NUREG/CR-2409
SAND81-7168
RP
Printed July 1982
CONTRACTOR REPORT

Requirements for Establishing Detector Siting Criteria in Fires Involving Electrical Materials

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Prepared by
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for the United States Department of Energy
under Contract DE-AC04-76DP00789

Prepared for
U. S. NUCLEAR REGULATORY COMMISSION

SF 2900-Q(6-82)

Available from
GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

and

National Technical Information Service
Springfield, Virginia 22161

ABSTRACT

Due to increased public awareness and regulatory actions, significant strides have been made in the capabilities of fire technology as it applies to fire detection systems. However, these advances in detector selection, siting, reliability and approvals tests have not substantially addressed the overall fire protection requirements within nuclear reactors.

This report emphasizes some of the basic requirements and considerations needed for establishing siting criteria for early-warning detection of electrical cable fires. Recent research in electrical cable flammability and damageability characteristics are discussed. Also current work in systemizing detector siting criteria is also described.

Confirmatory tests linking assessment of electrical-cable damageability with electrical cable fire detection is stressed.

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1.0 INTRODUCTION

Throughout the nuclear industry and cognizant regulatory body there has been considerable responsive action relative to nuclear safety-related fire protection and incorporating sound fire-protection principles in nuclear-facility design. New standards, new regulatory guides, and new criteria have been promulgated since the fire at the Browns Ferry nuclear power station.

Basic fire protection guidance for nuclear power plants contained in Branch Technical Position Auxiliary Power Conversion System Branch BTP APCSB 9.5-1, "Guidelines for Fire Protection for Nuclear Power Plants" and its attendant appendices, namely, Appendix A & R, mandate the need for early warning fire-detection systems as part of a plant's general and specific fire protection requirements for assurances of performing a safe shutdown in the event of a fire. However, recommended guidelines for the selection and installation of early warning fire detection systems are currently based upon national standards and guides that do not realistically take into account a number of environmental and plant safety requirements that are unique to nuclear facilities.

Early warning fire detector siting and selection must have fuller accountability of:

(1) the environmental factors such as ventilation, room size/configuration/congestion, background radiation on detector response;

(2) the flammability characteristics of the types of combustibles existing in nuclear power plants; and,

(3) the need to limit fire damage to systems required to achieve and maintain safe shutdown conditions.

A prime common denominator in addressing the above three issues, in concert, is the ability to prevent/detect fires involving electrical cables - a major combustible within the plant and at the same time crucial in performing an effective safe shutdown.

Recognizing early this unique dual characteristic of electrical cables, significant contributions to the assessment of exposure fire hazards to electrical cable and cable tray installations have been made through EPRI- and NRC-funded research programs that have included: 1) exposure fire characterization, 2) exposure fire environment within enclosures, and 3) preliminary evaluation of the effectiveness of water, gas and/or baffle protection for specific combination of cable type, tray configuration, and exposure fire.

Also, recent NBS- and UL-funded efforts have been expended in establishing a more reconcilable means of siting aerosol detectors, in establishing a more cogent set of standards' tests and in formulating a viable set of maintenance procedures that take into account the environmental factors listed above.

Notably in this connection is the series of studies by Factory Mutual Research Corporation (FMRC), under EPRI sponsorship, investigating the characteristics of electrical cable fires(1,2,3,4) and their work done under NBS sponsorship, in developing and in corrolating design information for detectors(5) which has been summarized in a report prepared for the Fire Detection Institute(6). Much of this design data has been utilized in Reference 7 for formulating an interim guide on detector-system assessments for nuclear power plants. However, the design charts used have been noted to lack corroborative evidence of detector spacing required for electrical cable fires.

Thus, it seems propitious at this stage in the state-of-the-art in: a) the assessment of exposure fire hazards to cable trays and in b) the development of design information for aerosol detectors and detector siting, that confirmatory tests be undertaken linking these correlations and aerosol detector siting criteria to flaming fires involving electrical cables. However, before a test program can be scoped out, a brief review of the aforenoted work is deemed warranted so that one may synthesize some of the aspects of fire detection analyses with electrical cable fire protection.

2.0 FLAMMABILITY/DAMAGEABILITY/DETECTABILITY OF ELECTRICAL CABLE FIRES - An Overview

Specification of the required spacing of aerosol fire detectors generally requires that the following detection parameters be known: (1) the growth rate of the fire, (2) the acceptable fire size at detection, and (3) the response characteristics of the detectors to the particular aerosol generated. Determination of the growth rate of an electrical cable fire, or for that matter the general flammability characteristics of electrical cables is difficult because these cables, which are an integral part of today's power generating facilities, are manufactured with various synthetic polymers, plasticizers and flame-retardant additives.

Using a laboratory-scale combustibility apparatus, Tewarson(1) attempts to categorize the flammability of electrical cables of various sizes, conductors and materials. The following section will discuss some of the data extracted from this program and how it may be factored into the above three requirements for detector spacing.

If electrical cables were considered simply as a combustible material, its fire-hazard classification can be assessed from this information. But to effect a safe-shutdown, one must also assess the damageability of cables that are subjected to abnormal thermal environments such as a fire. Lee(2) extends the work previously cited by formulating damageability indices under varying thermal environments. Thus, quantifying cable damage potential through these indices, which are also reviewed in this section, allows one to appraise the possible acceptable fire size at detection.

However, in order to classify the various cables as to their total damage potential for a specific application, appraisals must be made of the effect of the environment on the potential hazard presented by a realistic fire scenario in a facility. Newman and Hill(4) consider fires from flammable liquid spills as a realistic scenario and formulate a decision-making process, which together with data on the flammability/damageability of electrical cable from the laboratory-scale apparatus, may provide planners and engineers with more rationale guidelines for cable selection, fire detection and protection. Major highlights from this study are also discussed as well as how they would factor into the above three requirements on detector siting.

Finally, this section also reviews briefly the corrolations formulated by Heskestad and Delichatsios(5) for evaluation of the initial convective flow of idealistic fires and how this approach can be extended to generate guidelines for detector spacing. Preliminary experimental work in extending this approach to electrical cable fires, generated by Delichatsios(3) is also described herein.

2.1 Categorization of Electrical Cable Flammability Data

The present method for qualification of an electrical cable is the IEEE-383 test for cable qualification. Although this test provides a single set of fire source and cable conditions and is a "go or no go" test, categorization of cables by Tewarson(1) under various radiant heat exposures with both auto- and piloted-ignition indicated that cable damage varies with radiant heat source. Initially the objective had been to provide a laboratory test basis for assessing cable-insulation damage on a comparative basis. Although the experimental method has shown the damageability to be a complex phenomenon depending on the oxides formed, the materials, the jacket material, the number of conductors, 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.

In this study, 22 types of cable samples (see Table 1) were examined in a test apparatus depicted in Figure 1. In this test procedure, small samples ($81 \times 10^{-4} m^2$) of cables are subjected to different magnitudes of external, radiant heat flux during which time measurements were made as to 1) time to ignition (auto and piloted), 2) mass loss rate, 3) heat release rate, 4) rates of generation of gaseous combustion products, and 5) optical transmission through the evolving aerosol. With these measurements the combustibility characteristics including ignition and flame spread behavior, (Table 2); critical mass loss rate for ignition, (Table 3); fire intensity in a changing thermal environment and fire hazard in terms of heat release rate (Table 4) can be determined. Details on applying global energy and mass balances together with the measurements indicated, are described in the cited reference. These data suggest that polyethylene/polyvinylchloride cable (#5), polyethylene-polypropylene/ chlorosulfonated polyethylene cable (#9) and silicone cable (#22) samples represent "high, intermediate, and low fire hazard based upon mass loss rate and heat release rate in the flaming fire".

2.2 Categorization of Electrical Cable Damageability

Although electrical cable flammability data is considered crucial in assessing the inherent fire hazard, factors other than insulation/jacket degradation, ignition, fire growth, maximum burning, etc. must also be considered critical to the safe operation of a facility where cables play such an integral part of the entire system. These additional factors quantifying cable impairment which may occur before a fire is fully developed may be due to the effect of changes in cable properties, such as insulation resistance,

Table 1

Samples Used in Cable Flammability Study *

Number	Insulation/Jacket Materials[a]	Conductor No.	Conductor Size (AWG)	Outer Cable Diameter in. (m)	Insulation/Jacket Materials (% of total cable weight	Insulation Jacket Materials remaining as char (% of initial wt. of insulation/jacket materials)	IEEE-383 Rating
				Polyethylene (PE)/No Jacket			
1	Low density PE (LdPE), no jacket	1	14	0.128(0.003)	23.9	0.10	-
				Polyethylene/Polyvinyl chloride (PE/PVC)			
3	PE/PVC	1	-	0.945(0.024)	15.6	21.9	
4	PE/PVC	1	12	0.164(0.004)	26.5	0.6	Fail
5	PE/PVC	3	-	0.438(0.011)	49.9	20.8	Fail
6	PE/PVC	5	-	0.748(0.019)	51.0	25.6	
7	PE/PVC	12	-	1.000(0.025)	57.8	24.4	
				Polyethylene, Polypropylene/Chlorosulfonated Polyethylene (PE, PP/Cℓ·S·PE)			
8	PE,PP/Cℓ·S·PE (silicone coating)	1	-	0.445(0.011)	23.2	41.6	Pass
9	PE,PP/FRCℓ·S·PE[b]	1	6	0.368(0.009)	40.2	46.4	Pass
10	PE,PP/Cℓ·S·PE	1	12	0.192(0.005)	42.9	45.6	Pass
11	PE,PP/Cℓ·S·PE	5	14	0.668(0.017)	77.1	48.3	Pass
12	PE,PP/Cℓ·S·PE	2	16	0.426(0.011)	77.4	40.5	Pass
				Cross-Linked Polyethylene/Cross-Linked Poyethylene (XPE/XPE)			
13	XPE/FRXPE[b]	3	12	0.458(0.012)	61.4	44.9	Pass
14	XPE/XPE	2	14	0.377(0.010)	73.5	-	Pass
				Cross-Linked Polyethylene/Chlorosulfonated Polyethylene (XPE/Cℓ·S·PE)			
15	FRXPE/Cℓ·S·PE[b]	4	16	0.368(0.009)	56.2	29.5	Pass
16	XPE/Cℓ·S·PE	4	16	0.442(0.011)	62.1	31.0	Pass
				Cross Linked Polyethylene/Neoprene (XPE/Neo)			
17	XPE/Neo	3	16	0.369(0.009)	73.2	43.9	Pass
2	XPE/Neo	7	12	0.630(0.016)	53.6	-	
				Polyethylene, Nylon/Polyvinyl chloride, Nylon (PE, Ny/PVC, Ny)			
18	PE, Ny/PVC, Ny	7	12	0.526(0.013)	39.9	-	
19	PE, Ny/PVC, Ny	7	12	0.520(0.013)	43.5	-	
					Teflon		
20	Teflon	34	-	0.516(0.013)	48.9	3.9	Pass
					Silicone		
21	Silicone, glass braid	1	-	0.363(0.009)	34.0	-	
22	Silicone, glass braid/asbestos	9	14	0.875(0.022)	70.5	59.4	Pass

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[a] Generic class as given by the suppliers. Cable samples belonging to similar generic class may not be similar because of different types and amounts of unknown additives in the cable samples.

