UMTA-MA-06-0025-83-6
DOT-TSC-UMTA-83-4,I

U.S. Department
of Transportation

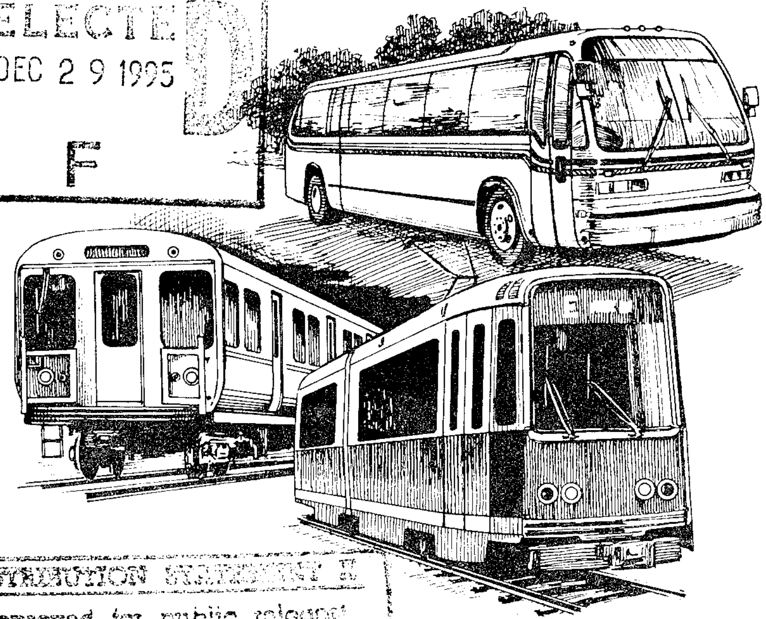
**Urban Mass
Transportation
Administration**

Combustibility of Electrical Wire and Cable for Rail Rapid Transit Systems

Volume I: Flammability

Factory Mutual Research
Corporation
1151 Boston-Providence Turnpike
Norwood MA 02062

MAY 1983
Final Report



UMTA Technical Assistance Program

(18) (19)

Technical Report Documentation Page

1. Report No. UMTA-MA-06-0025-83-6	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Combustibility of Electrical Wire and Cable for Rail Rapid Transit Systems Volume I: Flammability		5. Report Date May 1983 6. Performing Organization Code TSC/DTS-77
7. Author(s) A. Tewarson, M.M. Khan and J. Steciak		8. Performing Organization Report No. DOT-TSC-UMTA-83-4,1 (14)
9. Performing Organization Name and Address Factory Mutual Research Corporation* 1151 Boston-Providence Turnpike Norwood, MA 02062 (21)		10. Work Unit No. (TRAIS) UM378/R3615 11. Contract or Grant No. DTRS-57-80-C-00073
12. Sponsoring Agency Name and Address U.S. Department of Transportation Urban Mass Transportation Administration Office of Technical Assistance Washington, DC 20590		13. Type of Report and Period Covered Final Report April 1981-April 1982 14. Sponsoring Agency Code URT-6

15. Supplementary Notes

*Under contract to:
U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center (35)
Cambridge, MA 02142

16. Abstract

The combustibility of 31 wire and cable samples submitted by 12 manufacturers was evaluated using the Factory Mutual Small-Scale Combustibility Apparatus under simulated external radiation for large-scale fire conditions. Samples of wire and cable were ranked according to seven parameters: ignition/surface flame spread, electrical failure, corrosivity of the fire products, generation of fuel vapors, generation of heat, generation of gaseous compounds, and light obscuration.

The hazards expected in wire and cable fires depend not only on the generic nature of the insulation/jacket materials, but also on the additives, size and construction of the wire and cable. An increase in the size of the wire and cable sample is expected to reduce the fire hazard with the degree of hazard reduction dependent on the generic nature of the insulation/jacket materials.

A combined hazard index for wire and cable may be possible for end-use application in the future depending on confirmation of predictions based on the seven parameters.

17. Key Words Electrical Wire and Cable, Rail Rapid Transit System, Fire Hazard, Combustibility Ranking	18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report) UNCLASSIFIED	20. Security Classif. (of this page) UNCLASSIFIED	21. No. of Pages 120	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

This report was prepared by the Factory Mutual Research Corporation, Norwood, Massachusetts under U.S. Department of Transportation, Transportation Systems Center Contract No. DTRS-57-80-C-00073. The program was administered under the technical direction of the Transportation Systems Center, Kendall Square, Cambridge MA 02142 with Mr. I. Litant as the Technical Project Officer and Mr. Milton Holzman as the Contract Administrator.

The report discusses the quantification of hazards associated with fires involving wires and cables in rail rapid transit systems. Specifically, it delineates the effects of the generic nature of the insulation/jacket materials, additives, and size and construction of the wires and cables.

This report is organized in three parts: 1) a simplified overall summary of the report; 2) experimental details, results and discussion; and 3) appendices providing detailed calculations for determining the different parameters used in the report.

The experiments were performed by Messrs. S.D. Ogden and R.L. Haigis of the Factory Mutual Research Corporation. The authors gratefully acknowledge the technical guidance received through numerous discussions with Mr. I. Litant of DOT/Transportation Systems Center.

The authors wish to express their thanks to various cable manufacturers who participated in this program by providing wire and cable samples; and to the members of the APTA Liaison Board for their valuable reviews and comments.

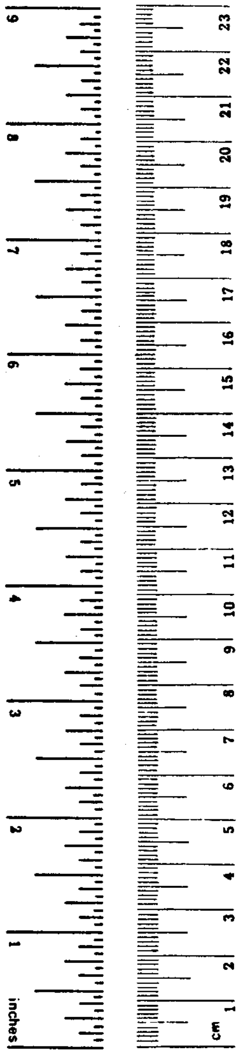
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

---

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

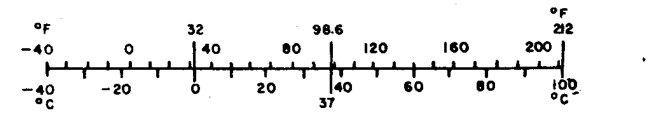


TABLE OF CONTENTS

Section Title Page

I INTRODUCTION 1

II EXPERIMENTAL APPROACH 4

2.1 General Background 4

2.2 Experimental Apparatus And Procedure 6

2.3 Details Of Test Measurements 9

III WIRE AND CABLE SAMPLES 17

3.1 Wire And Cable Sample Identification Scheme 17

3.2 Physical Properties Of The Wire And Cable Samples 17

IV EXPERIMENTAL RESULTS 25

4.1 Piloted Ignition 25

4.2 Generation Rate Of Fuel Vapors 25

4.3 Generation Rate Of Fire Products 36

4.4 Light Obscuration Through "Smoke" 39

4.5 Electrical Integrity 44

4.6 Corrosivity Of Fire Products 46

V CONCLUSIONS AND RECOMMENDATIONS 49

5.1 Conclusions 61

5.2 Recommendations 61

APPENDIX A - Total Volumetric And Mass Flow Rates Of Product-Air 62
Mixture Through The Sampling Duct 65

APPENDIX B - Ignition

APPENDIX C - Generation Rate Of Combustible Vapors Per Unit Sample 67
Surface Area 71

APPENDIX D - Generation Rates Of Fire Products - Heat And Chemical 75
Compounds

APPENDIX E - Optical Properties Of Smoke 81

APPENDIX F - Corrosivity Of Fire Products Of Wire And Cable Samples 90

APPENDIX G - Report Of New Technology 93

REFERENCES 95

LIST OF ILLUSTRATIONS

Number	Title	Page
1	Factory Mutual Combustibility Apparatuses	5
2	FM Small-Scale Combustibility Apparatus	7
3	Schematic Of Electrical Integrity Failure Experimental Setup	11
4	Contact Points Of The Nichrome Wire With The Cable Surface	12
5	Collection Method For Corrosive Products	14
6	Corrosion Measurement With Electrical Resistance Probe	16
7	1/ (Time To Piloted Ignition x External Heat Flux) As A Function Of External Heat Flux	26
8	Asymptotic Ignition Energy Versus Ratio Of Thermal Capacity Of Conductor To That Of Insulation	37
9	Piloted Ignition Parameter For Horizontal And Vertical Wire And Cable Samples Under Different Air Flow Conditions	38
10	Electrical Failure Parameter As A Function Of Piloted Ignition Parameter	53
11	Cumulative Corrosion (Microns) Per PPM Of Cable Fire Products On Mild Steel As A Function Of Exposure Time	57
B-1	Piloted Ignition Parameter As A Function Of External Heat Flux	68
E-1	Optical Density Per Uhit Path Length As A Function Of Time For Cable Samples Exposed To 60 kW/m^2 Of External Heat Flux	84

LIST OF TABLES

Number	Title	Page
I	Supplier Or Manufacturer Identification Code	18
II	Conductor Size Identification Code	18
III	Insulation Jacket Material Identification Code	19
IV	Detailed Description Of Wire And Cable Samples	20
V	Single Conductor Wire And Cable Samples Used In This Study And The Previous Study	21
VI	Piloted Ignition Parameter And Critical Heat Flux For Wire And Cable Samples In Vertical Configuration Under Forced Normal Air Flow Conditions	28
VII	Relationship Between Piloted Ignition Data From This Study And From Boeing Study Expressed In Terms Of Total Cable Surface Area	29
VIII	Piloted Ignition Parameter For Single Conductor Wire And Cable Samples in Vertical Position Under Forced Normal Air Flow In Terms Of Total Cable Surface Area	30
IX	Time To Piloted Ignition Under Natural Air Flow Conditions For Large Wire And Cable Samples Using Fisher Burner Technique	35
X	Fuel Vapor Generation Parameter For Wire And Cable Samples For Combustion In Normal Air	40
XI	Heat Generation Parameter Of Wire And Cable Samples In Normal Air	42
XII	CO Generation Parameter For Wire And Cable Samples in Normal Air	43
XIII	Light Obscuration Parameter Of "Smoke" Generated From Wire And Cable Samples In Normal Air	45
XIV	NBS Smoke Chamber Data For The Flaming Fires Of Wire And Cable Samples	47
XV	Comparison Of "Smoke" Data From The NBS Smoke Chamber And From The FM Small-Scale Apparatus	48
XVI	Electrical Failure And Ignition Parameters Of Wire And Cable Samples Under Natural Air Flow	50
XVII	Cumulative Corrosion (in micron) Of Wire And Cable Sample Fire Products On Mild Steel As A Function Of Exposure Time	55
XVIII	Cumulative Corrosion (micron) Per PPM Of Wire And Cable Sample Fire Products On Mild Steel As A Function Of Exposure Time	56
XIX	Corrosion Potential Of Fire Products Of Wire And Cable Samples Relative To The Corrosion Potential Of HCl On Mild Steel	58
E-1	Comparison Of Optical Density Per Unit Path Length From The FM Small-Scale Apparatus And NBS Smoke Chamber	89

