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Nuclear Power Plant Electrical Cable Damageability Experiments

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NUCLEAR POWER PLANT ELECTRICAL CABLE DAMAGEABILITY EXPERIMENTS

L. L. Lukens

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Sandia National Laboratories
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for the
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ABSTRACT

Under the direction of the Nuclear Regulatory Commission, Sandia National Laboratories has been conducting confirmatory research in fire protection for nuclear power plants. As a part of this research, a program was developed to determine the damageability of electrical cable insulation to thermal radiation in a loaded cable tray. The critical flux or threshold level at which cable damage occurs in the form of electrical failure (short from conductor to tray) and nonpiloted ignition was determined for two types of electrical cable, one an IEEE-383 qualified cable and the other an unqualified cable. The critical flux for electrical failure was determined to be about 18 kW/m^2 for the IEEE-383 qualified cable and about 8 kW/m^2 for the unqualified cable. The critical flux for nonpiloted ignition was determined to be about 28 kW/m^2 for the IEEE-383 qualified cable and about 22 kW/m^2 for the unqualified cable.

A program was also developed to determine the damageability of electrical cable insulation to constant temperature, thermal exposure. Experimental results indicate that exposure of the IEEE-383 qualified cable to temperatures greater than 250°C (480°F) for periods of 60 minutes can cause discoloration, blistering, smoking, loss of flexibility, and failure to pass a voltage withstand test as described in the report. Experimental results indicate that exposure of the unqualified cable to temperatures greater than 130°C (265°F) for periods of 60 minutes can cause electrical failure in the form of shorts between conductors. In addition, the thermal forming temperature of the unqualified cable jacket material was determined to be between 170°C (340°F) and 200°C (390°F).

These results apply only to the two particular types of electrical cables examined and described in this report, and would need to be evaluated for any other type of electrical cable. Thermal aging and radiation exposure efforts were not included in the investigation.

ACKNOWLEDGMENTS

The tests described in this report were ably performed by L. D. Lambert and S. L. Ogan in conjunction with J. T. Nakas and other Radiant Heat Facility personnel.

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EXECUTIVE SUMMARY

Under the direction of the Nuclear Regulatory Commission, Sandia National Laboratories has been conducting confirmatory research in fire protection for nuclear power plants. On October 27, 1980, the Nuclear Regulatory Commission (NRC) approved Appendix R to 10 CFR Part 50,[1] which is a new rule of fire protection. Section III.G.2.b, "Fire Protection of Safe Shutdown Capability," in Appendix R to 10 CFR Part 50 allows the separation of cables/equipment by a horizontal distance required to protect redundant divisions exposed to a single transient exposure fire. The 20-ft separation requirement represents the collective judgment of the NRC staff and its fire protection consultants following onsite observation at operating plants.

The Office of Nuclear Reactor Regulation requested that a full-scale fire experiment program[2] be developed and implemented to determine the adequacy of the 20-ft separation criterion. As a part of this program, experiments were performed at Sandia National Laboratories to provide information on the damageability of electrical cables exposed to a fire environment.

Two basic types of experiments were performed on electrical cables, one in which cables were exposed to thermal radiation at constant flux levels and one in which cables were exposed to a constant temperature environment with heating primarily by convection. These experiments were designed to determine the radiant heat flux levels and temperatures above which the physical and electrical properties of electrical cables begin to degrade. The experiments were performed on two particular types of <u>unaged</u> electrical cables, an IEEE-383[2] qualified cable and a PE/PVC unqualified cable.

This information is important for determination of an acceptance criterion for electrical cables exposed to a fire environment. The analytical determination of electrical cable damage for any given configuration of cable trays and fuel packages also requires this type of information.

The critical fluxes or threshold levels, at which electrical cable damage occurs in the form of electrical failure and nonpiloted ignition, have been determined for the two types of cable examined. The critical flux for electrical failure (short from conductor to tray) was

determined to be about 8 kW/m^2 for unqualified cable and 18 kW/m^2 for IEEE-383 qualified cable. These results, along with the approximate time to electrical failure as a function of heat flux, were determined. The critical flux for nonpiloted ignition was determined to be about 22 kW/m^2 for unqualified cable and 28 kW/m^2 for IEEE-383 qualified cable. These results, along with the approximate time to nonpiloted ignition as a function of heat flux, were determined.

The critical flux values for cable damage in the forms of electrical failure and nonpiloted ignition determined for the two cable types tested are based on a very limited amount of test data. This limited amount of data and the stochastic nature of the processes being investigated introduce a margin of uncertainty in addition to that of instrumentation accuracy to the results presented in this report.The possible sources of error mentioned for these results should be considered in their acceptability for any particular application.

Experimental results indicate that exposure of the particular IEEE-383 qualified cable examined in this study to temperatures greater than 250°C (480°F) for periods of 60 minutes can cause discoloration, blistering, smoking, loss of flexibility, and failure to pass a voltage withstand test as described in this report. Experimental results indicate that exposure of the particular unqualified cable examined in this study to temperatures greater than 130°C (265°F) for periods of 60 minutes can cause electrical failure in the form of shorts between conductors. In addition, the thermal forming temperature of the unqualified cable jacket material was determined to be between 170°C (340°F) and 200°C (390°F).

The properties of electrical cables and threshold values for electrical cable damage identified in this report should not be interpreted as an acceptance criterion for electrical cables exposed to a fire environment. They are applicable to two particular types of <u>unaged</u> electrical cable identified specifically in this report and would need to be evaluated for any other type of electrical cable.

INTRODUCTION

On October 27, 1980, the Nuclear Regulatory Commission (NRC) approved Appendix R to 10 CFR Part 50,[1] which is a new rule of fire protection. Section III.G.2.b, "Fire Protection of Safe Shutdown Capability," in Appendix R to 10 CFR Part 50 allows the separation of cables/equipment by a horizontal distance of 20 ft (6.1 m). The purpose of the 20-ft separation requirement is to provide a uniform safe distance required to protect redundant safety divisions exposed to a single transient exposure fire. More specifically, the 20-ft separation of equipment must be capable of limiting fire damage so that one train of systems necessary to achieve and maintain hot shutdown conditions from either the control room or emergency control station(s) is free of fire damage. The 20-ft separation requirement represents the collective judgment of the NRC staff and its fire protection consultants following onsite observation at operating plants.

The Office of Nuclear Reactor Regulation requested that a full-scale fire experiment program[2] be developed and implemented to determine the adequacy of the 20-ft separation criterion. As a part of this program, experiments were performed at Sandia National Laboratories to provide information on the damageability of electrical cables exposed to a fire environment.

Two basic types of experiments were performed on electrical cables, one in which cables were exposed to thermal radiation at constant flux levels and one in which cables were exposed to a constant temperature environment with heating primarily by convection. These experiments were designed to determine the radiant heat flux levels and temperatures above which the physical and electrical properties of electrical cables begin to degrade. The experiments were performed on two particular types of unaged* electrical cables, an IEEE-383[2] qualified cable and a PE/PVC unqualified cable.

This information is important for determination of an acceptance criterion for electrical cables exposed to a fire environment. The analytical determination of electrical cable damage for any given configuration of cable trays and fuel packages also requires this type of information.

*Thermal aging and radiation exposure effects were not included in the investigation

The two types of experiments performed will be described separately in this report. The experiments in which electrical cables were exposed to thermal radiation will be referred to as "Radiant Heat" experiments and the experiments in which electrical cables were exposed to a constant temperature environment will be referred to as "Oven" experiments.

