V/cm.

Figure 5.1.4-2 summarizes test results. Results were evaluated on the basis of varied strike distances using identical voltage stress. Deposition and sticky tape counts were measured in fibers/cm². Depositions represent the average density of fiber on a 1.9 cm wide piece of cellophane tape the length of the strike distance. Sticky tape counts represent fiber deposition on a horizontal surface removed as much as possible from the influence of the electric field. The sticky tape data for abscissas 8.3 and 10.3 of Figure 5.1.4-2 is probably low because of the influence of the electric fields.

Test results indicate that average flashover deposition remains constant for various strike distances provided voltage stress remains constant. Because the exposure which results in flashover deposition varies greatly, any trends relating flashover exposure to insulator strike distance and voltage class are not clear. However, the data indicate that if voltage stress remains constant flashover exposure does not decrease. Indeed, flashover exposure appears to increase as strike distance increases. These data combined with similar voltage

stresses at transmission voltages indicate that flashover exposure results from distribution voltage tests may be reasonably applied to transmission class insulation.

For suspension insulators, the most typical transmission insulation, flashover exposures were much higher than for typical distribution insulation. In summation, flashover exposures of 10^8 fiber-sec/m³, similar to distribution voltages, are adequate for and applicable to transmission voltages.

Flashover exposures for station, distribution and transmission insulation are listed in Table 5.1.5-1. Exposures are presented in two columns, the first column is measured test data and the second represents minimal, suggested exposures for computational purposes. The mean exposure for distribution class insulation is given for 2 mm length fiber contamination. This is the fiber length that would most probably be released in an aircraft crash. The mean exposure for station and transmission insulation are extrapolated values. Derivations were made from flashover exposures of 9 mm fiber contamination. The extrapolated 2 mm exposure was obtained utilizing the graph in Figure 5.1.1-1.

TABLE 5.1.5-1
Mean Flashover Exposure for 2 mm Fibers

		<u>Measured Flashover Exposure</u>	<u>Projected 2 mm Exposure</u>
Distribution Class Insulation	2 mm data (9 mm data)	1×10^8 (4×10^6)	1×10^8
Transmission Class Insulation	9 mm data	1.3×10^7	$> 1 \times 10^8$
Station Class Insulation	9 mm data	3×10^7	$> 1 \times 10^8$

Figure 5.1.5-2 puts the short-fiber flashover exposure in perspective. The insulator shown was energized at rated voltage and contaminated to an exposure over 10^8 fiber-sec/m³ with 2 mm fibers. The insulator shown had not yet flashed over when the photograph was taken. It is highly unlikely that contamination of this degree would occur in a natural environment where wind and other weather conditions exist.

Figure 5.1.5-2 7.5 kV Pin Insulator After Contamination but Prior to Flashover

5.1.6 Re-Energization of Insulators After Flashover

During several tests insulator re-energization was attempted. In every case insulators were able to be re-energized. It was observed that upon re-energization fibers would stand up on end and some would fly off the insulator. Exposure levels after continued contamination sometimes proved to equal the level that caused the primary flashover. This characteristic indicates that after an insulator flashover causes a line outage, reclosing relays can operate and the line will re-energize without difficulty.

5.2 Detailed Test Results

In this section the results of tests to determine flashover exposure are presented. Fiber length distributions and mean flashover exposures are presented and the probability distributions, including confidence intervals, are discussed.

5.2.1 Fiber Length Distribution

Fiber length distributions were determined from sticky tape length measurements. The fiber length distribution for 2 mm fibers is shown in Figure 5.2.1-1. The 2 mm fiber length distribution is approximately Normal. The 4.3-mm and 9-mm length distributions are positive skew extreme value as shown in Figures 5.2.1-2 and 5.2.1-3. The 10.8 mm fiber length distribution is negative skew Extreme Value and is shown in Figure 5.2.1-4.

Testing was performed with the insulator being simultaneously exposed to multiple fiber lengths to test applicability of the concept of superposition. Multiple fiber lengths were cut by setting the cutter wheel to produce two different lengths simultaneously. The fiber length distribution for 4.3 and 9 mm combined fiber lengths is shown on Extreme Value paper in Figure 5.2.1-5. The distribution is positive skew Extreme Value. The fiber length distribution for 9 and 10.8 mm combined fiber lengths is shown on Extreme Value paper in Figure 5.2.1-6 and is negatively skewed.

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. Table 5.2.1-1 summarizes mean, mode, and standard deviation for each fiber length used during the test program.

TABLE 5.2.1-1
Fiber Length

<u>Nominal Length</u>	<u>μ(Mean)mm</u>	<u>u(Mode)mm</u>	<u>σ(Standard Deviation)mm</u>
2	2.06	2.06	.67
4.3	4.3	4.3	.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

Figure 5.2.1-1 The 2 mm Fiber Length Distribution Plotted on Normal Probability Paper

Figure 5.2.1-2 4.3 mm Fiber Length Distribution

Figure 5.2.1-3 9 mm Fiber Length Distribution

Figure 5.2.1-4 The Fiber Length Spectrum for 10.8 mm Fibers Plotted on Extreme Value Paper

-06-

Figure 5.2.1-5 The Fiber Length Spectrum for 4.3 and 9 mm Fibers Combined,
Plotted on Extreme Value Paper

Figure 5.2.1-6 The Fiber Length Spectrum for 9 and 10.8 mm Fibers Combined,
 Plotted on Extreme Value Paper

The flashover exposure 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 5.2.1-7 shows 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 study.

5.2.2 Flashover Exposure Results

The data on exposure to flashover are presented in Appendix A. For uniformity and to facilitate comparisons, all data are presented on Weibull paper because the data usually fit a Weibull distribution best. The Weibull is typically used for strengths of materials and insulation strength. The Weibull equation is given by:

$$F(x) = 1 - \{ \exp [- (x - \alpha_0) / \alpha] \}^\beta$$

This gives the cumulative distribution function. The Weibull distribution fits negative or positive skewed data. β indicates the skew of the data. Most of the exposures to flashover curves are not Extreme Value nor Normal distributions, but fit the Weibull shape. However, the data on pin insulators tested with 9 mm fibers is described by a Normal distribution as well as it is by a Weibull distribution. α_0 is the theoretical minimum exposure at which flashover is possible. It is a parameter necessary in making a Weibull curve fit. For most of these data an $\alpha_0 = 0$ was selected because zero is certainly a lower limit to flashover exposure. Also, most of the data fit best when $\alpha_0 = 0$. β is a measure of slope and is determined graphically. α is a measure of the displacement of the data along the abscissa on Weibull paper and is also determined graphically.