SYMBOLS AND ABBREVIATIONS

A	total exposed cable surface area (m^2)
CP	chemical compound generation parameter (g/kJ)
c	concentration of fire products (g/mℓ or g/m^3)
c_p	specific heat (J/gK)
D	optical density per unit path length of light (m^{-1})
D_s	specific optical density (-)
d	orifice opening diameter (cm)
E	energy per unit surface area of the cable (kJ/m^2)
$\dot{G}''_j$	generation rate of chemical compounds per unit cable surface area (g/m^2s)
$\dot{G}''_{comb}$	generation rate of fuel vapors per unit cable surface area (g/m^2s)
HP	heat generation parameter (-)
H_T	net heat of complete combustion (kJ/g)
H_{CO}	net heat of complete combustion of CO (kJ/g)
H_A	actual heat of combustion (kJ/g)
H_C	convective heat of combustion (kJ/g)
H_R	radiative heat of combustion (kJ/g)
IP	ignition parameter (m^2/kJ)
I	optical transmission through "smoke" (mv)
I_o	optical transmission through air (mv)
K	flow coefficient of the orifice in the duct
k_{CO}	maximum yield of CO calculated on the basis of complete conversion of carbon in the sample to CO without any CO_2 (-)
k_{CO_2}	maximum yield of CO_2 calculated on the basis of complete conversion of carbon in the sample to CO_2 without any CO (-)
LP	light obscuration parameter (m^2/kJ)
L	heat of gasification of cable sample (kJ/g)
ℓ	optical path length (m)
MW	molecular weight of the gaseous mixture
$\dot{m}$	mass flow rate of the gaseous mixture (g/s)

p_d	pressure of the gaseous mixture in the duct (g/cm^2)
Δp_m	pressure drop across the orifice (g/cm^2)
$\dot{Q}''_A$	actual heat release rate per unit cable surface area (kW/m^2)
$\dot{Q}''_C$	convective heat release rate per unit cable surface area (kW/m^2)
$\dot{Q}''_R$	radiative heat release rate per unit cable surface area (kW/m^2)
$\dot{q}''_e$	external heat flux per unit cable surface area (kW/m^2)
$\dot{q}''_{cr}$	critical heat flux per unit cable surface area (kW/m^2)
$\dot{q}''_{fs}$	flame heat flux received per unit cable surface area (kW/m^2)
$\dot{q}''_{rr}$	surface reradiation loss (kW/m^2)
$R_{corr.}$	rate of corrosion (micron/ppm hr)
T_a	ambient temperature (K)
T_d	bulk gas temperature in the duct
t_{ig}	time to ignition (s)
VP	fuel vapor generation parameter (g/kJ)
V	volume of insulation or inner conductor per unit length (m^3)
$\dot{v}$	volumetric flow rate of fire products mixture (m^3/s)
y_j	yield of compound j (-)
Z	cumulative corrosion per unit concentration of the corrosive compounds (micron/ppm)
α	surface absorptance
σ	mass attenuation coefficient of "smoke" (m^2/g)
ρ	density (g/m^3)

Superscripts

$\cdot$	per unit of time (s^{-1})
"	per unit exposed surface area of cable sample (m^2)

Subscripts

A	actual
a	ambient
cr	critical
C	convective
comb	fuel vapors
CO	carbon monoxide
CO_2	carbon dioxide
e	external

fs	flame heat flux received by the cable surface
ig	ignition
j	individual fire products
R	radiative
rr	reradiation
s	specific (optical density)
T	complete combustion

EXECUTIVE SUMMARY

The objective of this study was to examine the combustibility of wires and cables used in rail rapid transit systems. The following items were investigated in the study:

S.1 REVIEW OF STUDIES ON WIRE AND CABLE FIRES

In the study a review was made of literature on the combustibility of wires and cables, which included the study performed by Boeing(1), U.S. Department of Transportation(2), review of wire and cable fire problems by Factory Mutual Research Corporation (FMRC) performed in 1975 and 1979(4,5); cable tray fire studies at FMRC sponsored by the Electric Power Research Institute(5-10,12,13), cable tray fire studies at Sandia sponsored by the U.S. Nuclear Regulatory Commission(20), and others(14-19). The review was performed to establish: 1) the advantages and disadvantages of the tests used for the evaluation of wire and cable combustibility; 2) possible improvements in the test methods; and 3) additional test methods that may be required.

From the review, it was concluded that current "standard" or other test methods do not appear to be suitable for the combustibility evaluation of wires and cables for large-scale fire conditions. It was also concluded that a test method is needed which is capable of: 1) testing wires and cables in their end-use configurations; 2) simulating large-scale fire environments; 3) measuring all aspects of combustibility simultaneously; and 4) establishing the accuracy of the predictions of fire hazards in large-scale fires.

S.2 SELECTION OF TEST METHOD FOR COMBUSTIBILITY EVALUATIONS OF WIRES AND CABLES

Based on the review and the work performed by FMRC during the last 12 years on the combustibility of polymeric materials(21-31), the Factory Mutual (FM) Small-Scale Combustibility Apparatus was selected for the combustibility evaluation of wires and cables used in rail rapid transit systems.

S.3 TESTING OF WIRES AND CABLES

A total of 31 wire and cable samples submitted by 12 manufacturers were tested in the study. A scheme was developed for sample identification by manufacturer, conductor size, and insulation-jacket material. A detailed description of the samples tested in the study is included.

The following measurements were made as functions of the external heat flux applied to the sample: 1) time to piloted ignition; 2) time to electrical failure; 3) generation rate of fuel vapors; 4) generation rate of heat; 5) generation rate of CO_2, CO, and total gaseous hydrocarbons; 6) light obscuration by "smoke"; and 7) corrosivity of the fire products generated by wire and cable samples. These parameters were obtained from the individual measurements divided by the external heat flux applied to the cable sample. All parameters for ignition, electrical failure, fuel vapor generation, heat generation, "smoke," toxic and corrosive compounds, and light obscuration were normalized by cable sample length times the cable circumference (see Section 3.2). In this fashion the total exposed cable surface area is taken into account which is more important in fires than either the length or the circumference of the cable sample taken separately. For corrosion, the data were normalized by the ratio of total mass of fuel vapors produced to the total volume of water through which the vapors were passed to dissolve the water-soluble compounds present in the vapors.

Since flame heat flux was not quantified in the study, a high value of external heat flux (60 kW/m^2) was used to reduce the effect of flame heat flux.

In order to express general relative ranking of the wire and cable samples, ethylene propylene/Hypalon sample No. 8-14-8-1 was arbitrarily selected as a reference, against which other wire and cable samples were ranked. All the cables ignited in ambient air in the presence of applied external heat flux, except halogenated samples (Halar and Teflon), for which oxygen concentration in the inlet gas was increased well above the ambient air value and an external heat flux was applied. This was defined as the combined simulation of flame and external radiation for large-scale fires.

The general relative rankings of representative wire and cable samples are listed in Table S-1 and shown in Figures S-1 through S-3. The higher the ranking or the value of each parameter, the higher is the relative hazard expected in fires of the representative wire and cable samples.

S.3.1 Definition Of Individual Parameters

Individual parameters are defined very briefly in this section. For details see Section IV and the Appendices.

TABLE S-1. GENERAL RELATIVE RANKING OF REPRESENTATIVE WIRE AND CABLE SAMPLES USING ETHYLENE PROPYLENE/HYPALON SELECTED ARBITRARILY AS A REFERENCE SAMPLE[a]

		Relative Combustibility Ranking						
Sample No.	Insulation/Jacket Materials	Ignition/ Flame Spread	Electrical Failure	Corrosion	Fuel Vapors	Heat	Carbon Monoxide	Light Obscuration[d]
8-14-8-1	EPR/FR/Hypalon[b]	1.0	1.0	1.0	1.0	1.0	1.0	1.0
9-14-13-1	EPDM/Hypalon	0.87	1.6	1.1	0.95	1.0	0.19	1.6
9-12-13-1	EPDM/Hypalon	0.87	2.5	N	N	N	N	N
8-10008-1	EPR/Hypalon	0.82	NF	N	0.59	0.62	0.88	0.65
7-12-7-1	XLPO,FR/None	0.62	2.6	1.2	N	N	N	N
1-12-15-1	EPR/Low Smoke PO	0.58	2.1	N	N	N	N	N
10-12-10-1	EPR/XLPO,FR,Smoke Suppress.	0.56	2.2	0.54	N	N	N	N
4-12-4-1	XLPO/None	0.49	2.1	1.1	N	N	N	N
4-12-9-1	Mica-Mat,Gemex Tape/XLPO	0.49	1.6	N	N	N	N	N
4-646-6-1	EPR/Neoprene	0.49	0.30	N	0.35	0.89	0.083	0.26
4-646-4-1	XLPO/None	0.43	NF	N	N	N	N	N
3-12-5-1	EPR,FR,Low Smoke/XLPO	0.38	1.6	0.51	1.2	2.1	0.40	1.7
1-250-15-1	EPR/Low Smoke PO	0.34	0.30	N	N	N	N	N
5-12-4-1	XLPO/None	0.34	2.9	1.4	N	N	N	N
10-500-10-1	EPR/XLPO,FR,Smoke Suppress.	0.31	NF	N	0.57	1.3	0.11	0.22
3-500-5-1	EPR,FR,Low Smoke/XLPO	0.27	NF	N	0.62	1.2	0.21	0.40
9-2000-14-1	EPDM/PO	0.26	NF	N	N	N	N	N
2-12-3-1	Polyrad XLPO/None	0.23	1.1	0.97	N	N	N	N
5-0000-4-1	XLPO/None	0.23	0.40	N	0.43	0.83	0.25	0.38
3-1000-5-1	EPR,FR,Low Smoke/XLPO	0.22	NF	N	0.59	0.83	0.11	0.30
1-12-2-1	Silicone, Low Smoke/PO	0.19	0.80	0.79	N	N	N	N
7-313-7-1	XLPO,FR/None	0.18	0.30	N	0.46	0.85	0.19	0.28
1-250-2-1	Silicone, Low Smoke/PO	0.17	0.50	N	0.95	0.92	1.3	1.1
2-444-3-1	Polyrad XLPO/None	0.17	0.40	N	0.81	1.2	0.88	0.92
3-1500-5-1	EPR,FR,Low Smoke/XLPO	0.17	NF	N	0.46	0.59	0.060	0.17
6-0000-12-1	Halar (ECTFE)	NI 0.10[c]	1.1 -	N N	N 0.65[c]	N 0.35[c]	N 0.053[c]	N 0.24[c]
6-12-12-1	Halar (ECTFE)	NI N	2.4 -	N 3.4	N N	N N	N N	N N
11-00-1-1	Teflon (PTFE)	NI 0.078[c]	NF 0.50	N N	N 1.1[c]	N 0.56[c]	N 1.1[c]	N <0.00083[c]
11-12-1-1	Teflon (PTFE)	NI	0.50	3.5	N	N	N	N
11-10-11-1	Kapton/Teflon (FEP)	NI	NF	N	N	N	N	N
12-12-16-1	ZeroHal	N	N	0.090	N	N	N	N

---

[a] Samples in vertical configuration; forced normal air flow in the FM Small-Scale Combustibility Apparatus. Ranking based on parameters for ignition, generation of combustible vapors, heat, and carbon monoxide, light obscuration, and corrosivity.

[b] Sample used as a reference for comparative purposes only.