RADIANT HEAT EXPERIMENTS

Apparatus

A device was constructed at the Radiant Heat Facility[3] to expose a cable tray, 2.44 cm (8 ft) long by 30 cm (1 ft) wide to thermal radiation at power levels of up to 60 kW/m^2. The cable tray was mounted under a semi-circular cylindrical steel shroud which was heated by three banks of quartz infrared lamps. The ends of the shroud were open to permit ventilation between the cable tray and the shroud and to permit observation of the exposed cable during the testing. The entire device was located in a building which has a large bay door on the north side and four ceiling fans for forced ventilation during the testing. The orientation of the device was with the long axis of the cable tray running north/south and the north end of the device just inside the bay door. A photograph of the experimental apparatus showing the radiant heat device with the cable tray covered by an insulated shutter and the quartz lamps energized is shown in Figure 1.

The cable tray was filled with five bundles, eight loops each, (approximately 244 m, (800 ft)) and three 2.44-m (8-ft) lengths of cable for thermocouple placement. Two types of unaged cable were used in these experiments. One type was IEEE-383 qualified 3 conductor, no. 12 AWG tinned copper, 30 mil Exane II insulation, silicon glass tape, 65 mil Exane II jacket, 600 volt. The other type was non-IEEE-383 qualified 3 conductor, no. 12 AWG copper, 20/10 PE/PVC insulation, 45 mil PVC jacket, 600 volt.

The cable was energized during experiments with 320 VDC and 5 amps AC. Cable currents, both AC and DC, were recorded during testing and current from cable to cable tray was recorded to detect electrical failure (a short from cable to cable tray) during experiments.

Cable temperatures during experiments were measured by a set of 10 chromel/alumel thermocouples positioned in the cable tray as shown in Figure 2. Thermocouples 102, 105, 106 and 107 were located inside the cable jacket, and thermocouples 100, 101, 103, 104, 108 and 109 were located around the cable.

Heat flux from the steel shroud to the cables was measured with six water-cooled calorimeters positioned in the cable tray as shown in Figure 2. Three of the calorimeters, numbers HF7, HF8, and HF9, were monitored by the Radiant

Heat Facility personnel for control purposes and the other three, numbers 113, 114, and 115, were monitored by Systems Safety Technology Division personnel.

The experimental data, including electrical information, temperatures, and heat fluxes, are recorded on magnetic tape with a complete scan taken every 30 seconds. The accuracy of the thermocouple is approximately $\pm$ 3°C (5.5°F) and the accuracy of the calorimeters is approximately $\pm$ 5 percent. The weight measurements of the cable trays before and after each experiment are accurate to about $\pm$ 0.05 kg (0.1 lbs).

Procedure

The first steps in this program were a series of calibration tests on the radiant heat device. The purpose of the initial calibration testing was to determine the approximate power level supplied to the quartz infrared lamps to produce the desired power level of heat flux from the steel shroud to the cables for the different heat flux levels to be tested. These calibration tests were conducted with a dummy load in the cable tray and also served to verify the function of the radiant heat device both in terms of uniform flux distribution over the cable tray and structural integrity over the range of heat flux levels anticipated.

The procedure followed for each of the ten experiments performed with actual cable loading was as follows: The cable tray was filled with cable, weighed, and photographed. The instrumentation was installed as shown in Figure 2. The bay door on the building was opened to a height just above that of the top of the radiant heat device, approximately 2 m above the ground (see Figure 1). An insulated shutter was placed between the shroud and the cables to protect the cables until the shroud was heated to the proper temperature for the experiment being conducted. The power to the cables was turned on and the recording device was started. The quartz lamps were energized to heat the shroud to the proper temperature. When the shroud was heated to the proper level the insulated shutter was removed exposing the top of the cable tray to thermal radiation. The three calorimeters monitored by the Radiant Heat Facility personnel were used to control the heat flux to the desired level throughout the experiment. The cable was exposed for a period of 30 minutes or until ignition (flames) occurred. If the cable started smoking, the elapsed exposure time was recorded and the ventilation in the building was started to remove excess smoke from the test area. If flames developed, the power was cut to the quartz lamps, the fire was extinguished using portable

CO_2 fire extinguishers, and the experiment terminated. If no flames developed, power was cut to the quartz lamps after 30 minutes and the experiment was terminated. After the cable tray had cooled, it was removed from the radiant heat device, weighed to determine cable weight loss, and photographed.

Results

A total of ten experiments were conducted, five each on IEEE-383 qualified cable and unqualified cable. The experiment number, cable type, and nominal heat flux level for each experiment are listed in Table 1.

A brief summary of the results of the experiments is listed in Table 2, which includes a time-weighted average of the heat flux level from calorimeters 113, 114, and 115, the total exposure time, the elapsed time to electrical failure, the elapsed time to cable fire, and the cable weight loss for each experiment. As noted in Table 2, the total exposure time for experiment number 2 is 10 minutes longer than the 30-minute period specified in the procedure. The additional exposure time was added to test number 2 to verify that the cable temperatures at the top of the tray had reached their maximum for this heat flux level. The additional exposure time had no significant effect on cable damage, which was exhibited by only slight discoloration and a weight loss of 0.05 kg (0.1 lb) which is on the order of the accuracy of the weight measurement. The time to electrical failure for experiment number 1 is listed as greater than 30 minutes because the current from cable to tray was nonzero but below the threshold value of 1 amp used to describe electrical failure. The time to cable fire for experiment number 7 is listed as greater than 30 minutes because the cable temperature was very close to ignition temperature at the end of 30 minutes exposure (T_{max} = 587°C (1089°F)) and it was assumed that ignition would occur if the exposure were continued.

The threshold levels of heat flux for damage in the form of electrical failure and nonpiloted ignition were calculated for the IEEE-383 qualified cable and the unqualified cable used in these experiments. These values are listed in Table 3 and shown graphically in Figures 3 and 4. The critical flux for electrical failure was determined to be about 8 kW/m^2 for unqualified cable and 18 kW/m^2 for IEEE-383 qualified cable. The critical flux for nonpiloted ignition was determined to be about 22 kW/m^2 for unqualified cable and 28 kW/m^2 for IEEE-383 qualified cable. These values were calculated using a linear least squares analysis of the data summarized in Table 2. The data points from experiments number 1 and number 7, in which the time to electrical failure and the time to ignition are listed as greater than 30 minutes, were included in the least squares analyses, and are shown as a point with an error bar in Figures 3 and 4.

The maximum temperatures reached during each experiment, prior to ignition or termination of the test, are listed in Table 4 along with the thermocouple number(s) which registered those temperatures. These maximum temperatures are shown graphically in Figure 5. The lines in Figure 5 represent a linear least squares data fit of maximum temperature vs. external heat flux for both types of cable. Thermocouple locations can be determined from Figure 2. In experiments 3, 9 and 10 the heating was very rapid and probably uneven and the maximum temperature recorded may not reflect the actual maximum temperature reached in the cable tray. These data points were not included in the least squares analyses. These temperatures cannot be used for the determination of the temperature at which electrical failure occurred because electrical failure may have taken place before the termination of the experiment where the maximum temperature would have occurred.

Table 1

Radiant Heat Experiment Outline

Radiant Heat Experiment Number	Cable Type	Nominal Heat Flux kW/m^2
1	IEEE-383 Qualified	20
2	IEEE-383 Qualified	10
3	IEEE-383 Qualified	40
4	IEEE-383 Qualified	30
5	IEEE-383 Qualified	5
6	Unqualified	10
7	Unqualified	20
8	Unqualified	5
9	Unqualified	30
10	Unqualified	30

Table 2

Summary of Results for
Radiant Heat Experiments

Radiant Heat Experiment Number	Measured Heat Flux kW/m^2	Time of Exposure min	Time to Electrical Failure min	Time to Ignition min	Weight Loss lbs
1	21	30	t 30*	--	1.0
2	11	40	--	--	.1
3	41	6.5	6.0	6.5	3.0
4	31	26.5	9.5	26.5	7.4
5	7	30	--	--	0.0
6	11	30	22.5	--	0.2
7	23	30	7.5	t 30	5.1
8	6	30	--	--	0.2
9	30	7	4	7	2.3
10	29	6	4	6	1.2

* Partial electrical failure had developed at 30 minutes and it is assumed that total failure would occur if the exposure were continued.