To determine how well the Weibull curve fits the data, the values of α , β , and α_0 were used to determine a mean and standard deviation for the tests shown in Figures A-4, A-7 and A-11. This is illustrated in Table 5.2.2-1. Since the graphical mean and standard deviation of the Weibull curve agree with the mean and standard deviation of the raw data, the Weibull curve is a good curve fit.

Table 5.2.2-2 summarizes data for all AC tests. 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.

The technique used in placing confidence intervals about mean flashover exposure of an experiment is described below. Because the data distribution is non-Gaussian, the technique utilized in finding 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.

Figure 5.2.1-7 Comparison of 2 mm Fiber Length Distribution with the Expected Length Distribution of an Actual Release.

Table 5.2.2-1

Comparison of the Mean and Standard Deviation of the Weibull Distribution with that of the Data.

Figure Number	Weibull Parameters			Calculated from α_0, α, β		Calculated from Data		Fiber Length	Insulator	
	α_0	α	β	μ	σ	μ	σ		Voltage	Type
A-4	1×10^7	4×10^7	.92	5.15×10^7	4.53×10^7	5.11×10^7	4.14×10^7	4.3 mm	7.5kV	pin
A-7	1×10^6	3.3×10^6	2.55	3.93×10^6	1.23×10^6	3.90×10^6	1.20×10^6	9 mm	7.5 kV	pin
A-11	1.2×10^6	1×10^6	1.4	2.11×10^6	$.66 \times 10^6$	2.08×10^6	$.59 \times 10^6$	9 mm	15kV	pin

Table 5.2.2-2

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	7	2.0	8.4×10^7	3.4×10^7		4.9×10^7	28%	2.3×10^4
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
69 kV Line Post	3	2.0	2.8×10^8	1.2×10^8		1.6×10^8	54%	2.1×10^4
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	$> 4.0 \times 10^8$					$1.5 \times 10^4^{**}$
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	21%	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
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

Table 5.2.2-2

Compilation of Results of Tests on Insulator Specimens (cont.)

Insulator	n	Fiber Length	Exposure		Confidence Interval	Minimum Exposure	P < min*	Concentration Mean
		mm	μ	σ	About Mean 95%			
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
69 kV Line Post	9	9.0	5.3×10^6	4.4×10^6		1.9×10^6	23%	2.1×10^3
7.5 kV Suspension Vert (tested 3 at a time)	13	9.0	7.9×10^6	4.8×10^6		2.7×10^6	16%	2.9×10^3
10 kV Suspension Ins.	4	9.0	4.9×10^7	1.6×10^7		2.7×10^7	44%	3.0×10^3
7.5 kV Pin	17	9.0+10.8	5.0×10^5	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	$2.35 \times 10^5 < \mu < 4.7 \times 10^6$	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.

*** All insulators were tested at listed voltage $\div \sqrt{3}$ (rated l-g voltage) except the 10 kV suspension insulators which were tested 3 at a time at 30 kV.

> Indicates flashover exposure is greater than value stated. The insulator did not flashover.

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:

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

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 5.2.2-3 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.

Confidence intervals and limits provide boundaries for mean exposures and probability of flashover below a given exposure. It has been observed, however, that extraneous variables may affect exposure to flashover. For example, experimental results for a 7.5 kV pin insulator contaminated with 9 mm fibers initially yielded a mean exposure of 3.9×10^6 and a standard deviation of 1.2×10^6 . An additional 16 tests were performed yielding a mean exposure of 6.9×10^6 and a standard deviation of 4.4×10^6 . The resulting overall mean exposure and standard deviation are 4.8×10^6 and 2.9×10^6 respectively.

We speculate that possible causes of the variation are changes in relative humidity and fiber distribution in the chamber. During the first series of tests the relative humidity was low, approximately 40%. During the second series the relative humidity was nearly 80%. A higher humidity may cause fiber filaments to stick together resulting in a different dispersal in the chamber.

Table 5.2.2-4 summarizes the DC test data. The table reveals two main characteristics of DC data. First, the positive polarity flashover exposures are lower than for negative polarity. A similar result was noticed by other researchers during work on SF₆ particle initiated breakdown.⁽¹⁾ They observed a positive polarity flashover voltage lower than negative polarity. Second, the table shows that the effect of fiber length on flashover exposure is more pronounced for AC than DC. For AC voltages, short fibers have much higher exposures to flashover than long fibers. For DC voltages, short fiber exposure to flashover is nearly the same as the long fiber exposure. AC and DC short fiber exposure to flashover are similar. Researchers with SF₆ also observed that longer particles gave a much lower breakdown voltage for AC and only slightly lower for DC.⁽¹⁾ The lower flashover exposures for long fibers in AC tests are probably a result of AC forces causing fibers to swirl

(1) A. H. Cookson, P. C. Bolin, H. C. Doepken, Jr., R. E. Wooten, C. M. Cooke and J. G. Trump, "Recent Research in the United States on the Effect of Particle Contamination Reducing the Breakdown Voltage in Compressed Gas-Insulated Systems", CIGRE Paper for Paris Meeting (1976).

Table 5.2.2-3

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 5.2.2-4
DC Test Results

<u>Polarity</u>	<u>Fiber Length (mm)</u>	<u>Insulator Specimen</u>	<u>Test Voltage</u>	<u>Sticky Tape Count (fibers/cm²)</u>	<u>Time (minutes)</u>	<u>Exposure (fibers-sec/m³)</u>	<u>Concentration (fibers/m³)</u>
+	9	10-kV susp.*	12.8 kV	> 63.1	60	2.1 x 10 ⁷	5800
+	9	"	12.8 kV	> 76.4	244	2.5 x 10 ⁷	1700
-	9	"	12.8 kV	> 43.4	200	1.4 x 10 ⁷	1200
+	2	"	12.8 kV	619	170	2.1 x 10 ⁸	20200
-	2	"	12.8 kV	>342	172	1.1 x 10 ⁸	11000
+	9	15-kV dist **	12.2 kV	44	164	1.5 x 10 ⁷	1490
+	9	"	12.2 kV	65	115	2.2 x 10 ⁷	3140
+	2	"	12.2 kV	200	58	6.7 x 10 ⁷	19200
+	2	"	12.2 kV	149	38	5.0 x 10 ⁷	21800
+	2	"	12.2 kV	263	97	8.8 x 10 ⁷	15100
+	2	"	12.2 kV	460	57	1.5 x 10 ⁸	44800
+	2	"	12.2 kV	392	101	1.3 x 10 ⁸	21600
+	2	"	12.2 kV	362	65	1.2 x 10 ⁸	30900
-	2	"	10.8 kV	> 493	178	1.6 x 10 ⁸	15400
-	2	"	12.2 kV	> 498	195	1.7 x 10 ⁸	14200

> Means No Flashover occurred

* 10 kV is rated line to ground voltage

** 15 kV is rated line to line voltage

around, staying in high field regions near insulator surfaces for longer periods of time, resulting in greater probability of fiber landing on the insulator and causing flashover. Fibers acted on by DC forces move quickly in and out again instead of swirling about in the region of the conductor.