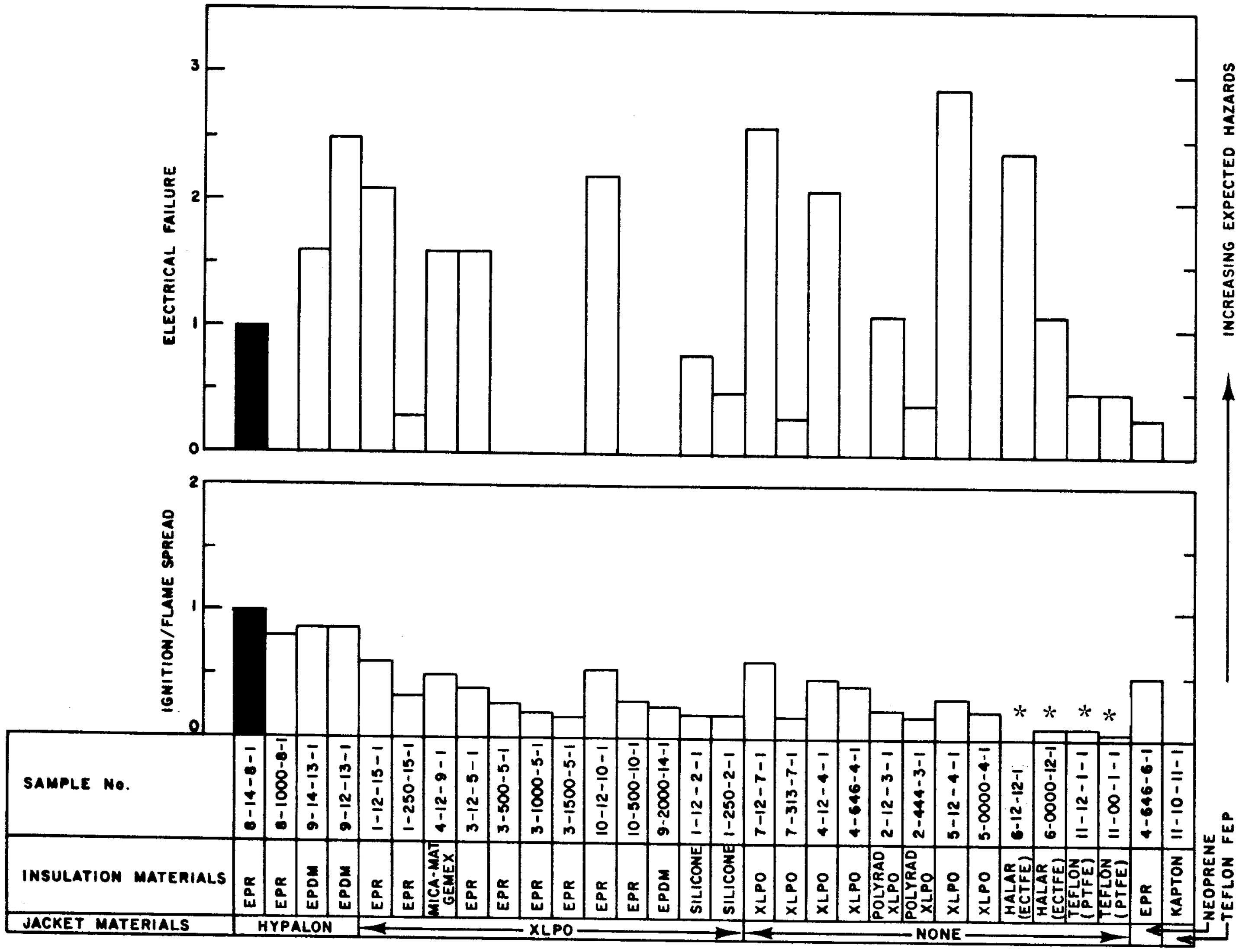
[c] Under simulated conditions of flame and external radiation for large-scale fire conditions, achieved by increasing oxygen concentration well above ambient value and also applying external heat flux.

[d] For wavelength 0.624µ of the light source (visible range)

N: Not tested.

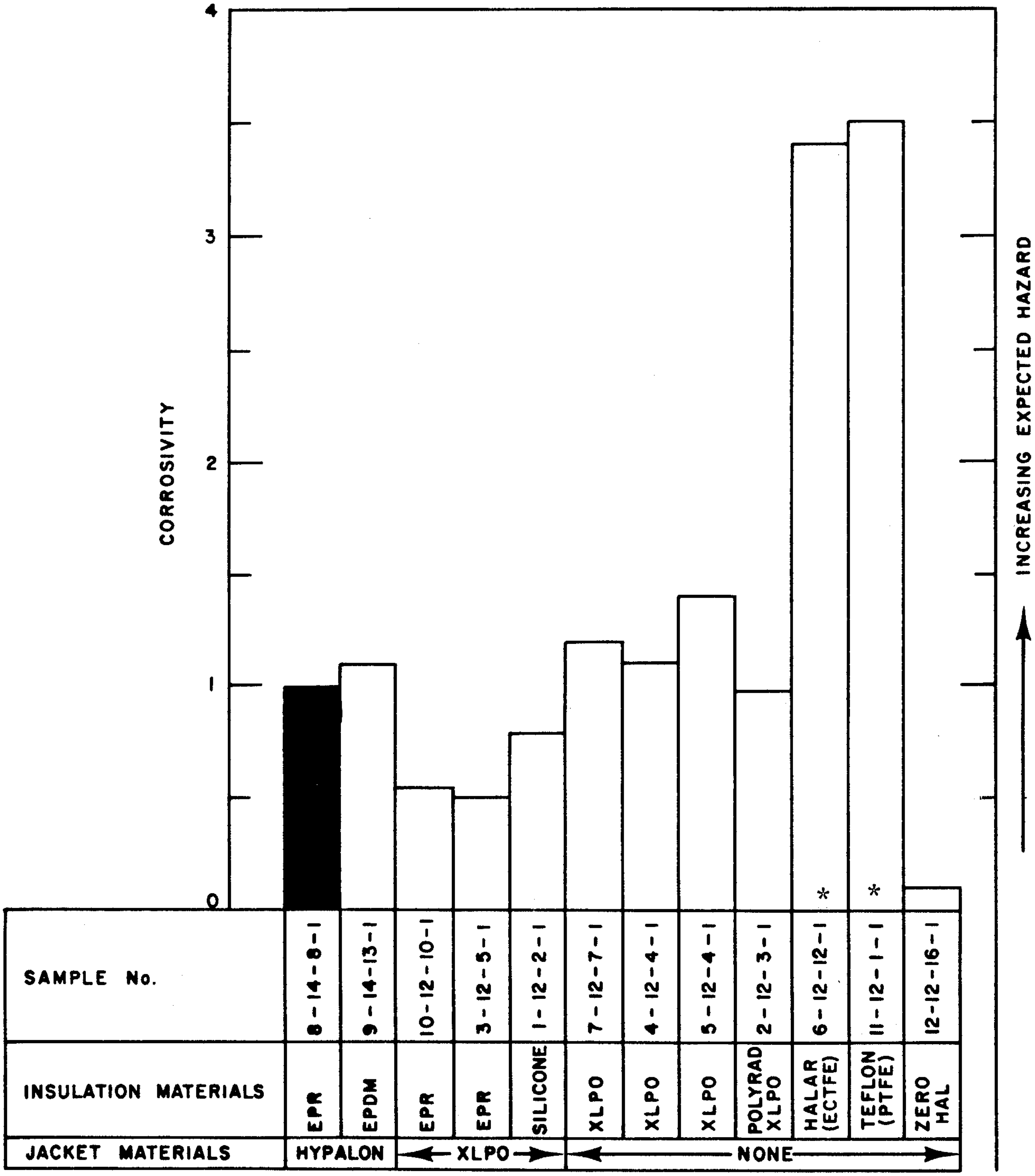
NI: No ignition occurred.

NF: No electrical failure



S-1 RELATIVE RANKING OF WIRES AND CABLES FOR IGNITION/FLAME SPREAD AND ELECTRICAL FAILURE CHARACTERISTICS UNDER NORMAL AIR

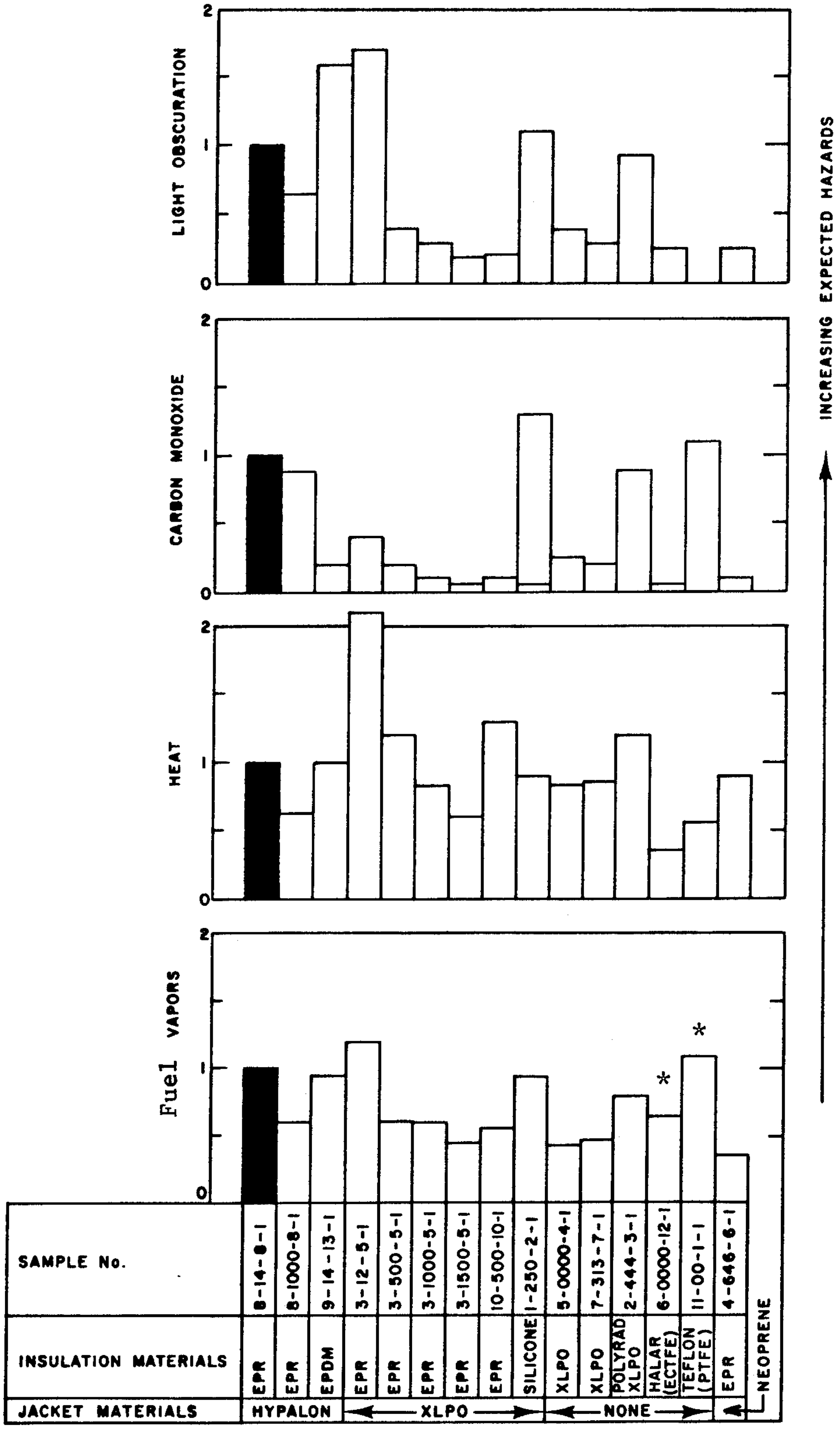
*Under high flame radiation achieved by increasing oxygen concentration well above the ambient value together with external heat flux



SAMPLE No.	8-14-8-1	9-14-13-1	10-12-10-1	3-12-5-1	1-12-2-1	7-12-7-1	4-12-4-1	5-12-4-1	2-12-3-1	6-12-12-1	11-12-1-1	12-12-16-1
INSULATION MATERIALS	EPR	EPDM	EPR	EPR	SILICONE	XLPO	XLPO	XLPO	POLYRAD XLPO	HALAR (ECTFE)	TEFLON (PTFE)	ZERO HAL
JACKET MATERIALS	HYPALON		← XLPO →			← NONE →						

S-2 RELATIVE RANKING OF WIRES AND CABLES FOR CORROSIVITY OF FIRE PRODUCTS UNDER COMBUSTION

*Under pyrolysis



S-3 RELATIVE RANKING OF WIRES AND CABLES FOR FUEL VAPORS, HEAT, CARBON MONOXIDE, AND LIGHT OBSCURATION CHARACTERISTICS FOR COMBUSTION IN NORMAL AIR

*For combustion under high flame radiation as achieved by increasing oxygen concentration well above the ambient value together with external heat flux

S.3.1.1 Ignition Parameter - The ignition parameter (IP) is defined as the inverse of the ignition energy (time to ignition x external heat flux applied to the sample). By measuring time to ignition as a function of the external heat flux applied to the sample, IP is calculated and plotted as a function of the external heat flux. From the data, critical heat flux, below which ignition is not expected to occur, can also be determined.

