A Study of Damageability of Electrical Cables in Simulated Fire Environments

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

This is a report (under RP1165) concerned with the damage aspects of electrical fires on cable insulation. It should be noted that in reviewing aspects of cable insulation failure, it is not the intent to eliminate fire protection but rather to provide basic information which will allow the fire protection designer to make his protection system most effective. Cables were exposed to varied radiant levels of energy. Electrical failures were determined by impressing a voltage on the cable to sense a shorted condition upon failure of the insulation. Both auto- and piloted-ignition fire risks were simulated in the testing, and HCl generation was also recorded.

PROJECT OBJECTIVES

The present method for qualification of an electrical cable is the IEEE-383 test for cable qualification. This test provides a single set of fire source and cable conditions and is a "go or no go" test. Our earliest categorization of cables (EPRI Interim Report NP-1200) by various radiant heat exposures with both auto ignition and piloted ignition indicated that cable damage varies with the radiant heat source. The object of this testing was to provide a laboratory test basis for assessing cable insulation damage on a comparative basis. This method has shown the damageability to be a complex phenomenon depending on the oxides formed, the materials, the jacket material, etc. It was found that there is a critical heat flux for damage and that the cables are affected by the amount of energy applied above this level.

PROJECT RESULTS

In evaluating the results, the report summary emphasizes that the study results should not be used as a basis for delay of fire suppression. The damage from a fire is limited by early extinguishment, and this should be an overriding consideration.

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ABSTRACT

In a fire accident in a facility, full trays of cables may be exposed to varying thermal environments. Cables may begin to melt, expand, disintegrate, and short circuit causing cable malfunction even before ignition occurs. The study investigates the damage processes that take place in a cable under varying thermal environments. Damageability in this study is defined as a change in the properties of a cable causing impairment to the normal function of the cable. To quantify the cable damage, insulation/jacket degradation, ignition, and electrical integrity failure were processes chosen to evaluate cable damage potential. For each of these three processes critical flux and critical energy parameters (expressed in terms of damage indices) are derived for expressing the damage potential of each cable.

With a proper assessment of the potential hazard presented by exposure fires in a facility and the information on the particular scenario, the damage indices can be used by planners and engineers for selecting appropriate cables and types of detection and protection systems.

In addition, a preliminary study on HCl generation from three chlorine-containing cables was performed.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance of the following persons toward the completion of this study: Dr. R. A. Hemstreet for overall program direction and support; Dr. A. Tewarson for his continuous guidance and valuable suggestions; Mr. R. F. Pion and Mr. M. Dieselman, for their tireless efforts in preparing cable specimens and conducting the experiments; Mr. A. P. Symonds, for his contribution toward the design of the electrical failure measurement devices; and Mr. L. A. Post and Ms. J. L. Dower, for assistance in preparing this report.

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NOMENCLATURE

C - concentration of HCl (ppm)

E_{id} - critical energy of degradation (kJ/m^2)

E_{ef} - critical energy of electrical failure (kJ/m^2)

$E_{ig,n}$ - critical energy of non-piloted ignition (kJ/m^2)

$E_{ig,p}$ - critical energy of piloted ignition (kJ/m^2)

$\dot{G}$ - generation rate of HCl (g/s)

$\dot{q}''_e$ - external heat flux (kW/m^2)

$\dot{q}_{id}$ - critical flux of degradation (kW/m^2)

$\dot{q}''_{ef}$ - critical flux of electrical failure (kW/m^2)

$\dot{q}''_{ig,n}$ - critical flux of non-piloted ignition (kW/m^2)

$\dot{q}''_{ig,p}$ - critical flux of piloted ignition (kW/m^2)

t - time (s)

T_s - surface temperature (°C)

V - volume (m^3)

α - insulation degradation parameter (s^{-1})

ξ - piloted ignition parameter (s^{-1})

η - electrical failure parameter (s^{-1})

ρ_{air} - density of air (g/ℓ)

SUMMARY

S.1 PURPOSE AND OBJECTIVE

The purpose of this study is to evaluate the damageability characteristics of various cables under varying thermal environments. Damageability in this study is defined as a change in the properties of a cable causing impairment to the normal function of the cable.

In a fire accident in a facility, cable trays may be exposed to varying thermal environments, resulting in a series of fire stages such as insulation/jacket degradation, ignition, fire growth, maximum burning, electrical integrity failure, and fire decay. Of these stages, insulation/jacket degradation, ignition, and electrical integrity failure were chosen to represent cable damage processes. To express quantitatively the damage potential of these three processes, two parameters were derived from experimental data: critical flux (the minimum heat flux below which the damage process will not occur) and critical energy (the energy required to effectively initiate the damage process). Critical energy is simply the product of the available heat flux and the time to initiate the damage process.

S.2 EXPERIMENTAL APPROACH

Throughout the program, the *FM combustibility apparatus was used to evaluate the damage potential of the different cables under varying thermal environments. It is generally recognized that cable fires originate mostly from an external source such as a burning pool of spilled flammable liquid or debris. In this study, this external thermal environment from the exposure fire was simulated by exposing the 0.1 m long cable sample to external heat flux from four coaxially arranged radiant heaters. The maximum flux to which cable samples were exposed was 70 kW/m^2. Fourteen different cable samples of five basic generic groups were chosen for this program. It should be emphasized that cables of the same basic generic group of insulation do not necessarily imply the same damageability behavior due to their intrinsic differences in manufacturing processes, construction type, number and size of conductors, amount of additives as retardants and plasticizers, etc. The samples are listed in Table S-1.

*Factory Mutual Research Corp.

Table S-1

CABLE SAMPLES USED IN THIS STUDY[a]

No.	Insulation/Jacket Material	Conductor No.	Conductor Size (AWG)	Outer Cable Diameter in.	Outer Cable Diameter (m)	Insulation/Jacket Material (% of Total Cable Weight)	IEEE-383 Rating
2	XPE/Neoprene[b]	7	12	0.630	(0.016)	53.6	-
17	XPE/Neoprene	3	16	0.394	(0.010)	73.2	Pass
5	PE/PVC[c]	3	-	0.433	(0.011)	49.9	Fail
6	PE/PVC	5	-	0.709	(0.018)	51.0	-
8	EPR/Hypalon[d]	1	2	0.433	(0.011)	23.2	Pass
11	EPR/Hypalon	5	14	0.669	(0.017)	23.9	Pass
59	EPR/Hypalon	7	9	0.984	(0.025)	57.5	-
20	Teflon/Teflon	34	20	0.472	(0.012)	48.8	Pass
56	Teflon/Teflon	7	16	0.394	(0.010)	28.1	-
60	Teflon/Teflon	7	20	0.276	(0.007)	32.7	-
21	Silicone (Glass Braid)	1	-	0.354	(0.009)	34.0	-
22	Silicone, Glass Braid/Asb.[e]	9	14	0.827	(0.021)	70.5	Pass
58	Silicone, Glass Braid/Asb.	3	-	1.142	(0.029)	37.3	-
57	Silicone, Glass Braid/Asb.	7	12	0.787	(0.020)	58.4)	-

[a] Cables Nos. 2, 5, 6, 8, 11, 17, 20, 21, and 22 are the same as those used in the previous study[(1)].

[b] Cross-linked polyethylene insulation with Neoprene jacket cable.

[c] Polyethylene insulation with polyvinyl chloride jacket cable.

[d] Ethylene propylene rubber insulation with chlorosulfurated polyethylene jacket cable.

[e] Silicone rubber insulation with asbestos, glass braided jacket cable.

S.2.1 Insulation/Jacket Degradation

The degradation process of the cable insulation/jacket material was investigated under varying thermal environments in the absence of a pilot flame. The amount of insulation/jacket material vaporized as a function of time in the preignition region was used for quantifying the degradation process.

S.2.2 Ignition

Cable samples were exposed to heat flux both with and without a pilot flame. The times to ignition of the cable samples as functions of heat flux under both piloted and non-piloted conditions were used for the quantification of the ignition process.

S.2.3 Electrical Integrity Failure

These tests were performed in the presence of a pilot flame under varying thermal environments. A variable power source was used to energize the cable samples to 70 V in each conductor. The times to electrical shorting between conductors or to ground as functions of heat flux were used for the quantification of electrical integrity failure. No moisture effects were included in these tests so the failure is the result of heat flux and does not take into account any effect of water sprays. Continued fire damage, in our opinion, is a far more serious effect than possible limited shorting of electrical circuits when water is applied. In any fire situation the fire must be extinguished as soon as possible.

S.2.4 Hydrogen Chloride Generation

In addition to evaluating the foregoing cable damage processes, the generation of hydrogen chloride (HCl) from the chlorine-containing cables was also examined. A chloride ion electrode analyzer was used.

S.3 EXPERIMENTAL RESULTS

Section 3 presents in detail the four categories of experimental results of the program. A summary is presented in Tables S-2, S-3, and S-4.

S.3.1 Insulation/Jacket Degradation

Table S-2 presents values of critical energy and critical flux for cable insulation/jacket degradation. As presented in the table, the critical flux for insulation/jacket degradation of all cable samples tested are around 20 ± 4 kW/m^2 except for samples 8 and 11. With these exceptions, the classification of these cables

Table S-2

INSULATION DEGRADATION PARAMETERS OR CABLE SAMPLES

No.	Cable Sample	Critical Energy of Insulation Degradation E_{id}[a] (kJ/m^2)	Critical Flux of Degradation $\dot{q}''_{id}$[b] (kW/m^2)	Surface Temperature T_s[c] (°C)
56	Teflon/Teflon	9160	16	456
11	EPR/Hypalon	3390	6	297
20	Teflon/Teflon	3190	18	478
8	EPR/Hypalon	1792	11	391
22	Silicone/Asbestos	1620	18	478
59	EPR/Hypalon	1420	19	488
2	XPE/Neoprene	1150	24	534
6	PE/PVC	1000	18	478
17	XPE/Neoprene	900	22	516
57	Silicone/Asbestos	760	21	507
5	PE/PVC	530	18	478

[a] E_{id} is the critical energy of insulation degradation defined as the energy required to initiate the insulation degradation process provided the available heat flux exceeds the minimum requirement.

[b] $\dot{q}''_{id}$ is the critical flux of degradation defined as the minimum heat flux below which no significant insulation degradation can occur (see Section 3.1).

[c] T_s is the surface temperature calculated from $\dot{q}''_{id}$.

Table S-3

IGNITION PARAMETERS FOR PILOTED AND AUTOIGNITION OF CABLES

		Piloted Ignition		Autoignition		
Sample	(No.)	Critical Flux of Piloted Ignition $E_{ig,p}$ [a] (kJ/m^2)	Minimum Flux for Ignition $\dot{q}''_{ig,p}$ [b] (kW/m^2)	Critical Flux Non-Piloted Ignition $E_{ig,n}$ [c] (kJ/m^2)	Minimum Flux for Non-Piloted Ignition $\dot{q}''_{ig,n}$ [d] (kW/m^2)	Difference Piloted to Non-Piloted Ignition $\Delta\dot{q}''$ [e] (kW/m^2)
PE/PVC	(5)	460	18	6010	5	-13
PE/PVC	(6)	690	23	9480	15	- 8
XPE/Neoprene	(2)	1040	21	11290	4	-17
XPE/Neoprene	(17)	510	27	7180	18	- 9
Silicone/ Asbestos	(22)	660	26	3000	31	+ 5
Silicone/ Asbestos	(57)	590	23	4420	27	+ 4
EPR/Hypalon	(8)	-	-	∞ [f]	NA	-
EPR/Hypalon	(11)	640	23	∞ [f]	NA	-
EPR/Hypalon	(59)	390	27	∞ [f]	NA	-
Teflon/Teflon	(56)	4680	24	∞ [f]	NA	-
Teflon/Teflon	(20)	-	-	∞ [f]	NA	-
Teflon/Teflon	(60)	3011	40	-	-	-

[a] $E_{ig,p}$ is the critical energy of piloted ignition defined as the energy required to carry out the ignition process by maintaining a flammable cable sample vapor/air mixture near the surface provided the available heat flux exceeds the minimum requirement.

[b] $\dot{q}''_{ig,p}$ is the critical flux of piloted ignition defined as the minimum flux below which no ignition can occur.

[c] $E_{ig,n}$ is the critical energy of non-piloted ignition defined the same as a.

[d] $\dot{q}''_{ig,n}$ is the critical flux of non-piloted ignition defined the same as b.

[e] $\Delta\dot{q}''$ is the difference between $\dot{q}''_{ig,p}$ and $\dot{q}''_{ig,n}$.

[f] no autoignition was observed at least up to 70 kW/m^2.

Table S-4

ELECTRICAL FAILURE PARAMETERS FOR CABLES UNDER PILOTED IGNITION CONDITION

Sample	(No.)	Critical Energy of Electrical Failure E_{ef} [a] (kJ/m^2)	Critical Flux of Electrical Failure $\dot{q}''_{ef}$ [b] (kW/m^2)
Silicone/Asbestos	(22)	∞ [d]	NA
Silicone/Asbestos	(58)	∞ [d]	NA
Teflon/Teflon	(56)	∞ [d]	NA
EPR/Hypalon	(59)	23,700	17
EPR/Hypalon	(11)	19,600	9
XPE/Neoprene	(2)	19,500	– [c]
EPR/Hypalon	(8)	16,950	14
PE/PVC	(5)	9,070	– [c]
PE/PVC	(6)	6,530	24
XPE/Neoprene	(17)	5,560	19

[a] E_{ef} is the critical energy of electrical failure defined as the energy required to break down the insulation to cause electrical shorting of the conductors provided the available heat flux exceeds the minimum requirement.

[b] $\dot{q}''_{ef}$ is the critical flux of electrical failure defined as the minimum heat flux below which no electrical failure can occur.

[c] The critical flux of electrical failure cannot be determined for these cable samples.

[d] No electrical failure was observed at least up to 70 kW/m^2.

can be based on energy requirements alone. In this classification, Teflon/Teflon cable is ranked highest with critical energy of 9169 kJ/m^2 while PE/PVC cable is ranked lowest with critical energy of 530 kJ/m^2.

S.3.2 Ignition

Table S.3 presents the values of critical energy and critical flux for both piloted and non-piloted ignition of cables. As seen from the table, the energy requirement of the cables for piloted ignition is of the same order of magnitude as that for insulation/jacket degradation in Table S-2; this is because the pilot flame ignites the sample vapor shortly after the polymer begins to degrade. This implies that the time required for the vapor/air mixture to achieve flammable ratio is very close to the time to initiate insulation degradation. As for the minimum flux requirement, all except one cable (Sample 60) show values within 22 $\pm$ 5 kW/m^2. The similarity of these values simplifies the problem to some extent in providing planners and engineers with a guideline for safety considerations.

For non-piloted ignition, the energy requirements are comparatively much higher than for piloted ignition because of the absence of an external ignition source such as a pilot flame. By comparing the results in Table S-3 of piloted and non-piloted ignition, it is shown that the critical flux values of the chlorine-containing cables under non-piloted ignition are lower than those under piloted ignition. This difference in minimum flux requirement is shown as $\Delta\dot{q}''$ in Table S-3. These lower values of the minimum flux requirement for non-piloted ignition situation could have been a result of exothermic reactions occurring on sample surfaces upon prolonged heating(12). These reactions were not evident for piloted ignition experiments because the ignition initiated by the pilot occurred shortly after the insulation degradation began. A more detailed investigation on the chemical kinetics of these polymers upon heat flux exposure is needed in order to examine the actual process occurring at the polymer surface.