5.3 Special Tests

A number of tests were performed to verify observed trends, determine qualitatively the flashover mechanism, and show fiber movement patterns.

5.3.1 High Speed Photographs

During the course of the study, questions developed concerning the characteristics of the flashover. Video recordings of arc initiation were inconclusive as to flashover path. In an attempt to determine if the flashover followed the surface of the insulator, high speed photographs were taken. Figure 5.3.1-1 shows an AC arc initiated on a 15 kV distribution post. To assure the insulator flashed over while the film was running, the insulator was heavily contaminated with carbon fibers and energized above rated voltage. Frame (a) is the first frame in which an arc appears. As can be seen from the sequence, the arc tends to follow along the left surface, swing toward the front of the insulator, under the second skirt, and back down along the left surface of the third skirt.

Particularly interesting is the observation of the second half cycle. Photographs show that AC arcs extinguish as the flashover current cycles through zero, then current begins flowing through the ionized arc path again as the cycle continues. Frames (a) through (f) show the arc during the first half cycle and frames (g) through (h) show the second half cycle.

Figure 5.3.1-2 shows a DC flashover sequence. The seven frame sequence represents 7/2000 of a second. High speed motion pictures show the differences between AC and DC fault current magnitudes. Supply measurements show that DC arcs occurred quickly and with high energy. Photographs also show very fast, high energy arcs. DC arcs only last five frames and wash out the picture, indicating very hot, high energy arcs. Comparatively, AC arcs last much longer and are lower energy.

High speed photographs confirm previously observed burnt fiber tracks which indicated that flashover occurred along insulator surfaces. Some arcs were observed to skip sections of the surface, but reasons are inconclusive because of high voltage stresses, large exposures, and high fiber concentrations at the time of flashover. Observations of burnt fiber tracks made during normal airborne contamination flashover give a better indication of the arc path. The tracks show that AC flashover is usually along the insulator surface, while DC flashover frequently skips sections of insulator surface. Fiber tracks and visual observations show that flashover does not normally follow the shortest creepage path. Since flashover follows the path of least resistance, the arc path often does not follow the shortest path, particularly on upper surfaces where fibers pile up on the upper insulator surfaces because of gravity. Instead, it goes through piled-up fibers. On occasion, the arc path may go half-way around the insulator.

(a)

(b)

(c)

(d)

(h)

(i)

(j)

(k)

Figure 5.3.1-1 AC Flashover Each Frame = 1/500 Second.

(e)

(f)

(g)

(l)

(m)

(n)

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Figure 5.3.1-2 DC Flashover Each Frame = 1/2000 Second

5.3.2 Fiber Movement Observations

Experiments were made with light positioning to obtain the best view of the fibers during a test. The transparent chamber made changing light positioning simple. Three 150-watt spot-lights mounted in a triangle arrangement over the test object were found to allow good visual observation of the airborne fiber movements.

Since the fibers are conductive, they align with electric field lines. Fibers were observed to align radially around the high voltage conductor. At higher voltages the alignment extended further since high field gradients extended further. Fibers also move in the direction of flux lines. If field lines are perpendicular to insulator surfaces, fibers move along the field lines and land on the surface. If field lines parallel the surface, fibers move along them until they are off the insulator surface. Differences were observed between AC and DC voltages and their effect on fiber movement. AC forces cause fibers to swirl around, staying in high field regions near insulator surfaces for longer periods of time. Fibers acted on by DC forces move quickly in and out again instead of swirling about in the region of the conductor.

5.3.3 Fall Velocity Measurements

After good lighting was obtained and fibers were visible, approximate fiber velocity measurements were made by timing the fibers as they fell known distances. The observed velocities of 3 cm/sec confirmed Rome Air Development Center (RADC) observations for Celanese GY-70 fiber.

A second 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 fiber 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

S₁ = Fiber count on sticky tape uncovered at chopper shutdown

S₂ = 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:

$$E = \frac{S_2}{V} = \bar{C} \times T$$

Solving for V:

$$V = \frac{S_2}{\bar{C} \times T}$$

but if it is assumed that average concentration is approximately the concentration at shut-down:

$$\bar{C} \cong C = \frac{S_1}{\text{vol}}$$

So,

$$V \cong \frac{S_2 \times \text{vol}}{S_1 \times T}$$

This method provides an alternate way of determining fiber fall velocity. Several tests were made and the average velocity for 2 mm tests was determined to be 2.5 cm/sec.

5.3.4 Corona Measurements and Observations

Corona measurements were performed to determine if there was a correlation between corona inception voltages and corona levels, and fiber exposures and concentrations. A diagram of the corona instrumentation used during the tests is shown in Figure 5.3.4-1.

The main components of the corona measurement system are a Biddle balanced partial discharge detector used in a single ended input configuration, and a 2000 pF coupling capacitor. As applied for the carbon fiber tests, corona current pulses which appear on the high voltage conductor are coupled to the corona detector by means of the coupling capacitor and low voltage arm of the bridge, R_b . The input matching transformer maintains a time constant of approximately three microseconds so that separate corona pulses are not superimposed. The amplifier/detector circuit produces a meter reading in picocoulombs which is equal to the highest current pulse occurring over several cycles of power frequency. An oscilloscope output is available for displaying the corona pulses superimposed on the power frequency voltage. The oscilloscope display provides additional information about the source and number of pulses occurring during each cycle of power frequency. A calibration source is available from the corona bridge for injection of a known level of charge pulses across the test object.

The corona instrumentation was used during airborne contamination of a 7.5 kV pin insulator. The instrumentation was turned on shortly after contamination was initiated and it indicated about 150 picocoulombs of corona. The corona levels gradually increased with exposure up to 2000 picocoulombs when the test was terminated. Observation of the corona pulses on the oscilloscope indicated that a large number of individual pulses were occurring on both the positive and negative half cycles of each power frequency cycle.

Corona measurements were made at the time arcs occurred across the insulator surface on a 25 kV pincap insulator furnished by the Ballistics Research Laboratory (BRL). There was no observable change in corona level prior to flashover. Flashover caused a single corona spike against the background corona level.

Figure 5.3.4-1 Corona Measurement System

After one contamination test, the chamber was cleaned as well as possible with a vacuum cleaner, and corona measurements were made to determine if corona levels returned to the original near zero levels. The measured corona levels were approximately 100 picocolumbs. The residual corona was probably due to fibers which escaped the cleaning process.