[b] FR - with fire retardant chemical

* From Reference (1)

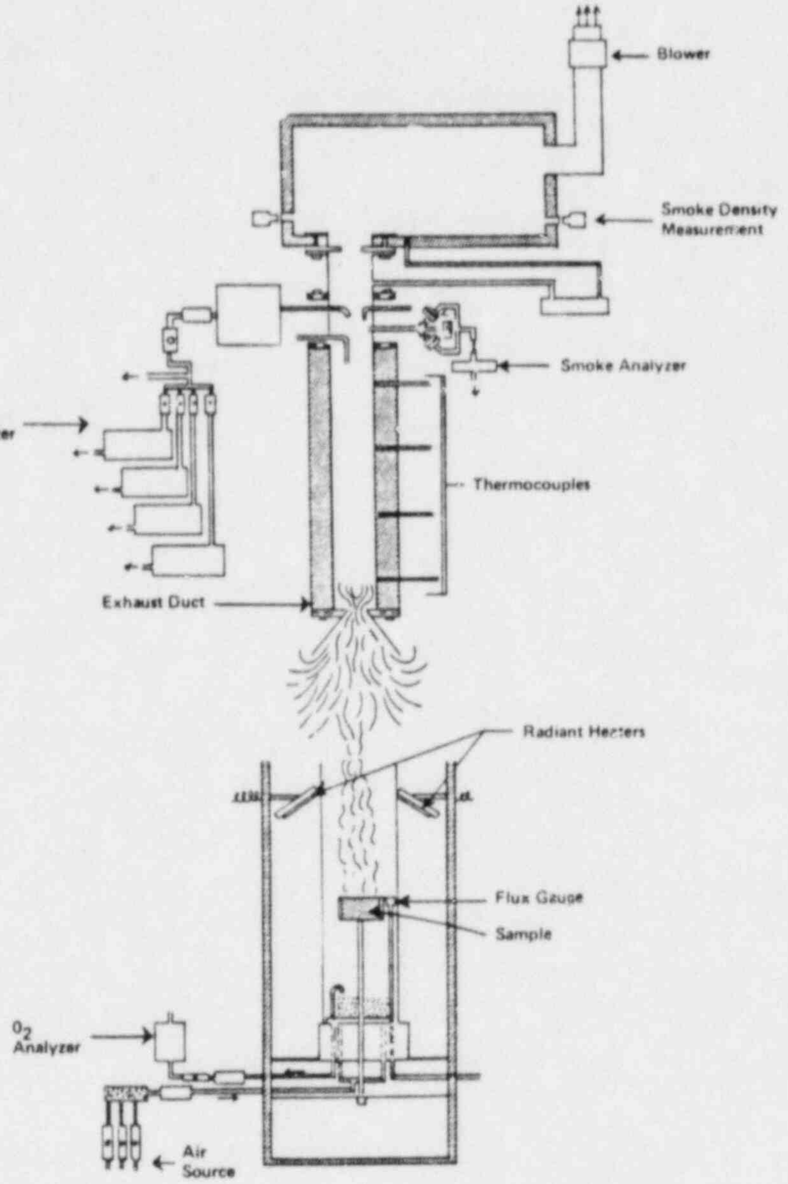

Fig. 1. Laboratory scale combustibility apparatus. (From Ref. 1)

Table 2

PILOTED IGNITION PARAMETERS FOR CABLE SAMPLES *

No.	Cable Sample	E_{eff}[a] (kJ/m^2)	$\dot{q}''_o$[b] (kW/m^2)	T_S[b] (K)	IEEE-383 Rating[c]
20	Teflon	8,696	43	933	Pass
	Polyethylene (granular)[d]	3,744	19	761	NA
	Polyvinyl chloride (granular)[d]	3,320	21	780	NA
21	Silicone, glass braid	3,125	29	846	
	Polyethylene/25%Cℓ (granular)[d]	3,011	26	823	NA
	Polyethylene/42%Cℓ (granular)[d]	1,969	22	789	NA
	Polyethylene/36%Cℓ (granular)[d]	1,891	26	823	NA
13	XPE/FRXPE	1,688	22	789	Pass
	Polyethylene foam (rigid)[d]	1,641	22	789	NA
16	XPE/Cℓ·S·PE	1,105	33	873	Pass
9	PE,PP/FRCℓ·S·PE	890	36	893	Pass
17	XPE/Neo	826	34	880	Pass
22	Silicone, glass braid/asbestos	778	14	705	Pass
	Polyurethane foam (rigid)[d]	772	23	798	NA
4	PE/PVC	728	36	893	Fail
5	PE/PVC	347	22	789	Fail

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[a] E_{eff} is defined as the 'effective' energy associated with maintaining flammable cable sample vapor/air mixture near the surface

[b] $\dot{q}''_o$ or T_S is defined as the critical heat flux or temperature at or below which ignition cannot be achieved

[c] IEEE-383 rating as provided by the suppliers

[d] Research samples, data from Ref. (8)

NA - Not applicable

* From Reference (1)

Table 3

CRITICAL MASS LOSS RATE FOR PILOTED IGNITION IN NORMAL AIR[a] *

Cable Sample	Critical Mass Loss Rate Per Unit Sample Area (g/m^2s)
PE, PP/Cℓ•S•PE (#11)	2.6
XPE/Cℓ•S•PE (#16)	2.9
FRXPE/Cℓ•S•PE (#15)	3.3
PE, Ny/PVC, Ny (#18)	3.4
XPE/XPE (#13)	3.7
PE, PP/FR Cℓ•S•PE (#9)	4.0
XPE/Neoprene (#17)	4.3
XPE/XPE (#14)	4.4
PE/PVC (#4)	4.4
Silicone, glass braid, asbestos (#22)	4.5
PE, PP/Cℓ•S•PE (#10)	4.8

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[a] Average peak values

PE,PP = polyethylene, polypropylene; Cℓ•S•PE = chlorosulfonated polyethylene;

XPE = crosslinked polyethylene, PE = polyethylene; Ny = Nylon, PVC = polyvinyl chloride; FR - with fire retardant.

* From Reference (1)

Table 4

HEAT RELEASE RATE PER UNIT AREA AND HEAT OF COMBUSTION FOR FLAMING FIRE OF CABLE SAMPLES IN NORMAL AIR AT 60 kW/m^2 [a] *

Cable Sample	IEEE 383 Rating	Heat Release Rate Per Unit Area (kW/m^2) Actual	Convective	Radiative	Heat of Combustion (kJ/g) Actual	Convective	Radiative
ℓd PE (#1)	NK	1071	398	673	31.3	11.6	19.7
PE/PVC (#5)	Fail	589	325	264	24.0	13.0	11.0
XPE/FRXPE (#13)	Pass	475	207	268	28.3	12.3	16.0
PE/PVC (#4)	Fail	395	175	220	25.1	11.1	14.0
PE/PVC (#6)	NK	359	228	131	22.0	14.0	8.0
XPE/Neoprene (#2)	NK	354	166	188	12.6	5.9	6.7
PE,PP/Cℓ·S·PE (#12)	Pass	345	131	214	17.4	6.6	10.8
PE/PVC (#3)	NK	312	185	127	30.8	18.3	12.5
XPE/Neoprene (#17)	Pass	302	144	158	10.3	4.9	5.4
PE, PP/Cℓ·S·PE (#8)	Pass	299	160	139	29.6	15.6	13.9
PE, PP/Cℓ·S·PE (#11)	Pass	271	172	99	26.8	17.0	9.8
FRXPE/Cℓ·S·PE (#15)	Pass	258	112	146	17.3	7.5	9.8
PE, Nylon/PVC, Nylon (#19)	NK	231	120	110	9.2	4.8	4.4
PE, Nylon/PVC, Nylon (#18)	NK	218	107	111	10.2	5.0	5.2
XPE/Cℓ·S·PE (#16)	Pass	204	135	69	13.9	9.2	4.7
Silicone, glass braid, asbestos (#22)	Pass	182	152	30	24.0	20.0	4.0
XPE/XPE (#14)	Pass	178	107	71	12.5	7.5	5.0
PE,PP/Cℓ·S·PE (#10)	Pass	177	114	62	19.0	12.3	6.7
Silicone, glass braid (#21)	NK	128	89	39	25.0	17.5	7.3
Teflon (#20)	Pass	98	82	16	3.2	2.7	0.4

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[a] Average peak values   NK - Not known

* From Reference (1)

dielectric strength, and bending characteristics, upon heat flux exposure. Of these stages, insulation/jacket degradation, ignition, and electrical integrity failure were chosen in a follow-on study(2) by FMRC to represent cable damage. In this study, also conducted in the laboratory-scale apparatus alluded to above, the damage potential of these three processes is expressed quantitatively by two parameters derived from experimental data, viz, the critical flux which is the minimum external heat flux below which the damage process will not occur and the critical energy which is the energy required to effectively initiate the damage process. This energy is considered simply the product of the available external heat flux and the time to initiate the damage process. For control and power cables that are subjected to exposure fires and which are required to effect a safe shutdown, consideration of these times together with the necessary detector response time must be considered in effecting an adequate, overall, fire detection system plan.

The following tables summarize the pertinent results from the cited reference.

Fourteen different cable samples (Table 5) of five basic generic groups were exposed to varying degrees of radiant heat flux (up to 70 kW/m^2) to simulate the thermal environment of an exposure fire hazard. By recording the amount of insulation/jacket material vaporized as a function of time during the preignition phase, the degradation parameters as summarized in Table 6 were determined. Also, the times to ignition of the cable samples as functions of external heat flux under both piloted and non-piloted conditions were used for the quantification of the ignition process as indicated in Table 7. Additional tests were performed in the presence of a pilot flame (similar to the piloted-ignition study) under varying thermal environments and with a variable power source to energize the cable samples to 70V in each conductor. The times to electrical shorting between conductors or to ground as functions of heat flux were used for assessment of electrical integrity failure (Table 8).

Based upon this type of information and the two parameters defined above, i.e., the critical energy and critical flux which is generated from data typically plotted in Figure 2, three indicies comparatively relating the damage process can be tabulated. These indices are respectively: the insulation degradation, the piloted ignition, and electrical failure indices defined as follows:

Table 5

Samples Used in Cable Flammability Study[a] *

No.	Insulation/Jacket Material	Conductor		Outer Cable Diameter		Insulation/Jacket Material (% of Total Cable Weight)	IEEE-383 Rating
		No.	Size (AWG)	in.	(m)		
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.

* From Reference (2)

Table 6

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 $\dot{q}''_{id}$.

* From Reference (2)

Table 7

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.

* From Reference (2)

Table 8

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.