S.3.3 Electrical Integrity Failure

Table S-4 presents the values of critical energy and critical flux for electrical failure of cables. The energy requirement for this process is the highest among the three damage processes chosen. The critical heat flux levels are similar to those of insulation/jacket degradation. It is important to realize that the process of electrical failure is not entirely dependent on insulation/jacket degradation. This failure is primarily a result of the conductors shorting with one another which depends strongly on how the insulation degrades under thermal exposure and the product formed after exposure (both in flaming and non-flaming situations); silicone cable is a good illustration. The formation of silicon oxide in the flaming fire situation provides the conductors with a layer of insulation to prevent their being shorted with one another. Thus, a cable which has high insulation/jacket degradation potential does not necessarily imply poor performance in maintaining electrical integrity. Insulation/jacket degradation depends on the properties of the source material, while electrical failure is directly related to the products that are formed during degradation.

S.3.4 Hydrogen Chloride Generation

It has been reported(7,8,9) that the generation of HCl from chlorine-containing cables could be hazardous with regard to toxicity and corrosivity. In this program, a preliminary study was conducted on the generation rate of HCl from three chlorine-containing cables under a given thermal environment. The results are presented in Figure S-1. Of the three cables tested, the most hazardous was PE/PVC, then XPE/Neoprene, and finally EPR/Hypalon. A 0.1 m sample of PE/PVC burning under a thermal environment of 60 kW/m^2 can generate 67 ppm of HCl within a 5 m x 5 m x 3 m compartment in a 5-min period. In a report by Tewarson(8) on the toxicity of HCl generation in fire, a level of 50 ppm was considered to be critical for human escape. Therefore, the toxicity and corrosivity hazards presented by the chlorine-containing cables in fires is not to be ignored. However, because of the scope of this work, only a preliminary study was conducted in this area. Further work is needed to investigate in detail the mechanisms of HCl generation from chlorine-containing polymers and its interaction with different damage processes in fire environment.

S.4 CONCLUSION, DAMAGEABILITY INDEX

In conclusion, it is apparent that the damage potential of a cable cannot be expressed by a single parameter alone but by a combination of parameters. Each process can be represented by a critical flux level and a critical energy level. Based on the definition of these two parameters, critical energy and critical flux of the three damage processes can be related by the following indices:

$$IDI = \frac{\dot{q}''_e - \dot{q}''_{id}}{E_{id}} \quad \text{(insulation degradation index)} \tag{S-1}$$

$$PII = \frac{\dot{q}''_e - \dot{q}''_{ig,p}}{E_{ig,p}} \quad \text{(piloted ignition index)} \tag{S-2}$$

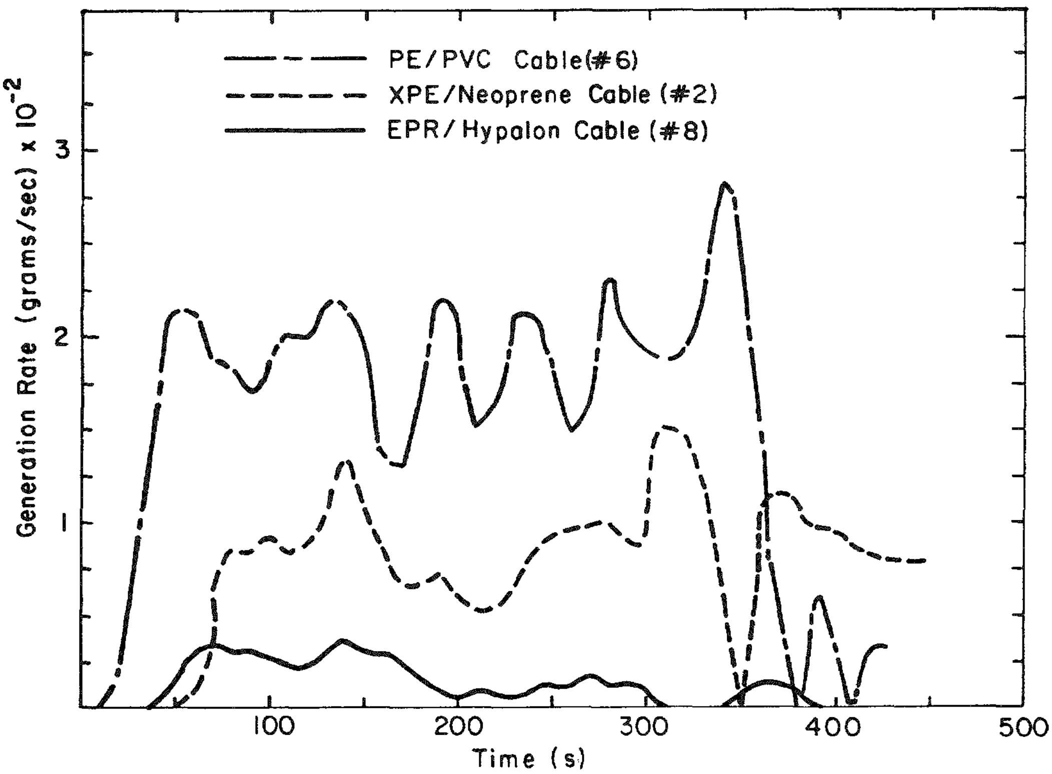

Figure S-1. HCL Generation Rate of Chlorine-Containing Cables at External Heat Flux of 60 kW/m^2

$$EFI = \frac{\dot{q}''_e - \dot{q}''_{ef}}{E_{ef}} \qquad \text{(electrical failure index)} \qquad \text{(S-3)}$$

where:

IDI, PII, and EFI: the combined damageability indices of the insulation degradation, piloted ignition and electrical failure processes respectively (s^{-1}).

$\dot{q}''_e$: external heat flux (kW/m^2).

E_{id}, $E_{ig,p}$ and E_{ef}: the critical energy of insulation degradation, piloted ignition and electrical failure processes respectively (kJ/m^2).

$\dot{q}''_{id}$, $\dot{q}''_{ig,p}$ and $\dot{q}''_{ef}$: the critical flux of insulation degradation, piloted ignition and electrical failure processes respectively (kJ/m^2).

Figures S-2 to S-4 show the relationship of these three damageability indices with external heat flux. The many criss-crossings which appear in the figures imply the heat flux dependency of the cable damage potential. A cable showing higher damage potential than another at one heat flux level may turn out to be the opposite at another level. This fact infers the difficulties in classifying cables based on the damageability determined under one set of test conditions. Classification is possible if one knows the particular scenario of interest and the order of importance of the three damage processes previously mentioned. If this information is known priori, it is possible to use the cable damageability results from the laboratory-scale apparatus to estimate the damage potential of cables in the selected scenario. Thus planners and engineers would be provided with useful guidelines for designing protective systems or optimizing the selection of materials installed in the facility for improving the safety.

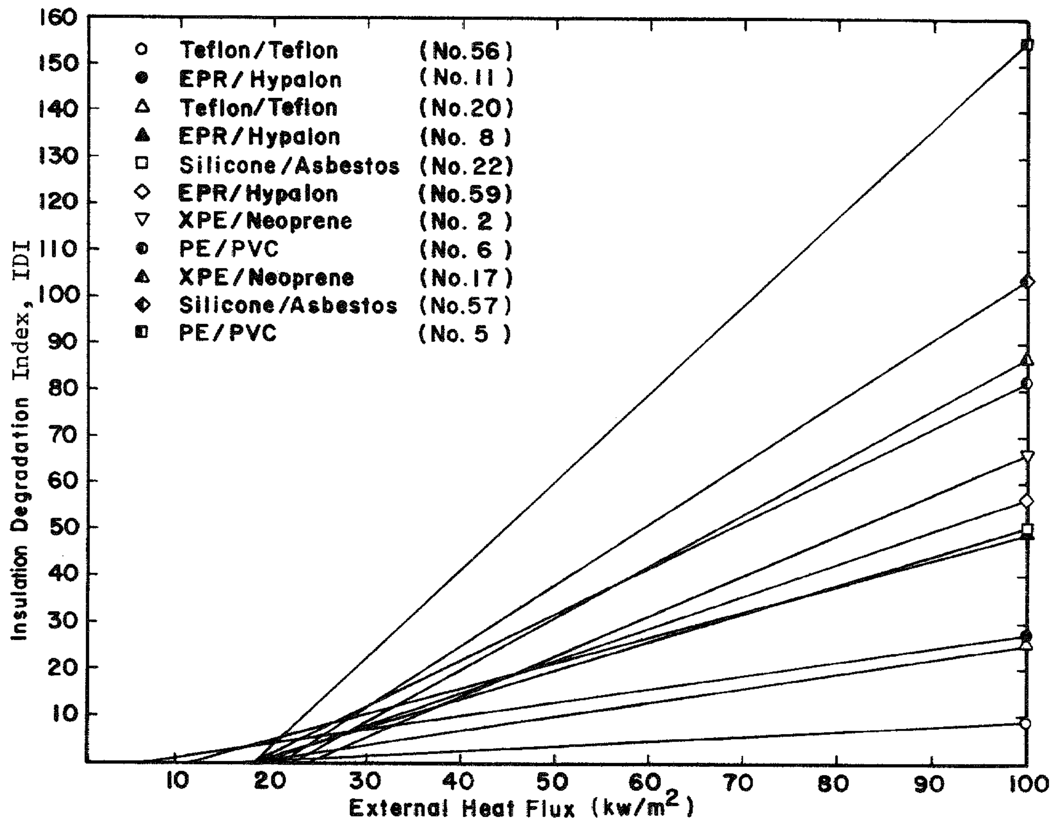

Figure S-2. The Variation of Insulation Degradation Index, IDI, with External Heat Flux for Various Cables

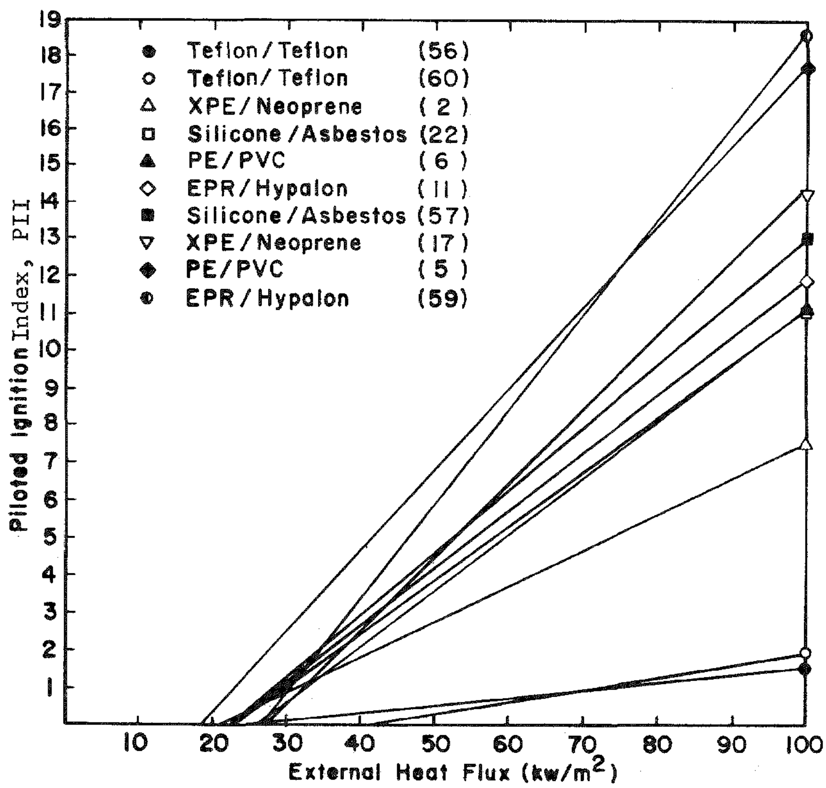

Figure S-3. The Variation of Piloted Ignition Index, PII, with External Heat Flux for Various Cables

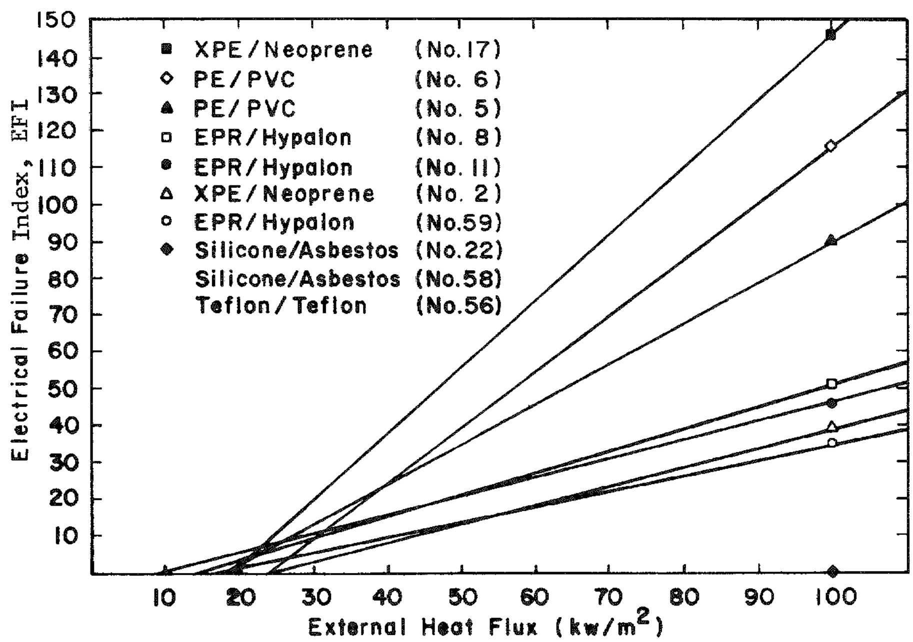

Figure S-4. The Variation of Electrical Failure Index, EFI, with External Heat Flux for Various Cables

Section 1

INTRODUCTION AND BACKGROUND

Electrical cables, an integral part in today's power generating facilities, are insulated with various synthetic polymers such as polyvinyl chloride, silicone rubber, and neoprene. Chemical additives, such as retardants, plasticizers, etc., are combined in these polymers to improve the performance of the cables for different applications. A description of some of these polymers and the additives are presented in reference 1. In fires, cables with and without additives under certain conditions may present a hazard. Thus, a program was undertaken by Factory Mutual Research Corporation (FMRC) under contract with Electric Power Research Institute (EPRI) to investigate 1) the combustibility of cables by using a laboratory-scale apparatus (Part I)(1); 2) the detection of fires in cable tray installations (Part II)(2); and 3) the protection by sprinklers against fires in cable trays (Part III)(3). Under Part I, FMRC had examined 22 different types of cables under flaming fire condition to determine the combustibility characteristics including ignition and flame spread behavior, critical mass loss rate for ignition, fire intensity in changing thermal environment, fire hazard in terms of heat release rates, and optical transmission properties through products. These results were presented in a previous report(1).