Visual observations were made of corona on insulators contaminated with 9 mm fibers. To allow visual observation, the test room was sealed so no light could enter. After 4 or 5 minutes of adjustment, the naked eye could detect the small amount of light emitted from fibers in corona. This was photographed with a Polaroid Land camera using black and white ASA 3000 film. When the shutter was held open 10 minutes corona around the top part of the insulator was recorded, but corona on other insulator surfaces was not. The eye detected these low light levels much better than the Polaroid camera. Better photographs were obtained using ASA 400 film in a 35 mm camera.

Observations indicated that the fibers actually in contact with the conductor and some of those in contact with the insulator were in corona. Some fibers would settle and move about on the conductor with one end touching and the other directed radially. Initially, only a few fibers resting on the insulator surface near the high voltage conductor were observed in corona, but as contamination continued more particles in this area evidenced corona activity. Since no corona was observed on fibers not actually touching either the conductor or the insulator surface, nothing could be learned about the effect of corona activity on movement of airborne fibers. However, fibers are held in contact with conductor or insulator surfaces, sometimes with only the end of the fiber touching the insulator or conductor surface.

5.3.5 Capacitance Measurements

Capacitance measurements were performed to determine differences between contaminated and clean insulators. Two precautionary steps were taken to increase the accuracy of measurement. The test leads to the impedance bridge were run through two, short, cables (individually-shielded) which were also twisted together and shielded. The shields were grounded to the impedance bridge ground. Also, the insulator to be measured was shielded from the effects of stray capacitance by a grounded metal sheet. The insulator was placed on, but insulated from, the grounded metal sheet as shown in Figure 5.3.5-1. These precautions minimized the effects of stray capacitance.

Tests were performed by contaminating 7.5-kV station posts with a given amount of fiber. Capacitance of the contaminated insulator was compared to that of a clean insulator. Insulator capacitances are very small, 5 to 6 pF for 7.5-kV station posts and less than 2 pF for 34.5-kV station posts.

Airborne exposure of 8×10^6 fiber-sec/m³ with 9 mm fiber was found to decrease clean insulator capacitance by about 10%. However, capacitance of slurry-coated insulators was greater than for clean insulators. After slurry-coated insulators were flashed over, the capacitance was found to be similar to clean insulator capacitance.

Insulator capacitances are very small and difficult to measure. Measured capacitances varied widely between insulators even though contamination was the same. Capacitance

Figure 5.3.5-1 Capacitance Measurements

changes need to be consistent and correlatable to degree of contamination to be useable in determining deposition. Results obtained were too inconsistent to permit measurement of deposition by capacitance.

5.3.6 Wind Test and Exposure to Flashover

To determine the effect of wind on flashover exposure, a wind was simulated by drawing air past a 7.5-kV pin insulator using a 10 cm (4-inch) diameter tube on a suction blower. Figure 5.3.6-2 is a diagram of the test setup and Figure 5.3.6-1 is a photograph of the actual test. Air velocity past the insulator was measured with a hot wire anemometer and averaged about 2.1 m/sec(7 ft/sec).

A mean flashover exposure of 2.4×10^8 fiber-sec/m³ obtained from three tests with 2 mm fiber was very near the mean of 2.8×10^8 fiber-sec/m³ obtained from four tests on the same insulator without wind. Few tests were performed because each test took several hours. Exposure for both test series was measured using sticky tapes located away from the influence of the air flow. Some differences were noted in deposition patterns on insulator surfaces. Wind deposited more fibers where the air flow impacted the insulator surface. Greatest fiber concentrations occurred on upper insulator surfaces where fibers fell on the insulator in calm air. From this limited experiment no effect of wind velocity on exposure to flashover was observed.

Figure 5.3.6-1 Air Suction Across Insulator for Wind Test.

5.3.7 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. Figure 5.3.7-1 is a picture of the wet

Figure 5.3.6-1 Wind Test on 7.5 kV Pin Insulator

testing equipment and test set-up. 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. 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 under surfaces which are normally shielded for vertically falling fibers. 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. 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 greater than that of one wet from pouring rain because water running over the insulator's surface would clean the insulator.

Figure 5.3.7-1 Vaporizer and 7.5-kV Pin Cap Positioned for Wet Tests.

5.3.8 Effects of Weathering

Insulators installed outdoors on a utility distribution system have received a certain amount of weathering. These weathered insulators, although ideal for testing, are difficult to obtain in the numbers and variety necessary to this test program. Tests on clean, new insulators are necessary to establish that the behavior of new insulators 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 5.3.8-1. It can be seen that there is no statistical differences between the mean exposure to fail at 95% 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.

Figure 5.3.8-1 Exposure to Flashover for Weathered Versus Non-Weathered 7.5 kV Pin Insulators with 9 mm Fibers

5.3.9 Slurry Tests

The purpose of the slurry development and the efforts to discover trends relating voltage to flashover exposure was to permit the extrapolation of distribution class insulation data to transmission class insulation. The objective was to avoid the necessity of higher voltage airborne contamination testing. 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 readily in a slurry. For this reason, 2 mm fibers were used for testing.
2. Resistance measurements do not work in determining the density of fibers 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 qualifications of a slurry were investigated. First, a correlation between slurry flashover and airborne contamination flashover must exist. The discovery of the correlation was approached either by fixing the fiber content in the slurry and correlating flashover voltage to airborne contamination flashover exposure or by correlating the fiber content in the slurry to airborne contamination flashover exposure. It was found that varying the voltage was more useful and practical because it was more easily performed.

A second qualification requires 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. The similar weight method was finally decided upon.

Several slurry mediums were tested, among the agents were water, acetone, fotoflo, soap and water, Cab-O-Sil and water, and Metylan and water. A desirable slurry medium should allow for even dispersal of fiber in the slurry and permit an even deposition on an insulator when applied. Different slurries were evaluated for uniform fiber deposition and flashover near rated l-g voltage using a 7.5-kV pin cap insulator. Cab-O-Sil with water and Metylan with water were found to be best suited for further study and development.

Cab-O-Sil and water held fibers in suspension whereas Metylan and water suspended fibers only after being stirred. Fibers settled to the bottom in the Metylan solution after a few hours. The Metylan slurry bound fibers to the insulator so they would not move when the insulator was handled. The Cab-O-Sil slurry held fibers loosely on the surface and would crumble and flake when handled. When testing Cab-O-Sil slurry contaminated insulators, it was noticed that fibers would re-align themselves and sometimes fly off the insulator surface when energized. Because the Cab-O-Sil slurry yielded more desirable flashover characteristics, more extensive testing was done with this slurry than with the Metylan slurry.