* From Reference (2)

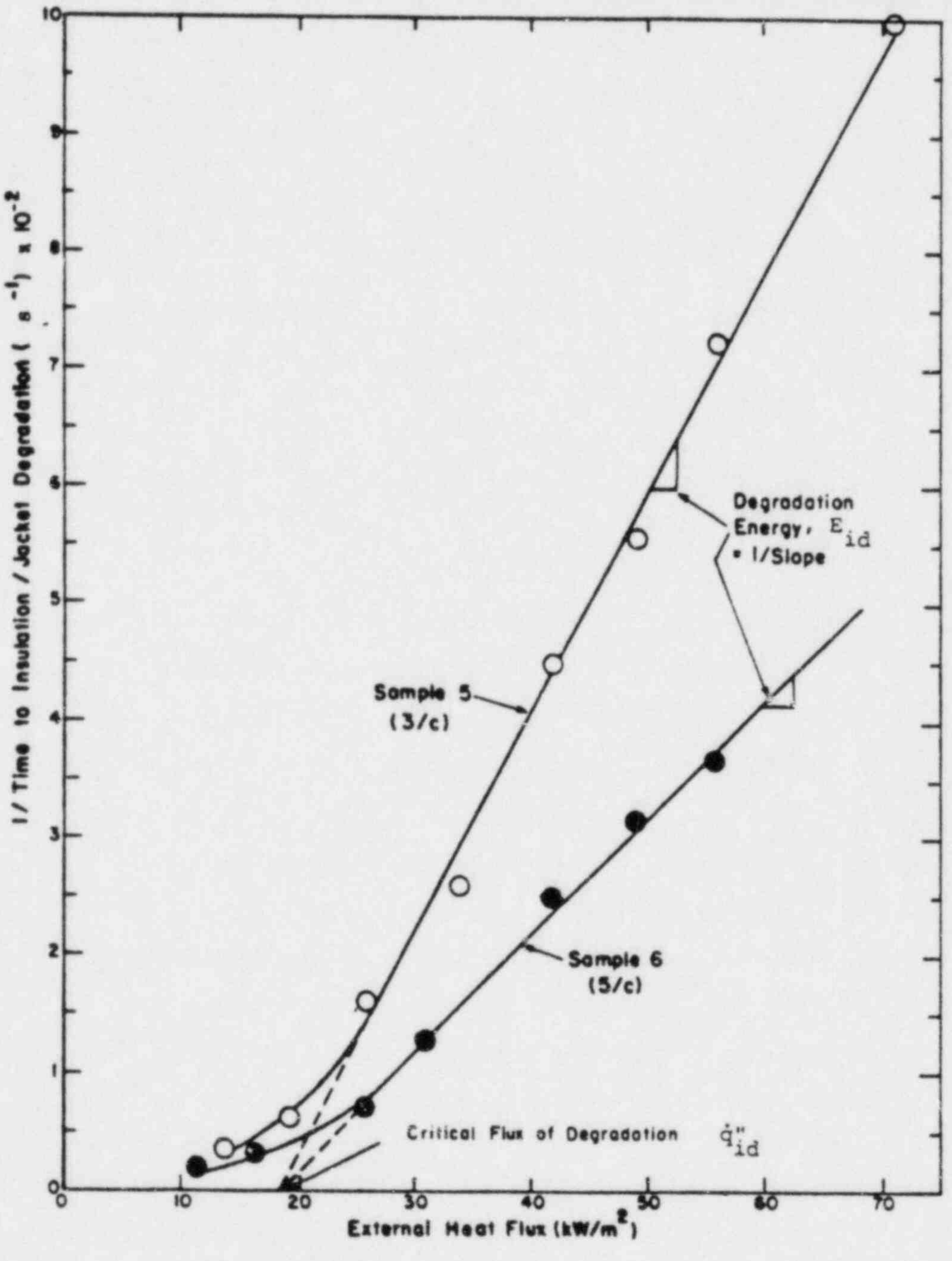

Fig. 2. Experimental determination of thermal degradation energy and critical flux of thermal degradation for PE/PVC cables.
(From Reference 2)

$$IDI = (\dot{q}''_e - \dot{q}''_{id})/E_{id}$$

$$PII = (\dot{q}''_e - \dot{q}''_{ig,p})/E_{ig,p}$$

$$EFI = (\dot{q}''_e - \dot{q}''_{ef})/E_{ef}$$

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).

Ideally, from a detector siting point of view, these indices provide an extremum value of time available for detector response for a given external thermal condition such that the particular form of cable damage is minimized.

This study has indeed shown that the damage potential of a cable under thermal exposures cannot be expressed by a single parameter but by a combination of parameters. Fortunately, interpretation of the test results indicate, to some extent, that the critical flux values for each of the damage processes studied all fall within a narrow range of values (around 20 kW/m^2); thus, the critical energy is the predominant differentiator. Furthermore, amongst the cables tested some did demonstrate low potential in all three damage processes with Teflon/Teflon rated highest; PE/PVC rated the lowest; and EPR/Hypalon having a median rating. This ordering in the degree in cable damageability seems to be consistent with the ordering in the fire-hazard potential previously discussed. As indicated in the cited references on cable flammability/damageability, cables of the same generic group do not necessarily imply the same behavior under thermal exposure due to intrinsic differences in manufacturing processes, construction type, number and size of conductors, amount of additives as retardants and plasticizers, etc.

Accordingly, how this type of information can be factored into the overall detector siting/selection methodology requires a priori assessment of the effect of the environment on the potential hazards presented by exposure fires. Detector threshold response must be part of the decision process which considers the order of importance of the three electrical cable damage processes applicable to the particular facility. This information will provide, in part, the necessary boundary condition or guidelines so that planners and engineers may select the appropriate cable and type of detector/protection systems. How this type of information can be factored into the overall decision-making process for detector-siting appraisal is discussed in the following sections.

2.3 Fire Detection/Cable Flammability Relationship

Data acquired from the FMRC laboratory-scale flammability apparatus in delineating the combustibility characteristics of polymeric materials$^{(8)}$ and cables were subsequently used to derive pertinent information regarding aerosol detector response. The following briefly describes how this information on smoke generation is evaluated.

Light obscuration by "smoke" is conventionally* expressed in terms of optical density per unit path length, D,

$$D = (1/\ell)\ln(I_0/I) \qquad (1)$$

where ℓ is the optical path length (m), and I/I_0 is the fraction of light transmitted through the "smoke." The light obscuration parameter of the aerosol can be expressed in terms of D and the mass-loss rate per unit volume of the product-air mixture, i.e.,

$$\sigma = D/(\dot{m}''/V_T'') \qquad (2)$$

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*Current research in "smoke" properties, their relationship with aerosol detector response, and development of standards tests indicates that measurement of optical density alone is insufficient for classification of all generic aerosol detectors.

where τ is the light obscuration parameter (m^2/g); $\dot{m}''$ is the mass loss rate of the pyrolyzing/burning material per sample surface area (g/sm^2), and $\dot{V}_T''$ is the total volumetric flow rate of the product-air mixture through the apparatus per unit surface area of the material (m/s). Under actual burning condition this parameter will be related to initial buoyant plume velocity.

If the external heat flux, $\dot{q}_e''$, is sufficient to only pyrolyze then the energy balance at the surface of the sample yields

$$\dot{m}'' = \dot{m}_p'' = (\dot{q}_e'' - \dot{q}_{rr}'')/L \qquad (3)$$

where L is the heat required to generate a unit mass of vapors (kJ/g) and q_{rr}'' is the surface re-radiation loss. For conditions where the sample is burning the energy balance must account for the heat flux to the surface by the flame, i.e.,

$$\dot{m}'' = \dot{m}_b'' = (\dot{q}_e'' + \dot{q}_{fc}'' + \dot{q}_{fr}'' - \dot{q}_{rr}'')/L \qquad (4)$$

where $\dot{q}_{fc}''$ and $\dot{q}_{fr}''$ are respectively the convective and radiative components from the flame to the cable sample. Measurements of the mass loss rate as a function of external radiative heat flux allows one, as Tewarson describes, to determine the other parameters. Ideally, $\dot{q}_e''$ would be the heat flux the cable "sees" due to say an exposure fire; $(\dot{q}_{fc}'' + \dot{q}_{fr}'')$ would be the heat flux the sample "sees" due to the burning of the samples' pyrolysis products; $\dot{q}_{rr}''$ would be the amount of heat flux lost from the sample due to re-radiation back into the environment. Note however, that conduction losses through the actual burning configuration cannot be assessed from these laboratory-scale tests. Thus with the mass-energy balance the optical density can be expressed as:

$$D = (\tau/L)\dot{q}_n'' \qquad (5)$$

where $\dot{q}_n'' \equiv \dot{q}_e'' - \dot{q}_{rr}''$ for pyrolysis of this sample and $\dot{q}_n'' \equiv \dot{q}_e'' + \dot{q}_{fc}'' + \dot{q}_{fr}'' - \dot{q}_{rr}''$ for combustion of the sample. From the above (and the test limitations), the optical density, thus, depends on: (1) the thermal environment, $(\dot{q}_n - \dot{q}_{rr})$; (2) over- or under-ventilated environment, $\dot{V}_T$; (3) optical system and fraction of products responsible for light obscuration, τ; and (4) the material,

τ/L and q''_{rr}. The data on polymeric materials, as shown in Figure 3, suggest that it may be possible to classify cable materials for τ values based upon their generic nature. For example, for cable #4 (see Table 1) which is considered a highly chlorinated cable, the data from Reference 1 indicates that at an external heat flux of 60 kW/m^2 applied to a sample of size $81(10)^{-4}$ m^2 with an airflow rate of about $1.4(10)^{-3}$ m^3/s (thus $\dot{V}''_T = 1.4(10)^{-3}/\ 81(10)^{-4} = 0.173$ m/sec) the optical density is 5.5/m. From Figure 3, with this value of D, the correlation for highly chlorinated materials indicate that the quantity $(1/\dot{V}''_T)\ (\dot{q}''_n/L)$ is approximately 100; thus, $\dot{q}''_n/L = 17.3$ which is close to value of the average peak steady-state value for mass loss rate $(\dot{m}''_b \approx \dot{q}''_n/L)$ of 15.8 that is recorded in Table 5-4 of Reference 1.

The question remains as to how one can relate this parameter, τ, a property measured at the burning/pyrolyzing source with those properties of smoke normally ascribed to the "environment" just surrounding the detector. For a plume rising in a quiescent environment, Heskestad$^{(9)}$ notes that the radial distribution of concentration of the products of combustion along the ceiling of an enclosure is, except for scale, expected to be practically identical to the radial distribution of excess enthalpy per unit mass of plume fluid, $c_p \Delta T$, since both quantities are dispersed by the same turbulence mechanism; i.e., $c_j/\Delta T$ is a constant for the material where c_j is the concentration of product, j, and ΔT is the gas temperature above ambient. Tewarson$^{(8)}$ shows that indeed this is the case for over-ventilated fire conditions where the yield of the product, j, compared to that under stoichiometric conditions is approximately constant. Under similar arguments then$^{(5,8)}$ the ratio of the optical density per unit path length to gas temperature above ambient, i.e., $D/\Delta T$, is suggested to be a parameter for the evaluation of response and spacing of fire detectors. This ratio has been analyzed in terms of the properties of polymeric materials$^{(8)}$ and evaluated for various cable samples$^{(1)}$. Table 9 lists the results of the study on cable flammability data under an imposed external heat flux of 60kW/m^2. It is expected that for flaming, over-ventilated, fire conditions this ratio is a weak function of external heat flux.