S.3.1.2 Electrical Failure Parameter - The electrical failure parameter, EP, is defined as the inverse of energy required for electrical failure; where energy is equal to the product of time to electrical failure and external heat flux applied to the sample.

S.3.1.3 Corrosivity Of The Fire Products Generated From Wires And Cables - Corrosivity was defined in terms of the cumulative corrosion to mild steel as a function of time per unit concentration of the water-soluble corrosive compounds.

S.3.1.4 Fuel Vapor Generation Parameter - The fuel vapor generation parameter (VP), is defined as the ratio of the generation rate of fuel vapors to the external heat flux applied to the sample. Thus, VP is the amount of fuel vapors generated per unit amount of heat received by the sample.

S.3.1.5 Heat Generation Parameter - The heat generation parameter (HP) is defined as the ratio of actual heat release rate to the external heat flux applied to the sample. Thus, HP is the amount of heat produced per unit amount of heat received by the sample.

S.3.1.6 "Smoke", Toxic And Corrosive Compounds Generation Parameter - The "smoke", toxic and corrosive compound generation parameter (CP) is defined as the ratio of the generation rate of "smoke" or toxic or corrosive compound to the external heat flux applied to the sample. Thus, CP is the amount of "smoke" or toxic or corrosive compound generated per unit amount of heat received by the sample.

S.3.1.7 Light Obscuration Parameter - The light obscuration parameter (LP) is defined as the ratio of the optical density per unit path length corrected for dilution of smoke to the external heat flux applied to the sample.

S.4 EVALUATION OF RANKING

S.4.1 General Relative Ranking

Examination of the general relative rankings of wires and cables in Table S-1 and Figures S-1 to S-3 indicates that:

1. Ignition/flame spread, electrical failure, corrosivity, generation of fuel vapors, heat, and CO and light obscuration are not only functions of the generic nature of the insulation/jacket materials, but also depend on the additives, size and construction of the wires and cables.

2. Wires and cables with similar size and generic nature of the insulation/jacket materials from different manufacturers show similar rankings for the seven characteristics considered in this study.

3. Ranking of wires and cables is different for different characteristics. For example, Teflon and Halar wire and cable samples under combined simulation[*] of flame and external radiation for large-scale fire are ranked low for ignition/surface flame spread, heat, and light obscuration, but high for corrosion,[**] and intermediate to high for electrical failure[***]; Hypalon-jacketed samples, on the other hand are ranked intermediate to high for all characteristics[***]; and Kapton/Teflon sample is ranked lowest for all characteristics.[*,***]

4. As the size of the wires and cables is increased, there is a decrease in general relative rankings for ignition/flame spread, generation of fuel vapors, heat, light obscuration, and electrical failure. This is due to enhanced charring at the surface.

5. A combined ranking of wires and cables for end-use applications may be possible in the future, depending on confirmation of the predictions based on the seven parameters, where the importance of each parameter would be a function of end-use applications.

S.4.2 Detailed Ranking Evaluation

A detailed examination of the rankings of wires and cables indicates the following:

---

[*] Oxygen concentration well above the ambient value in the inlet gas with external heat flux

[**] Under pyrolysis conditions;pyrolysis is defined as thermal decomposition in air under nonflaming condition. Combustion is defined as burning in air under flaming conditions

[***] Under ambient air conditions

Ignition/Flame Spread

1. The ignition parameter (IP) is useful for ranking wires and cables.

2. It is possible to translate the ignition data measured in the previous study(1) and to establish a general ranking for ignition/flame spread characteristics for all single-conductor wires and cables tested in this and in the previous study(1).

3. IP is expected to show some variations due to local aerodynamic conditions (forced and natural air flow), cable configurations (horizontal and vertical) and flame radiation.

4. The Fisher burner technique recommended in the previous study(1) is not suitable for testing ignition/flame spread characteristics of large wire and cable samples.

5. The ignition/flame spread characteristics are expected to vary with wire and cable size, because of variations in the physical properties such as density, specific heat, and thermal conductivity of the insulation/jacket materials and the conductor.

6. IP decreases as the size of the sample is increased; for example, for ethylene propylene rubber/cross-linked polyolefin with conductor sizes of 12 AWG, 500, 1000, and 1500 MCM, IP values are 0.29, 0.21, 0.17 and 0.13 x 10^{-3} m^2/kJ respectively. Thus, an increase in wire and cable size is expected to be beneficial in reducing the expected hazard due to ignition/flame spread.

7. IP value expressed in terms of the length of cable are listed in Table VI.

Electrical Failure

1. The electrical failure parameter (EP) is useful for ranking wire and cable.

2. There is a relationship between EP and the piloted ignition parameter (IP). In general EP is smaller than the IP or the electrical failure is expected to follow piloted ignition, except for wires and cables which melt or soften such as Teflon and Halar, where electrical failure is expected to occur independent of ignition.

3. EP is expected to show variations due to local charring of the cable surface, preventing the actual contact between the conductors. The larger the size of the cable (500 MCM or larger), the higher is the extent of local charring with no electrical failure recorded in the experiments. For example, for

12 AWG ethylene propylene rubber/cross-linked polyolefin, EP is 0.16×10^{-3} m^2/kJ, but is zero (no recorded electrical failure) for conductor size greater than or equal to 500 MCM.

Corrosivity Of The Fire Products Generated From Wires And Cables

1. The relative ranking of wires and cables for the experimental conditions used shows that fire products under pyrolysis conditions from Halar and Teflon wire and cable samples are highly corrosive to mild steel, whereas fire products under combustion conditions from ZeroHal wire and cable sample have the lowest corrosivity to mild steel. Fire products under combustion conditions from Hypalon-jacketed samples show corrosivity to mild steel very similar to that of (0.1 mole/litre) hydrogen chloride solution.

2. For some wire and cable samples, such as cross-linked polyolefin, it appears that corrosivity is due to the additives in the samples.

3. Corrosivity per unit length of the wire and cable samples are given in Section 4.6.

Generation Of Fuel Vapors

1. The fuel vapor generation parameter (VP) is useful for ranking of wires and cables.

2. Simulation of large-scale fires with combined flame and external radiation, shows that the VP value increases with the combined flux. For example, for ethylene propylene rubber/cross-linked polyolefin, VP = 0.44 g/kJ with simulation of external radiation, but increases to 0.55 g/kJ for combined simulation of flame and external radiation. Teflon and Halar samples did not ignite in normal air and thus VP could not be determined; however, for large-scale fire conditions, VP values were found to be in the high to intermediate range.

3. VP values decrease as the conductor size is increased, a beneficial effect. For example, for ethylene propylene rubber/cross-linked polyolefin with conductor sizes of 12 AWG, 500, 1000 and 1500 MCM, VP values are 0.44, 0.23, 0.22 and 0.17 g/kJ respectively. The decrease in VP values is due to increased charring at the surface. (This is also indicated by the decrease in the EP values as indicated previously.)

4. The generation rate of fuel vapors per unit length of wire and cable samples can be expressed by multiplying VP by the heat flux, wire and cable surface area and dividing it by the length.

Generation Of Heat

1. The heat generation parameter (HP), is useful for ranking wires and cables.

2. The HP value for research grade polyethylene is 18, but only 6 for wire and cable samples with cross-linked polyolefin insulation alone. Under combined simulation of flame and external radiation for large-scale fires, halogenated wire and cable samples (Teflon and Halar) have low HP values (3.7 to 2.3 respectively) compared with a value of 17.2 for ethylene propylene rubber/cross-linked polyolefin.

3. The HP value decreases as the size of the wire and cable increases, a beneficial effect. For example, for ethylene propylene rubber/cross-linked polyolefin with conductor sizes of 12 AWG, 500, 1000 and 1500 MCM, HP values are 14.1, 7.8, 5.5 and 3.9 respectively. This decrease is due to enhanced charring at the surface (also indicated by the decrease in the EP and VP values).

4. The generation rate of heat per unit length of the wire and cable is equal to HP x heat flux x wire and cable surface area divided by the length of the wire and cable.

Generation Of Toxic Compounds

1. The CO generation parameter (CP) is useful for ranking of wires and cables for CO generation tendencies. Similar parameters can be established for other toxic compounds.

2. Under combined simulation of flame and external radiation for large-scale fires, Teflon sample shows a CP value of CO equal to 0.043 g/kJ compared with a value of 0.0021 g/kJ for Halar sample and a value of 0.035 g/kJ for ethylene propylene rubber/cross-linked polyolefin. (For this sample the CP value for CO is 0.0083 g/kJ under simulation of external radiation only in normal air.)

3. CP value of CO decreases as the sizes of wires and cables increase, which is a beneficial effect. For ethylene propylene rubber/cross-linked polyolefin with conductor sizes of 12 AWG, 500, 1000 and 1500 MCM, CP values are 0.016, 0.0083, 0.0042 and 0.0024 g/kJ respectively. For ethylene propylene rubber/Hypalon with conductor sizes of 14 AWG and 1000 MCM, CP values of CO are 0.040 and 0.035 g/kJ respectively. The decrease in CP values of CO is expected on the basis of enhanced surface charring, very similar to decrease in the EP, VP and HP values.

4. The generation rate of toxic compounds per unit length of the wire and cable can be calculated by multiplying CP by heat flox and wire and cable surface area and dividing it by the length of the wire and cable.

Light Obscuration By "Smoke"

1. The light obscuration parameter (LP) is useful for ranking of wires and cables.

2. Light obscuration by "smoke" depends on the wavelength of the light source. For example, for incident light of wavelengths 1.06, 0.458 and 0.624µ, the LP values are 0.0084, 0.016 and 0.020 m^2/kJ, respectively, for the ethylene propylene rubber/cross-linked polyolefin sample.

3. Under combined simulation of flame and external radiation for large-scale fires, for a wavelength of 1.06µ for the light source, ethylene propylene rubber/cross-linked polyolefin has a LP value of 0.004 m^2/kJ, whereas Halar and Teflon samples have values of 0.0007 and <0.00001 m^2/kJ respectively.

4. LP decreases as the sizes of wires and cables increase depending on the materials, which is a beneficial effect. For example, for a fixed wavelength of light (0.624µ, visible range) for ethylene propylene rubber/cross-linked polyolefin for conductor sizes of 500, 1000 and 1500 MCM, the LP values are 0.0048, 0.0036 and 0.0020 m^2/kJ respectively; and for 12 AWG and 1000 MCM ethylene propylene rubber/Hypalon samples, LP values are 0.012 and 0.0078 m^2/kJ respectively. A decrease in LP values indicates enhanced surface charring as discussed previously for decrease in EP, VP, HP and CP values.

5. LP values can be used to correlate data reasonably well from various kinds of "smoke" test apparatus, such as the FM Small-Scale Combustibility Apparatus used in this study and the NBS Smoke Chamber, provided accurate values of wavelength of the light source, amount of fuel vapors produced, and the dilution of the vapors by air are known.