Note that experiment number 2 was run 10 minutes longer than normal.

Thermocouple readings indicate that the cables were very close to ignition temperature (600°C) and it is assumed that fire would develop if the exposure were continued.

Table 3

Critical Flux Levels for
Electrical Cable Failures

	IEEE-383 Qualified	Unqualified
Critical Flux Electrical Failure (kW/m^2)	18	8
Critical Flux Nonpiloted Ignition (kW/m^2)	28	22

Table 4

Maximum Cable Temperatures for Radiant Heat Experiments

Radiant Heat Experiment Number	Maximum Recorded Temperature °C	Thermocouple Location
1	409	106
2	301	104
3	607	104
4	667	104
5	167	106
6	285	105
7	587	106
8	186	106
9	510	103
10	362	101 & 105

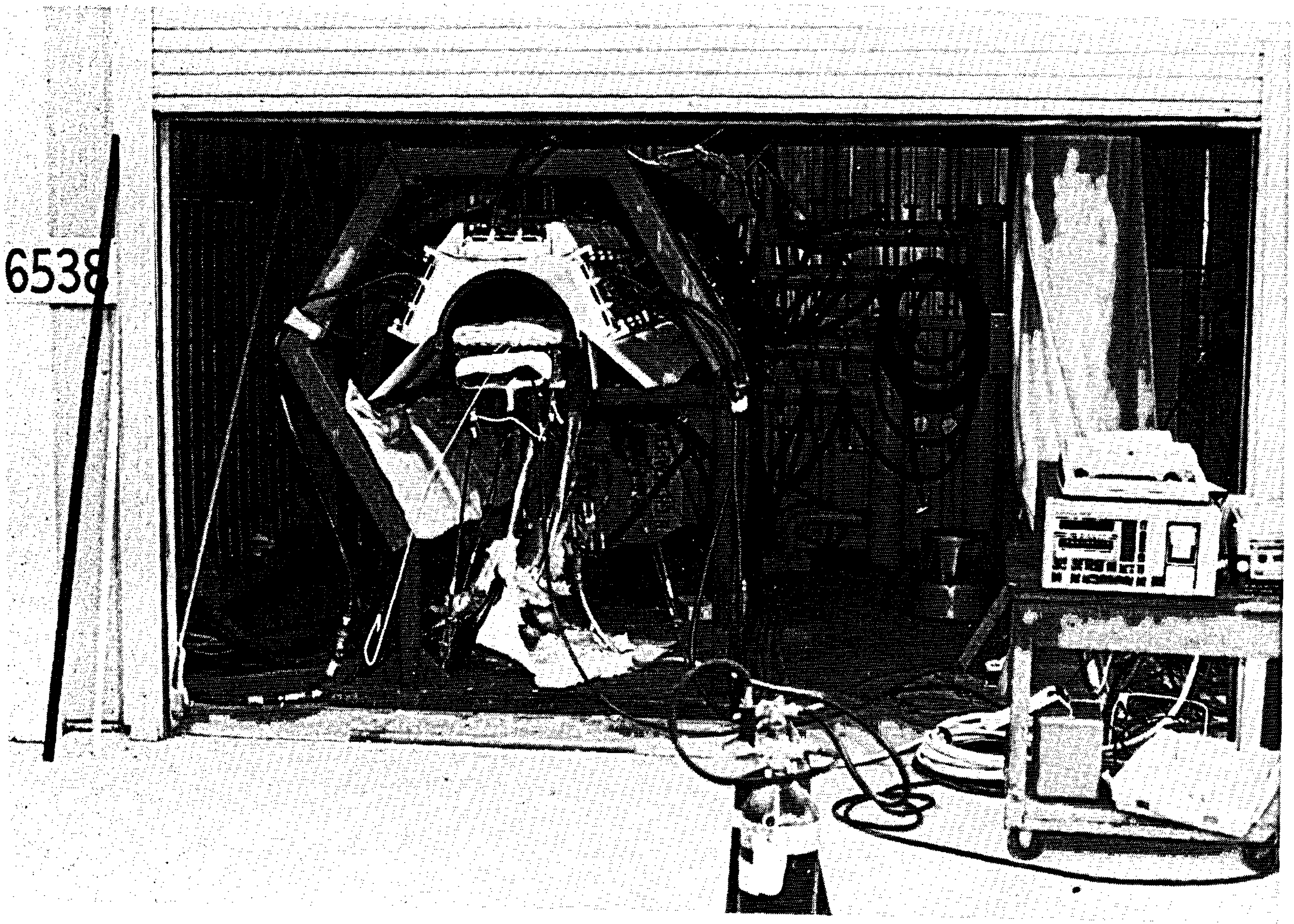

Figure 1. Radiant Heat Facility Experimental Apparatus

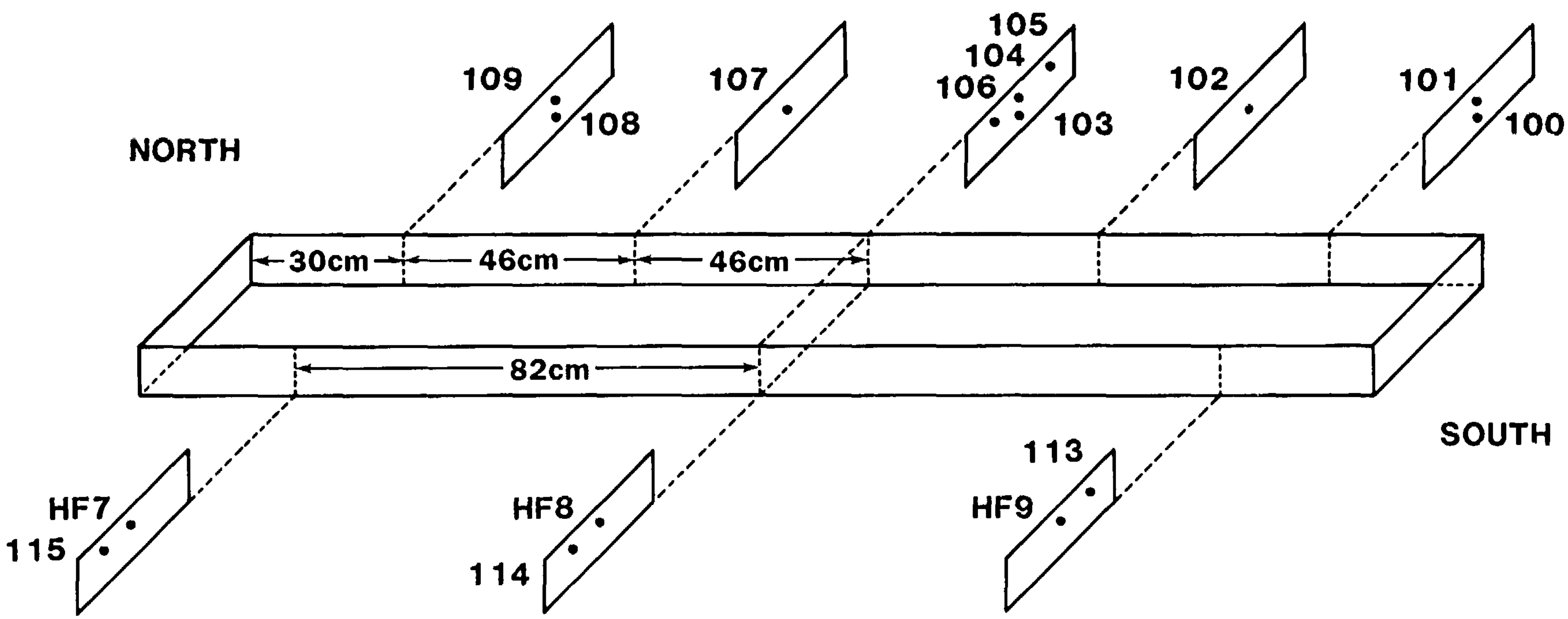

Figure 2. Radiant Heat Experiment Instrumentation Placement

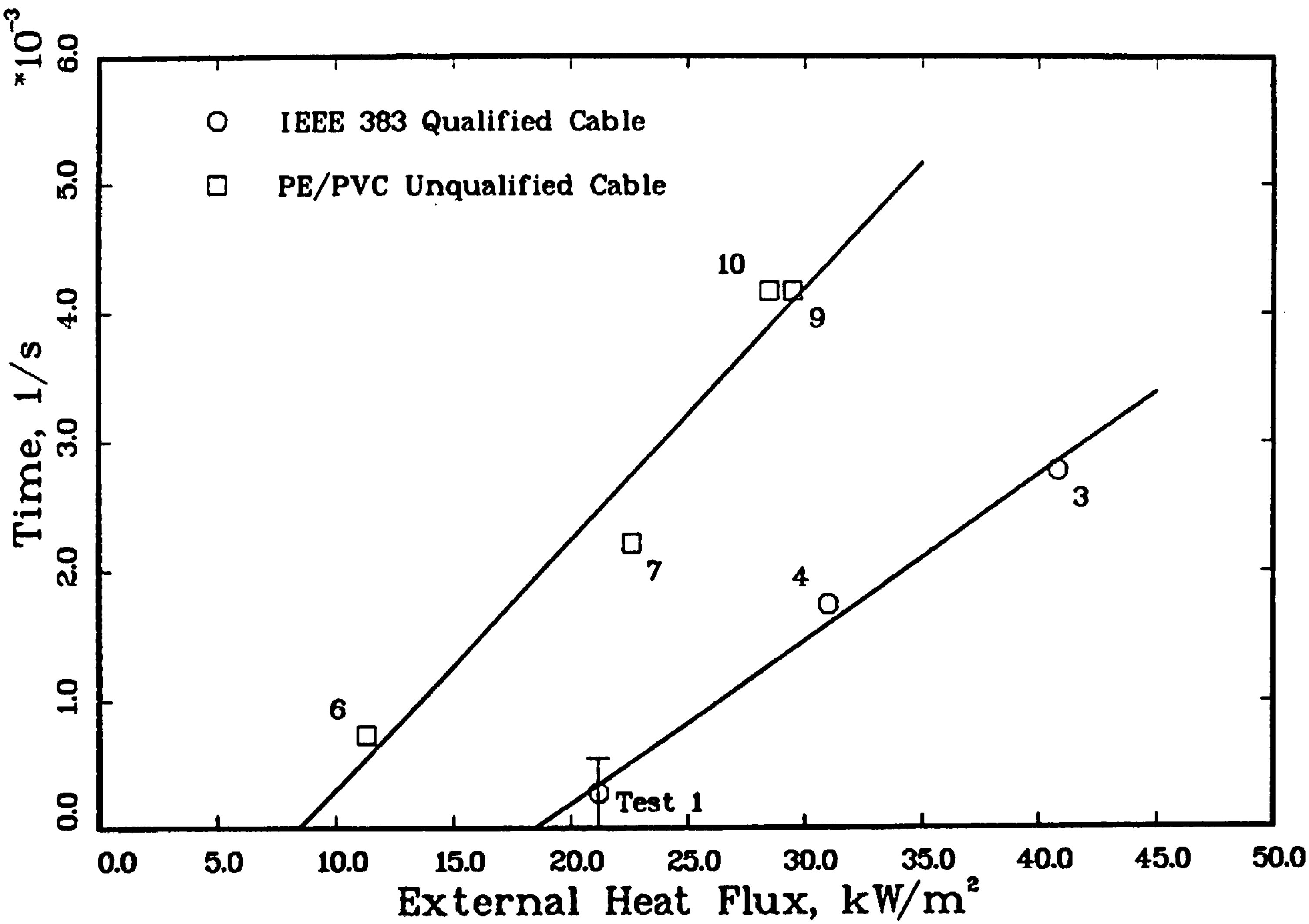

Figure 3. Reciprocal Time to Electrical Failure as a Function of External Heat Flux

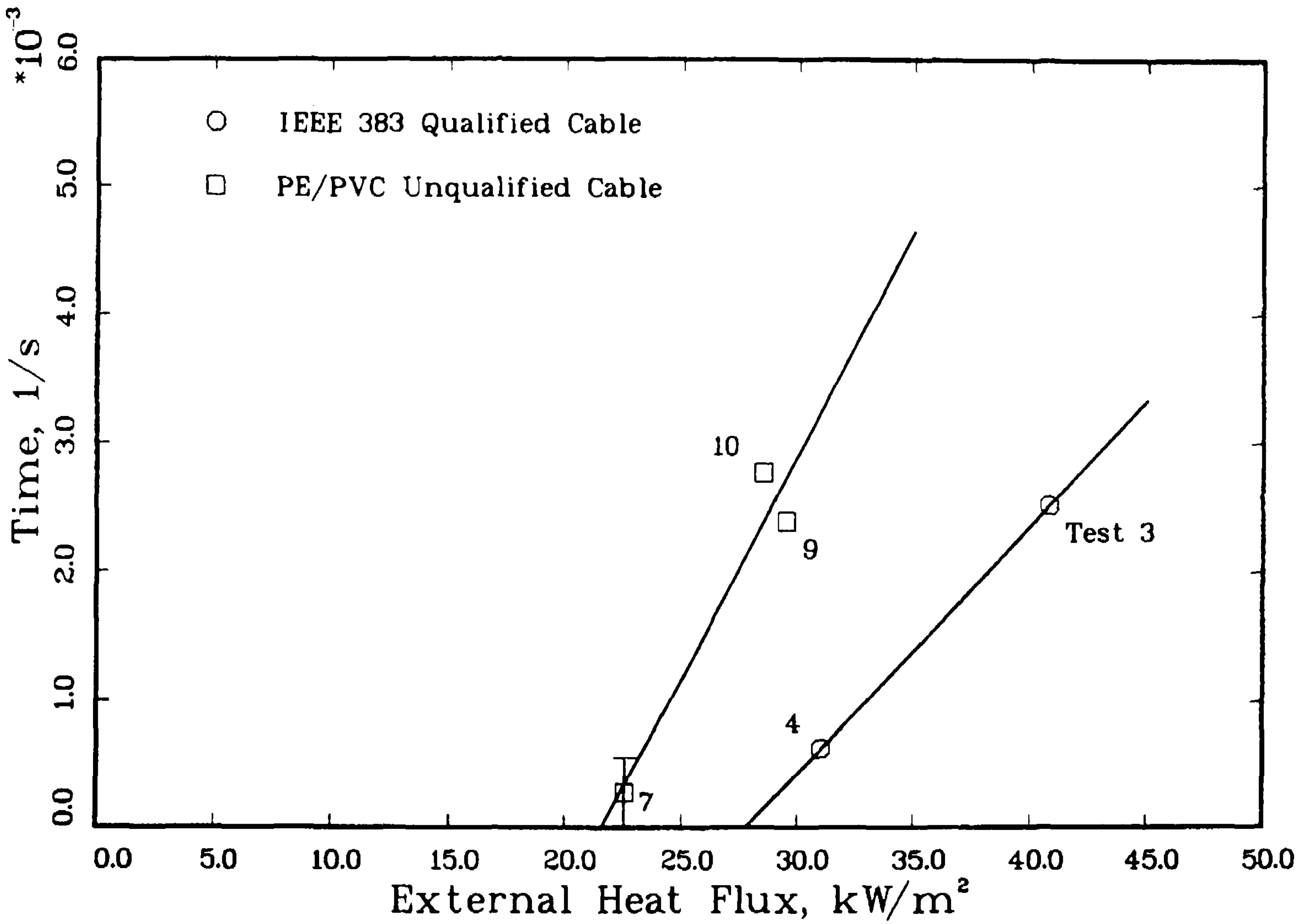

Figure 4. Reciprocal Time to Nonpiloted Ignition as a Function of External Heat Flux