Heskestad and Delichatsios$^{(5)}$ have used the ratio $D/\Delta T$ as a parameter for the evaluation of the response and location of fire detectors in flaming

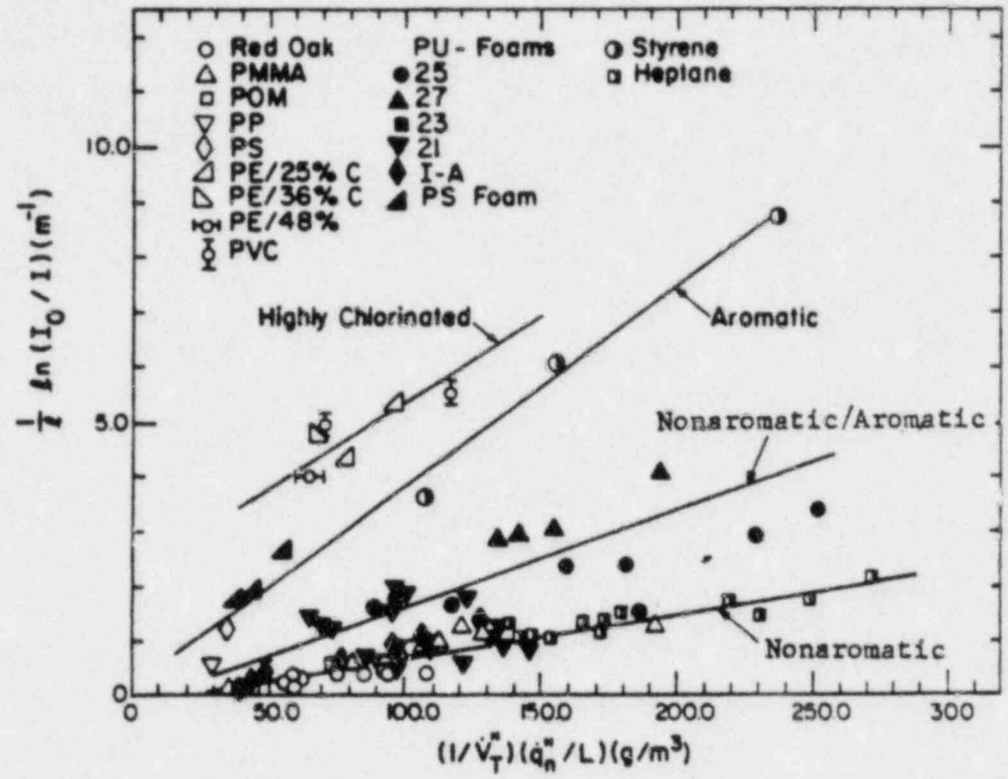

Fig. 3. Optical density per unit path length as a function of fuel vapor mass concentration; $\dot{q}''_n = \dot{q}''_e + \dot{q}''_{fs} - \dot{q}''_{rr}$

(From Reference 8)

Table 9

$D/\Delta T$ FOR THE COMBUSTION OF CABLE SAMPLES IN NORMAL AIR AT 60 kW/m^2 [a] *

Cable Sample	$D(m^{-1})$	$D/\Delta T\ (mK)^{-1}$
XPE/Neo (#2)	17.9	0.647
PE, PP/Cℓ·S·PE (#12)	17.4	0.630
FRXPE/Cℓ·S·PE (#15)	16.6	0.563
PVC (granular)[b]	5.5	0.550
PE/48%Cℓ (granular)[b]	4.0	0.395
PE/36%Cℓ (granular)[b]	4.8	0.387
PE, Ny/PVC, Ny (#19)	17.8	0.357
XPE/Neo (#17)	6.6	0.294
PE, Ny/PVC, Ny (#18)	8.2	0.269
PE/25%Cℓ (granular)[b]	5.4	0.250
PE/PVC (#4)	5.5	0.185
PE/PVC (#7)	6.5	0.166
PE/PVC (#6)	4.8	0.160
Silicone, glass braid (#21)	1.4	0.133
XPE/XPE (#13)	2.8	0.127
XPE/XPE (#14)	3.3	0.126
Silicone, glass braid/asbestos (#22)	2.8	0.125
XPE/Cℓ·S·PE (#16)	3.1	0.107
ℓdPE (#1)	2.8	0.082
PE, PP/Cℓ·S·PE (#11)	2.4	0.080
PE/PVC (#3)	2.4	0.069
Nylon (granular)[b]	2.6	0.062
ℓdPE (granular)[b]	2.1	0.039
Teflon (#20)	0.3	0.013

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[a] Average peak values, $D = \frac{1}{\ell} \ln (I_o/I)$; ℓ = optical path length (m); I_o = optical transmission through air; I = optical transmission through the mixture of products and air; $\Delta T = T_d - T_a$, T_d = gas temperature (K); T_a = ambient temperature (K)

[b] Research samples, data from Ref. 8

* From Reference (1)

fires. Basically the characteristic gas temperature rise at response is found by dividing the optical density (e.g. $0.06m^{-1}$) by the measured respective ratios of optical density to temperature rise found in the accompanying table. From the information presented in this table, the range of characteristic values of temperature rise at response would be from 1°C to 4.5°C if the optical density at response for all cables indicated is not larger than 0.06/m.

Detector spacing criteria, as described in Reference 5 and 6, is basically incorporating this characteristic temperature rise value with a fire plume/horizontal ceiling gas-dynamic interaction model from which ΔT versus radial extent along the ceiling can be predicted. Indeed a correlation of this type, which is the basis for the spacing criteria presented in Reference 6 and 7 has been derived by Heskestad and Delichatsios(10) for steady and parabolically growing fires. However, the detector siting design charts have not, as yet, considered completely the thermal/particulate environment generated from burning electrical cables. Extension of this type of work with electrical cable materials is one of the prime objectives of this report.

2.4 Initial Convective Flow in Fire

Heskestad and Delichatsios, under the auspices of the Fire Detection Institute, have considered the physical modeling of the <u>initial</u> environment generated by a fire in an enclosure that persists up to the time when recirculation of products of combustion begins to influence the further yield of products. This is an important fire interval for fire detection problems dealing with determining optimum spacing configurations of fire detectors.

Proposed modeling relations pertaining to idealized, yet realistic, classes of unsteady fires and referred to as "power law" fires have been corroborated with experiments. These "power law" fires are by definition defined as

$$Q_c = \alpha_c t^p \qquad (6)$$

which indicates that the convective heat release rate, Q_c (watts) varies with some power, p, of time, t, from ignition. For example, p=2, is often a good representation of flaming and radially spreading fires in low fuel piles.

The coefficient, α_c, determines the fire growth rate for a given power law fire. For parabolic growing fires, p=2, as illustrated in Figure 4, the coefficient, α_c, takes on the values of $4.44\ (10)^{-2}$ kw/sec^2 for a "fast" fire and $2.79\ (10)^{-3}$ kw/sec^2 for a slow fire. These values reflect arbitrary rate criteria but they do define within a practical range, the types of slow- and fast-developing fires that might be expected from common burning materials. Also, since that release rate can be represented by the product of the mass burning rate and the heat of combustion of the fuel, then the fire intensity coefficient, α_c, is directly proportional to the heat of combustion of the fuel.

Thus, fires can be sized by the rate of heat released, Q_c. The detector site location must be related to the size of the fire that one wishes to detect. The size of the fire at threshold response, (Q_{cr}), must reflect the amount of damage equipment (see Sections 2.1 and 2.2) can sustain before safety systems become impaired. Obviously, the smaller the critical fire or conversely the larger the damageability indices for cables the more sophisticated will be the detection requirements. To have a detector system respond before a fast developing fire grows to, say, 100 kw requires a idealistic response time of approximately 50 secs (i.e. $t = [(Q_c)_r/\alpha c]^{1/2} = [100/4.44(10)^{-2}]^{1/2}$). Increasing the threshold fire size by an order of magnitude indicates that the detector response time could be delayed by a factor of 3.

Integrating Equation 6 with time and assuming that the only contribution to the fire is from these hypothetical cables, the consumed cable material up to detection can be determined, viz,

$$m_c = \int_0^{t_r} (Q_c)dt/H_c \qquad (7)$$

where H_c is the heat of combustion of the cable (J/gr), a value that can be determined from small-scale tests (see Section 2.1). For a parabolically growing fire the mass loss is

$$m_c = [(Q_c)_r]^{3/2} \ / \ 3\alpha_c^{\ 1/2}/H_c \qquad (8)$$

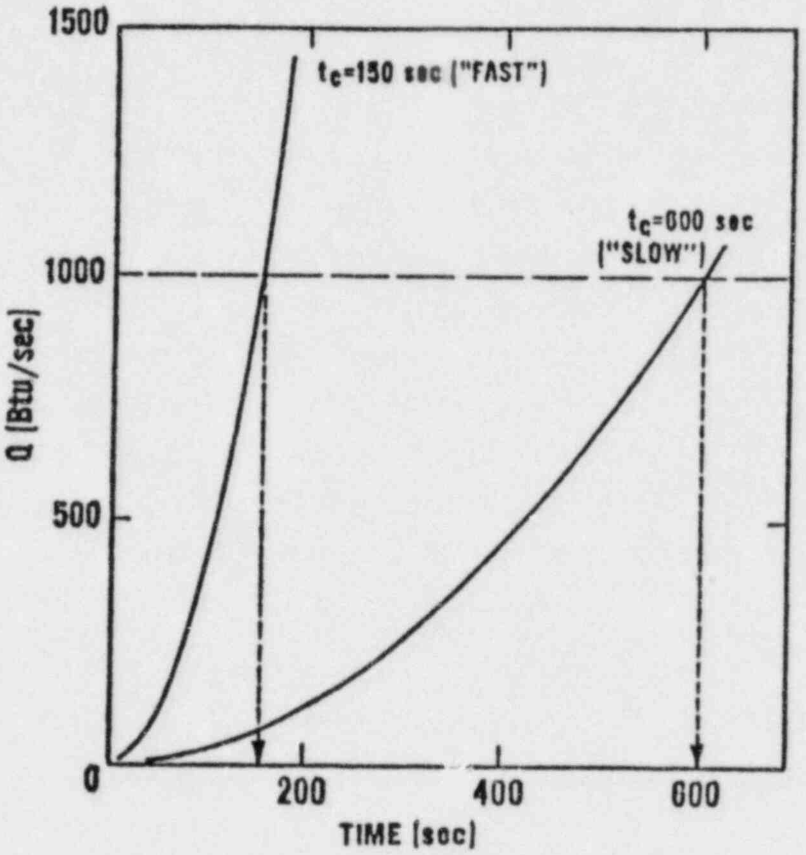

Fig. 4. Idealized Heat Release and Fire Growth Rates.
(From Reference 6)

Data on the total mass loss of generic cables before electrical short can also be used to determine approximately the range for early warning. The question that must be answered is how this concept can be translated into detector spacing. This requires knowledge of the dynamics of the fire plume generated by the aforenoted, power law, transient fire within an enclosure.

Heskestad does provide scaling relationships relating plume temperature rise and plume velocity as a function of radial distances from the fire axis and time with fire intensity and clearance distance between the ceiling and the fire source as parameters.