6. The effectiveness of low smoke additives in the wire and cable samples could not be quantified in this study, because samples without the additives were not tested. For some samples there appears to be some effect due to smoke suppressing additives in reducing the LP values, whereas, for others, there appears to be no effect.

7. Light obscuration per unit length of the wire and cable can be calculated by multiplying LP by heat flux and wire and cable surface area and dividing it by the length of the wire and cable.

I

INTRODUCTION

The objective of this study was to examine the flammability of wires and cables used in rail rapid transit systems. The overall goal of the study was to quantify the fire properties of wires and cables in a manner such that the relative fire hazards could be assessed under various fire scenarios expected in rail rapid transit systems.

The fire properties include: 1) critical heat flux and energy associated with ignition and flame spread; 2) heat required to generate a unit mass of the fuel vapors; 3) yields of fire products which include heat and various chemical compounds; and 4) optical properties of the fire products.

The fire scenarios are generalized representations of the interactions of fire properties of combustibles and fire environment. The fire environment includes: 1) convective and radiative heat flux from external heat sources and from the flame of the combustibles; and 2) natural air flow in open burning or ventilation in enclosed spaces which includes inflow of fresh air, accumulation and mixing of fire products and air, outflow of the mixture of fire products and air, and flow of hot contaminated air into the fire.

The purpose of using wires and cables is to carry electrical currents from one location to another. The conductors are insulated by various materials. Materials are usually used as insulation materials for the conductors and for jacketing materials which cover the insulated conductors; the combination of conductor, insulation and jacket materials is defined as a cable.

A cable is either a stranded conductor (single-conductor cable) or a combination of conductors insulated from one another (multi-conductor cable). The term "cable" is a general one and in practice is usually applied only to larger-size conductors. A small cable is more often called a stranded wire or cord.

Wires and cables used in rail rapid transit systems vary widely in terms of number and size of conductor and generic nature and thickness of insulation/jacket materials. Within these materials are added various chemical compounds such as fire retardants, plasticizers, antioxidants, colorants, vulcanizers, and smoke suppressants.

Wires and cables are used in a variety of applications, e.g., wiring in a series of vehicles as in a train; in wayside and track installations; in tunnels and stations to provide power for lights and ventilation fans, and to carry train command and control information and communications. Various uses of electrical cables in rail rapid systems have been fully described in Reference 1. Because of this diversity in the application of wires and cables, it is possible to visualize numerous fire scenarios in transit systems involving insulation/jacket materials. Different types of fire hazards associated with the rail rapid transit systems are presented in References 1 and 2.

Although very little is known about the interactions between the fire properties of combustibles in wires and cables and the fire environments in various scenarios, some progress has been made in: 1) identifying fire problems associated with multiple cable installations(3-5); and 2) reducing the hazard associated with cable fires by using fire retardants and cable coatings and installing early-warning fire detectors and sprinklers(6-20).

In order to assess fire hazards and protection needs, interactions between the fire properties of combustibles present in wires and cables and the fire environment must be quantified under both simulated and real fire environments.

Several "standard" test methods are available for the evaluation of flammability of wires and cables(1). From such tests it should be possible to quantify the fire properties of the combustibles present. Unfortunately, such quantification is extremely difficult, because tests are performed at one specified condition, without any correlation between the test condition and the environments expected in real fires. Furthermore, for each fire property, separate tests are used with widely varying test conditions.

Since wires and cables consist of a combination of synthetic polymeric materials and metal conductors which vary in thickness and size, the fire properties must be quantified in terms of final configurations, rather than by individual materials. For example, insulation materials with and without jacket materials will show significantly different fire properties(5). Furthermore, the synthetic polymeric materials are modified extensively by additives to satisfy various requirements for proper functioning of the wires and cables; fire properties of the modified materials are altered significantly compared to the original materials. It has been shown(5) that the fire properties of the same insulation/jacket materials from various manufacturers show very different fire properties, probably due to differences in types and amounts of additives and construction of wires and cables.

For the quantification of wire and cable fire properties and the interactions of fire properties with the fire environment, it is thus necessary to employ an apparatus that is capable of: 1) testing wire and cable samples in their end-use configurations; 2) simulating large-scale fire environments; 3) measuring all the important fire properties simultaneously; and 4) establishing the accuracy of the predictions of fire hazards for large-scale fires, based on the interactions of fire properties and simulated fire environments.

II

EXPERIMENTAL APPROACH

2.1 GENERAL BACKGROUND

The experimental approach taken in this study is based on work performed during the last 12 years on the combustibility of polymeric materials(21-31) at Factory Mutual Research Corporation (FMRC). To simulate the fire environment, the following parameters are varied: 1) external heat flux (by exposure of samples to varying heat flux from radiant heaters); 2) flame radiation (by varying oxygen concentration in air); and 3) ventilation (by varying inlet air flow rate, temperature and contaminants in the air).

By using small-samples and proper combinations of external heat flux, oxygen concentrations and inlet air flow rate (including temperature and contaminants), the generalized fire behavior of materials is established for variable fire size, flame radiation and ventilation (defined as the combined simulation of flame and external radiation). Predictions are then made for a particular fire scenario and confirmed by direct measurements using larger-scale fires. For this purpose, the following three apparatuses, shown in Figure 1, are used:

1) Factory Mutual Small-Scale Combustibility Apparatus, for samples ~0.1-m diameter, ~0.1-m high, and ~0.01 to 0.02-m thick. The external heat source is simulated by using four coaxially placed quartz-tungsten radiant heaters (peak at 1.15 μ). Flame radiative heat flux is simulated by varying the mass fraction of oxygen in air. Ventilation is provided by introducing air at the bottom of the apparatus with variable flow rate, temperature, and contamination. Experiments can also be performed under natural air flow. A small pilot flame is provided for ignition.

2) Factory Mutual Intermediate-Scale Combustibility Apparatus, for samples ~0.3 x 0.3 x 1-m high. The external heat source is simulated by using liquid pool fires of methanol and heptane under the test fuel. Flame radiation and ventilation are provided in a fashion similar to that used in the Small-Scale Apparatus.

3) Factory Mutual Large-Scale Apparatus for samples ~3 x 3 x 3-m high. No external heat source is used and experiments are performed under natural air flow.

In all three apparatuses, fire products are captured in the respective sampling ducts, diluted with ambient air, and well mixed before sampling. In

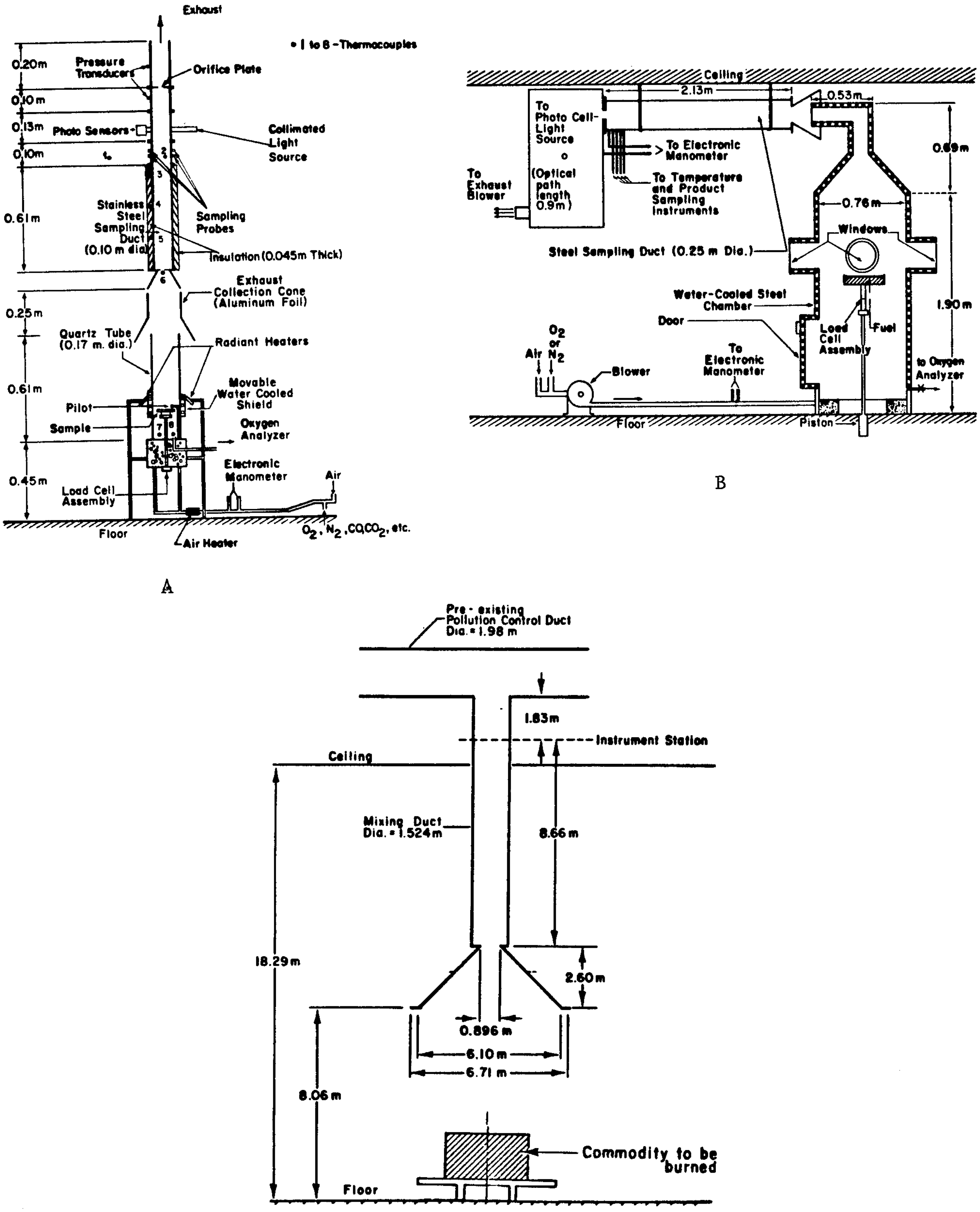


FIGURE 1 FACTORY MUTUAL COMBUSTIBILITY APPARATUSES: A, SMALL SCALE; B, INTERMEDIATE SCALE; C, LARGE SCALE

the sampling ducts, measurements are made for total flow rate, gas temperature, concentrations of CO, CO_2, O_2, total gaseous hydrocarbons, "smoke" (defined as a mixture of soot and low vapor-pressure liquids), HCl, HCN and NO_x, and optical transmission through fire products. Other measurements include time to ignition, generation rate of combustible vapors, and water application rate for fire suppression and extinguishment. For toxicity evaluations, animal exposure experiments can also be performed. Standard methods are used for the measurement of elemental composition of the sample and "smoke", heat of complete combustion of the sample and "smoke", and corrosion properties of the fire products.

All measurements are made at intervals of ~1 s (or longer) for the entire fire duration. Analog-to-digital data acquisition systems collect data for analysis.

It has been shown that reliable predictions can be made for overventilated large-scale horizontal pool fires, based on small-scale apparatus results. In addition, the fire properties of materials obtained from the small-scale apparatus can be used as input parameters for various fire models for the evaluation of fire hazards and protection from such hazards(32-37). All important fire properties can be measured simultaneously in the small-scale apparatus with accuracy and repeatability. For these reasons, as well as the fact that the small-scale apparatus has been used successfully in other studies of wires and cables(5,10,11), only the small-scale apparatus was selected for flammability evaluations of wires and cables used in the rail rapid transit systems.