Several tests were performed holding fiber concentration constant and varying Cab-O-Sil concentration. Results of these tests are shown in Figure 5.3.9-1. Increases in Cab-O-Sil concentration beyond 55 gm/l result in marginal decrease in mean flashover voltage. Figure 5.3.9-2 shows that when Cab-O-Sil concentration was held constant and fiber concentration varied, after 3 gm/l increases in fiber concentration resulted in minimal decreases in

Figure 5.3.9-1
Effects of Cab-O-Sil Concentration on Flashover Voltage
on a 7.5 kV Pin Cap Insulator with 4 gm/l of Fiber

Figure 5.3.9-2. Effects of Fiber Concentration on Flashover Voltage on a 7.5 kV Pin Cap Insulator With 62 gm/l of Cab-O-Sil

Table 5.3.9-1

Cab-O-Sil Slurry Test Results

<u>Insulator</u>	<u>Slurry Components</u> <u>Dip</u>		<u>Slurry Components</u> <u>Flow</u>		<u>Mean Flashover Voltage kV</u>
	<u>Cab-O-Sil gm/l</u>	<u>Fiber gm/l</u>	<u>Cab-O-Sil gm/l</u>	<u>Fiber gm/l</u>	
7.5 kV Pin	45	3.5			6.6
7.5 kV Pin	50	4			6.5
7.5 kV Pin	55	4.5			5.8
15 kV Dist. Post	55	4.5			9.8
34.5 kV Dist. Post	55	4.5			20.7
7.5 kV Stat. Post	55	4.5			11.6
15 kV Pin	55	4.5			10.6
10 kV Susp.	55	4.5			10.8
7.5 kV Susp.	55	4.5			4.7
7.5 kV Pin	55	4.5*			4.3
7.5 kV Susp.	55	4.5			5.6
10 kV Susp.	55	4.5			12.9
7.5 kV Stat. Post	55	4.5			9.0
15 kV Dist. Post	55	4.5			9.1
34.5 kV Dist. Post	55	4.5			19.2
15 kV XFMR Bush	55	4.5			12.1
7.5 kV Pin	62	2			9.4
7.5 kV Pin	62	3			5.7
7.5 kV Pin	62	4			5.3
7.5 kV Pin	55	1	50	2	12.9
7.5 kV Stat. Post	55	1	50	2	20.3
15 kV Dist. Post	55	1	50	2	16.0
7.5 kV Pin	55	1	50	4.5	11.6
7.5 kV Stat. Post	55	1	50	4.5	12.6
15 kV Dist. Post	55	1	50	4.5	10.8
7.5 kV Pin	55	1**	50	4.5	11.2
15 kV Pin	55	1	50	4.5	32.2
7.5 kV Stat. Post	55	1	50	4.5	28.4
34.5 kV Dist. Post	55	1	50	4.5	95.1
15 kV Dist. Post	55	1	50	4.5	25.0
7.5 kV Susp.	55	1	50	4.5	17.6
10 kV Susp.	55	1	50	4.5	29.2
15 kV XFMR Bush	55	1	50	4.5	27.9
69 kV Line Post	55	1	50	4.5	114.0
34.5 kV Dist. Post	55	1	50	4.5	56.1

* Slurry dried and was sprayed with Metylan solution and dried again.

** Fiber length 9 mm, all other fiber lengths are 2 mm.

Table 5.3.9-2

Metylan Slurry Test Results

<u>Insulator</u>	<u>Slurry Components Dip</u>		<u>Slurry Components Flow</u>		<u>Mean Flashover Voltage kV</u>
	<u>Metylan gm/l</u>	<u>Fiber gm/l</u>	<u>Metylan gm/l</u>	<u>Fiber gm/l</u>	
7.5 kV Pin	9	2			6.4
7.5 kV Pin	10	2.5			9.8
7.5 kV Stat. Post	10	2.5			19.4
15 kV Dist. Post	10	2.5			14.8
34.5 kV Dist. Post	10	2.5			25 +
7.5 kV Stat. Post	11	1.9			8.2
15 kV Dist. Post	11	1.9			7.2
7.5 kV Pin	11	3.7			5.6
7.5 kV Stat. Post	11	3.7			12.0
15 kV Pin Cap	11	3.7			11.0
15 kV Dist. Post	11	3.7			10.1
34.5 kV Dist. Post	11	3.7			20.2
7.5 kV Pin	12	3			6.0
7.5 kV Pin	11	1.5	11	2	11.0
7.5 kV Stat. Post	11	1.5	11	2	19.7
15 kV Dist. Post	11	1.5	11	2	21.0
7.5 kV Pin	11	1.5	11	3	6.4
7.5 kV Stat. Post	11	1.5	11	3	13.9
15 kV Dist. Post	11	1.5	11	3	9.0
7.5 kV Pin	11	1.5*	11	3	4.4
7.5 kV Stat. Post	11	1.5	11	3	9.2
15 kV Dist. Post	11	1.5	11	3	10.5
15 kV Pin	11	1.5	11	3	10.7
34.5 kV Dist. Post	11	1.5	11	3	24 +

* Fiber length 9 mm, all other fiber lengths are 2 mm.

Figure 5.3.9-3
Cab-O-Sil Slurry – 55 gm Cab-O-Sil/l, 4.5 gm fiber/l

Figure 5.3.9-4
Cab-O-Sil Slurry – 55 gm Cab-O-Sil/l, 4.5 gm fiber/l
Metylan Spray over Dried Slurry

Figure 5.3.9-5

Cab-O-Sil Slurry — 55 gm Cab-O-Sil/l, 1 gm fiber/l underside
50 gm Cab-O-Sil/l, 2 gm fiber/l top side

Figure 5.3.9-6

Cab-O-Sil Slurry — 55 gm Cab-O-Sil/l, 1 gm fiber/l under side
50 gm Cab-O-Sil/l, 4 gm fiber/l top side

Figure 5.3.9-7
 Cab-O-Sil Slurry — 55 gm Cab-O-Sil/l, 1 gm 9 mm fiber/l under side
 50 gm Cab-O-Sil/l, 4 gm fiber/l top side

Figure 5.3.9-8
 Metylan Slurry — 11 gm Metylan/l, 1.5 gm fiber/l underside
 11 gm Metylan/l, 2 gm fiber/l top side

Figure 5.3.9-9

Metylan Slurry — 11 gm Metylan/l, 1.5 gm fiber/l under side
11 gm Metylan/l, 3 gm fiber/l top side

Figure 5.3.9-10

Metylan Slurry — 11 gm Metylan/l, 1.5 gm 9mm fiber/l underside
11 gm Metylan/l, 3 gm fiber/l top side

Figure 5.3.9-11
Metylan Slurry – 10 gm Metylan/l, 2.5 gm fiber/l

Figure 5.3.9-12
Metylan Slurry – 11 gm Metylan/l, 3.7 gm fiber/l

flashover voltage. When fiber concentration became too great, clumping and uneven deposition occurred on the insulator. Similar relationships existed between fiber concentration, Metylan concentration, and flashover voltage in the Metylan slurry. Tests were performed when the slurry was wet and dry. Flashover voltage was lower for dry insulators. Also, results tended to be more reproducible for dry insulators.