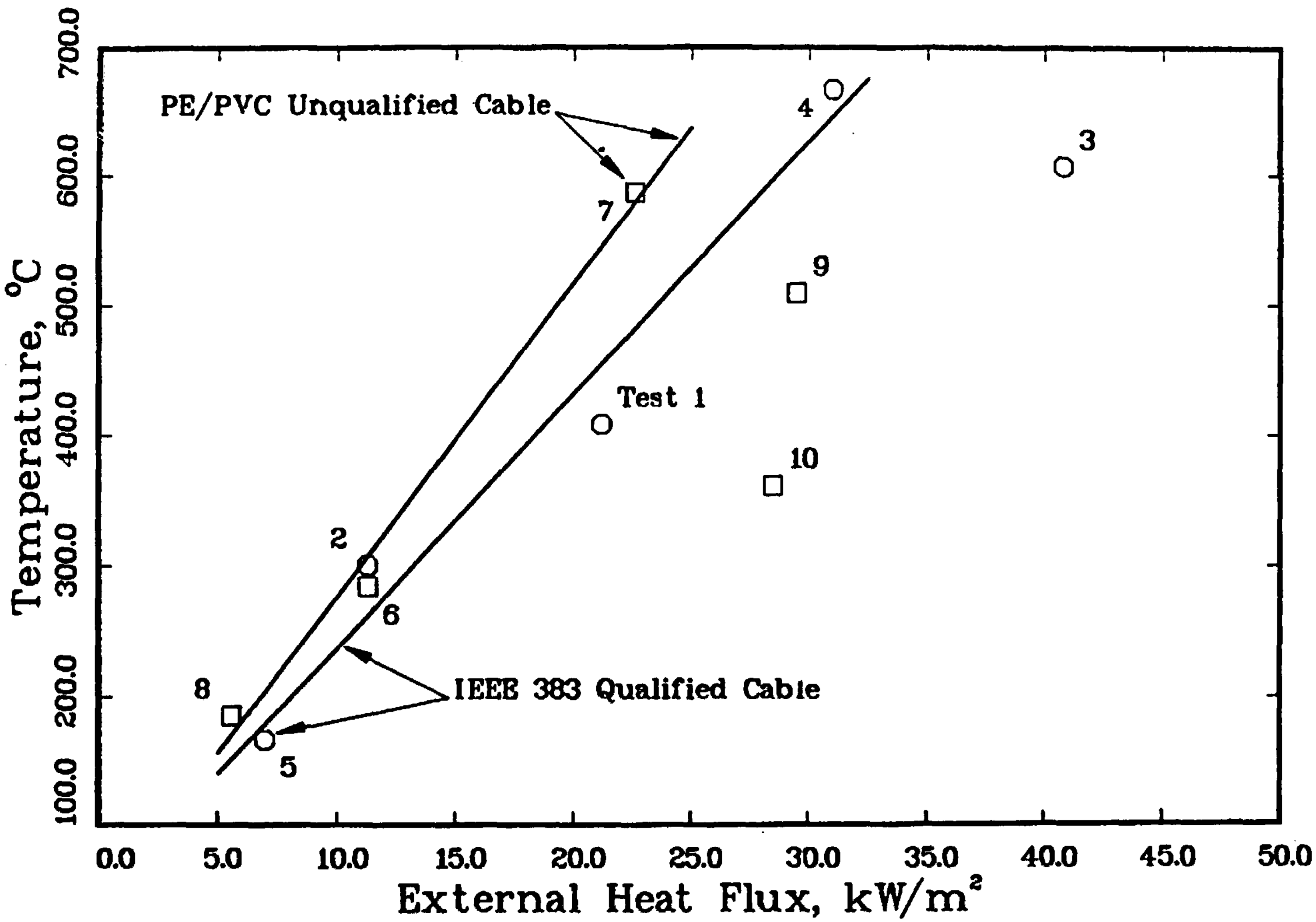

Figure 5. Maximum Temperature Reached During Experiment as a Function of External Heat Flux

OVEN EXPERIMENTS

Apparatus

Two convection type ovens at Sandia National Laboratories Albuquerque (SNLA) were used for the exposure of electrical cables to a constant temperature. One oven was capable of producing temperatures up to 300°C (570°F), and one capable of producing temperatures up to 500°C (930°F). The oven capable of producing temperatures up to 300°C was the larger of the two ovens and was used for all except four of the experiments (nos. 12, 13, 14 and 15). The large oven is roughly 1 m^3 (35 ft^3) in volume with all sides roughly the same length. The smaller oven has approximately one-eighth the volume with the dimensions about one-half those of the larger oven. The electrical cables were exposed in the ovens in four basic configurations which will be referred to as A, B, C, or D. The four configurations are:

A. Segments of electrical cable were placed directly on a mesh type shelf in the oven.

B. Segments of electrical cable were placed in a segment of a cable tray with one end of the cable bent at a 90° angle over a rung of the cable tray and pulled down by a weight to simulate additional cable length hanging down (see Figure 6).

C. Segments of electrical cable were placed in a segment of a cable tray supported by the rungs of the tray and covered a with large weight to simulate a distributed load of electrical cables (see Figure 7).

D. Segments of electrical cable were wrapped around an aluminum mandrel approximately 46 cm (18 in) in diameter (see Figure 8).

Two types of unaged cable were used in these experiments. One type was IEEE-383 qualified 3 conductor, no. 12 AWG tinned copper, 30 mil Exane II insulation, silicon glass tape, 65 mil Exane II jacket, 600 volt. The other type was non-IEEE-383 qualified 3 conductor, no. 12 AWG copper, 20/10 PE/PVC insulation, 45 mil PVC jacket, 600 volt. Oven temperature was measured during experiments with a chromel/alumel thermocouple positioned near the cables. Cable temperatures during experiments were measured with chromel/alumel thermocouples placed inside (under the jacket) of cables. The accuracy of these thermocouples is approximately ± 3°C (± 5.5°F).

Procedure

A total of 30 experiments were conducted in which electrical cable segments were exposed to a constant temperature environment for periods of up to 60 minutes. The experiments can be grouped into one of four categories based on the basic configuration, previously described, of the electrical cable segments during experiment.

There were 12 experiments conducted with the electrical cable segments in configuration A (flat on the oven shelf). The experiment number, type of cable, number of cable segments, exposure temperature, and exposure period are listed in Table 5, for these experiments. The procedure followed for these experiments was as follows. The thermocouples were installed in the oven and in the cable segments. The oven was turned on and allowed to stabilize at the proper temperature for the experiment. For all experiments in this configuration except 1 through 5, the electrical cable segments were checked for internal shorts or opens. The cable segments were placed in the oven and exposed for the period of time shown in Table 5. In experiments 2 through 5, one cable segment was removed at the end of each interval. In the other experiments, all of the cable segments were removed at the end of the period shown in Table 5. The cable segments were allowed to cool to room temperature and examined for physical damage. For all experiments in this configuration except 1 through 5 the cable segments were checked for internal shorts or opens.