2.2 EXPERIMENTAL APPARATUS AND PROCEDURE

2.2.1 FM Small-Scale Combustibility Apparatus

Figure 2 shows an enlarged version of Figure 1A for the FM Small-Scale Combustibility Apparatus as modified for this study. The apparatus and general test procedures are described in detail in References 5,10,11,21-28,31. The cable sample, about 0.06 m in length, was placed vertically inside the apparatus (identified as "sample" in Figure 2) and was surrounded by a quartz tube (0.17 m diameter and 0.61 m long). The cable sample was held by two wires attached to a rod on the sample platform. All cable samples were cleaned with isopropanol before each experiment in order to remove possible contaminants on the sample surface. The platform was connected to a water-cooled load-cell assembly (Universal Transducing Cell, Model No. UC3, Statham Instruments, Inc., Oxnard, California) for monitoring the fuel vapor generation rate. For

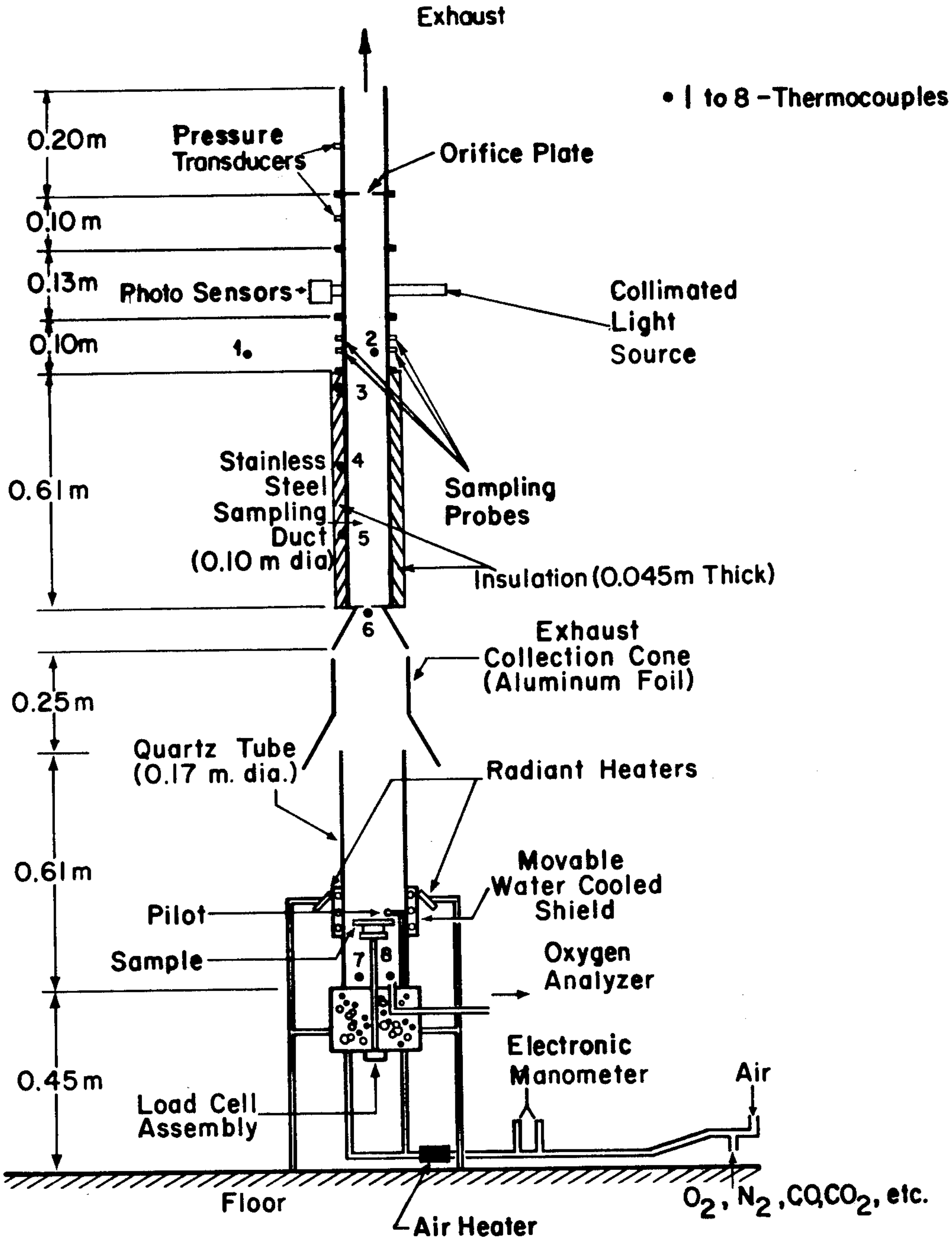


FIGURE 2 FM SMALL-SCALE COMBUSTIBILITY APPARATUS

experiments under forced air flow conditions, dry air was introduced at the bottom of the apparatus at a rate of ~0.003 m^3/s and was passed through a layer of glass beads to ensure even flow distribution. An air flow rate of ~0.003 m^3/s ensures that overventilated fire conditions would be maintained in the experiments. The air flow rate was monitored by an electronic flow meter (Model 2015, Thermo System Inc., St. Paul, Minn.).

For experiments under natural air flow conditions, the quartz tube was not placed around the sample and no forced air was introduced at the bottom of the apparatus.

A small premixed ethylene-air pilot flame about ~0.01 m in length was positioned about 0.01 m above the top surface of the cable sample to ignite combustible vapors. Four high-density radiant heaters of tungsten quartz lamps (Model 5208, Research Inc., Minneapolis, Minn.) placed coaxially as shown in Figure 2, were used to provide external heat flux to the sample. The output of all four radiant heaters was controlled by a single controller (Model 646, Research Inc., Minneapolis, Minn.). The radiant heat flux at the cable sample location was precalibrated with a heat flux gauge (Model No. 16-10-GTW63, Medtherm Corporation, Huntsville, Alabama) for different controller settings covering the range up to about 70 kW/m^2.

All fire products were captured in a sampling duct together with ambient air, where the product-air mixture was well mixed before measurements were made. The sampling duct was used for the following measurements: 1) total mass and volumetric flow rates of product-air mixture (see Appendix A), using pressure transducers, (Model 239, Setra Systems Inc., Natick, MA); 2) bulk gas temperature in the sampling duct (K-type Chromel-Alumel Thermocouple), and ambient temperature (K-type Chromel-Alumel Thermocouples; 3) optical transmission through "smoke" (Photo Sensor, Model UTD-500D, United Detector Technology, California in a 0.10 m path length of collimated light source across the sampling duct); and 4) concentrations of CO, CO_2 and total gaseous hydrocarbons (CO IR-Analyzer, Model 315A; CO_2 IR-Analyzer, Model 315A; and Hydrocarbon Flame-ionization Analyzer, Model 400; all instruments were purchased from Beckman Instruments Inc., Fullerton, California).

The output from all the instruments, as well as output from the load cell, inlet air electronic flow meter and oxygen analyzer were monitored at intervals of 1 s (or longer depending on the test) by a MINC (Model LSI-1103, Digital Equip. Corp., Northboro, MA) analog-to-digital data acquisition system.

The experimental procedure consisted of: 1) initializing the MINC with pertinent cable sample information, test number, date, experimental conditions, operator, etc.; 2) turning on the inlet air flow, exhaust blower and pilot flame; 3) weighing the cable sample and placing it in the apparatus; 4) raising the water-cooled shield around the sample; 5) turning on the radiant heaters 3 min before the test began, with the controller set at the desired heat flux to the sample, and taking 1 min of background readings with the MINC during the middle minute; 6) starting the MINC to take test data; 7) at 60 s from the time the MINC began taking test data, lowering the shield to expose the sample to the external heat flux; 8) measuring time to ignition (other measurements are taken automatically by the MINC); and 9) measuring the corrosivity of fire products using a separate test setup.

2.3 DETAILS OF TEST MEASUREMENTS

2.3.1 Ignition

In the experiments, the time to sustained piloted ignition of various cable sample vapor/air mixtures were measured for different values of external heat flux. The relationship was used to determine the critical heat flux and piloted ignition parameter (IP) (see Appendix B).

2.3.2 Generation Rate of Fuel Vapors

The generation rate of fuel vapors was measured at a high value of external heat flux (60 kW/m^2)* in normal air under forced air flow conditions. Limited experiments were also performed with combined simulation of flame** and external radiation. The data were used to determine the fuel vapor generation parameter, VP of the wire and cable samples (see Appendix C).

2.3.3 Generation Rates of Fire Products

Fire products consist of heat and various chemical compounds. In this study measurements were made for the generation rate of heat as well as of CO, CO_2, and

---

* A value of 60 kW/m^2 of external flux was used to reduce the influence of flame heat flux. (Flame heat flux was not quantified in the study (Appendices C,D and E).)

**Flame radiation was enhanced by increasing oxygen concentration in the inlet gas well above ambient value (Appendix C) in the presence of external heat flux, for halogenated cable samples, which did not ignite in normal ambient air.

total gaseous hydrocarbons at a high value of external heat flux (60 kW/m^2) in normal air under forced air flow conditions. Limited experiments were also performed with combined simulation of flame and external radiation. The data were used to determine the fire product generation parameter (heat, HP, and chemical compounds CP) (see Appendix D).

2.3.4 Optical Transmission Through "Smoke"

The optical transmission per unit optical path length for a known volumetric flow rate of fire product-air mixtures was measured for a high value of external heat flux (60 kW/m^2) in normal air under forced air flow conditions. Limited experiments were also performed with combined simulation of flame and external radiation. The data were used to determine the light obscuration parameter of "smoke" generated from the wire and cable samples (LP) (see Appendix E).

2.3.5 Electrical Integrity of Wire and Cable Samples

The electrical integrity of the wire and cable samples was examined in the presence of a pilot flame, at a high value of external heat flux (60 kW/m^2)* in normal air under natural-air flow conditions. A schematic of test setup is shown in Figure 3. As shown in the figure, the cable sample (about 0.8 m in length) was mounted horizontally with minimum tension along the major axis under the heat flux exposure zone of the apparatus. Only the middle 0.3 m portion of the cable sample was exposed to external heat flux. A pilot flame was placed about 0.015 m above the cable surface. A piece of Nichrome wire (0.64 x 10^{-3} m dia; 22 gage) was placed over the surface of the cable with the two ends attached with a freely hanging, 300-g nominal weight (aluminum slab, 0.089 x 0.089 x 0.013 m). The Nichrome wire was tapered at the top so that the arms of the wire made two contact points on the cable surface as shown in Figure 4. The aluminum slab was electrically connected to a 24 VDC power supply and one end of the conductor of the cable was connected to a normally closed relay. At the beginning of the experiment, the timer was started as the power switch was turned on. The timer stopped as soon as the Nichrome wire touched the conductor and shorted to ground. This type of shorting was defined as the electrical integrity failure and the time at which shorting occurred was defined

---

*A value of 60 kW/m^2 of external heat flux is sufficient to achieve the asymptotic value of EP.