Briefly, for fires growing with the second power of time explicit relations for a nondimensional temperature and velocity in the hottest layer under large flat ceilings is given by

$$\Delta T^* = \left\{ \left[t^* - 0.954(1+r/H) \right] \;/\; \left[0.188 + 0.313(r/H) \right] \right\}^{4/3} \tag{9}$$

$$U^*/(\Delta T^*)^{1/2} = 0.59(r/H)^{-0.63} \tag{10}$$

where the ( )* are nondimensional quantities defined as

$$\Delta T^* \equiv \left[A^{-2/5}\, T_\infty^{-1} g \right] \alpha^{-2/5} H^{3/5}\, \Delta T \tag{11}$$

$$U^* \equiv \left[A \alpha_c H \right]^{-1/5} U \tag{12}$$

$$t^* \equiv \left[A \alpha_c / H^4 \right]^{1/5} t \tag{13}$$

where $A \equiv g/C_pT_\infty\rho_\infty$; c_p is the specific heat; ρ_∞, T_∞ are the ambient density and temperature; g is gravity, and H is the clearance height between the ceiling and the combustible. These relations can be used to predict temperature and velocity histories for arbitrary combinations of ceiling clearance and fire growth rate.

This cited work of Heskestad and Delichatsios has been used, under the auspices of the Fire Detection Institute, NBS, HUD, US. Bureau of Mines, Navy Department and the Veterans Administration, to develop design siting information for aerosol and heat detectors(6) once the detector/burning material parameter, D/ΔT, is prescribed.

Before proceeding, it must be emphasized that this design information is strictly applicable to flaming, parabolically growing fires in quiescent enclosures having smooth ceilings. Additional experimental corroboration is required using cable material as combustibles.

2.5 Detection of Smoldering and Flaming Cable Fires

In accordance with the simple fire growth scenario presented previously, the distribution of the smoke aerosol depends on the burning mode of the material and its subsequent distribution within the enclosure. This latter factor depends on room geometry and configuration and ambient conditions such as temperature stratification and ventilation.

The three factors alluded to previously to specify the required spacing of aerosol detectors for flaming fires in quiescent environments, namely,

- the response characteristics of detectors;
- the growth rate of the flaming fire; and,
- the acceptable fire size at detection

in accordance with the correlations previously sited were investigated by Delichatsios(3) using electrical cable material (Cable #17 in Table 1) as the prime combustible. The effects of ceiling configuration and flow ventilation were also investigated within these preliminary tests in which two types of commercially available smoke detectors were used. The sub-scale test enclosure had a 2.44 m ceiling height with a length:width:height ratio of 5:0.5:1 (a corridor-type configuration).

The main conclusions drawn from this study indicate 1) that for these preliminary tests the correlation presented previously are applicable to corridors involving burning electrical cables with no forced ventilation, 2) that in still air smoldering fires larger than a size dictated by the ambient stratification within the enclosure can also be detected with spacing the same as in flaming fires; and, finally, 3) that forced ventilation is still a study area requiring additional testing.

Table 10 and Figure 5 summarize the spacing criteria developed for fires involving the particular cable tested and for the particular detectors utilized using the corrolative approach previously described. For the tests, however, the actual fire growth rate can be classified as "slow", i.e., $\alpha_c \sim 2.79(10)^{-3}$ kw/sec^2.

Thus, in practice, the following curves demonstrate how for a given detector and ceiling height, detectors can be spaced, S, so that for a fast or slow burning fire releasing heat parabolically in time they should respond when the fire reaches a stage where its rate of heat value release is Q_d. Previously discussed, the value of Q_d chosen should be closely linked to the damageability indices of heat Q_d. The additional information required is the gas temperature rise, ΔT_r, at detector response which is a function of the material burning and the installed detector. Similar charts as shown in Figure 5 can be found in Reference 5 and 6 for combustibles other than electrical cables.

Table 10

DETECTION PARAMETERS *

Flaming Cable Fire (intensity)	Parabolic with Time (10^6 W in 20 min) - slow fire	Parabolic with Time (10^6 W in 10 min) - fast fire
Heat release at detection	10^4W, 5 x 10^4W, 10^5W	
Characteristic Smoke Detector Temperature Rise (ΔT_r)	5°C, 10°C, 25°C	

* From Reference (3)

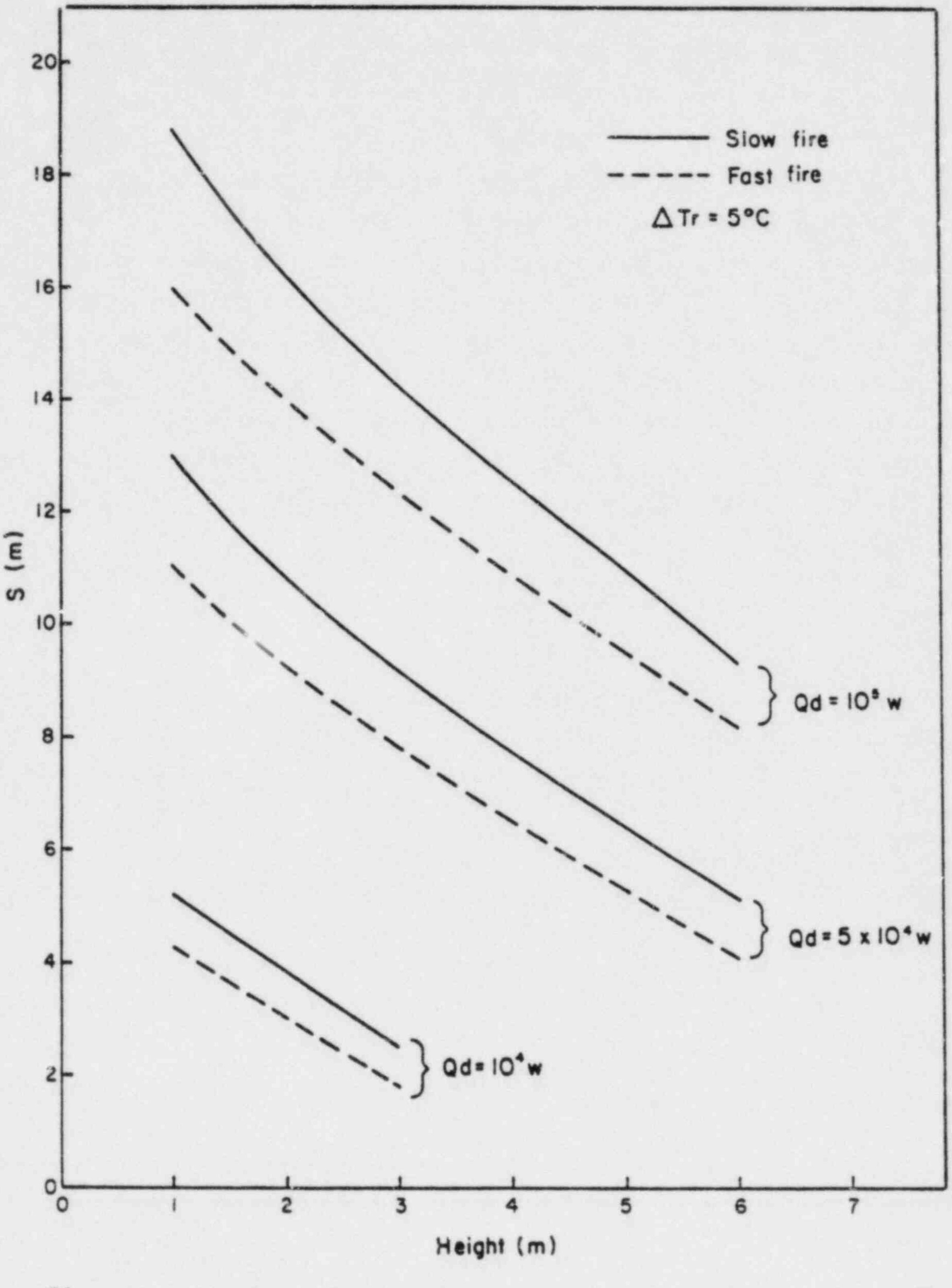

Fig. 5a. Spacings of smoke detectors on a square array under a flat extensive ceiling: $\Delta Tr = 5^{0}C$.

(From Reference 3)

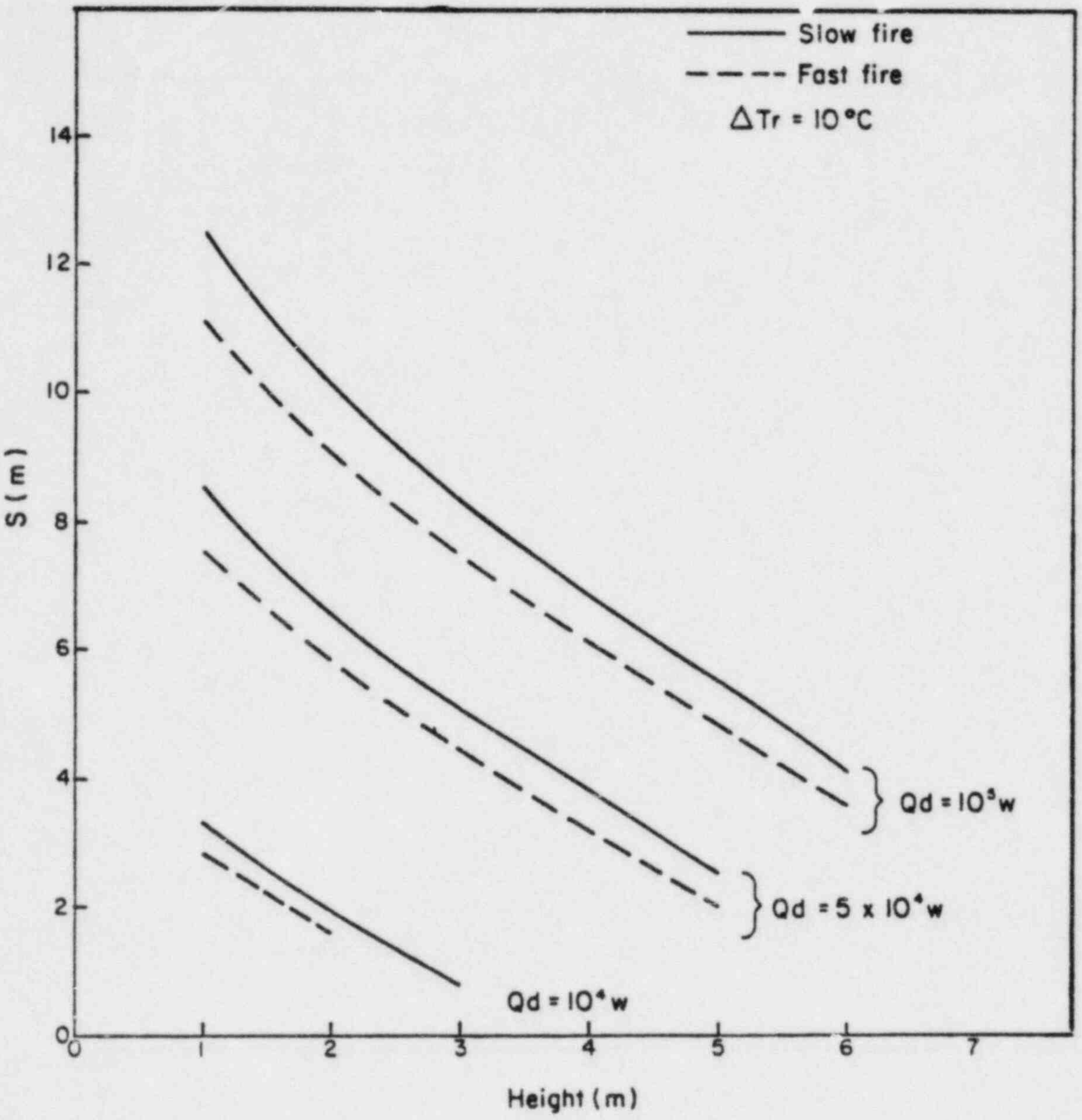

Fig. 5b. Spacings of smoke detectors on a square array under a flat extensive ceiling: $\Delta Tr = 10^{0}C$.