Testing indicated that flashover voltage was highly correlated with creepage. Tables 5.3.9-1 and 5.3.9-2 show results of slurry contamination testing. Figures 5.3.9-3 through 5.3.9-12 show the correlation between flashover voltage and creepage.

Because evenly coated insulators yielded a high correlation between mean flashover and creepage, an uneven slurry coating was applied to the insulators. This was accomplished by dipping the insulator in a slurry with a lower fiber concentration, allowing it to dry, and then coating the upper surfaces of the insulator with a slurry having heavier fiber concentration. Results from uneven slurry testing tended to have high correlations between flashover voltage and creepage as with the even coating. Figure 5.3.9-6 shows an exception.

At this point in time, a correlation between slurry flashover voltage and flashover for airborne exposures cannot be found. Even though significant airborne testing has been performed correlations cannot be found because of the variability of the data caused by randomness of fiber deposition, variation in testing concentration, unknown relationship between concentration and flashover exposure, and effects of voltage gradients about insulators with different geometries.

Because of these factors, correlations to flashover exposure are low and further work to create a slurry representative of airborne exposure is discouraged.

5.3.10 Clean Area

A clean area was noticed on the table near the conductor during distribution-class high-voltage tests. Experiments were performed to determine the distance the clean area extended from the conductor at various voltages. Figure 5.3.10-1 shows the test setup. Measured results are only accurate to within ± 5 cm due to the random nature of the deposition. Clean radius was measured two ways: first, by observing where heavy deposition began on the aluminum sheet; and second, by using clear cellophane tape to lift and preserve fibers from the metal sheet.

Test results are included in Figure 5.3.10-2. A line is a good curve fit as the high correlation indicates. A clean radius on the metal plate should not be taken to mean that the insulator in that region is clean. Instead, it means that fibers continue moving in that region so they do not settle on the metal plate. Fibers move until they fall down on the metal plate in a low stress region away from the conductor. Because fibers move more rigorously in the region of the insulator and remain near it longer, more fibers deposit on the insulator than if it were unenergized.

5.3.11 Glass Disc Experiment

Glass disc experiments were performed using AC voltages to determine the effect of geometry on flashover exposure. Glass discs were arranged to simulate suspension insulators. Three discs were suspended in series, as shown in Figure 5.3.11-1, with the top grounded

Figure 5.3.10-1 Clean Radius Test

Figure 5.3.10-2 Line to Ground Test Voltage Vs. Clean Radius

Figure 5.3.11-1 Glass Disc Experiment to Simulate Suspension Insulators

Figure 5.3.11-3 Glass Disc Experiment to Measure Deposition Effects

Figure 5.3.11-2 Equipotential Lines Given in Percent of Test Voltage for Glass Disc Geometries

and the bottom energized. Tests were performed on various diameter discs at fixed voltage per creepage. The discs were energized at the same voltage per creep distance, as was the 10-kV suspension insulator (342 V/cm). Tests were performed using 9-mm fibers. Figure 5.3.11-2 is a field plot showing the equipotential lines around glass disc insulators. Since fibers move perpendicular to these lines, they tend to be shielded from the under-surfaces. Small 10.2 cm diameter glass discs flashed over at reasonable exposures (1.8×10^6 fiber-sec/m³) but larger, 30.5 cm, discs required very large exposures to flashover ($> 1.8 \times 10^7$). This occurred because the highly stressed under-surfaces were protected from falling fibers. This test suggests a reason why flashover exposures were so high for the 10-kV suspension insulator, but were much lower for the 7.5-kV suspension insulator.

Tests were also performed with glass discs to determine deposition effects. Glass discs were constructed with a 2 cm diameter center electrode and a metal tape electrode about the circumference as shown in Figure 5.3.11-3. Discs were placed on a grounded metal sheet and tests were performed at 394 V/cm on 20 and 40 cm diameter discs. Both discs flashed over at exposures around 4.5×10^5 fiber-sec/m³. Depositions were much greater on the stressed horizontal surface than on a nearby horizontal sticky tape indicating the attractive effect on the fields as discussed in Sections 5.1.3 and 5.3.2. There was little fiber alignment on insulator surfaces because field lines were perpendicular to surfaces.

Another experiment was performed with the same glass disc but with the disc suspended in air away from the ground plane so stress would parallel the surface. In this case fibers did align along the surface, but flashover exposure was greater than before and fiber deposition per exposure was smaller (although flashover deposition was similar). This may be a result of fibers moving along flux lines away from the insulator surface. If field lines are perpendicular to insulator surfaces, fibers move along the field lines and land on the surface. If field lines parallel the surface, fibers move along them until they are off the insulator surface.

5.3.12 Deposition Tests

Deposition was measured to study fiber alignment and the effect of voltage stress on deposition density, especially along the flashover path. Deposition was correlated to test voltage and concentration. Three insulators were placed in the test chamber as shown in Figure 5.3.12-1. Two unenergized insulators were placed at the same relative height as the energized insulator. A sticky tape was placed between the unenergized insulators in order to measure exposure.

Fiber was injected into the contamination chamber for a recorded period of time at a fixed rate. Deposition was determined after contamination. Cellophane tape was placed along the surface of energized and unenergized insulators and marked, dividing the insulator into upper and under surfaces. Figure 5.3.12-2 shows how the surfaces were divided into sections. The tape was removed and placed on a sheet of paper to retain the fiber positions for counting. The deposition fiber counts were recorded for analysis.

The method used for finding fiber distribution between sections is described below. After the fibers are lifted from the insulator, they are counted and the number recorded for each section. The average number of fibers is represented in fibers/cm². The fiber deposition for

Figure 5.3.12-1 Insulator Locations in Chamber for Deposition Testing

Figure 5.3.12-2 Insulator Sectional Divisions for Fiber Deposition Measurements

each section was divided by the sticky tape count for that test. This normalized the depositions to allow comparisons between tests. Similarly located sectional depositions were averaged for like tests to eliminate some variability from the data. The percentage of fiber deposition for each section relative to the total fiber deposition was found. The data from sectional depositions for the insulators tested are shown in Figure 5.3.12-3.

The 7.5-kV station post was tested at rated line-to-ground voltage (4.3 kV) and at concentrations from 1550 f/m^3 to 7000 f/m^3 . The time of contamination was modified for each concentration in order to keep exposures approximately the same. Comparisons of fiber deposition between upper and under surfaces are shown in Figure 5.3.12-4.