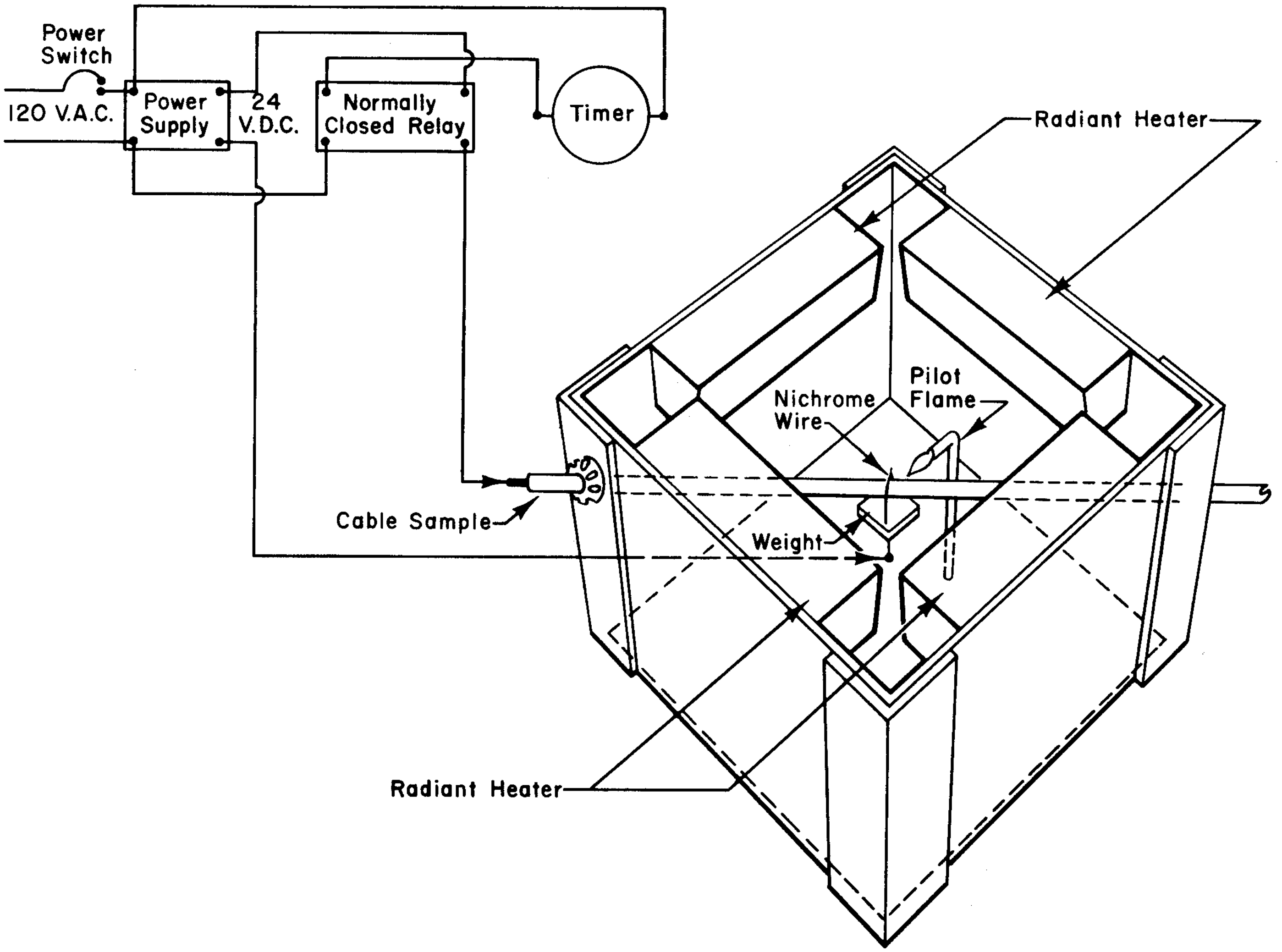


FIGURE 3 SCHEMATIC OF ELECTRICAL INTEGRITY FAILURE EXPERIMENTAL SETUP

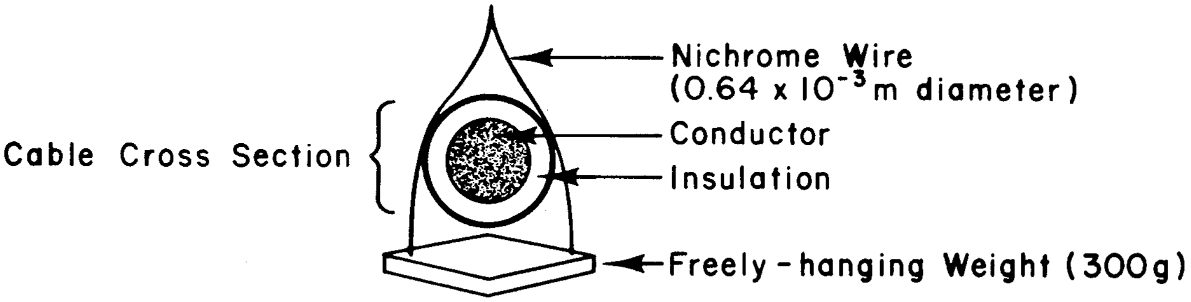


FIGURE 4 CONTACT POINTS OF THE NICHROME WIRE WITH THE CABLE SURFACE

as the time to electrical failure. The time to electrical failure at the applied external heat flux value was used to calculate the electrical failure parameter (EP); the calculations were very similar to those used for the ignition parameter (IP) (Appendix B).

2.3.6 Corrosivity of Fire Products

The corrosive fire products generated from the wire and cable samples were collected in an apparatus shown in Figure 5. A Nichrome wire of known resistance (3.9 ohms/m) was coiled uniformly around the surface of a 0.06 m long cable sample. The ends of the Nichrome wire were connected to a variac for voltage application. The sample was surrounded by a cylindrical Plexiglas vessel (0.2 m diameter and 0.30 m long). An inverted glass funnel was set tightly on the top of the Plexiglas vessel and connected to the inner tube of a gas collecting jar by a Tygon tube (about 0.013 m I.D.). The inner tube of the gas collecting jar extended close to the bottom which was filled with 100 mℓ of distilled water and glass beads. The outlet at the top of the gas collecting jar was connected to a vacuum pump. A small premixed natural gas-air pilot flame (~0.025 m in length) was placed about 0.01 m above the cable surface for piloted ignition. The cable sample was held in horizontal position by two vertical wires attached to a platform. The Plexiglas vessel was raised about 0.01 m for natural flow of air into the vessel. The heat flux, per unit surface area, applied to the cable was calculated from the ratio V^2/RA, where V is the applied voltage, R is the resistance of the Nichrome wire (3.9 ohms/m) and A is the surface area of the cable. The surface area of the cable was calculated from the measured outer diameter and length of the cable.

All the fire products generated from the sample were bubbled through 100 mℓ of distilled water in the gas collecting jar. The solution was kept overnight at room temperature (294K) and filtered to remove soot particles before corrosion measurements were taken. The weight loss of the insulation/jacket materials was measured from the original weight and the weight of the residue. The concentration of fire products was expressed as the ratio of total weight loss of the sample to the volume of the distilled water in the gas collecting jar and was expressed in parts per million (ppm).

The corrosivity of the fire products was then determined by placing a probe (S4/8001 Model 1032 Corrosometer Probe, Rohrback Instruments, Sante Fe, Calif.) into the solution. To take measurements, the probe was connected to a meter

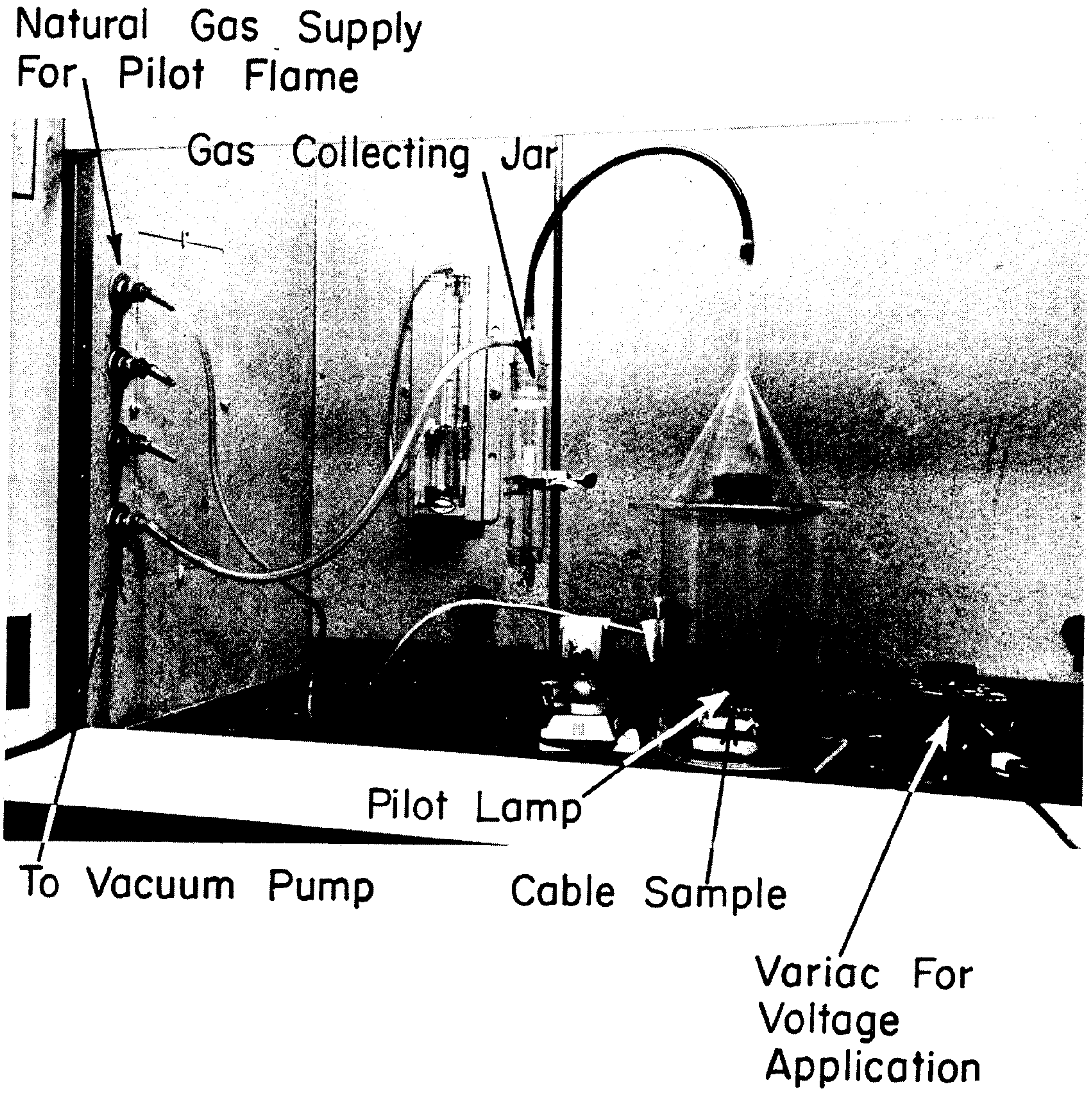


FIGURE 5 COLLECTION METHOD FOR CORROSIVE PRODUCTS

(Corrosometer, Model CK-3, Rohrback Instruments, Sante Fe, Calif.) (see Figure 6). The measuring element of the probe is made of mild steel (4 mils thick) and operates on the principle that electrical resistance increases as the cross-sectional area of the element is reduced due to corrosion. The increase in resistance is measured using a meter with a null-balance bridge circuit, which compares the resistance of the measuring elements with that of a protected reference element (the meter reads the corrosion of the element directly in micro-inches of metal loss).

The probe was left in the solution at room temperature for about 30 hr and measurements of cumulative corrosion were made at intervals of about 5 hr. After the measurements, the probe was rinsed thoroughly with distilled water, dried with air and rinsed with propanol. Finally, the probe was cleaned with warm 8 N hydrochloric acid, rinsed with distilled water, and dried with air and was ready for the next measurement.

Prior to the measurements for the corrosivity of fire products generated from wire and cable samples, the probe was calibrated by using distilled water alone and a standard chloride ion solution (0.1 mole/litre of HCl, Orion Research, Inc., Cambridge, MA). Further, the accuracy of the corrosivity measurements was evaluated by using research grade powdered polyvinyl chloride (PVC) and polymethyl methacrylate (PMMA) (Aldrich Chemical Company Inc., Milwaukee, Wisconsin). Research grade PVC and PMMA do not contain significant amounts of additives. PVC and PMMA were heated by a natural gas burner in separate experiments inside the vessel, at the same location as the wire and cable sample. The collection of the fire products, weight and corrosivity measurements were identical to those used for the wire and cable samples. In addition, corrosivity measurements were also made by using the natural gas burner alone for background correction for PVC and PMMA. It should be noted that 58% of the weight of PVC vapors are expected to be HCl, which is corrosive, whereas the PMMA vapors are expected to contain negligible amounts of corrosive products.