There were 12 experiments conducted with the electrical cable segments in configuration B (shown in Figure 6). The experiment number, type of cable, number of cable segments, exposure temperature, and exposure period are listed in Table 6, for these experiments. The procedure followed for these experiments was as follows: The thermocouples were installed in the oven and in the cable segments. The cable segments were positioned in the cable tray, as shown in Figure 6, and a weight equivalent to 1.5 m (5 ft) of cable was attached to each cable segment. For experiment number 21, the weights were equivalent to 3 m (10 ft) of cable. For experiment number 9, the rung of the cable tray over which the cable was bent was replaced with a piece of tubing 5.7 cm (2.25 in) in diameter. The oven was turned on and allowed to stabilize at the proper temperature for the experiment. The electrical cable segments were checked for internal shorts or opens. The cable tray and cable assembly were placed in the oven and exposed for the period of time shown in Table 6. The cable tray and cable assembly were removed from the oven and allowed to cool until all cables were below 90°C (195°F) in temperature. The electrical cable segments were checked for internal shorts or opens.

There were two experiments conducted with the electrical cable segments in configuration C (shown in Figure 7), experiments 8 and 10. The procedure followed for these experiments was as follows: The thermocouples were installed in the oven and in the cable segments. Four segments of nonqualified cable were used in each experiment. The cable segments were positioned in the cable tray, as shown in Figure 7, and a distributed load equivalent to a layer of electrical cables 5 cables deep was placed on the cables. The oven was turned on and allowed to stabilize at a temperature of 170°C (340°F). The electrical cable segments were checked for internal shorts or opens. The cable tray and cable assembly were placed in the oven and exposed for a period of 30 minutes in experiment number 8 and 60 minutes in experiment 10. The cable and cable assembly were removed from the oven and allowed to cool until all cables were below 90°C (195°F) in temperature. The electrical cable segments were checked for internal shorts or opens.

There were three experiments conducted with the electrical cable segments in configuration D (shown in Figure 8), experiments 28, 29, and 30. The procedure followed for these experiments was as follows. The thermocouples were installed in the oven and in the cable segments. Two segments of IEEE-383 qualified cable approximately 3 m (10 ft) long were used in each experiment. The cable segments were wrapped around the mandrel shown in Figure 8. The oven was turned on and allowed to stabilize at a temperature of 250°C (480°F) for experiment 28 and a temperature of 275°C (530°F) for experiments 29 and 30. The electrical cable segments were checked for internal shorts and opens. The mandrel and cable assembly were placed in the oven and exposed for a period of 60 minutes. The mandrel and cable assembly were removed from the oven and allowed to cool to room temperature. The cable segments were removed from the mandrel, straightened and rewrapped around the mandrel. The cable segments (on the mandrel) were immersed in tap water at room temperature, 20°C (68°F), and subjected to a voltage withstand test at a potential of 2400 vac for a period of 5 minutes.

The leakage current which constitutes failure of the voltage withstand test is not specified in the IEEE Std. 383-1974. The equipment available to SNLA for performing similar voltage withstand tests utilized a 5 ma breaker to indicate failure and that was the value for these tests. The above procedure is based on IEEE Std. 383-1974,[4] section 2.4, "Testing for Operation During Design Basis Event."

In addition to the experiments in which electrical cable segments were exposed to constant temperature environments, two experiments were run in which pieces of cable jacket and insulation materials were exposed to constant temperature environments to examine the effect of thermal exposure on the tensile elongation of the cable jacket and insulation materials. The procedure followed for these experiments was as follows: The jacket was stripped from a segment of IEEE-383 qualified cable and test strips 5.6 mm (7/32 in) wide were prepared. The insulation from the cable conductors was stripped off. Three strips of cable jacket material and three pieces of cable insulation, one from each color of conductor insulation, were tested for tensile elongation. A thermocouple was installed in the oven. The oven was turned on and allowed to stabilize at a temperature of 250°C (480°F) for one experiment and 275°C (530°F) for another. Two strips of cable jacket material were placed in the oven and exposed for a period of 60 minutes and three pieces of insulation material were placed in the oven with their ends folded over and clamped and exposed for a period of 45 minutes. The cable material samples were removed from the oven and allowed to cool to room temperature. The cable material samples were tested for tensile elongation.

Results

A total of 29 experiments were completed in which electrical cable segments were exposed to a constant temperature environment, and two experiments were completed in which pieces of cable jacket and insulation materials were exposed to a constant temperature environment. The results of these experiments will be reported in groups according to the basic configuration of the electrical cables during the experiments.

There were 12 experiments conducted with the electrical cable segments in configuration A, (flat on the oven shelf). In these experiments the exposure effects were very uniform for cables of the same type exposed at the same temperature for the same length of time. For all 12 experiments the electrical cable segments took about 15 to 20 minutes to heat up to the exposure temperature. The cables from experiments 1 through 5 were not checked for electrical shorts or opens and the other experiments in this group showed no shorts or opens after exposure. The effects of exposure on the IEEE-383 qualified cable jacket material related to temperature and time of exposure were as follow:

250°C (480°F), 10 to 60 minutes, slight discoloration.

275°C (530°F), 60 minutes, discoloration, blistering, a decrease in flexibility, and smoking during exposure.

300°C (570°F), 10 minutes, slight discoloration with light smoking during exposure.

300°C, 20 to 60 minutes, discoloration, blistering, a decrease in flexibility, and smoking during exposure.

350°C (660°F), 60 minutes, discoloration, heavy blistering, rough surface, very brittle, and smoking during exposure.

400°C (750°F), 60 minutes, charred appearance, large cracks, very brittle, and smoking during exposure.

450°C (840°F), 60 minutes, cable insulation and jacket material underwent smoldering combustion reaching temperatures of about 750°C (1380°F), and were reduced to ash.

The effects of exposure on the unqualified cable jacket material related to temperature and time of exposure were as follow:

170°C (340°F), 10 to 60 minutes, slight shrinkage (2-3 percent).

200°C (390°F), 10 minutes, slight shrinkage (2-3 percent).

200°C, 20 to 60 minutes, slight shrinkage (2-3 percent), deformation of jacket where cable rested on oven rack, a decrease in flexibility, and smoking during exposure.

There were 12 experiments conducted with the electrical cable segments in configuration B (shown in Figure 6). In these experiments the electrical cable segments were checked for electrical failure in the form of electrical shorts or opens. For all 12 experiments the electrical cable segments took about 15 to 20 minutes to heat up to the exposure temperature. The results of the checks for electrical failure are listed in Table 7 along with cable type, exposure temperature, and exposure period.

There were two experiments conducted with the electrical cable segments in configuration C (shown in Figure 7). In these experiments the electrical cable segments were checked for electrical failure in the form of internal shorts or opens. For these two experiments the electrical cable segments took about 25 to 30 minutes to heat up to the exposure temperature. The increased heating time over other experiments is probably caused by reduced convection heat transfer due to shielding by the distributed load. Of the four segments of unqualified cable exposed at 170°C (340°F) for 30 minutes, none showed electrical shorts or opens. Of the four segments of unqualified cable exposed at 170°C (340°F) for 60 minutes, one showed electrical shorts and none showed opens. The results of these experiments are summarized in Table 8.