It was reported(4) that the likelihood of a cable ignition due to electrical short circuiting or arcing is very slight; rather, the most probable source of ignition is external to the cable tray arrangement and could be a burning pool of spilled flammable liquid or accumulated debris. With this consideration, a second program was undertaken by FMRC under the same contract with EPRI to investigate 1) the ignition characteristics of spilled flammable liquids (Part I)(5); 2) the hazards involved in an exposure fire (Part II)(4); 3) the damageability of the electric cables under varying thermal environments (Part III). Under Part III, FMRC utilized the FM combustibility apparatus to examine the response of cable insulation/jacket material and circuit integrity to varying thermal environments. The present report presents the results of this part of the program. The supposition behind this study is that under a given thermal environment, the cables in tray arrangement may undergo a series of fire stages such as insulation/jacket degradation, ignition, fire growth, maximum burning, fire decay, etc. However, before the fire is fully developed, damage has already occurred in the cables which may cause impairment to the normal function of the cables. This impairment may be due to the effect of changes in the cable properties, such as insulation resistance, dielectric strength, and bending characteristic, upon heat flux exposure. These changes are considered critical to the operation of a facility where cables play such an integral part of the entire system.

Thus, in this study (Part IV), the following tasks were undertaken to quantify the damage potential of cables:

1) generation of data for evaluating the damageability of cables exposed to varying thermal environments;

2) generation of data for establishing a system of classifying cables based on their damageability characteristic;

3) examination of the generation of HCl from chlorine-containing cables under flaming fire environment for assessing its hazard potential.

Section 2

DESCRIPTION OF APPARATUS AND THE EXPERIMENTAL PROCEDURE

A detailed description of the FM combustibility apparatus was presented in Section 3 of reference 1. A brief description of the apparatus (Figure 2-1) and the experimental procedure applicable to the study of cable damageability are presented in the following subsections. The samples used throughout the testing program refer to a single 0.1 m long cable except for the electrical failure experiments which required much longer cables. Four tests on each sample exposed to four different heat fluxes were conducted in each test category.

2.1 INSULATION/JACKET DEGRADATION

The cable sample was placed on a flat aluminum platform above a water-cooled load cell assembly which continuously monitored the amount of fuel vaporized under heat flux exposure (see Figure 2-1). The tests were conducted under non-piloted ignition environment in order to examine in detail the insulation/jacket degradation behavior. The output of the load cell was monitored by a strip chart recorder where the weight loss against time was plotted out instantaneously. The time to initiate degradation is determined by a linear extrapolation of the steady rise portion of the curve to the time axis. This is a method widely adopted by many disciplines for describing the baseline intercept of a gradual increasing function(6).

Figure 2-2 shows a typical set of weight loss curves for a PE/PVC cable exposed to five different heat fluxes and the inspective degradation initiation times.

2.2 IGNITION

In the same apparatus, ignition experiments were carried out for both piloted and non-piloted ignition. For the piloted ignition case, a pilot flame about 2.5 cm long was located 1 cm above the sample surface. For non-piloted ignition experiments, the pilot flame was removed. In both cases, the time to ignition was recorded.

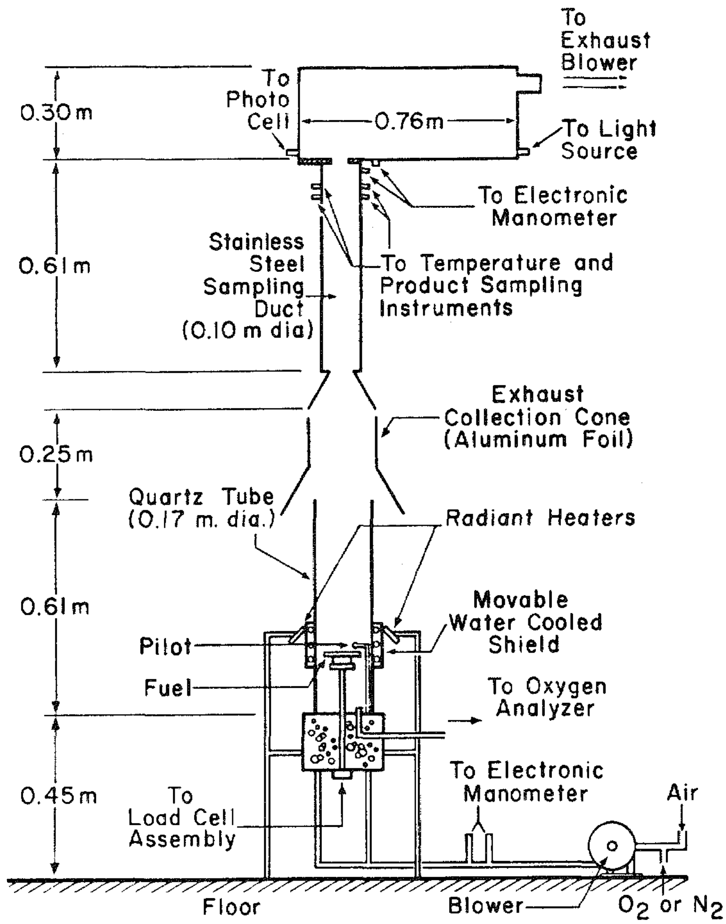

Figure 2-1. FM Combustibility Apparatus

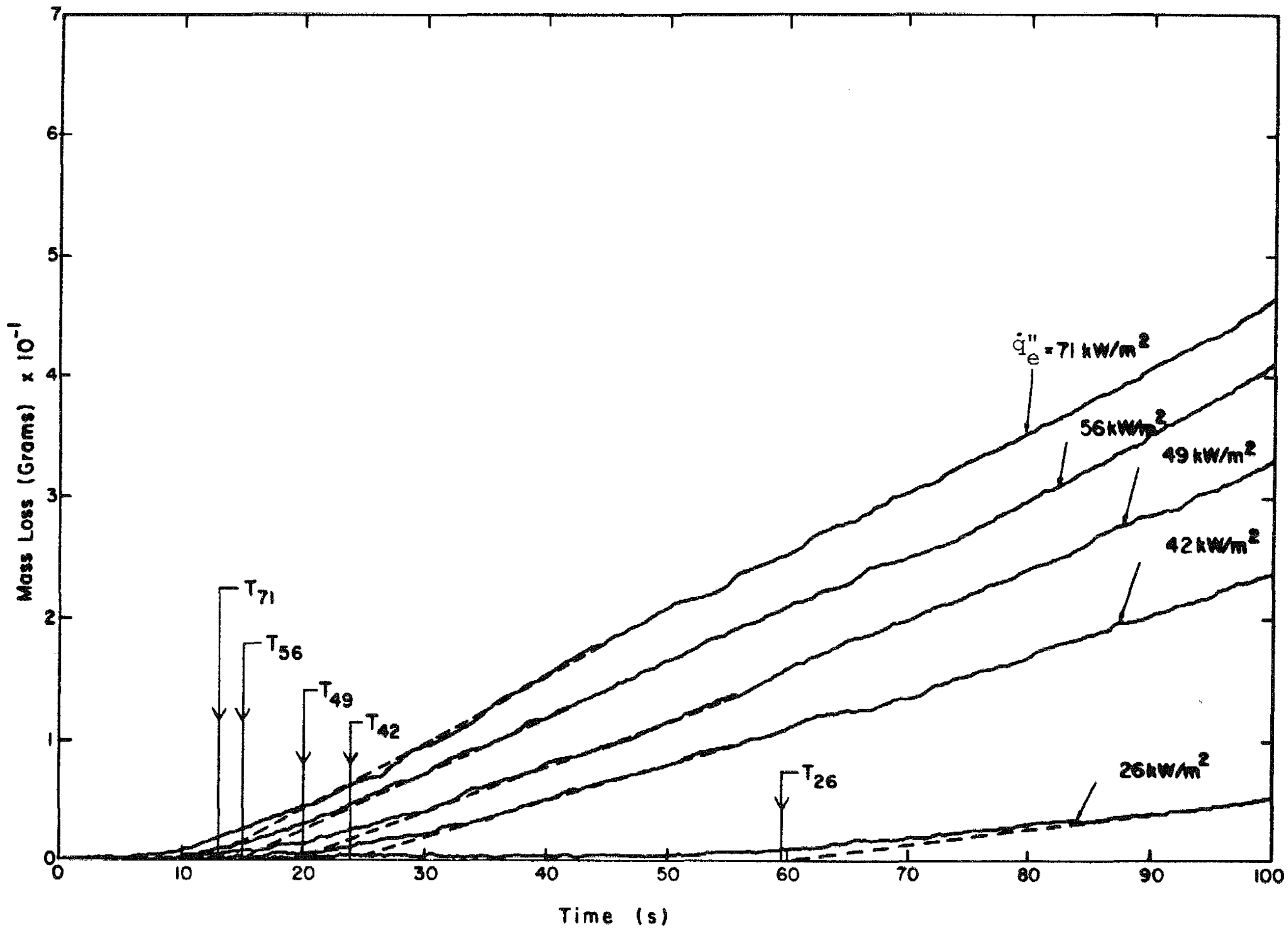

Figure 2-2. Time History of Mass Loss of PE/PVC Cable (#5) at Various External Heat Flux ($\dot{q}_e''$). $T_{\dot{q}_e''}$ is the time to initiate insulation degradation process.

2.3 ELECTRICAL INTEGRITY FAILURE

In this set of experiments, the conductors of the cable sample on the aluminum platform were extended 0.5 m long at each end of the cable and clamped to a terminal strip located outside the heat flux exposure zone. Only the middle 0.1 m portion of the cable sample was exposed to heat flux.

A simple voltage drop principle was utilized in this experiment by connecting known resistors between conductors at the terminal strips, thus making all the conductors one continuous wire interconnected by these resistors. One additional resistor was placed at the end of this connected conductor, across which the voltage drop was measured. Voltage was applied between the two ends of the connected conductor such that the voltage drop across each resistor was about 70 V dc. When any two or more conductors were shorted together, the voltage drop measured across the last resistor would increase. In the case of the cable shorting to ground, the voltage drop would indicate zero. In either situation, the total time required to initiate electrical failure was determined by the change in voltage. These tests were conducted under piloted ignition condition. A schematic of the test setup is shown in Figure 2-3.

2.4 HCl GENERATION

For the chlorine-containing polymers such as polyvinyl chloride (PVC), Hypalon, and Neoprene rubber, etc., the gases generated during combustion were passed continuously through a 1-liter vessel containing distilled water of known volume. The dissolved chloride ion (Cl^-) concentration was measured by a chloride ion electrode together with an Orion digital ion analyzer.

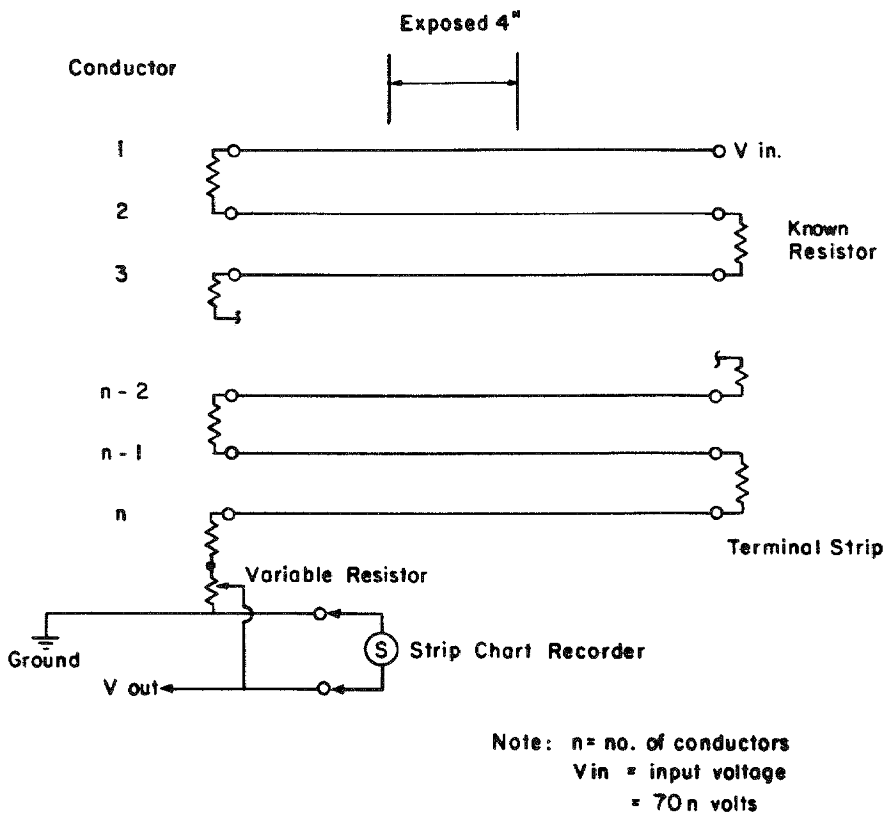

Figure 2-3. Schematic of Electrical Integrity Failure Experimental Setup

Section 3

EXPERIMENTAL RESULTS

A physical description of the 14 cable samples tested is presented in Table 3-1. Samples consisted of five generically different types of polymers: cross-linked polyethylene/Neoprene; polyethylene/polyvinyl chloride; ethylene propylene rubber/Hypalon; Teflon/Teflon; and silicone rubber/asbestos. Although some cables were of the same generic type, this was no implication that they should behave in exactly the same manner because of their intrinsic differences in manufacturing processes, construction type, number and size of conductors, amount of additives, etc. In this study, our goal is to evaluate the damage incurred by a cable when exposed to varying thermal environments. The "damage" here is defined as a change in cable properties, such as insulation resistance, dielectric strength, bending characteristic, electrical integrity, etc., as a result of thermal exposure. These changes are not all measurable and, therefore, only three quantifiable damage processes which are considered critical to the normal functioning of cables were chosen to measure the cable damage potential. The processes chosen were: insulation/jacket degradation, ignition, and electrical integrity failure.

Insulation/jacket degradation is measured by the vaporization process of the material upon heat flux exposure. This degradation implies possible changes in insulation properties such as swelling, shrinking, melting, cracking, and disintegration due to thermal exposure.

Ignition is the extreme event in the insulation/jacket degradation. When ignition occurs, the cable is considered totally damaged.

From the viewpoint of electrical integrity, even though the insulation/jacket may remain intact, as long as the conductors are shorted causing electrical failure, the cable is definitely "damaged" because its intended function to carry power is impaired. Thus, electrical shorting is also used as a quantitative measure of cable damageability. It should be noted that no investigation was made of the effects of water on partially damaged cables. The results reported are based solely upon heat flux and 70-V circuit voltage.

Table 3-1

CABLE SAMPLES USED IN THIS STUDY[a]

No.	Insulation/Jacket Material	Conductor No.	Conductor Size (AWG)	Outer Cable Diameter in.	Outer Cable Diameter (m)	Insulation/Jacket Material (% of Total Cable Weight)	IEEE-383 Rating
2	XPE/Neoprene[b]	7	12	0.630	(0.016)	53.6	-
17	XPE/Neoprene	3	16	0.394	(0.010)	73.2	Pass
5	PE/PVC[c]	3	-	0.433	(0.011)	49.9	Fail
6	PE/PVC	5	-	0.709	(0.018)	51.0	-
8	EPR/Hypalon[d]	1	2	0.433	(0.011)	23.2	Pass
11	EPR/Hypalon	5	14	0.669	(0.017)	23.9	Pass
59	EPR/Hypalon	7	9	0.984	(0.025)	57.5	-
20	Teflon/Teflon	34	20	0.472	(0.012)	48.8	Pass
56	Teflon/Teflon	7	16	0.394	(0.010)	28.1	-
60	Teflon/Teflon	7	20	0.276	(0.007)	32.7	-
21	Silicone (Glass Braid)	1	-	0.354	(0.009)	34.0	-
22	Silicone, Glass Braid/Asb.[e]	9	14	0.827	(0.021)	70.5	Pass
58	Silicone, Glass Braid/Asb.	3	-	1.142	(0.029)	37.3	-
57	Silicone, Glass Braid/Asb.	7	12	0.787	(0.020)	58.4)	-

[a] Cables Nos. 2, 5, 6, 8, 11, 17, 20, 21, and 22 are the same as those used in the previous study[(1)].