(From Reference 3)

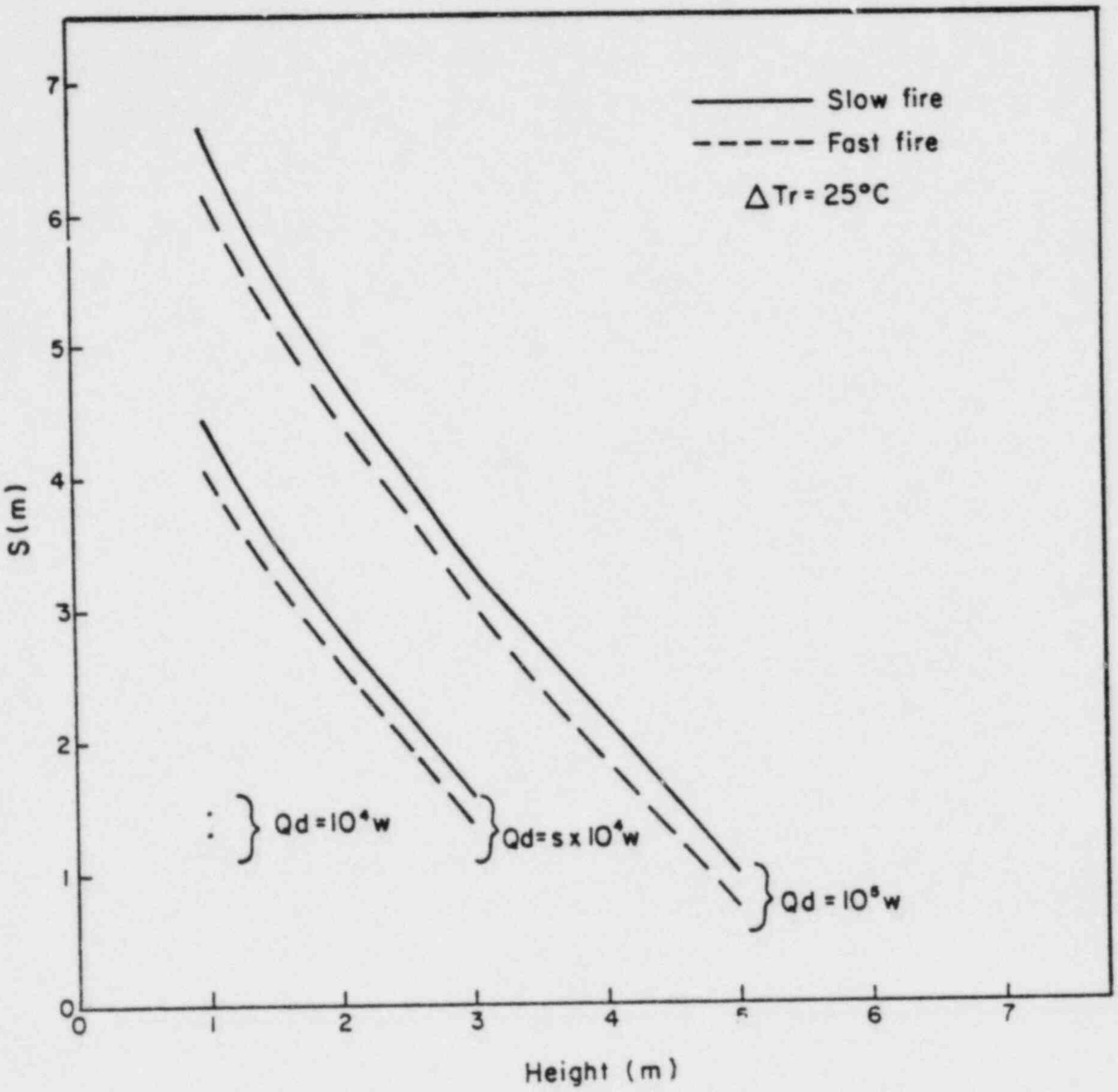

Fig. 5c. Spacings of smoke detectors on a square array under a flat extensive ceiling: ΔTr = 25°C.

(From Reference 3)

2.6 Exposure Fire Hazards to Cable Trays

The research programs described thus far have dealt with categorizing cable flammability and damageability using small cable samples within laboratory-scale and/or sub-scale enclosures. A first, and in our estimation, notable step in incorporating these results into a quantitative assessment of exposure fire hazards to full-scale cable tray configurations in a large scale test enclosure has recently been completed(4). The evaluation of exposure fire hazards to cable trays has been conducted by an experimental test/analytical program in the areas of (1) exposure fire categorization in open environments, (2) exposure fire categorization within a sub-scale enclosure, and (3) sprinkler and/or baffle protection requirements for cable trays within a large-scale enclosure.

In this study, the time available for response to a particular exposure fire hazard (a pool spill) is, reportably, predictable within certain limitations, from a combination of the following parameters:

- the enclosure ceiling height, floor area, and ventilation rate
- the location of cable tray
- the characteristic time constant and heat release rate of "pool" fire
- the maximum heat flux spatial distribution within the enclosure
- the critical heat flux for the particular cable type.

The potential application of the enclosure fire tests is discussed in great detail by Newman and Hill in the cited reference. An example of the use of the data is also illustrated therein and repeated here as well. Illustrated in Figure (6) is the transient variation in "near ceiling" average heat flux and temperature resulting from the burning of 80 liters of methanol fuel in a 1.74 m pan located centrally on the floor of a test enclosure having a ceiling height of 4.57 m and length-width-height proportions in this ratio (L:W:H = 2:1:1). Forced ventilation provided 12 room changes/hour. Also shown in this figure are:

1. Estimates of the time at which a smoke detector would activate based upon a prescribed value of temperature rise at detector response, i.e. ΔT_r as discussed by Heskestad & Delichatsios(3), (5)

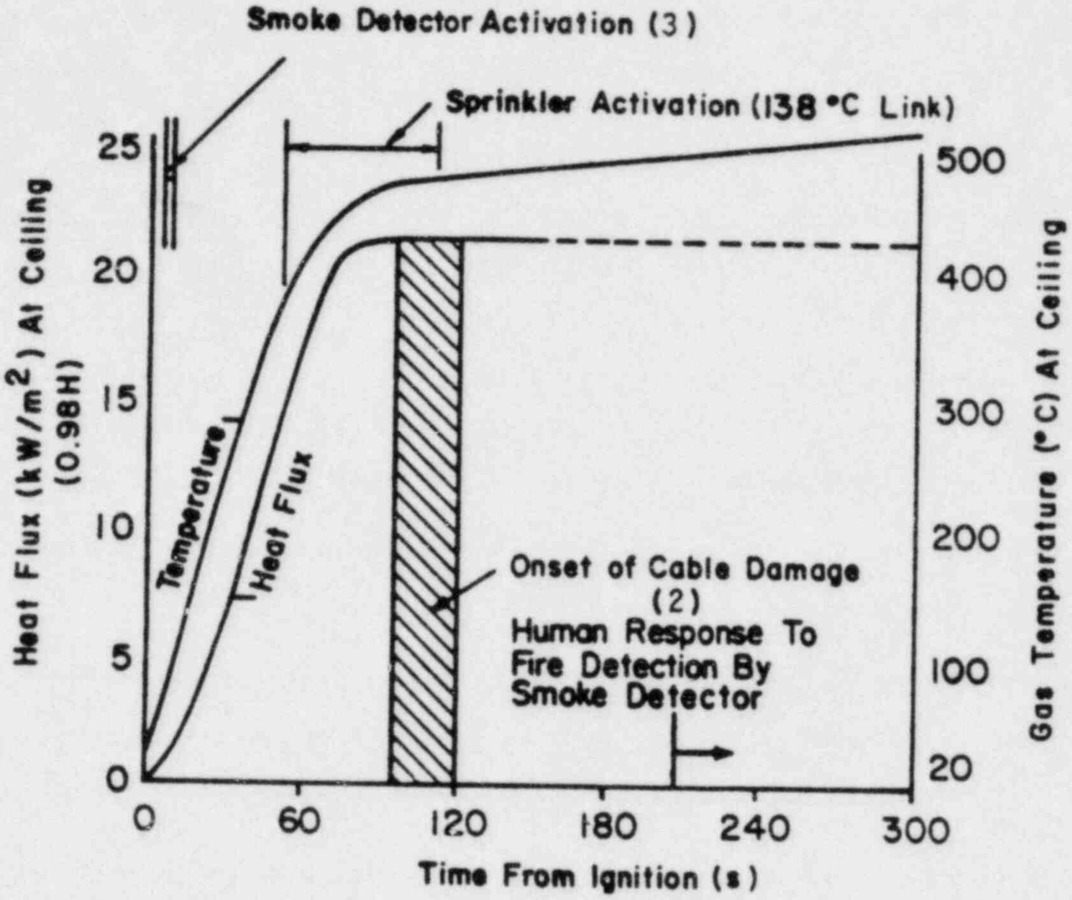

Fig. 6. Heat flux and gas temperature at ceiling versus time from ignition.

(From Reference 4)

2. The time for activation of a fusible link sprinkler
3. The onset of cable damage (if a cable had been located in the area of the measurements) based upon the laboratory-scaled experiments of Tewarson(1) or Lee(2)
4. The time for manual response.

Detail evaluation of "exposure fire" test in open environment as well as enclosures has lead to correlations relating the average heat flux with time, vertical position, ventilation rate, pool spill characteristics, and floor area. The following equation

$$\dot{q}''_m/\dot{Q}''_r = (A/H^2)\left\{0.24 - (4.73)\,\dot{V}_f/H^{5/2}\right\}(h/H)^{1/2} \qquad (14)$$

correlates the maximum heat flux, qm, (kw/m^2) to be expected at any point, h, (vertical height, m) in the enclosure with the enclosure characteristics, namely, ceiling height, H, (m) and ventilation rate, $\dot{V}_f$, (m^3/s) and fuel spill characteristics, namely fuel heat release rate, $\dot{Q}''_r$ (kw/m^2) and spill size, A, (m^2). Furthermore, a correlation of the instantaneous heat flux, $\dot{q}''$ normalized with respect to the aforenoted maximum heat flux, $\dot{q}''_m$, is represented by the relation

$$\dot{q}''/\dot{q}''_m = (h/H)^{1/2}\left\{0.52 + 13\,\dot{V}_f/H^{5/2}\right\}(t/\tau)^{0.9} \qquad (15)$$

where τ is a time constant that characterizes the time required for a pool of a given combustible and size (in terms of diameter, D) to reach the steady-state heat release rate, $\dot{Q}''_r$.