Depositions were also determined for the 15-kV distribution post. This insulator was tested at rated line-to-ground voltage (8.6 kV). Concentration was varied as it was with the 7.5-kV station post. The insulator was also stressed at different voltages while being contaminated. Test voltages for these experiments ranged from 6.45 kV to 17.32 kV. After contamination, depositions were determined for these insulators and recorded as they were for the 7.5-kV station post. Comparisons of depositions between upper and under insulator surfaces are shown in Figure 5.3.12-5.

The 7.5-kV station post and the 15-kV distribution post have geometric similarities and only slight creepage differences. Figure 5.3.12-6 shows the relative shapes of the insulators.

In order to make comparisons between different tests, results were normalized by dividing the deposition fiber count by the insulators' total exposure (sticky tape count). There was little correlation between sectional depositions. Attempts were made, as described earlier, to find relationships between upper and under surface depositions but no significant correlations were found.

A larger percentage of fibers are deposited on the upper surfaces of the 7.5-kV station post than the 15-kV distribution post. This difference may result from differences in insulator design. 53% of the station posts' creepage is undershed creepage, whereas, 44% of the distribution posts' creepage is undershed. Since many fibers land on the top surfaces due to gravity, the relative percentage of fiber deposition per unit area is greater on the upper surfaces of the 7.5-kV station post. Another reason for the difference between upper and lower surface fiber distribution is the stress placed on the insulator. The higher stress placed across the 15-kV distribution post seemed to attract more fibers which then had a larger effect on the fiber deposition relative to gravity. Therefore, the part of the total fiber deposition on underneath insulator surfaces became greater.

Another conclusion that can be drawn from the comparison of total deposition deals with the 15-kV distribution post. Figure 5.3.12-7 shows that as the voltage gradient increased the deposition per exposure increased. Tests made to justify this result were run for approximately 30 minutes or until flashover at which time depositions were taken. At 6.45-kV the mean exposure for the test series was $2.9 \times 10^6 \text{ fiber-sec/m}^3$, whereas, at 17.32-kV the mean exposure was $5.1 \times 10^5 \text{ fiber-sec/m}^3$. The mean time of exposure for these tests was 31 minutes for the former and 5 minutes for the latter. The shorter time interval for the latter is due to flashovers resulting from higher voltage stress.

Figure 5.3.12-3 Insulator Sectional Depositions

Figure 5.3.12-4 Percent of Fiber Deposition Between Upper and Underside of Insulator Sheds on 7.5 kV Station Post at Different Concentrations

Figure 5.3.12-5 Percent of Fiber Deposition Between Upper and Underside of Insulator Sheds on 15 kV Distribution Post at Different Voltages and Concentrations

15 kV Distribution Post

7.5 kV Station Post

Figure 5.3.12-6 Insulation Used for Deposition Testing

Figure 5.3.12-7 Voltage Stress Versus Deposition Rate

Depositions were also removed and counted on the unenergized insulators. Data acquired from these depositions were compared to the energized depositions. The relative deposition percentages between upper and lower surfaces are shown in Figures 5.3.12-8 and 5.3.12-9. By comparing these figures to Figures 5.3.12-4 and 5.3.12-5 an increase in percentage fiber deposition on the under surface is observed. Table 5.3.12-1 gives empirical comparison of mean total fiber deposition for energized insulators and unenergized insulators. At least twice as many fibers are deposited on the energized 7.5-kV station post as on the unenergized post, and at least three times as many fibers are deposited on the unenergized 15-kV distribution post as on the same unenergized post. From these results we find that the energized insulator attracts more fibers than the unenergized and the percentage increase in fiber attraction is greater on the under surface area of the energized insulator.

Deposition test data was also compiled by concentration. As concentration increases the deposition per exposure increases. Low correlation of the data to a line shows that the exact nature of the correlation is not clear, Figure 5.3.12-10 shows available data. The effect of concentration on deposition was smaller for the 7.5-kV station post which had less voltage stress across it. These data indicate that exposure to flashover data mentioned in the previous quarterly reports may be conservative because concentrations much higher than would be expected in an accidental release were used.

Deposition results are inconclusive for determining trends for EHV insulation. Although average deposition per area is similar at flashover for all tests, deposition patterns on different insulators were dissimilar. Deposition does not correlate to exposure, however, deposition at flashover is more consistent than exposure. This indicates that flashover is a function of deposition which is a function of exposure as well as other factors, as will be discussed in Section 5.3.13:

5.3.13 Cylinder Deposition Tests

Tests were performed on a simple cylindrical porcelain configuration to determine the effect of insulator height on flashover exposure. A simple geometry was used in an attempt to provide a basis for comparison between different voltage classes. By using identical voltage stress and diameter, and varying only the insulator height and voltage the effect of insulator skirts could be eliminated. Therefore, there were fewer differences between different height insulators. An 80 cm high cylinder of porcelain was used, Figure 5.1.4-1 shows the setup. Tests were performed by placing a band of metal tape at the top and bottom of the smooth cylindrical portion and tying the tape electrodes to ground and the energized conductors. Tests were performed with the bottom metal band (electrode) identically placed for every test, and moving the top band (electrode) to obtain the desired separation. All tests were performed using a voltage stress of 394 V/cm.

Figure 5.1.4-2 summarizes test results. The surface of the cylinder coincides with the direction of the electric field lines, so fibers aligned along creepage paths rather than being randomly oriented as for other insulator geometries.

Results were evaluated on the basis of varied strike distances using identical voltage stress. Deposition and sticky tape counts were measured in fibers/cm². Depositions represent the

Figure 5.3.12-8 Percent of Fiber Deposition Between Upper and Underside of Insulator Sheds on 7.5 kV Station Post at Different Concentrations (Unenergized)

Figure 5.3.12-9 Percent of Fiber Deposition Between Upper and Underside of Insulator Sheds on 15 kV Distribution Post of Different Voltages and Concentrations (Unenergized)

Table 5.3.12-1

Mean Total Depositions for Energized and Unenergized Insulation at Different Stress and Concentration

	Energized Fibers/cm ² $\mu (\sigma)$	Unenergized Fibers/cm ² $\mu (\sigma)$
7.5 kV Station Post at 4.3 kV and 1400 f/m ³	5.5 (2.7)	2.9 (0.8)
7.5 kV Station Post at 4.3 kV and 3067 f/m ³	4.8 (2.4)	2.4 (0.3)
7.5 kV Station Post at 4.3 kV and 6167 f/m ³	6.3 (2.2)	3.1 (0.9)
7.5 kV Station Post at 4.3 kV and 7000 f/m ³	7.3 (2.8)	3.3 (1.3)
15 kV Station Post at 6.45 kV and 1550 f/m ³	6.5 (1.9)	1.0 (0.6)
15 kV Station Post at 8.66 kV and 1550 f/m ³	5.1 (0.9)	1.1 (0.4)
15 kV Station Post at 10.8 kV and 1550 f/m ³	4.8 (0.5)	1.7 (0.7)
15 kV Station Post at 12.9 kV and 1550 f/m ³	2.4	0.5
15 kV Station Post at 17.32 kV and 1550 f/m ³	3.4 (.6)	0.4 (0.2)
15 kV Station Post at 8.6 kV and 4300 f/m ³	3.7 (1.0)	1.1 (0.2)
15 kV Station Post at 8.6 kV and 7000 f/m ³	4.8 (.9)	0.9 (0.2)
20 cm glass disc at 3.5 kV and 690 f/m ³ *	3.7 (.75)	1.5 (.45)
40 cm glass disc at 7.5 kV and 960 f/m ³ *	1.2 (.14)	1.3 (.50)
20 cm glass disc at 3.5 kV and 780 f/m ³ **	6.3	3.6
20 cm glass disc at 7.0 kV and 1280 f/m ³ **	5.3	3.9

* Glass Disc placed on metal sheet.