[b] Cross-linked polyethylene insulation with Neoprene jacket cable.

[c] Polyethylene insulation with polyvinyl chloride jacket cable.

[d] Ethylene propylene rubber insulation with chlorosulfurated polyethylene jacket cable.

[e] Silicone rubber insulation with asbestos, glass braided jacket cable.

3.1 INSULATION/JACKET DEGRADATION

Experiments on degradation of insulation/jacket material were all conducted under non-piloted ignition environment, thus allowing examination of the polymer degradation process without interference by early ignition. A few selected photographs of the thermally damaged cables are presented in Figures 3-1 to 3-4.

3.1.1 Inverse of Time to Insulation/Jacket Degradation versus External Heat Flux

When the inverse of the times to degradation are plotted against the respective heat flux, a relationship can be established from which two important parameters can be derived: 1) the effective energy of degradation, E_{id}, which is the inverse of the slope of the linear portion of the curve; and 2) the critical flux of degradation, $\dot{q}''_{id}$, which is the intercept on the abscissa of the linear portion of the curve. The relationship was examined for the five different generic groups of cables and the results are shown in Figures 3-5 to 3-9. As seen from these figures, the curves deviate from linearity as the external heat flux is reduced below a certain level except for the Teflon/Teflon cables. If the linear portion of the curve is extrapolated back to the heat flux axis, the critical flux of degradation, $\dot{q}''_{id}$, is obtained which is defined as the heat flux at or above which significant degradation will begin. From the same curve, taking the inverse of the slope of the linear portion of the curve, the critical energy of degradation, E_{id}, is obtained which is defined as the energy required to maintain a steady vaporization process in the polymer which is the product of the available heat flux and the time to insulation degradation. Figure 3-10 summarizes the relative degree of damage of the cables tested. Table 3-2 presents values of E_{id} and $\dot{q}''_{id}$ with the respective calculated surface temperatures T_s of the 11 cables tested in this set of the experiments.

Based on the definition of E_{id} and $\dot{q}''_{id}$, these two parameters can be related by the following equation:

$$IDI = \frac{\dot{q}''_e - \dot{q}''_{id}}{E_{id}} \qquad (3\text{-}1)$$

where IDI = insulation degradation index (s^{-1});

E_{id} = effective energy of degradation (kJ/m^2);

$\dot{q}''_{id}$ = minimum effective flux of degradation (kW/m^2); and

$\dot{q}''_e$ = external heat flux (kW/m^2).

Figure 3-1. Thermal Damage to PE/PVC Cable at 31 kW/m^2 Exposure (Sample 6)

Figure 3-2. Thermal Damage to XPE/Neoprene Cable at 31 kW/m^2 Exposure (Sample 2)

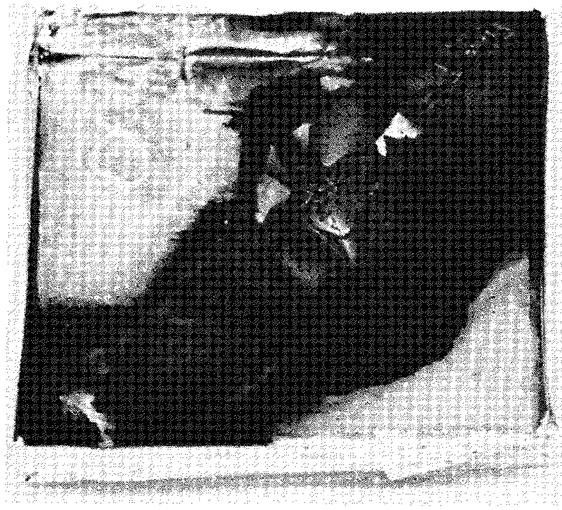

Figure 3-3. Thermal Damage to EPR/Hypalon Cable at 26 kW/m^2 Exposure (Sample 8)

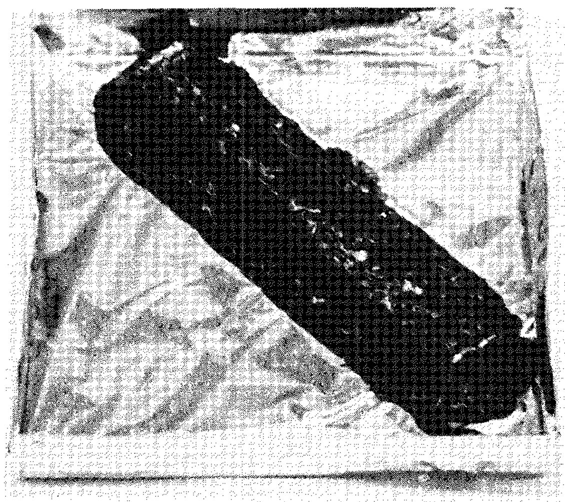

Figure 3-4. Thermal Damage to Teflon/Teflon Cable at 26 kW/m^2 Exposure (Sample 20)