There were three experiments conducted with the electrical cable segments in configuration D (shown in Figure 8). In these experiments the electrical cable segments were checked for electrical failure with a voltage withstand test. For these three experiments the electrical cable segments took about 20 to 25 minutes to heat up to exposure temperature. Of the two segments of IEEE-383 qualified cable exposed at 250°C (480°F) for 60 minutes, both passed the voltage withstand test. Of the four segments of IEEE-383 qualified cable exposed at 275°C (530°F) for 60 minutes, one segment passed and three segments failed the voltage withstand test. The results of these experiments are summarized in Table 9.

The experiments designed to examine the effects of thermal exposure on the tensile elongation of the cable jacket and insulation materials involved comparison of unexposed samples and samples exposed to temperatures of 250°C (480°F) and 275°C (530°F). The cable jacket material samples were exposed for 60 minutes and the cable insulation material samples were exposed for 45 minutes to account for the thermal lag of the cable interior noticed in earlier experiments. The results of these experiments are summarized in Table 10.

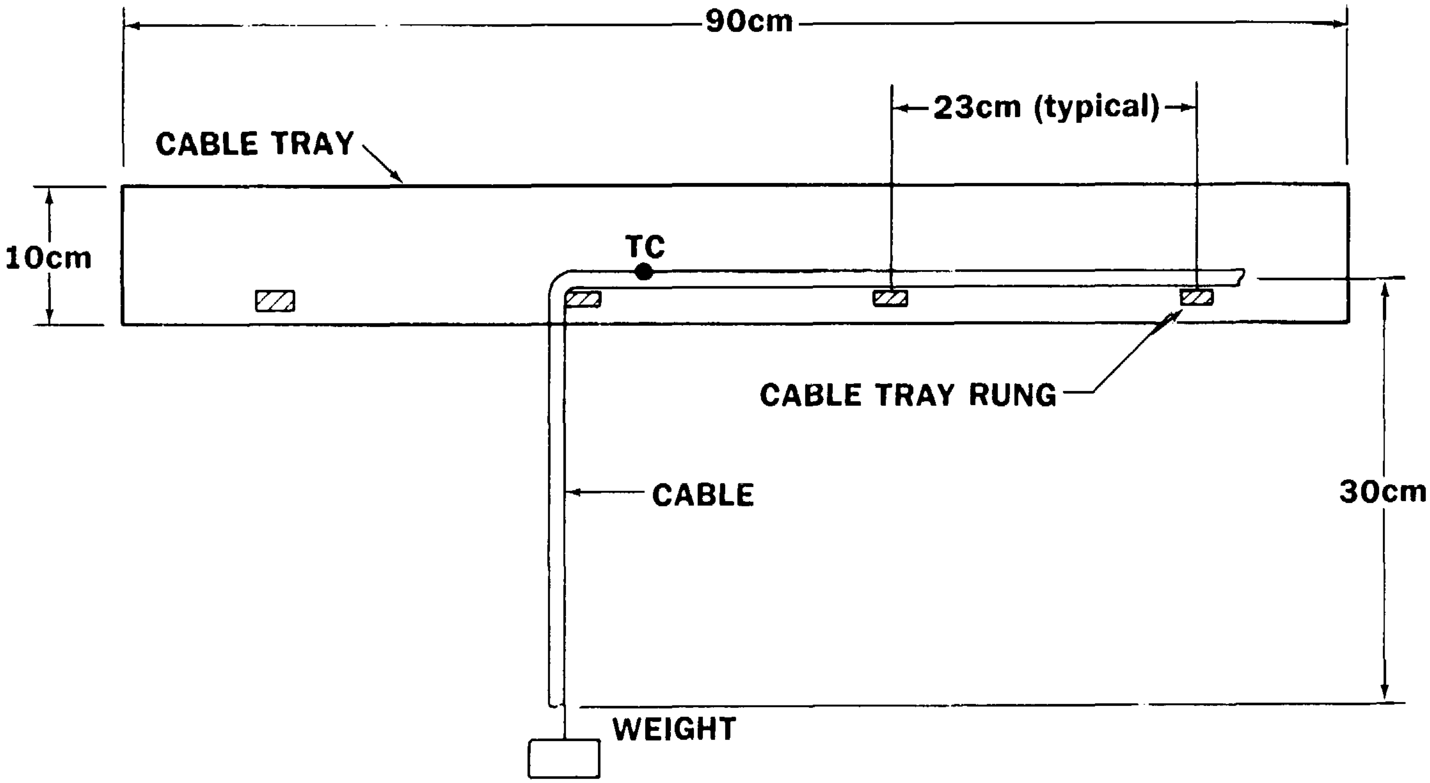

Figure 6. Oven Experiment Configuration B

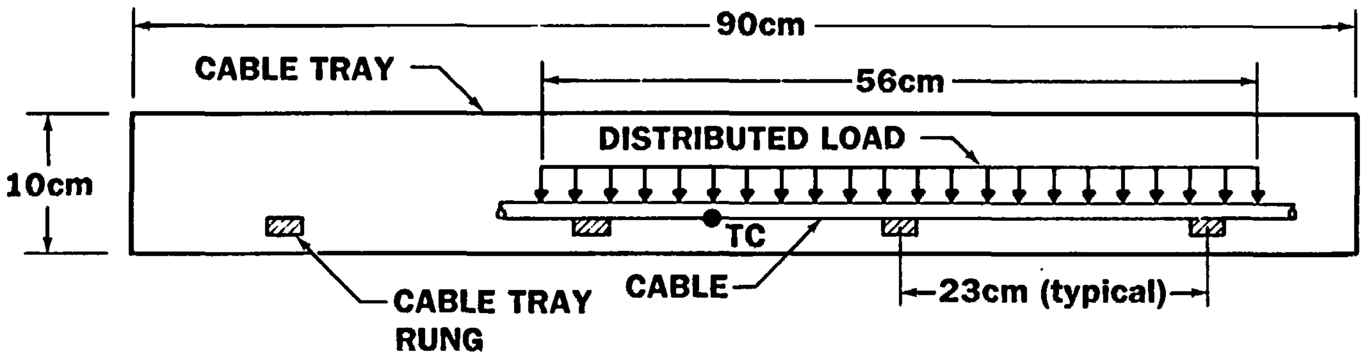

Figure 7. Oven Experiment Configuration C

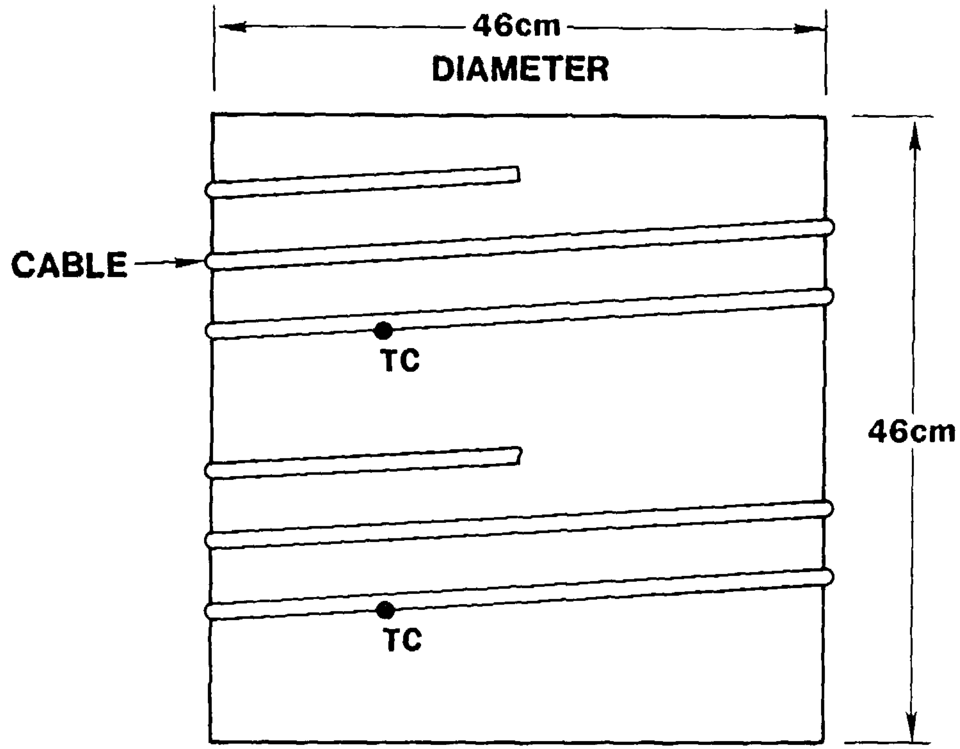

Figure 8. Oven Experiment Configuration D

Table 5

Oven Experiments With Cables in Configuration A

Oven Experiment Number	Cable Type	Number of Cables	Exposure Temperature °C	Exposure Period min
1	Unqualified	4	200	60
2	Unqualified	5	170	10, 20, 30, 40, 60*
3	Unqualified	5	200	10, 20, 30, 40, 60*
4	IEEE-383 Qualified	5	300	10, 20, 30, 40, 60*
5	IEEE-383 Qualified	5	250	10, 20, 30, 40, 60*
12	IEEE-383 Qualified	4	300	60
13	IEEE-383 Qualified	4	350	60
14	IEEE-383 Qualified	4	400	60
15	IEEE-383 Qualified	4	450	60
22	IEEE-383 Qualified	5	275	60
25	IEEE-383 Qualified	5	250	60
27	IEEE-383 Qualified	5	275	60

* One segment of cable removed from exposure at each interval.

These experiments utilized IEEE-383 qualified cable of the same type described in this report, but from a different lot. The cables from this lot were used in the 20-ft separation experiments at UL.

Table 6

Oven Experiments With Cables in Configuration B

Oven Experiment Number	Cable Type	Number of Cables	Exposure Temperature °C	Exposure Period min
6	Unqualified	4	170°C	60
7	IEEE-383 Qualified	4	250°C	60
9	Unqualified	4	170°C	30
11	Unqualified	4	170°C	60
16	Unqualified	5	150°C	60
17	Unqualified	5	150°C	60
18*	--	--	--	--
19	Unqualified	5	130°C	60
20	Unqualified	5	130°C	60
21	Unqualified	5	130°C	60
23	Unqualified	10	130°C	60
24	Unqualified	10	150°C	60
26	Unqualified	10	170°C	60

* Experiment number 18 was terminated with no data because the weight dropped off three of the five cable segments.

These experiments utilized unqualified cable of the same type described in this report, but supplied from a different manufacturer. The cables supplied by this manufacturer were used in the 20-ft separation experiments at UL.

Table 7

Summary of Results for Oven Experiments With Cables in Configuration B

Cable Type	Exposure Temperature °C	Exposure Period min	Number of Cables	Number* Shorted	Number Open
IEEE-383 Qualified	250	60	4	0	0
Unqualified	130	60	15	0	0
Unqualified	150	60	10	2	0
Unqualified	170	30	4	1	0
Unqualified	170	60	8	5	0
Unqualified	130	60	10	0	0
Unqualified	150	60	10	0	0
Unqualified	170	60	10	1	0

* Conductor-to-conductor internal shorts.

These experiments utilized unqualified cable from the batch used in the 20-ft separation experiments at UL.

Table 8

Summary of Results for Oven Experiments
With Cables in Configuration C

Cable Type	Exposure Temperature °C	Exposure Period min	Number of Cables	Number* Shorted	Number Open
Unqualified	170	30	4	0	0
Unqualified	170	60	4	1	0

* Conductor-to-conductor internal shorts.

Table 9

Summary of Results for Oven Experiments
With Cables in Configuration D

Cable Type	Exposure Temperature °C	Exposure Period min	Number of Cables Tested*	Number of Cables Failed
IEEE-383 Qualified	250	60	2	0
IEEE-383	275	60	4	3

* Voltage withstand test described in report.

Table 10