** Glass disc suspended in air.

Figure 5.3.12-10 Concentration Versus Deposition Rate for Insulators Tested at Rated Voltage

average density of fiber on a 1.9 cm wide piece of cellophane tape the length of the strike distance. Sticky tape counts represent fiber deposition on a horizontal surface removed as much as possible from the influence of the electric field. The sticky tape data for abscissas 8.3 and 10.3 of Figure 5.1.4-2 are probably low because of the influence of the electric fields.

Field plots of the cylinder geometry were made to show the effect of varying insulator heights on electric field distributions. Plots show that the electric field is more graded for shorter insulators. Figure 5.3.13-1 shows the equipotential lines for two insulator heights.

Test results indicate that average flashover deposition remains constant for various strike distances provided average voltage stress remains constant. Because the exposure which results in flashover deposition varies greatly, any trends relating flashover exposure to insulator strike distance and voltage class are not clear. However, the data indicate that if voltage stress remains constant flashover exposure does not decrease, indeed flashover exposure appears to increase as strike distance increases. These data indicate that flashover exposure results from distribution voltage tests may be conservatively applied to transmission class insulation.

Figure 5.3.13-1 Equipotential Lines Given in Percent for Different Height Cylinders

6. RECOMMENDATIONS

Although the results of this study show that carbon fiber contamination, under the release scenario postulated by NASA, is not a significant hazard to electrical insulation, there are several interesting topics worthy of further investigation. This section presents some areas of investigation which would enhance the understanding of the carbon fiber contamination phenomenon.

6.1 Concentration and Exposure Investigation

Test data and observations indicate that a relationship exists between concentration and the exposure required to cause flashovers. Observations indicate that tests performed at low concentrations tended to have higher flashover exposure than tests performed with larger concentrations. It would be interesting to find a relationship between flashover exposure and concentration for different insulator shapes.

6.2 Voltage Stress Investigation

While performing tests on various insulators it was noted that insulators with lower creep distances (higher voltage stress) tended to flashover at a lower exposure. Testing could provide a better understanding of the relationship between voltage stress and carbon fiber contamination.

6.3 Deposition Investigation

Flashover deposition was more consistent than flashover exposure. Deposition testing was performed mostly on the cylinder and glass disc. It would be interesting to evaluate in more detail the relationship between deposition and flashover exposure on various insulators including station, distribution and transmission insulation.

6.4 Weather Conditions Investigation

Weather tests performed in this project included both simulated wind and fog testing. The fog tests were performed with vaporizers spewing steam mist to the underside of the insulator. This action created an updraft which carried fibers toward the under side of the insulator. This is not the usual motion for carbon fiber in natural conditions. Further tests with conditions more similar to natural conditions would result in more accurate data.

The wind tests involved the suction of air past the insulator. The air flow was limited to a small circular area. More accurate data could be obtained with a larger area air flow. Testing of this sort would clarify the behavior of insulation in an environment exposed to the weather.

APPENDIX A

Test Results

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APPENDIX A

TABLE A-1

Insulator Description and Manufacture

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 Sales Company	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

Figure A-1 Exposure to Flashover for Wet 7.5 kV Pin Insulator, 2 mm Fibers.

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Figure A-2 Exposure to Flashover for Wet 15 kV Distribution Post, 2 mm Fibers.

Figure A-3 Exposure to Flashover for 34.5 kV Distribution Post, 2 mm Fibers.

Figure A-4 Exposure to Flashover for 7.5 kV Pin Insulators With 4.3 mm Fibers

Figure A-5 Exposure to Flashover for 7.5 kV Pin, 4.3 and 9 mm Fibers.

Figure A-6

Exposure to Flashover for 15 kV Distribution Post, 4.3 and 9 mm Fibers.

Figure A-7 Exposure to Flashover for 7.5 kV Pin Insulators With 9 mm Fibers

Figure A-8 Exposure to Flashover for 7.5 kV Suspension Insulator, 9 mm Fibers.

Figure A-9 Exposure to Flashover for Vertical 7.5 kV Station Post, 9 mm Fibers.

Figure A-10 Exposure to Flashover for Horizontal 7.5 kV Station Post, 9 mm Fibers.

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Figure A-11 Exposure to Flashover for 15 kV Pin Cap Insulators With 9 mm Fibers

Figure A-12 Exposure to Flashover for Vertical 34.5 kV Station Post, 9 mm Fibers.

Figure A-13 Exposure to Flashover for Vertical 5 kV Transformer Bushing, 9 mm Fibers.

Figure A-14 Exposure to Flashover for Horizontal 5 kV Transformer Bushing, 9 mm Fibers.

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Figure A-15 Exposure to Flashover for 7.5 kV Pin, 9 mm Fibers.

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Figure A-16 Exposure to Flashover for Vertical 15 kV Transformer Bushing, 9 mm Fibers.

Figure A-17 Exposure to Flashover for Vertical 15 kV Distribution Post, 9 mm Fibers.

Figure A-18 Exposure to Flashover for Horizontal 15 kV Distribution Post, 9 mm Fibers.

Figure A-19: Exposure to Flashover for Vertical 34.5 kV Distribution Post, 9 mm Fibers.

Figure A-20 Exposure to Flashover for 7.5 kV Pin, 9 and 10.8 mm Fibers.

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Figure A-21 Exposure to Flashover for 34.5 kV Distribution Post, 9 and 10.8 mm Fibers.

Figure A-22 Exposure to Flashover for Vertical 7.5 kV Station Post, 10.8 mm Fibers.

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Figure A-23 Exposure to Flashover for 7.5 kV Pin, 10.8 mm Fibers.

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Figure A-24 Exposure to Flashover for Vertical 15 kV Distribution Post, 10.8 mm Fibers.

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Figure A-25 Exposure to Flashover for 34.5 kV Distribution Post, 10.8 mm Fibers.

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