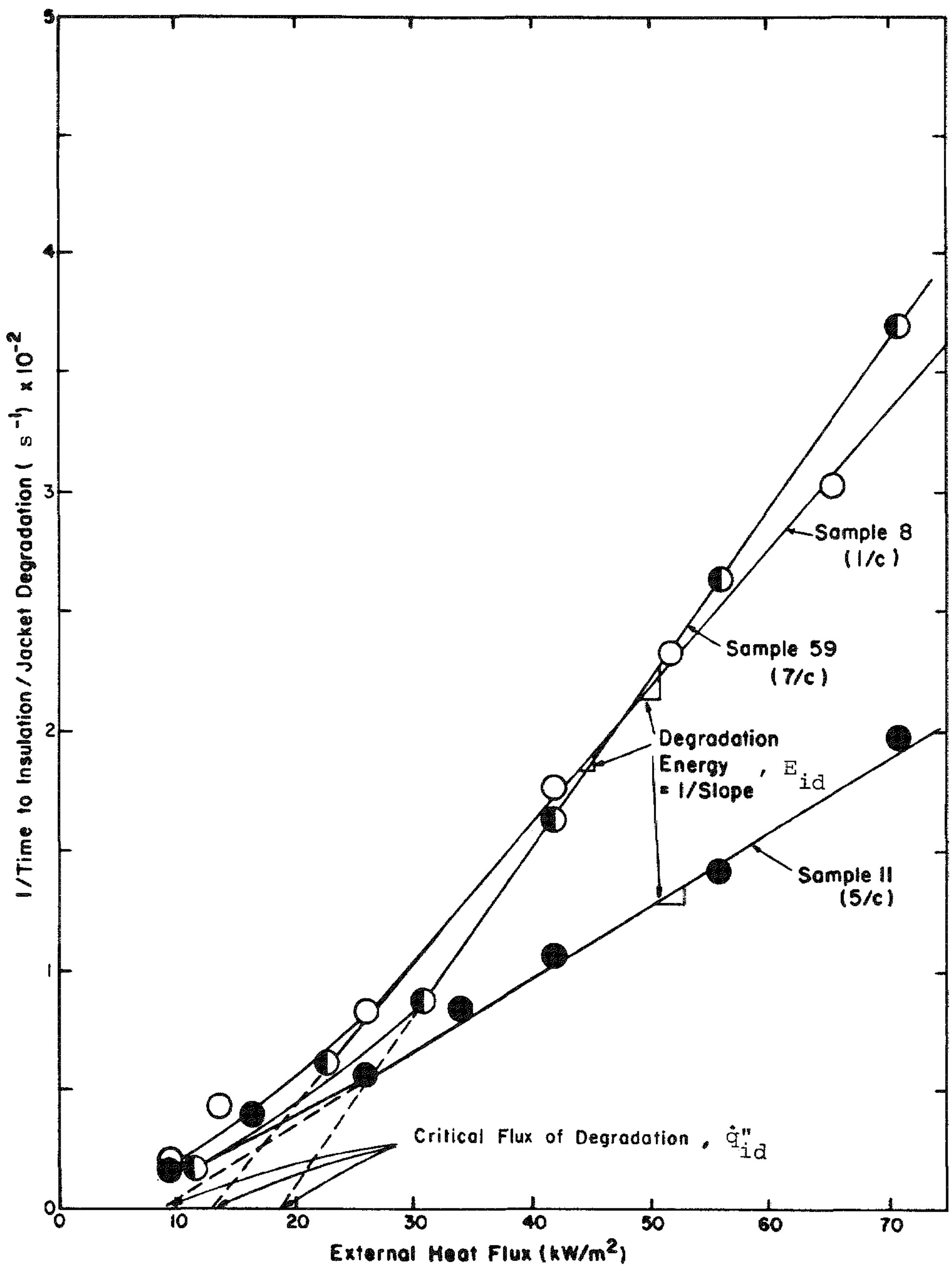

Figure 3-5 Thermal Degradation of EPR/Hypalon Cables

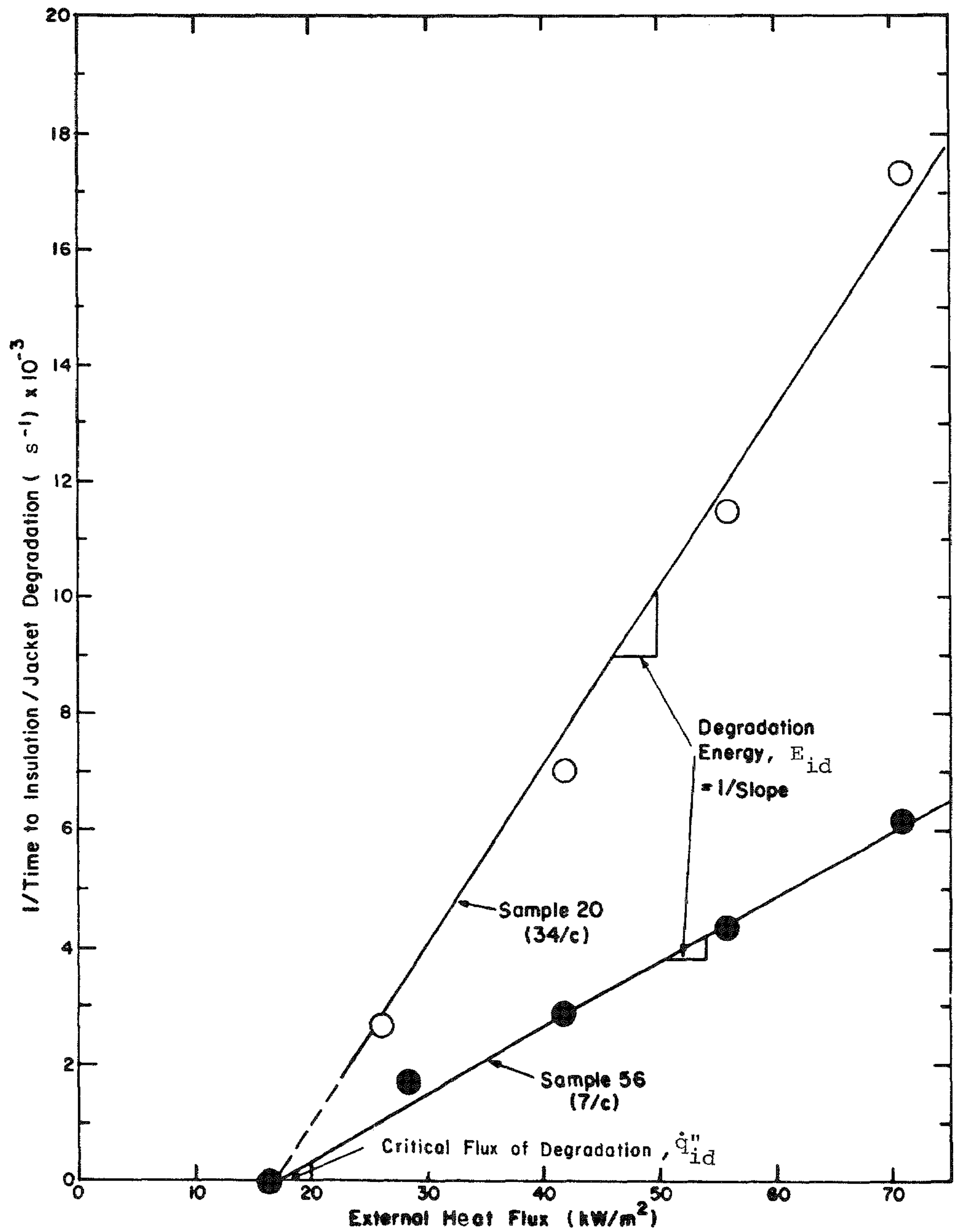

Figure 3-6 Thermal Degradation of Teflon/Teflon Cables

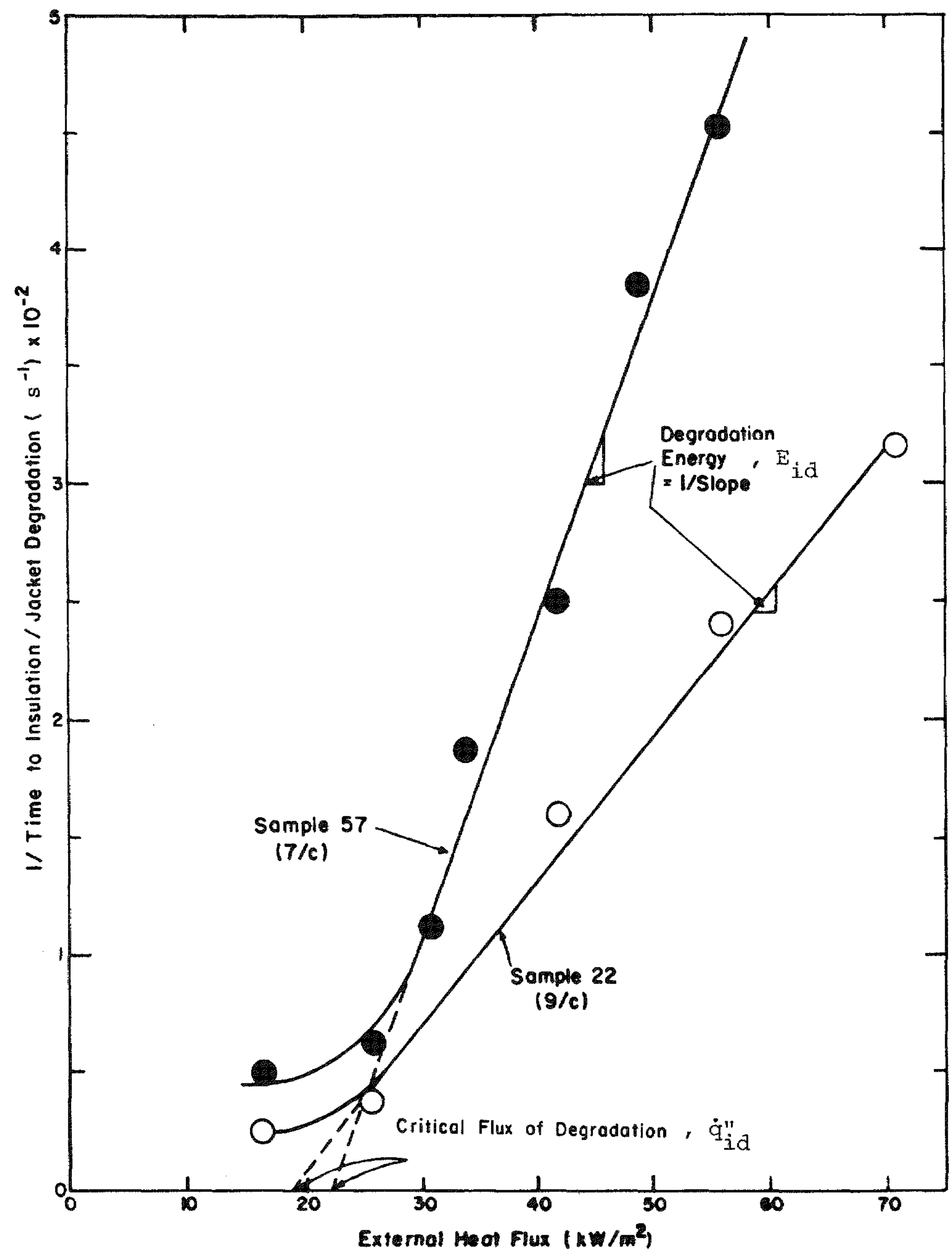

Figure 3-7 Thermal Degradation of Silicone/Asbestos Cables

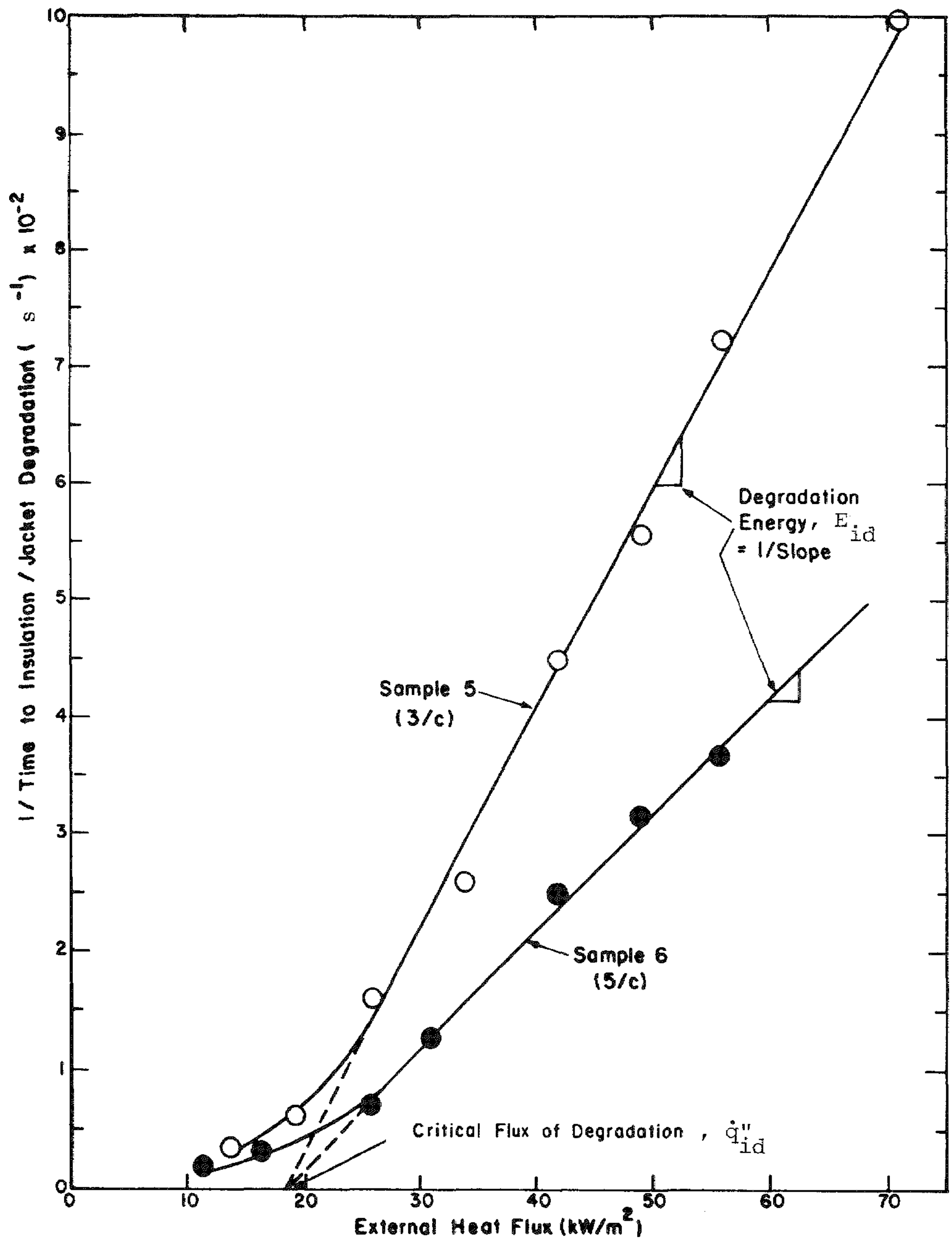

Figure 3-8 Thermal Degradation of PE/PVC Cables

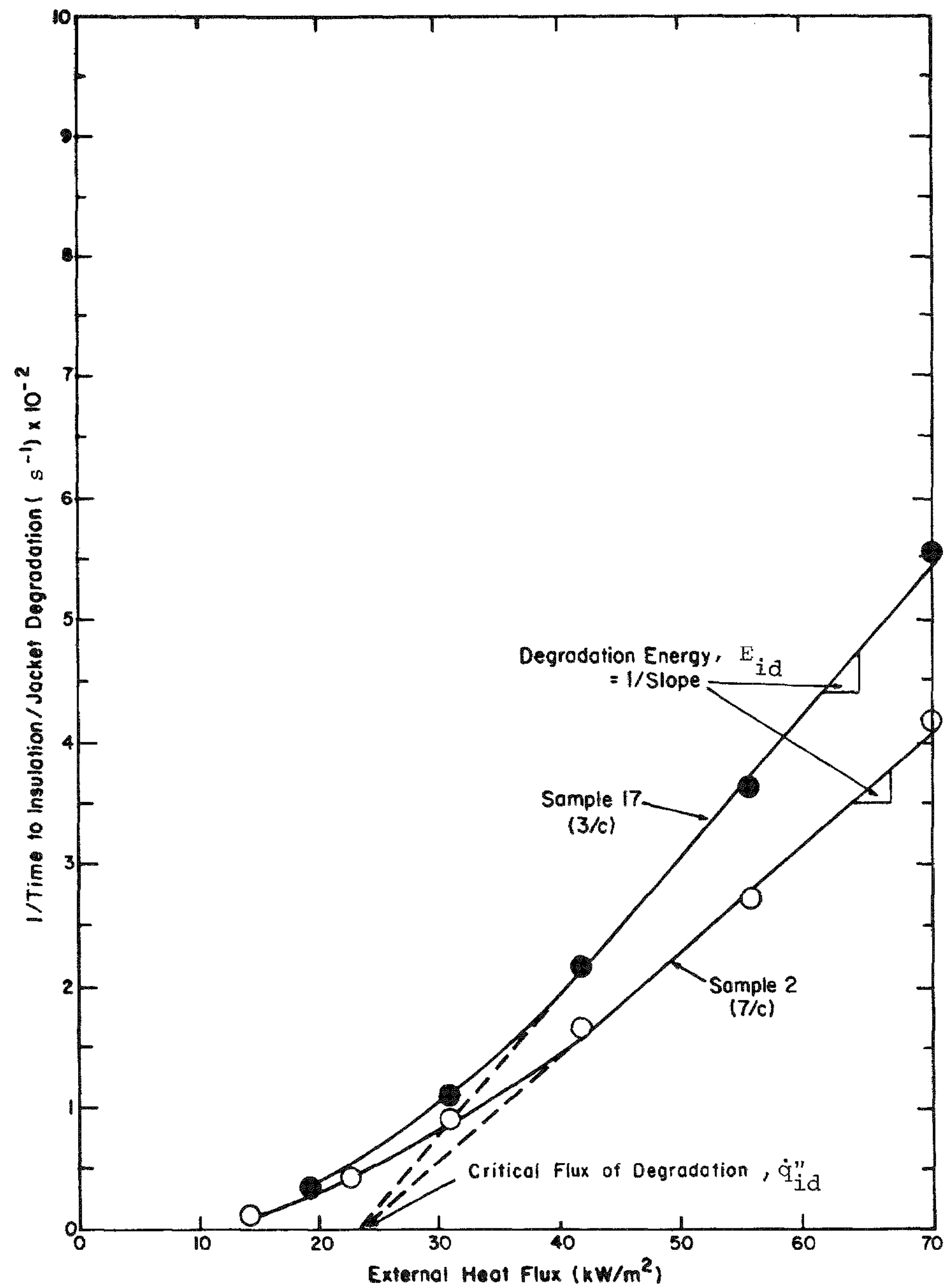

Figure 3-9 Thermal Degradation of XPE/Neoprene Cables

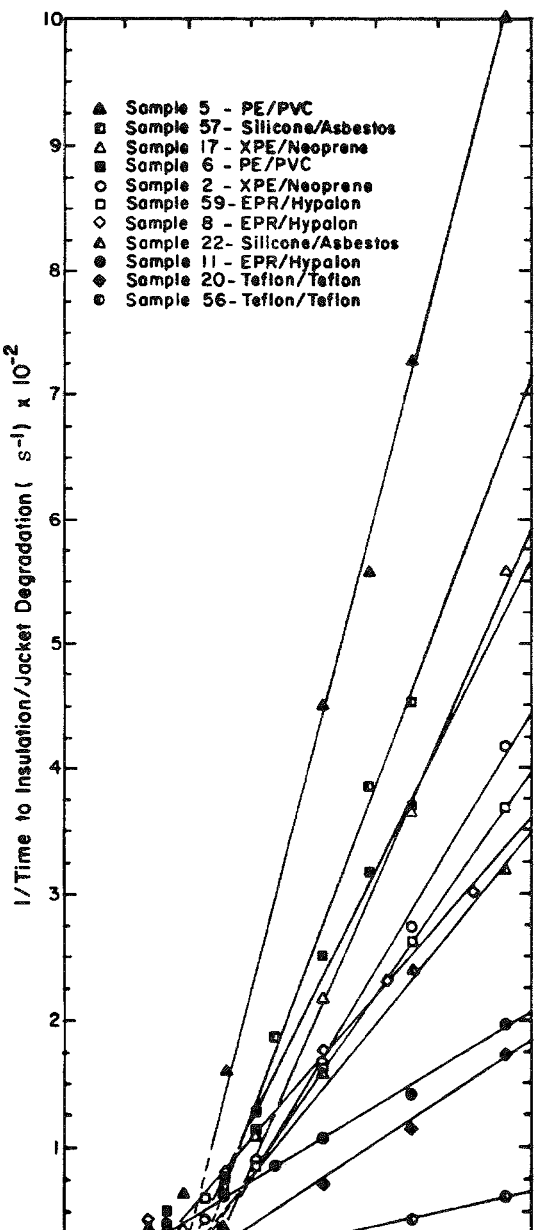

Figure 3-10 Thermal Degradation of Cable Insulations Under Various External Heat Flux

Table 3-2

INSULATION DEGRADATION PARAMETERS OR CABLE SAMPLES

No.	Cable Sample	Critical Energy of Insulation Degradation E_{id} [a] (kJ/m^2)	Critical Flux of Degradation $\dot{q}''_{id}$ [b] (kW/m^2)	Surface Temperature T_s [c] (°C)
56	Teflon/Teflon	9160	16	456
11	EPR/Hypalon	3390	6	297
20	Teflon/Teflon	3190	18	478
8	EPR/Hypalon	1792	11	391
22	Silicone/Asbestos	1620	18	478
59	EPR/Hypalon	1420	19	488
2	XPE/Neoprene	1150	24	534
6	PE/PVC	1000	18	478
17	XPE/Neoprene	900	22	516
57	Silicone/Asbestos	760	21	507
5	PE/PVC	530	18	478

[a] E_{id} is the critical energy of insulation degradation defined as the energy required to initiate the insulation degradation process provided the available heat flux exceeds the minimum requirement.

[b] $\dot{q}''_{id}$ is the critical flux of degradation defined as the minimum heat flux below which no significant insulation degradation can occur (see Section 3.1).

[c] T_s is the surface temperature calculated from $\dot{q}''_{id}$.

The index IDI can be calculated from known values of E_{id} and $\dot{q}''_{id}$ at various $\dot{q}''_e$ values (Figure 3-11), generalizes the insulation/jacket degradation potential for different magnitudes of exposure fire.

3.1.2 Discussion

An examination of the curves of each generic group of cables (Figures 3-5 to 3-9) shows that the actual minimum flux for degradation is lower than the projected critical flux for degradation, because the curves tend to deviate upward at lower heat flux values. This difference is most pronounced in silicone/asbestos cables and least in Teflon/Teflon cables. This deviation could be a result of some exothermic processes occurring at the sample surface under prolonged heating. However, from the appearance of the samples tested at these low heat flux levels. the damage was not significant. Thus, as far as cable damage is concerned, the minimum heat flux for degradation is determined by the critical flux of degradation which is the intercept of the abscissa of the linear portion of the curves in Figures 3-5 to 3-9.

It appears that cables of the same generic group show similar values of $\dot{q}''_{id}$ but different values of E_{id}. In general, the values of $\dot{q}''_{id}$ for the different generic groups of cables tested are within the range of 20 $\pm$ 4 kW/m^2 except two of the EPR/Hypalon cables which indicate 6 and 11 kW/m^2. The effective energy of degradation is highest for Teflon/Teflon cables and least for PE/PVC cables. The damageability of the cables is defined by both parameters: E_{id} and $\dot{q}''_{id}$. Some cables which have values of $\dot{q}''_{id}$ requiring higher heat flux input to initiate the damage process may have low values of E_{id} requiring little energy to carry on the process or vice versa. From Figure 3-11 it can also be seen that a cable's high rating on insulation degradation at one heat flux level does not imply the same relative rating at a higher heat flux level; this is demonstrated clearly by cable 11. Therefore it is not realistic to classify cables by only one heat flux exposure as is commonly used in many standard testing procedures; rather, the thermal history of the cables should be considered before classifying them on their overall performance.