Summary of Results for Oven Experiments on Tensile Elongation of IEEE-383 Qualified Cable Jacket and Insulation Material

Exposure Temperature °C	Exposure Period min	Sample Number	Elongation of Jacket %	Elongation of Insulation *%
Unexposed	--	1	168	205
Unexposed	--	2	215	162
Unexposed	--	3	165	208
250	60	1	81	100
250	60	2	92	118
250	60	3	No test	98
275	60	1	5	33
275	60	2	3	24
275	60	3	No test	23

* Cable insulation samples were exposed for 45 minutes.

CONCLUSIONS

The damageability of electrical cables, similar to those found in some nuclear power plants, to radiant heat flux and constant temperature thermal exposure have been examined. Two particular types of unaged electrical cables, one an IEEE-383 qualified cable similar to cables currently used, and one an unqualified cable similar to cables used in earlier power plants, were examined in this study.

The critical fluxes or threshold levels at which electrical cable damage occurs in the form of electrical failure (short circuit) and nonpiloted ignition have been determined for the two types of cable examined. The critical flux for electrical failure was determined to be about 8 kW/m^2 for unqualified cable and 18 kW/m^2 for IEEE-383 qualified cable. These results along with the approximate time to electrical failure as a function of heat flux are shown graphically in Figure 3. The critical flux for nonpiloted ignition was determined to be about 22 kW/m^2 for unqualified cable and 28 kW/m^2 for IEEE-383 qualified cable. These results along with the approximate time to nonpiloted ignition as a function of heat flux are shown graphically in Figure 4.

The critical flux values for cable damage in the forms of electrical failure and nonpiloted ignition determined for the two cable types tested are based on a very limited amount of test data. This limited amount of data and the stochastic nature of the processes being investigated introduces a margin of uncertainty in addition to that of instrumentation accuracy to the results presented in this report. The possible sources of error mentioned for these results should be considered in their acceptability for any particular application.

Experimental results indicate that exposure of the particular IEEE-383 qualified cable examined in this study to temperatures greater than 250°C (480°F) and periods of 60 minutes can cause discoloration, blistering, smoking, loss of flexibility, and failure to pass a voltage withstand test as described in this report. Experimental results indicate that exposure of the particular unqualified cable examined in this study to temperatures greater than 130°C (265°F) for periods of 60 minutes can cause electrical failure in the form of shorts between conductors. In addition, the thermal forming temperature of the unqualified cable jacket material was determined to be between 170°C (340°F) and 200°C (390°F).

RECOMMENDATIONS

The properties of electrical cables and threshold values for electrical cable damage identified in this report should not be interpreted as an acceptance criterion for electrical cables exposed to a fire environment. The meaning of the term "free of fire damage"[1] and, more specifically, what properties should be used to determine electrical cable functionability have not currently been defined by the NRC. The identification of the properties and their corresponding levels, which determine cable functionability, should be the first step in the establishment of an acceptance criterion. With the properties and levels identified, the types of thermal or fire environments which could cause cable damage can be quantified. An acceptance criterion can then be established in terms of both electrical cable properties and thermal exposure levels. This information is necessary for the proper design and interpretation of tests and experiments such as those run on the adequacy of 20-ft separation, and is also necessary in the development of analytical tools to predict electrical cable damage in a potential fire environment. It is therefore recommended that the NRC take steps to define the properties and their respective levels, which will be used to determine cable functionability after exposure to a fire environment.

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