The above two correlations (one quasi-steady and the other time dependent), which can predict heat fluxes from an exposure fire within an enclosure as a function of enclosure height, location of interest within the enclosure, ventilation rate, and exposure fire time and size, have been based upon the experimental observation of minimal horizontal variations in heat flux. As such, although it is reported that these empirical correlations can be applied directly to rooms of shape similar to the enclosure studied, i.e., rooms with length:width:height ratios of 2:1:1 care must be exercised in utilizing these correlations to other geometrically-shaped rooms. These limitations are discussed further in the cited reference. It would have been interesting, however, if correlations like the above could have been extended to include, in addition to enclosure-room thermal environment, properties of smoke which are directly attributable to detector response, viz. particle concentration and size.*

2.7 Summary

The previous discussions have briefly touched upon the most recent relevant work involving electrical cable flammability, damageability, hazard assessment and detection and, to some extent, indicates that evaluation of exposure fire scenarios is a complex problem requiring many types of interrelated data. Indeed, the consolidation of these studies can provide planners and engineers with useful information for formulating interim guidelines needed for designing protective systems and assessing fire hazards to electrical cables in utility environments.

However, from a fire detection point of view, the very complex nature of the properties of smoke and its transit, and the interrelationship between these properties and detector response characteristics require further extension into these particular endeavors to obtain additional representative data on the environmental characteristics of electrical cable fires considered necessary for the design of ionization detector siting criteria and applications. These studies should initially involve detection of fires where the only combustible present is the electrical cable.

3.0 ELECTRICAL CABLE FIRES AND FIRE DETECTOR ENVIRONMENTS - TEST PLAN

3.1 Scope

Regarding automatic fire detection, a prime consideration is the rate of smoke movement from the fire source to the detector. Under a no-fire condition air movement in a room or compartment is determined by forced convection for heating and air conditioning purposes; by external winds, or by free convec-

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*It is also believed that correlations of this type together with cable flammability and damageability indices can provide adequate guidelines for safe separation distances once a design basis exposure fire is chosen.

tion attributed to heat sources. For very small (or incipient) fires, the buoyancy effects of the fire heat are negligible and smoke will follow existing air circulation patterns. As the developing fire becomes larger, the hot plume can have sufficient buoyant lift to reach the ceiling and move radially outward thereby creating a new air circulation pattern within the compartment. It is possible also that temperature-induced stratification will alter this type of smoke movement. For early detection of fires, these foregoing factors are crucial in determining detector response.

A further consideration is the response characteristics of the automatic detector to the particular smoke, (and hence the burning material) which can vary with the time-dependent concentration and particle size of the smoke at the detector. Other factors include the smoke velocity past the detector, its orientation, its entry characteristics and its operating principle.

Indeed the problem of detector siting/response is highly complex but fortunately both analytical and experimental progress, highlighted above, has been made.

The purpose of this experimental program is, therefore, mainly confirmatory in nature in the sense that it should verify the siting criteria previously established but, now, involving electrical cables as the prime combustible material.

The overall effort envisioned should be divided into three major phases to assess the environment surrounding the fire detector, viz,

Phase 1: Effect of Fire Size, Ceiling Height and Cable Material

Phase 2: Effect of Fire Size, Ceiling Configuration and Cable Material

Phase 3: Effect of Fire Size, Room Volume and Ventilation.

3.2 General Considerations

The detectors involved in each of these phases should primarily be of the ionization type since these types of detectors are normally found in nuclear reactor utilities. In addition, the test should be conducted and measurements made so that optimum utilization of the results from the laboratory and sub-scale experiments, that are discussed above, could be implemented.

For example, the electrical cable flammability tests(1) have indicated that polyethylene/polyvinylchloride cable, polyethylene-polypropylene/chlorosulfonated polyethylene cable and silicone cable samples represent high, intermediate and low fire hazards based upon mass loss and heat release rates in flaming fires. These types of cables are, in most respects, consistent with the indices describing high, intermediate and low electrical failure rating(2). These studies have also shown that for the types of cables tested, the minimum external heat flux for the onset of the damage process is approximately 20 kw/m^2 (≈6345 BTU/hr.-ft.^{2}). As such, thermal exposure to the electrical cables should be based upon this minimum value.

This brings to bear as to how to generate the electrical cable fire. Measurements(4) on an enclosure's thermal environment due to liquid spill fires has been found to be 90-95% convective; the remaining attributable to radiative heat transfer. One could then possibly use a liquid, such as acetone which produces negligible smoke as the external thermal source. Indeed, this has been the case in the corridor-study(3) described above where light-extinction measurements were used to corrolate detector response. Since this form of optical measurement methods can be used to measure particulates only down to a few tenths of a micron range and since, in this study quantitative evaluation of the response of ionization-type smoke detectors is desired which can be sensitive to particles an order of magnitude smaller in size, it is expected that the use of a flammable liquid, negligible smoke producing notwithstanding, may give pre-mature indication of response to fires which are not directly attributable to the burning of electrical cable material. Also, possible condensation of water vapor on inherent dust may preclude, by the same reasoning, the use of gas-ribbon burners. Consequently, radiating panels are considered the likely candidate for supplying the external heat source.

Another factor which should be common to the overall test plan is the size of the cable tray, cable configuration and load, and cable area subjected to exposed heat flux. For consistency with past experiments in cable fires it is anticipated that standard open ladder cable trays between 2.5 to 3 meters in length be used with cables arranged in a "figure eight" pattern. Size of cable will then determine percent "fill." The length of cable tray subjected to the external heat load should be a parameter of the test ranging from 10% to 50% of the overall tray length.

Also, judging by the results of the laboratory-scale kits, external radiative heat loads should be parametrically varied from between 20 kW to 70 kW per square meter of expose cable area. The cable tray structure should be such that mass loss rate of the cable material could be monitored.. Also, the radiating panels should not duly interfere with the subsequent smoke movement.

3.3 Specific Considerations

Since the two major tasks for the Phase 1 program are to confirm recent detector spacing as a function of 1) burning material and 2) ceiling height, tests should be conducted in facilities that provide a rather large expanse of unobstructed ceilings so that the ionization detectors chosen can be positioned at various radial locations from the center of the plume/ceiling impingement point. Present thinking is three radial locations, viz, 20%, 50%, 100% of the ceiling height, where detector "boards" housing the various ionization detectors can be mounted. The facility (or facilities) must also provide sufficient flexibility so that ceiling height can be varied (eg. 3, 6, 9 m heights); sufficient volume so that any recirculation of products of combustion due to the confining walls do not affect the subsequent readings; and also provide a quiescent environment to the developing plume. For the higher ceiling tests, any pre-test thermal stratification should be determined and its effect on the developing plume assessed. Being confirmatory in nature, the test plan, test execution, and measurements should follow closely the procedure established in Reference 5 as well the improvements discussed therein.

There is one major exception, however, and this has to do with the exclusive use of beam-type optical density meters for determining the requisite smoke properties at the various detector locations. Present thinking (e.g., Reference 11) is that due to the complex nature of smoke, measuring instrumentation in detector standards tests, should react on only those properties of smoke which affect the detector under tests. This implies that the standard shall be based on similar operating principles as those of the detector. Presently, a standard ionization chamber is available(12) and should be utilized in the test program. The analog signal from this device is directly related to the product of smoke particle concentration, N, and mean particle size, d_p, - a combination of smoke-dependent parameter which also affects commercial detectors output voltage. These tests may prove that instead of corrolating the ratio D/ΔT one should attempt to correlate the ratio $(Nd_p)/\Delta T$ for purposes of establishing ionization detector siting criteria.

A typical fire test room along with ceiling-mounted instrumentation is depicted in Figure 7 where the standard ionization measuring device, denoted as MIC, is shown together with an optical beam density instrument. How the output of this device can, with the use of an analytical representation of a coagulating buoyant plume, be used to assess the relationship between fire size and threshold response has been discussed by Boccio.(13)

It is believed also that use of a reference ionization instrument in addition to an optical beam densitometer may provide the added information required for assessment of detector spacing under smoldering fire conditions that had been lacking in previous experimental programs. Smoldering cable fires can be generated using external radiative heat flux in the range of 16 to 24 kW/m^2.

For the Phase 2 subprogram the prime objective is to confirm the siting criteria for beamed ceilings.(6) As such, the addition geometric parameter that should be varied are beam depth, h, and beam spacing, L. Ratios of ceiling height to beam depth and beam spacing to beam depth should be consistent with those typically found at reactor utilities. Also, the experimental work cited in Reference 6 indicates that the presence of a "curtain" around the test ceiling has a profound effect on the temperature field everywhere under the ceiling except in the neighborhood of the plume/ceiling impingement region. However, unaccountability of walls or other obstructions have been reported to yield siting criteria that is conservative. As such, using a "free-standing" ceiling in Phase 1 and 2 sub-programs is considered satisfactory.

Since ventilation rate is the crucial parameter to be varied in the Phase 3 subprogram, construction of a representative test enclosure must be considered. With the idea of using and/or augmenting as much of the work on cable flammability, damageability, and fire detection already reported, a test cell with dimension and proportions (L:W:H = 2:1:1) used by Newman and Hill(4) in their assessment of exposure fire hazards to cable trays should be considered. The reasons for such a configuration as discussed in Reference 4

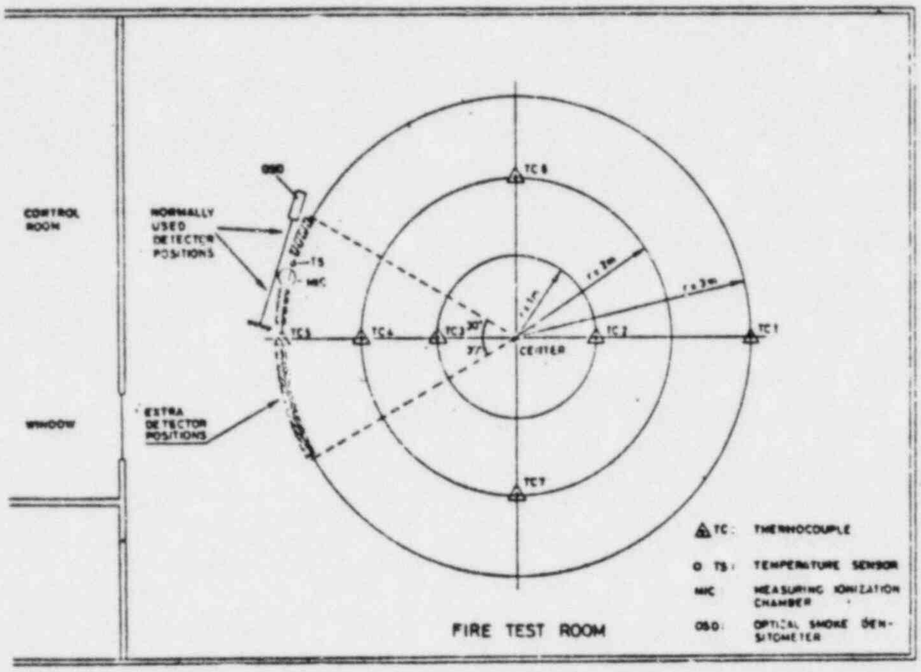


Fig. 7. Typical fire/detector sensitivity test room, L:W:H = 10m:8m:4m

are: (1) any test results would be more or less representative of an actual room (other than a corridor) in a utility, and (2) any test results can be applied, through in-house modeling relationships,(14) to typically much larger geometrically similar enclosures. This concept of applying the test results for one size of enclosure to other different sizes is discussed more fully in the cited reference along with its limitations.