3.2 IGNITION

The extreme event of the insulation/jacket degradation process is ignition. After ignition occurs, insulation degradation is caused both by external heat flux and the heat flux from the flame itself. Experience shows that there are two general modes of ignition(7): piloted and autoignition (non-piloted ignition). Autoignition is believed to be a result of an increase of the temperature of the gases

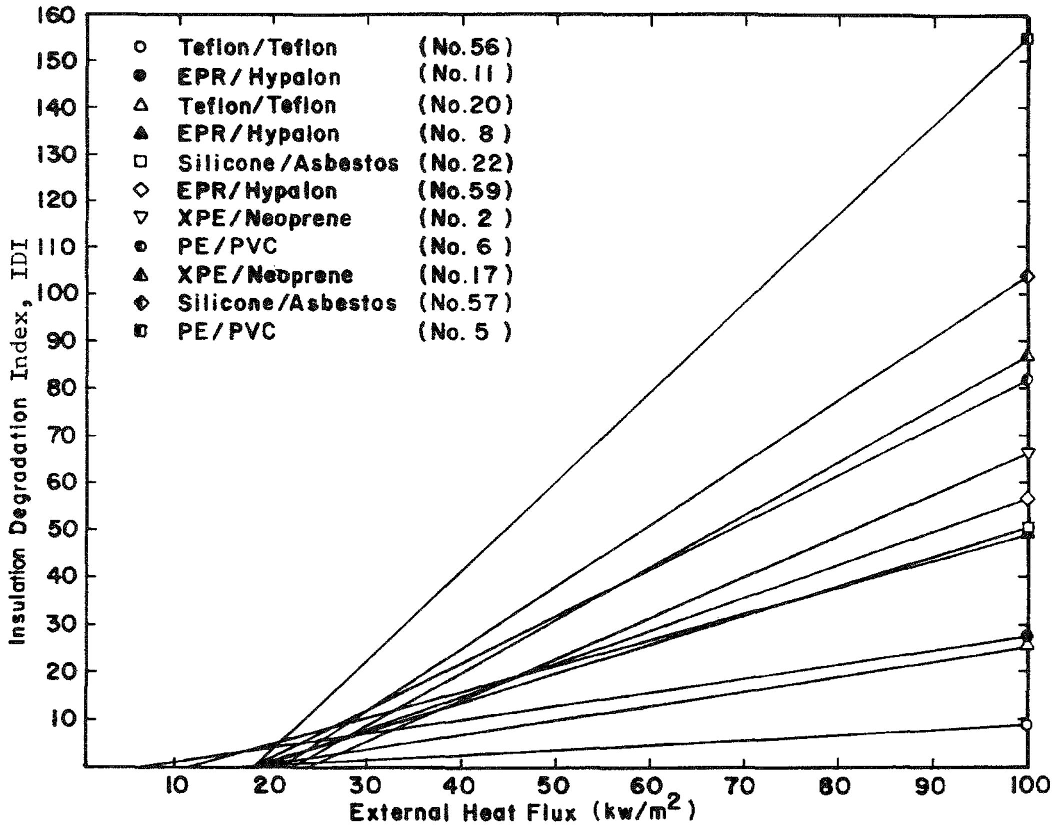

Figure 3-11 The Variation of Insulation Degradation Index, IDI, with External Heat Flux for Various Cables

evolved from the sample through an exothermic reaction, while piloted ignition occurs as a result of local energy addition from an external source such as a pilot flame, an electric spark, or an incandescent particle. Both modes require a basic supply of energy from an external source which could be a heated wall, an exposure fire, heaters, etc. In this program, ignition data were obtained under both piloted and non-piloted (or auto) ignition conditions.

3.2.1 Inverse of Time to Ignition Versus External Heat Flux

When the inverse of the times to ignition of a sample is plotted against the respective external heat flux, a relationship similar to that for insulation/jacket degradation may be established from which the two parameters, E_{ig} and $\dot{q}''_{ig}$, can be derived (see Figure 3-12). Table 3-3 shows the values of E_{ig} and $\dot{q}''_{ig}$ for both piloted and non-piloted ignition requirements for easy comparison. The relationship shown in Figure 3-12 is linear. The inverse of the slope of the curve is the effective energy of ignition, E_{ig}, defined as the energy required to maintain a flammable vapor/air mixture near the surface which is the product of the available heat flux and the time to ignition; the intercept of the abscissa of the curve is the critical flux of ignition, $\dot{q}''_{ig}$, defined as the heat flux below which no ignition can occur. These two parameters together define the ignition characteristic of the cable samples.

From the definition of E_{ig} and $\dot{q}''_{ig}$, these two parameters can be related by the following expression:

$$PII = \frac{\dot{q}''_e - \dot{q}''_{ig}}{E_{ig}} \qquad (3\text{-}2)$$

where $\dot{q}''_e$ = external heat flux (kW/m^2);

$\dot{q}''_{ig}$ = minimum effective flux of ignition (kW/m^2);

E_{ig} = effective energy of ignition (kJ/m^2); and

PII = piloted ignition index (s^{-1}).

The index, PII, can be calculated from known values of E_{ig} and $\dot{q}''_{ig}$ at various $\dot{q}''_e$ values for generalizing the ignition potential of the cable under different magnitudes of external heat flux. Figure 3-13 shows PII, an overall ignition characteristic of cables, under piloted condition, as a function of external heat flux.

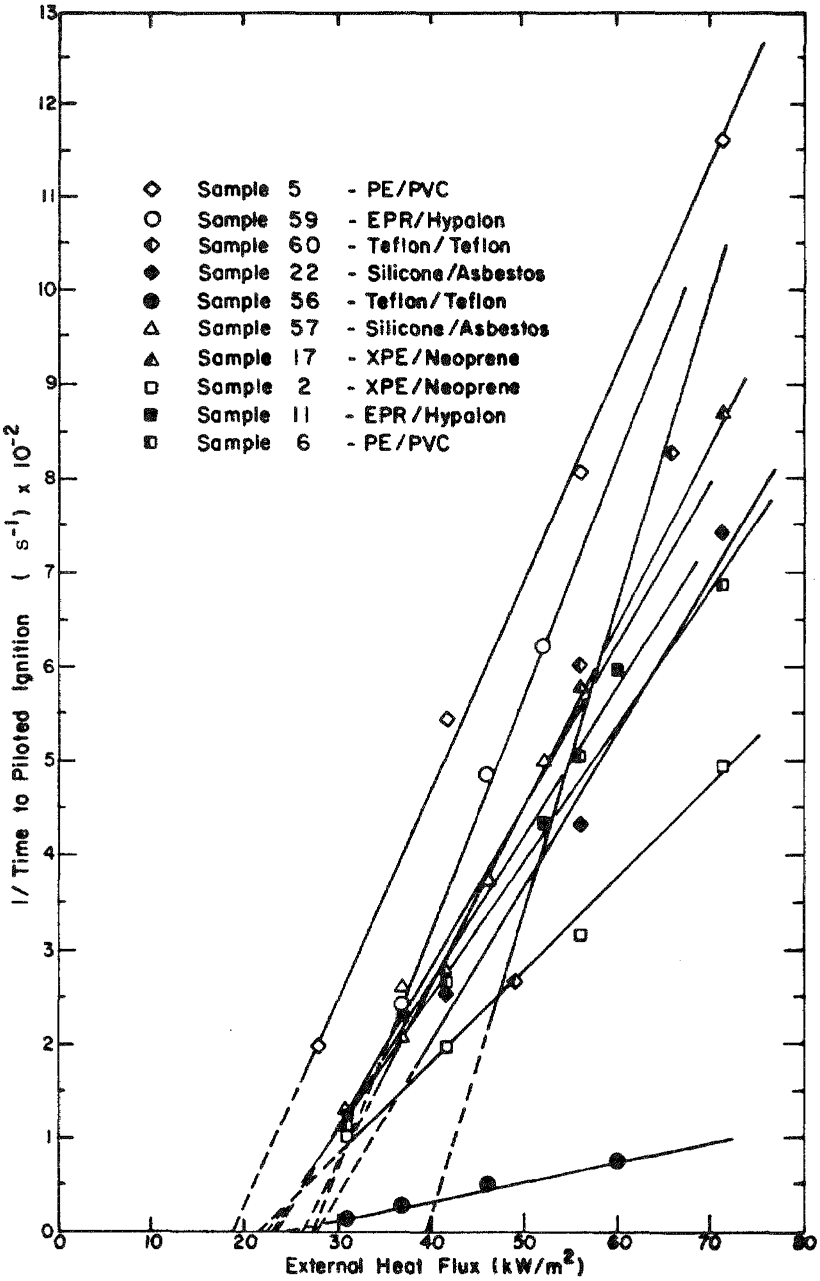

Figure 3-12. Piloted Ignition of Cables Under Various External Heat Flux

Table 3-3

IGNITION PARAMETERS FOR PILOTED AND AUTOIGNITION OF CABLES

		Piloted Ignition		Autoignition		
Sample	(No.)	Critical Energy $E_{ig,p}$[a] (kJ/m^2)	Critical Flux $\dot{q}''_{ig,p}$[b] (kW/m^2)	Critical Energy $E_{ig,n}$[c] (kJ/m^2)	Critical Flux $\dot{q}''_{ig,n}$[d] (kW/m^2)	$\Delta\dot{q}''$[e] (kW/m^2)
PE/PVC	(5)	460	18	6010	5	-13
PE/PVC	(6)	690	23	9480	15	- 8
XPE/Neoprene	(2)	1040	21	11290	4	-17
XPE/Neoprene	(17)	510	27	7180	18	- 9
Silicone/Asbestos	(22)	660	26	3000	31	+ 5
Silicone/Asbestos	(57)	590	23	4420	27	+ 4
EPR/Hypalon	(8)	-	-	∞[f]	NA	-
EPR/Hypalon	(11)	640	23	∞[f]	NA	-
EPR/Hypalon	(59)	390	27	∞[f]	NA	-
Teflon/Teflon	(56)	4680	24	∞[f]	NA	-
Teflon/Teflon	(20)	-	-	∞[f]	NA	-
Teflon/Teflon	(60)	3011	40	-	-	-

[a] $E_{ig,p}$ is the critical energy of piloted ignition defined as the energy required to carry out the ignition process by maintaining a flammable cable sample vapor/air mixture near the surface provided the available heat flux exceeds the minimum requirement.

[b] $\dot{q}''_{ig,p}$ is the critical flux of piloted ignition defined as the minimum flux below which no ignition can occur.

[c] $E_{ig,n}$ is the critical energy of non-piloted ignition defined the same as a.

[d] $\dot{q}''_{ig,n}$ is the critical flux of non-piloted ignition defined the same as b.

[e] $\Delta\dot{q}''$ is the difference between $\dot{q}''_{ig,p}$ and $\dot{q}''_{ig,n}$.

[f] no autoignition was observed at least up to 70 kW/m^2.

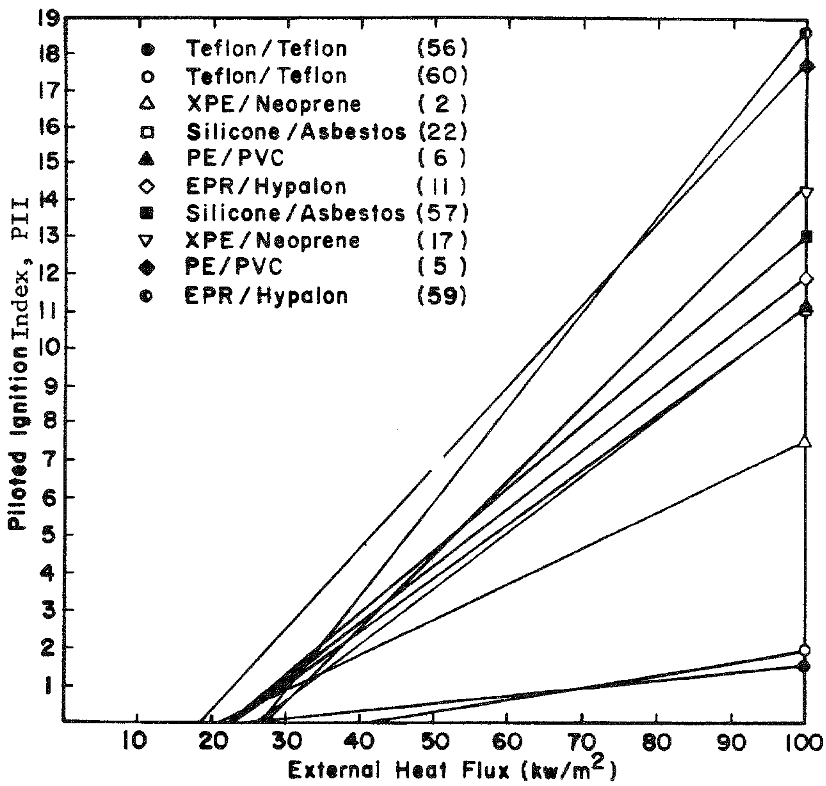

Figure 3-13 The Variation of Piloted Ignition Index, PII, with External Heat Flux for Various Cables

3.2.2 Discussion

Comparison of Tables 3.2 and 3.3 shows that the critical energy requirements of the cables under piloted ignition are of similar magnitude to those for insulation/jacket degradation. This implies that the time for the material vapor to reach flammable limit is very close to the time to initiate critical insulation degradation. Thus, the behavior of piloted ignition can be viewed as similar to that of insulation/jacket degradation.

Table 3-3 also shows that values of $\dot{q}''_{ig,p}$ for all cables except one (sample 60) under piloted ignition have values within 22 $\pm$ 5 kW/m^2. This is also similar to the results for insulation/jacket degradation. The narrow band of critical heat flux requirement provides designers and engineers with a simple reference level of heat flux allowable in a facility for optimal design of various fire protection systems.

The effect of the pilot flame is apparent in Table 3-3; the critical energy requirements of cables under non-piloted ignition environment are much higher than those under piloted ignition environment, due to removal of the additional ignition source provided by the pilot flame. Moreover, the $\dot{q}''_{ig,n}$ of the chlorine-containing cables under non-piloted ignition shows somewhat lower values than under piloted ignition. This discrepancy, shown as $\Delta\dot{q}''$ in Table 3-3, could be a result of some exothermic reactions occurring at the sample surface upon prolonged heat flux exposure. These reactions were not evident in the piloted ignition experiments because ignition occurred shortly after the vapor generation, when the vapor/air mixture reaches a flammable limit. This difference in $\dot{q}''_{ig}$ is demonstrated in Figure 3-14 for a XPE/Neoprene cable under both modes of ignition mechanism.

3.3 ELECTRICAL INTEGRITY FAILURE

This phase of the test program was carried under piloted ignition environment.

3.3.1 Inverse of the Time to Electrical Failure Versus External Heat Flux

When the inverse of the times to electrical failure are plotted against their respective external heat flux, a linear relationship is obtained as shown in Figure 3-15. From this relationship, the energy of electrical failure, E_{ef} and the critical flux of electrical failure, $\dot{q}''_{ef}$, can be derived. These results are presented in Table 3-4. The term $\dot{q}''_{ef}$ is defined as the critical flux below which

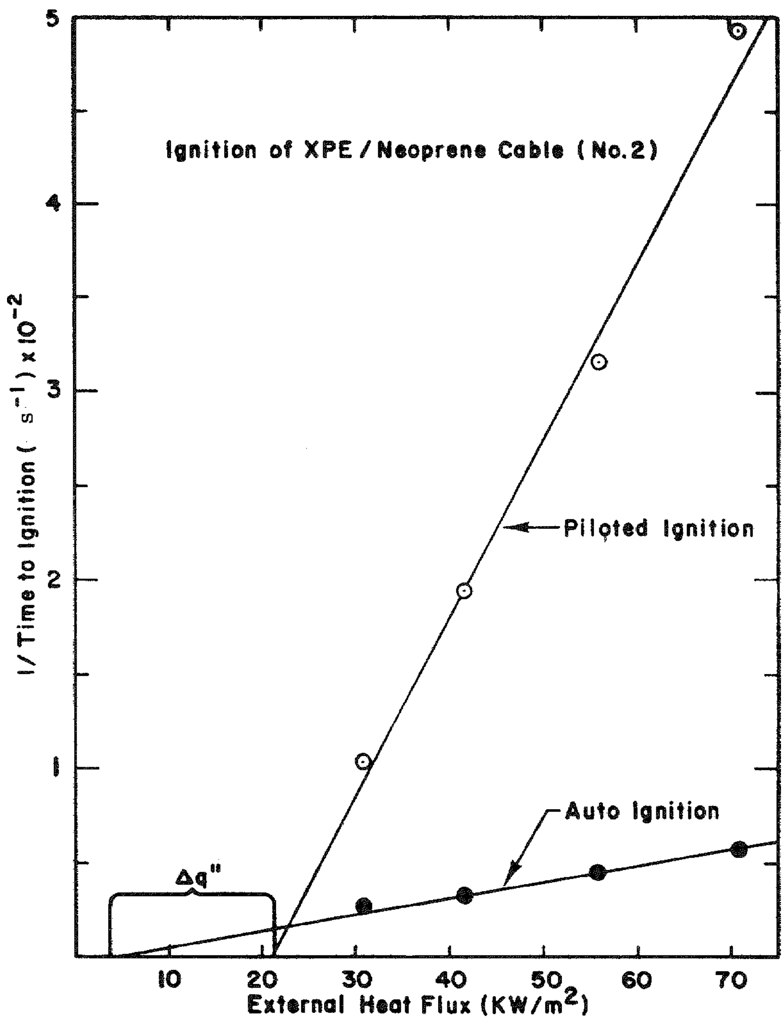

Figure 3-14. Auto and Piloted Ignition of XPE/Neoprene Cable (#2) at Various External Heat Flux. $\Delta\dot{q}''$ is the difference between the critical flux of piloted ignition and that of non-piloted ignition.

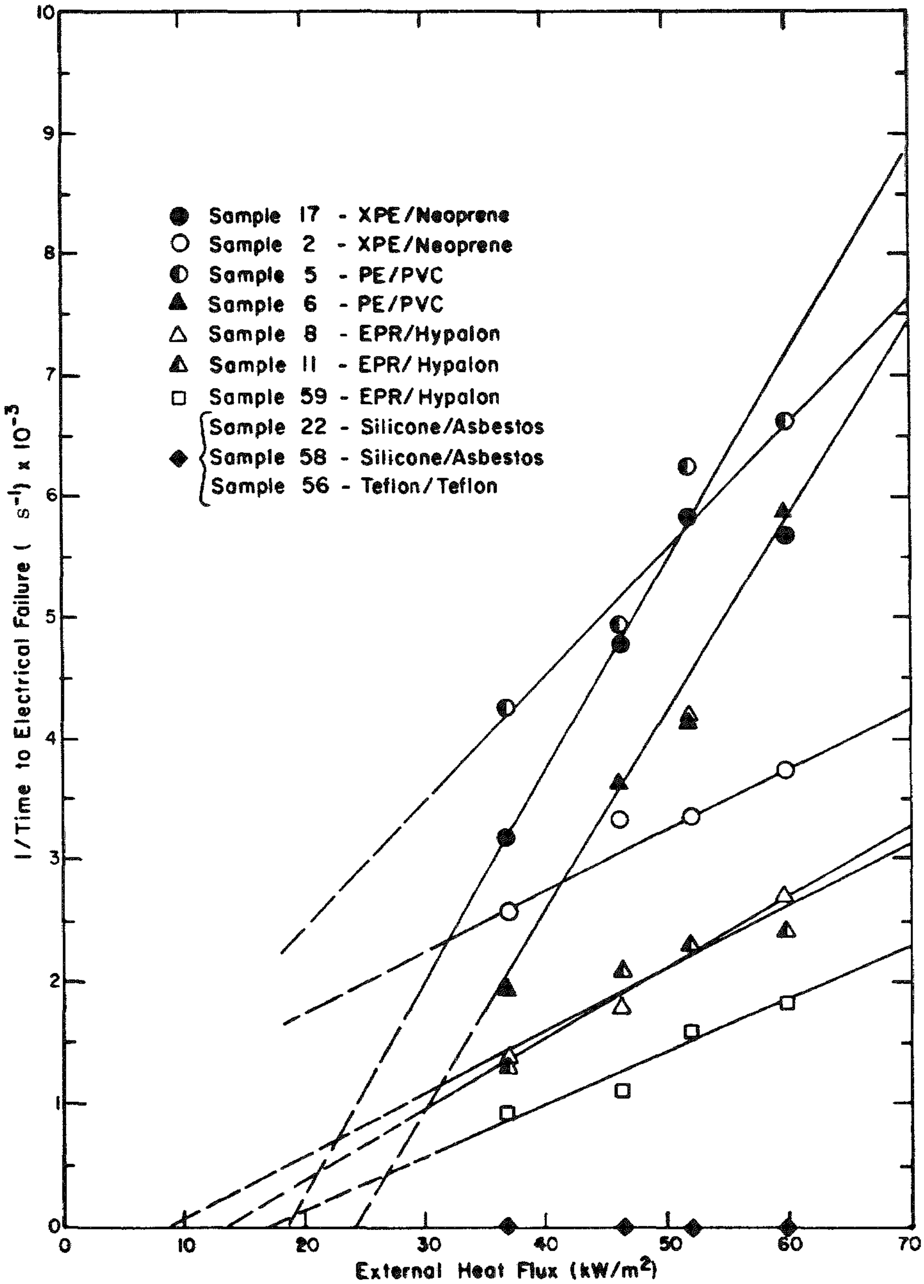

Figure 3-15. Electrical Failure of Cables Under Various External Heat Flux

Table 3-4

ELECTRICAL FAILURE PARAMETERS FOR CABLES UNDER PILOTED IGNITION CONDITION

Sample	(No.)	Critical Energy of Electrical Failure E_{ef} [a] (kJ/m^2)	Critical Flux of Electrical Failure $\dot{q}''_{ef}$ [b] (kW/m^2)
Silicone/Asbestos	(22)	∞[d]	NA
Silicone/Asbestos	(58)	∞[d]	NA
Teflon/Teflon	(56)	∞[d]	NA
EPR/Hypalon	(59)	23,700	17
EPR/Hypalon	(11)	19,600	9
XPE/Neoprene	(2)	19,500	-[c]
EPR/Hypalon	(8)	16,950	14
PE/PVC	(5)	9,070	-[c]
PE/PVC	(6)	6,530	24
XPE/Neoprene	(17)	5,560	19

[a] E_{ef} is the critical energy of electrical failure defined as the energy required to break down the insulation to cause electrical shorting of the conductors provided the available heat flux exceeds the minimum requirement.

[b] $\dot{q}''_{ef}$ is the critical flux of electrical failure defined as the minimum heat flux below which no electrical failure can occur.

[c] The critical flux of electrical failure cannot be determined for these cable samples.

[d] No electrical failure was observed at least up to 70 kW/m^2.

electrical failure will not occur and E_{ef} is defined as the critical energy required to achieve electrical failure which is simply the product of the available heat flux and the time to electrical failure, provided the available heat flux level is higher than the critical heat flux requirement. By the definition of E_{ef} and $\dot{q}''_{ef}$, these two parameters can be related by an expression similar to Eq. 3-1:

$$EFI = \frac{\dot{q}''_e - \dot{q}''_{ef}}{E_{ef}} \qquad (3\text{-}3)$$

where EFI = electrical failure index (s^{-1});

E_{ef} = effective energy of electrical failure (kJ/m^2);

$\dot{q}''_{ef}$ = minimum effective flux of electrical failure (kW/m^2); and

$\dot{q}''_e$ = external heat flux (kW/m^2).

EFI can be calculated from known values of E_{ef} and $\dot{q}''_{ef}$ for various $\dot{q}''_e$ values as shown in Figure 3-16 for generalizing the electrical failure characteristic of cables under varying intensity of exposure fires.

3.3.2 Discussion

Of all the cables tested, samples 2 and 5 appear to give abnormal results. We are not certain of the cause for this abnormalitiy; however, it could be a result of the generation of HCl from within the cable accelerating the insulation degradation process(8,9), causing early electrical failure. More work is needed to fully analyze the behavior of the HCl vapors and the additives in reacting with polymers under thermal environment. Except for these two cables, all cables tested indicate critical flux similar to that obtained from the insulation/jacket degradation experiments.

From a general point of view, the results show that silicone/asbestos cable is best in maintaining electrical integrity due to the formation of silicon oxide acting as an insulation between the conductors. One of the Teflon/Teflon cables also showed excellent behavior because it had an extremely high energy requirement to cause insulation/jacket degradation. Next in order of performance in maintaining electrical integrity are the EPR/Hypalon, the XPE/Neoprene, and PE/PVC cables.

From the results of this experiment, it can be concluded that the process for electrical failure is not entirely dependent on insulation/jacket degradation. Electrical failure is primarily a result of the conductors shorting with one another

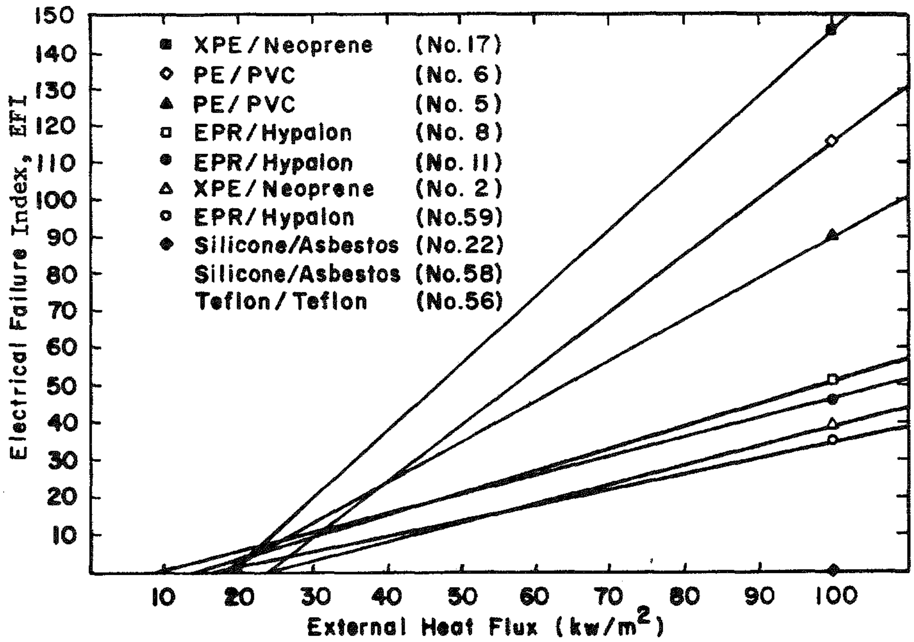

Figure 3-16 The Variation of Electrical Failure Index, EFI, with External Heat Flux for Various Cables

which depends strongly on how the insulation degrades under thermal exposure and the product formed after exposure (both in flaming and non-flaming situations); silicone/asbestos cable is a good illustration. The formation of silicon oxide in the flaming fire situation provides the conductors with a layer of insulation to prevent their being shorted with one another. Thus, a cable which has low insulation/jacket degradation potential does not necessarily imply poor performance in maintaining electrical integrity. Insulation/jacket degradation depends on the properties of the source material while electrical failure is directly related to the products that are formed during degradation.

In this program, a source of only 70 V dc was applied to each conductor. There could be different effects if the cables were tested under higher voltage supply. In addition, stresses placed on the cables, as well as cable arrangements, could also show different results.

3.4 HCl GENERATION

When a facility installed with electric cables is under a certain heat flux exposure, not only are there the possibilities of insulation/jacket degradation, ignition and/or electrical failure, but also the danger of the generation of hydrogen chloride if the cables contain chlorine. Hydrogen chloride has been known to be extremely hazardous in terms of toxicity and corrosivity(8,9,10). Polyvinyl chloride, a chlorine-containing polymer widely used for cable insulation, is known to decompose and release detectable amounts of hydrogen chloride (HCl) at relatively low temperatures (about 100°C, 212°F)(9,11). In some situations, damage due to hydrogen chloride generation may have already occurred even before major insulation degradation or ignition begins. Therefore, as far as the safety and protection of the facility personnel and equipment are concerned, HCl generation is an extremely important factor to be considered in the overall fire safety plan. Two literature reviews(9,10) discuss in detail the toxicity and corrosivity of the generation under flaming and non-flaming fire situations applicable for electrical cables.

In this program, three different types of chlorine-containing cables PE/PVC (No. 6) XPE/Neoprene (No 2) and EPR/Hypalon (No. 8) were examined under an external heat flux of 60 kW/m^2 and piloted ignition to assess their hydrogen chloride generation capacity. In each case, a single 0.1 m sample was used as test specimen. The same combustibility apparatus was utilized and a chloride ion (Cl^-) analyzer was put on line to measure the Cl^- concentration under flaming fire conditions (see Figure 2-4).

Figures 3-17 to 3-19 present the correlation between the mass loss rate and the HCl generation rate of the three cables. For the PE/PVC cable (No. 6), the total mass of HCl generated was 47% of the total mass of PVC in the cable. The theoretical amount of HCl contained in PVC(11) is 58%.

The HCl generation in a PE/PVC cable is initially very rapid upon heat flux exposure. Furthermore, HCl constituted more than 90% of the fuel consumed during the first 50 s. It may be noted from Figure 3-17 that the cable generated a significant amount of HCl even before ignition occurs. After 50 s, HCl generation reached an average rate of 0.02 g/s for 300 s.

The situation with the XPE/Neoprene cable (No. 2) was not as severe. The total mass of HCl generated was 39% of the total mass of Neoprene in the cable. This gives a value quite close to the theoretical figure of 41% HCl by mass of Neoprene(11). The generation rate of HCl in Neoprene cable appears to be a little slower (0.01 g/s average) than in PE/PVC but of approximately the same duration.

Among the three cables tested the least hazardous was EPR/Hypalon (No. 8). The HCl generated was measured to be 11% of the mass of Hypalon in the cable. (The theoretical value of Cl^- in hypalon is not available.) An average rate of 0.002 g/s was attained after 60 s for a period of 300 s.

To demonstrate the hazard of HCl generation in cable fires, the average HCl generation rate from a 0.1 m long PE/PVC cable (0.02 grams/sec) is used to estimate the toxic level in a room 5 m x 5 m x 3 m (17 ft x 17 ft x 10 ft). Taking the density of air at room temperature to be 1.193 g/ℓ and the duration of burning to be 5 min (300 s), the following equation expresses the HCl concentration level:

$$C = \frac{\dot{G}\, t\, 10^3}{V \rho_{air}} \qquad (3\text{-}4)$$

where $\dot{G}$ = average generation rate of HCl (g/s);

t = burning duration of the cable (s);

V = volume of the room in which the burning takes place (m^3);

ρ_{air} = density of air at room temperature (g/ℓ); and

C = concentration of HCl (ppm).