Also, using a test enclosure of the aforenoted proportions, it would be interesting to see if the correlations that have already been developed for the heat buildup would lead to similar lines for correlating the aerosol environment within the enclosure. That is, would the horizontally-averaged value of the product of particle concentration and particle size (Nd_p) scale to the source value have the form:

$$(Nd_p)/(Nd_p)o \sim (A/H^2)\,{}^{p}(h/H)^{d} \left\{ k_1 - k_2\,\dot{V}_f/H^{5/2} \right\}^{q} \qquad (15)$$

for $\dot{V}_f < k_1 H^{5/2}/k_2$.

Ventilation rates, therefore, should also be similar, i.e., volumetric throughput should be such as to provide 0, 6, and 12 enclosure room air changes/hour. These are considered to be representative of the ventilation extremes for typical room environments in utilities.

3.4 Measurement Considerations

For the Phase 1 and 2 subprograms instrumentation necessary for the measurements of gas temperature, plume velocity, convective heat flux, smoke parameters (optical density, particle number concentration and size or a combination thereof) should be concentrated along the ceiling in line with the installed ionization detectors. Also, in order to determine the heat release rate as a function of the externally-applied radiative flux means should also be provided to measure mass-loss rate of burning material, at least, and also oxygen depletion rate. The data of Tewarson(1) along with the mass depletion rate can be used to determine approximately the actual heat release rate.

A more realistic value would be obtained if in addition the oxygen depletion rate was also measured since from these two measurements the actual heat of combustion could also be determined. Assuming adiabatic conditions, the convective fraction of this heat release rate can be determined from the ceiling measurements of temperature and velocity. Complete knowledge of the developing plume would require an inordinate amount of instrumentation which is deemed to be unfeasible. As such pre-test planning should consider the best location for the limited number of instrumentation that may be considered adequate.

For Phase 3, the added complexion of forced ventilation requires, in addition to ceiling-mounted and fire source instrumentation, additional instrumentation (temperature, smoke, etc.) stations mounted vertically through the test enclosures to probe the local environment within the enclosure. In Reference 4, five instrumentation stations within room enclosure of surface area 27m^2 was deemed sufficient. Accordingly, the ratio of instrumentation stations per unit floor area should be approximately one station per 5 square meters. The actual number and vertical location of probes mounted at each station should be part of the pre-test plan.

Measurement of detector response along with the aforenoted variables would then supply the necessary preliminary data to: (1) confirm existing correlations (when applicable), (2) augment these correlations, and (3) provide additional data for detector siting criteria not already established.

3.5 Summary

This section has discussed in rather broad terms a three-phase confirmatory test program concerned with evaluating the performance of fire-detection systems within nuclear facility type environments. It should provide data which can be used with recent state-of-the-art advances in detection systems and cable damageability to establish a basis for a guide for detector selection and siting criteria. Detector siting criteria involve complex and highly coupled physical phenomena. This report, as such, has only delved into three of these broad areas, namely ceiling height, ceiling configuration, and ventilation, needed for assessing detector performance within a thermal environment generated by flaming electrical cables. An effective, comprehensive program requires a viable combination of detector standards tests together with environmental "fire" tests such as those which have been described.

Specific details of the overall test plan, especially the specific type of measuring instrumentation, gas-dynamic probes, etc. and the associated data reduction procedures necessary to determine the requisite parameters to confirm and/or augment existing correlations for detector siting criteria have not been discussed. Addressing these particular issues now is not considered crucial for meeting the immediate objectives of this report.

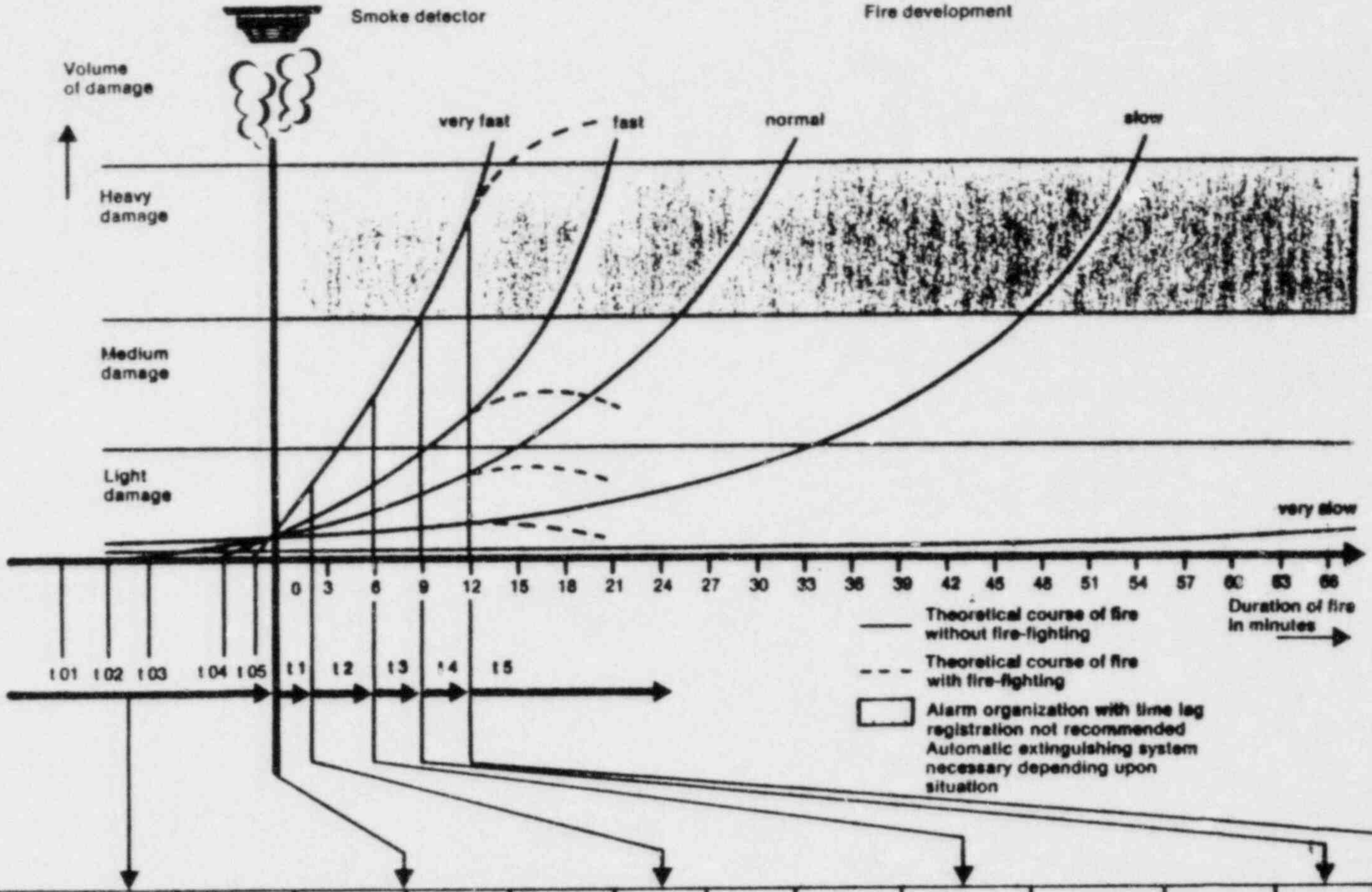
4.0 FINAL SUMMARY

Although the capabilities of technology, as it applies to fire detection systems, have made significant strides due to increased public awareness and regulatory actions, these advances in detector selection, siting, reliability, and approval tests have not substantially addressed the fire-protection requirements within nuclear reactors.

In particular, this report has stressed some of the basic requirements and considerations needed for establishing siting criteria for ionization detectors. Particular emphasis has been placed in establishing or confirming siting criteria for early warning detection of electrical cable fires.

An overall fire surveillance plan, typified in Figure 8, necessitates consideration of many factors which integrate technology and personnel in the decision chain. To properly design the detection phase of the overall system requires a more deterministic appraisal of electrical cable fire development and growth, the degree of damageability that electrical cable trays can sustain before impairing operation of safe-shutdown systems, and therefore, the time necessary for detector alarm.

Each of these factors involve highly complex and coupled fluid-dynamic and chemical-kinetic phenomena and, as such, detailed knowledge of all the physical ingredients and their interactions is beyond the capability of analysis.



Incident	Start of fire	Incipient phase before fire detection by detector	Early warning detector detects fire	Start of RS check 1*	Reaction of operating personnel	Cancelling of RS check 1*	Start of RS check 2*	Investigate source of signal	Decision: — Emergency: Press alarm push-button, alerting fire department	Start of initial rescue and fire-fighting operations	Assembly time of fire department	Turn-out time of fire department	Start co-ordinating fire-fighting
Time point	t 01 — 05	t 0 — 05/t 1	t 1	t 1	t 1 — t 2	t 2	t 2	t 2 — t 3	t 3	t 3	t 3 — t 4	t 4 — t 5	t 5
Time requirement ⌀	—	unknown	—	—	ca. 2 min.	—	—	ca. 4 min.	—	—	ca. 3 min.	ca. 3 min.	—
⌀ time requirement total	—	—	—	—	—	ca. 2 min.	—	—	ca. 6 min.	—	—	ca. 12 min.	—
Detection phase				Reaction, assembly and fire-fighting phase									

* RS check = Reconnaissance squad check

Fig. 8. Qualitative relationship between time and damage for different speeds of fire development and average detection, reaction and fire-fighting times. (From Reference 15)

However, laboratory-scaled and sub-scale tests discussed, which attempt to quantify 1) electrical cable flammability and damageability characteristics, together with 2) modelling and testing the initial convective flow of fire, both in sub-scale and full-scale facilities, will provide the necessary ground work in effecting an adequate set of guidelines for early warning fire detection systems.

By presenting an overview of this recent research, this report describes a set of confirmatory tests where the results of electrical fire development and growth are coupled with the parameters needed to assess detector response so that existing detector-siting criteria may be appraised.

The information acquired will help provide planners and engineers with adequate guidelines to select appropriate cables and type of detection protection systems, thus improving safety within the facility.

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REQUIREMENTS FOR ESTABLISHING DETECTOR SITING CRITERIA IN FIRES INVOLVING ELECTRICAL MATERIALS

August 1982

Sandia Project Officer: L. J. Klamerus

Prepared for

Sandia National Laboratories
Albuquerque, New Mexico 87185
operated by
Sandia Corporation
for the
US Department of Energy

Work performed under Sandia Contract No. 74-5093

Funded by
Division of Engineering Technology
Office of Nuclear Reactor Research
US Nuclear Regulatory Commission
Washington, DC 20555
Under Memorandum of Understanding DOE 40-550-75
NRC Fin No. A1010