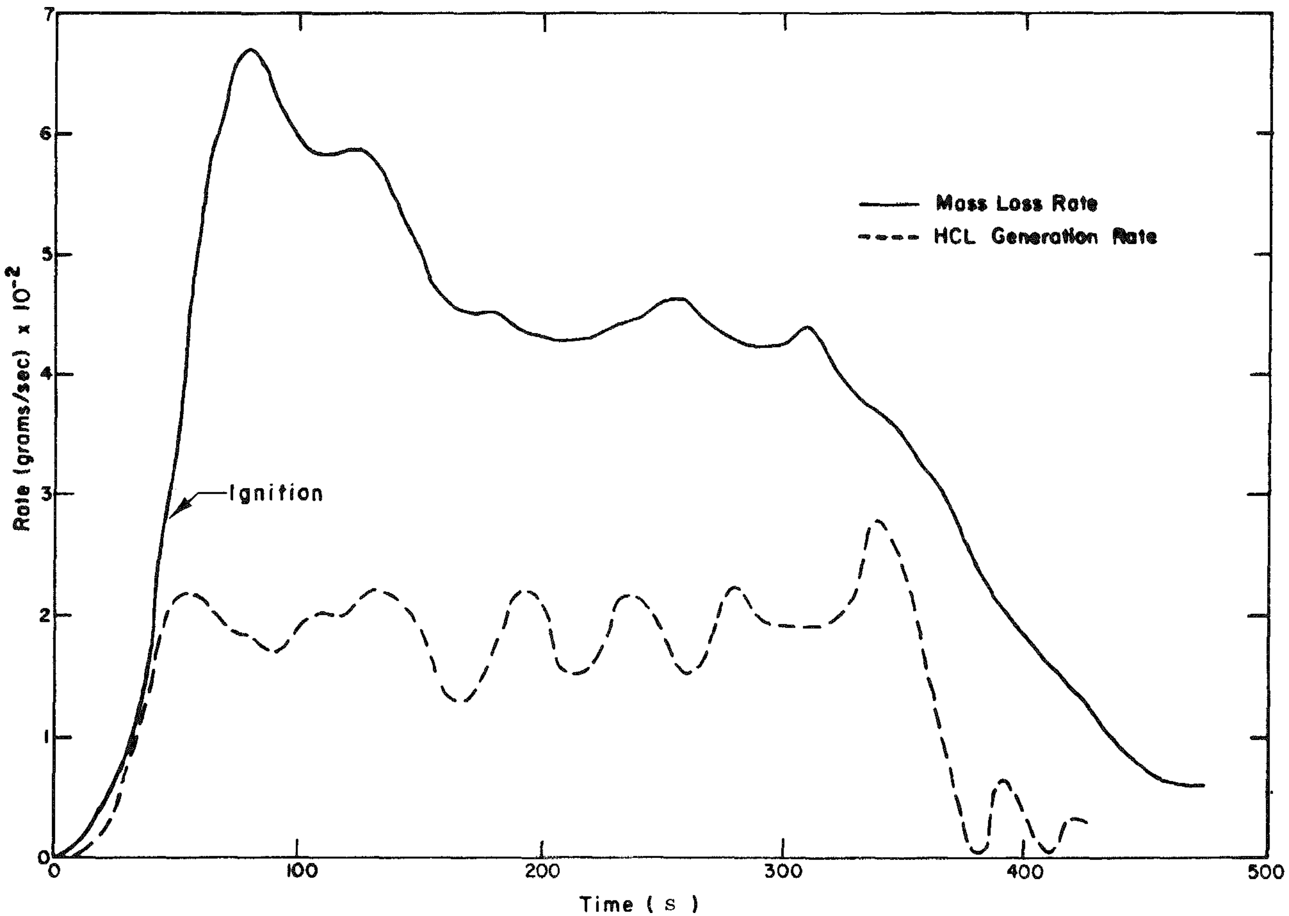

Figure 3-17. HCL Generation Rate versus Mass Loss Rate for PE/PVC Cable (#5) at External Heat Flux of 60 kW/m^2

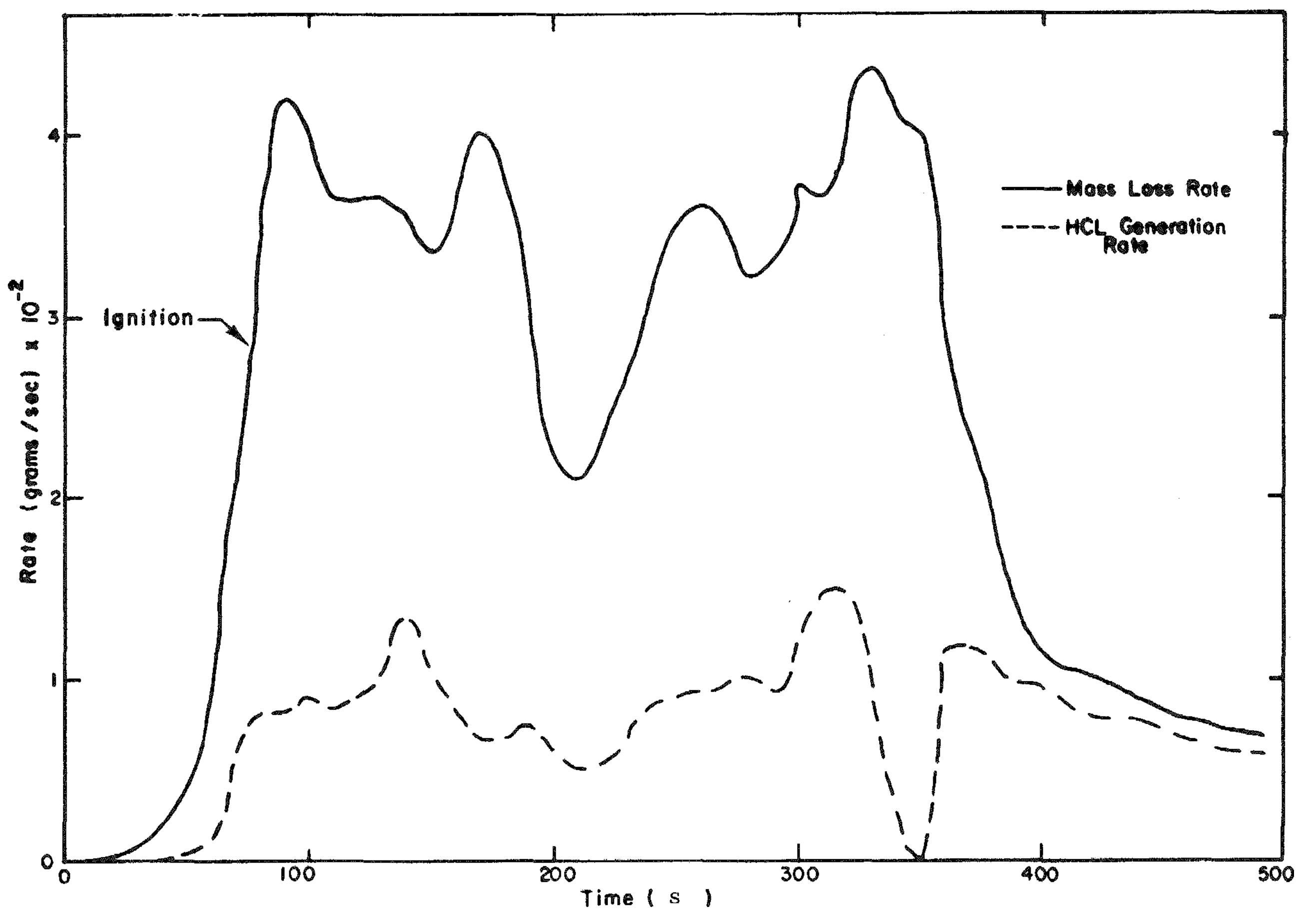

Figure 3-18. HCL Generation Rate versus Mass Loss Rate for XPE/Neoprene Cable (#2) at External Heat Flux of 60 kW/m^2

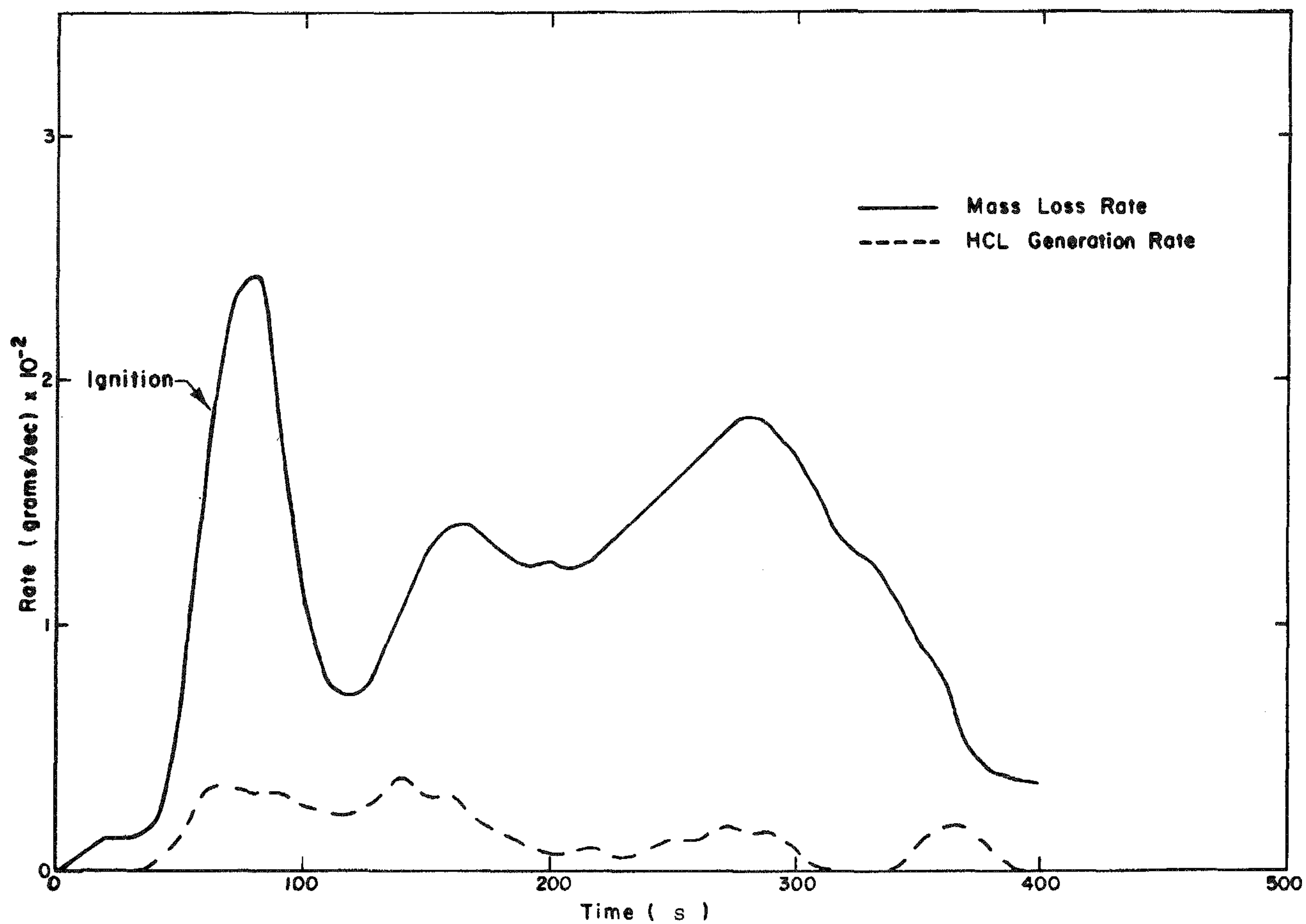

Figure 3-19. HCL Generation Rate versus Mass Loss Rate for EPR/Hypalon Cable (#11) at External Heat Flux of 60 kW/m^2

Inserting the values chosen for $\dot{G}$, t, v, and ρ_{air}, C is calculated to be 67 ppm which exceeds the critical value of 50 ppm for human escape as reported in one of the literature reviews(9). This is the amount of HCl generated by a 4-in. sample of PE/PVC under a thermal exposure of 60 kW/m^2. With increase in the amount of the polymer for larger cables, the amount of HCl will also increase. From the data it may be possible to estimate the amount of HCl that could be provided from the ratio of cable length to room volume used in practice, which would be useful for designers and safety engineers.

The above example illustrates the toxicity hazard posed by cables with insulation containing chlorine in their chemical composition. Obviously, this threat to safety and protection should not be overlooked. Further investigation is needed to examine in detail the mechanism of HCl generation and its interaction with other processes such as insulation/jacket degradation, ignition, and electrical continuity under varying thermal environments.

Section 4

CONCLUSIONS

It has been shown that the damage potential of a cable exposed to varying thermal environment can be evaluated in a systematic manner using a laboratory-scale apparatus. The results provide a relative basis for classifying cables with respect to their damage potential under thermal exposure and data for engineering calculations for the safety aspects of cable fires. The following conclusions are based on the results obtained in this study; possible applications to the design of adequate detection and protection systems are also presented.

- From the work on the behavior of insulation/jacket degradation, the minimum flux for degradation, $\dot{q}''_{id}$, of 9 of the 11 cables tested were found to lie within 20 $\pm$ 4 kW/m^2. The primary difference among those 9 cables was in their effective energy requirement, E_{id}. Teflon/teflon cable was found to have the highest rating while PE/PVC cable was rated the lowest. This narrow band of $\dot{q}''_{id}$ suggests the adoption of a common critical heat flux level allowable in a facility with cable installation. This critical level will govern the choice of the type of heat sensors and protective systems to be incorporated in the facility.

- Cable behavior under piloted ignition reflects an energy requirement similar to that of the insulation degradation process, whereas under non-piloted ignition a much higher energy requirement is evident. This implies that, under the same thermal environment, a cable with flame impinging upon its surface has a much higher damage potential than one without flame impingement. It appears that the use of shielding devices such as baffles may be effective in reducing the damage potential or fire hazard of the cables in a facility. The effect of these baffles and shield upon water sprinklers or hose access would have to be considered.

- Results of non-piloted ignition of cables in a thermal environment suggests the possibility of exothermic reactions occurring on certain cable surface upon prolonged heat flux exposure.

- Electrical integrity failure of cables is shown to be dependent on the mechanism of insulation degradation and the nature of the products formed upon heat flux exposure. The behavior is not entirely dependent on the insulation/jacket degradation potential. Thus, cables rated high in insulation jacket degradation will not necessarily have the same order of rating in electrical failure.

- HCl generation could be extremely hazardous as far as toxicity and corrosivity are concerned. Of the three chlorine-containing cables tested, the most severe in HCl generation was PE/PVC, then XPE/Neoprene and EPR/Hypalon. A 0.1 m specimen of PE/PVC cable burning in a heated room 5 m x 5 m x 3 m will generate 67 ppm of HCl in 5 min duration. This level of HCl is consi dered hazardous as far as human escape is concerned. Moreover the three chlorine-containing cables showed a rapid generation of HCl upon heat flux exposure. This sensitive response could be utilized for the design of a fire detection system based on HCl generation in a facility installed with chlorine containing cables.

In summary, it is shown that the damage potential of a cable under thermal exposure cannot be expressed by a single paramater, but by a combination of parameters derived from distinct processes such as insulation/jacket degradation, ignition, and electrical failure. Each of these processes in turn is expressed by two parameters, E and $\dot{q}''$. Fortunately, the study shows that the $\dot{q}''$ values the three processes among cables are all within a narrow range of values; the primary difference is in the critical energy requirement, E. Among the cables tested, some did demonstrate low potential in all damage processes: insulation/jacket degradation, ignition, and electrical failure. The cable rated highest among all three damage processes appears to be Teflon/Teflon, then EPR/Hypalon, while the lowest appears to be PE/PVC.

In order to actually classify the cables as to their total damage potential for a specific application, assessment must be made of the effect of environment on the potential hazard presented by exposure fires in a facility(4), and a decision must be reached on the order of importance of the three damage processes applicable to that facility. This information, together with data on the damageability of cable from the laboratory-scale apparatus, will provide planners and engineers with adequate guidelines to select the appropriate cables and type of detection and protection system, thus improving safety in the facility of interest.

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