Calculations for the evaluation of the corrosivity of fire products of wire and cable samples are given in Appendix F.

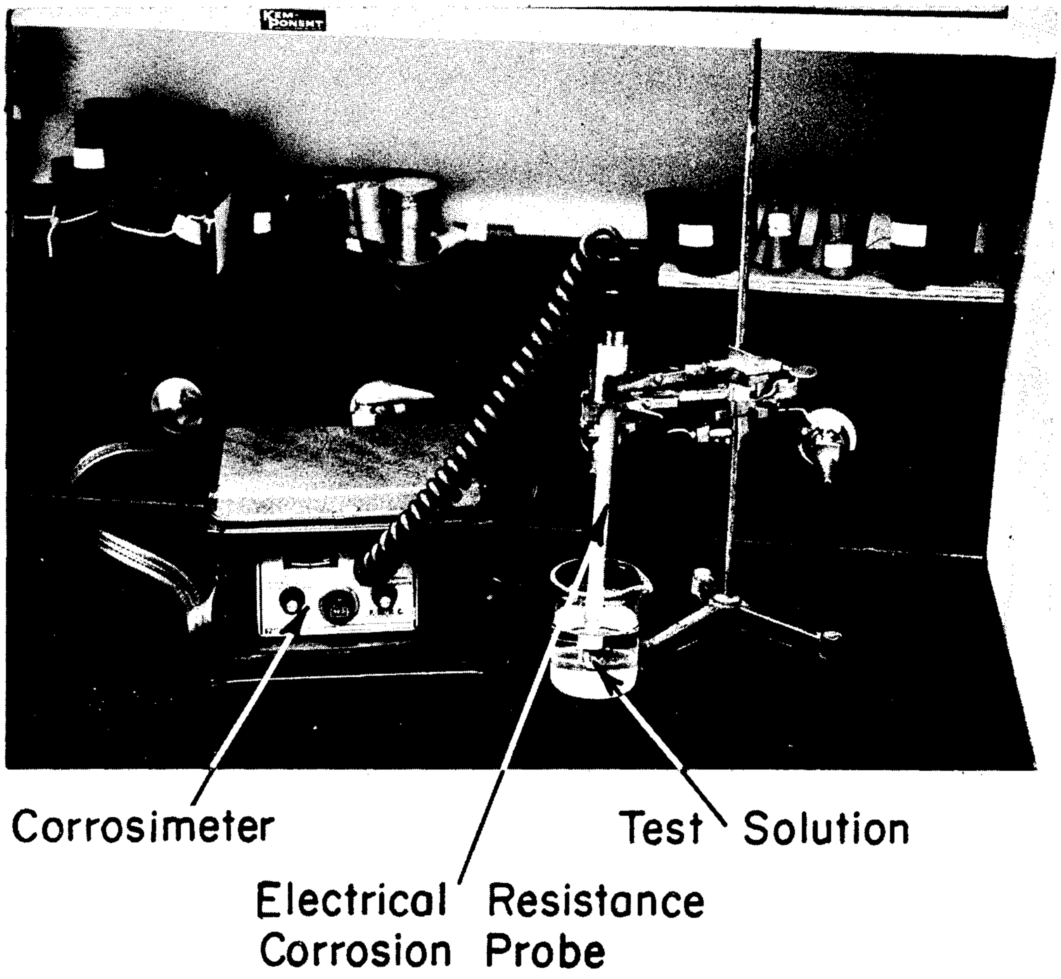


FIGURE 6 CORROSION MEASUREMENT WITH ELECTRICAL RESISTANCE PROBE

III

WIRE AND CABLE SAMPLES

A total of 31 wire and cable samples submitted by 12 manufacturers were used. (Five manufacturers had also submitted samples for the previous cable fire study(1).) A scheme was developed for sample identification in terms of manufacturer, conductor size and type of insulation/jacket materials, and number of wires and cables of the same-size, same insulation/jacket materials supplied by the same manufacturer.

3.1 WIRE AND CABLE SAMPLE IDENTIFICATION SCHEME

The sample identification scheme uses four groups of numbers. The first group is the supplier or manufacturer as shown in Table I; the second group is the conductor size as shown in Table II; the third group is the insulation/jacket material (single or combination of the two materials) as shown in Table III; the fourth group indicates the number of same-size wire/cable of the same material furnished by the same supplier or manufacturer. In this program, only one wire or cable sample of each size and material was submitted by each supplier or manufacturer. Therefore, the fourth number of the sample identification is always one.

Detailed description of the insulating materials and construction of the wires and cables is contained in Table IV.

Table V shows single conductor wire and cable samples and their sizes used in this and the previous study(1).

3.2 PHYSICAL PROPERTIES OF THE WIRE AND CABLE SAMPLES

The physical properties of the wire and cable samples are presented in Table IV. The total density of the cable was derived from the cable weight and volume calculated from the outer diameter and length of the cable. Similarly, the density of the insulation/jacket materials was derived from the weight and volume calculated from the outer diameter of the cable and diameter of the conductor and cable length.

Insulation/jacket materials as a percent of the total cable weight was calculated from the total cable weight and the weight of the insulation/jacket materials (for a known length of a wire and cable sample). The total linear density of the cable and insulation/jacket material was calculated from the

TABLE I

SUPPLIER OR MANUFACTURER IDENTIFICATION CODE

First Group of the Sample Identification	Supplier or Manufacturer
1	Boston Insulated Wire & Cable
2	Brand-Rex
3	Collyer
4	General Electric Wire & Cable
5	Champlain Cable Corporation
6	Hi-Temp Wires, Inc.
7	ITT, Suprenant Div.
8	Kerite Co.
9	The Okonite Company
10	Pirelli Cable Corporation
11	Tensolite
12	Ray-Chem

TABLE II

CONDUCTOR SIZE IDENTIFICATION CODE

Second Group of the Sample Identification	Conductor Size
14	14 AWG
12	12 AWG
10	10 AWG
00	2/0 AWG
0000	4/0 AWG
250	250 MCM
313	313 MCM
444	444 MCM
500	500 MCM
646	646 MCM
1000	1000 MCM
1500	1500 MCM
2000	2000 MCM

TABLE III

INSULATION JACKET MATERIAL IDENTIFICATION CODE

Third Group of the Sample Identification	Insulation/Jacket Materials
1	Mineral filled Teflon[a]/none
2	Silicone Low-Smoke/PO
3	Poly rad XLPO/none
4	XLPO/none
5	EPR, FR, Lo-Smoke/XLPO
6	EPR/Neoprene
7	XLPO, FR/none
8	EPR, FR/Hypalon
9	Mica-mat Gemex tape/XLPO
10	EPR/XLPO, FR, Smoke Suppress
11	Kapton/Teflon[b] film
12	Halar
13	EPDM/Hypalon
14	EPDM/PO
15	EPR/Lo-Smoke PO
16	Unspecified[c]

Teflon[a] = PTFE (polytetrafluoro ethylene)
PO = Polyolefin
XLPO = Cross-linked polyolefin
EPR = Ethylene propylene rubber
FR = Fire retardant
Hypalon = Chloro sulfonated polyolefin
Kaptan = polyimide
Teflon[b] = FEP (Fluorinated ethylene propylene)
Halar = ECTFE (Ethylene chlorotrifluoro ethylene)
EPDM = Ethylene propylene diene rubber

Unspecified[c] = Zerohal

TABLE IV. DETAILED DESCRIPTION OF WIRE AND CABLE SAMPLES (SINGLE CONDUCTOR, MULTI-STRAND)

Sample ID Number	Conductor Size	Insulation/Jacket Color	Insulation/Jacket Materials	Density (g/ml) Total	Density (g/ml) Insul./Jacket	Insul./Jacket Materials (% of Total Cable Weight)	Linear Density (g/m) Total Cable (incl. Cond.)	Linear Density (g/m) Insulation/ Jacket	Outside Diameter (m x 10^2) Cable	Outside Diameter (m x 10^2) Conductor	Insulation + Jacket Thickness (m x 10^2)	Effective Surface Area (m^2x 10^4)	Other
1-12-2-1	12 AWG	Brown/White	Silicone Lo-Smoke/PO	2.426	1.343	35.50	49.17	17.47	0.508	0.304	0.102	9.706	600V,Tinned
1-12-15-1	12 AWG	White/Black	EPR/Lo-Smoke PO	1.947	1.239	51.50	61.66	31.66	0.635	0.279	0.178	12.225	2KV,Tinned
1-250-2-1	250 MCM	Brown/Green	Silicone Lo-Smoke PO	3.580	1.360	20.60	1603.33	330.8	2.388	1.788	0.30	47.446	2KV,Tinned
1-250-15-1	250 MCM	Black/White	EPR/Lo-Smoke PO	2.462	1.144	27.70	1650.00	457.5	2.921	2.021	0.45	59.058	2KV,Tinned
2-12-3-1	12 AWG	Light Blue	Poly Rad. XLPO/None	2.546	1.628	45.0	50.0	22.5	0.500	0.272	0.114	9.563	2KV,Tinned
2-444-3-1	444 MCM	Grey	Poly Rad. XLPO/None	3.911	1.339	14.0	2547.50	356.66	2.880	2.28	0.30	56.951	2KV,Tinned
3-12-5-1	12 AWG	Grey	EPR, FR/XLPO	5.276	4.083	60.85	74.5	45.33	0.424	0.196	0.114	8.103	600V,Tinned
3-500-5-1	500 MCM	Black/Black	EPR, FR/XLPO	4.133	1.513	20.40	2840.00	579.66	2.958	1.958	0.50	59.587	600V,Tinned
3-1000-5-1	1000 MCM	Orange/Black	EPR, Lo-Smoke/XLPO	4.230	2.740	17.06	5486.77	936.27	4.064	2.964	0.60	83.88	1KV,Tinned
3-1500-5-1	1500 MCM	Orange/Black	EPR, Lo-Smoke/XLPO	4.350	1.449	16.50	8209.50	1356.72	4.902	3.602	0.65	101.76	2KV,Tinned
4-12-4-1	12 AWG	Grey	XLPO/None	2.547	2.446	37.86	44.0	16.66	0.469	0.225	0.122	8.909	2KV,Tinned
4-12-9-1	12 AWG	Grey	Mica-Mat Gemex/XLPO	2.360	1.273	40.32	51.67	20.80	0.528	0.266	0.131	10.116	2KV,Tinned
4-646-4-1	646 MCM	Grey	XLPO/None	3.829	1.138	14.82	3457.79	512.37	3.391	2.491	0.45	68.422	2KV,Tinned
4-646-6-1	646 MCM	Black	EPR/Neoprene	3.711	1.364	19.83	3781.66	750.00	3.602	2.602	0.50	73.395	2KV,Tinned
5-12-4-1	12 AWG	Dark Grey	XLPO/None	2.691	1.365	39.87	38.0	15.16	0.424	0.195	0.114	8.103	2KV,Tinned
5-0000-4-1	4/0 AWG	Light Grey	XLPO/None	4.00	1.431	11.13	1180.84	131.52	1.938	1.608	0.165	37.449	2KV,Tinned
6-12-12-1	12 AWG	White	Halar	4.193	1.356	17.52	33.30	5.80	0.318	0.216	0.051	6.037	
6-0000-12-1	4/0 AWG	White	Halar	4.608	2.080	9.76	1144.20	111.70	1.778	1.574	0.102	34.052	
7-12-7-1	12 AWG	Grey	FR, XLPO/None	2.643	1.334	42.0	46.83	19.66	0.475	0.195	0.140	9.101	2KV,Tinned
7-313-7-1	313 MCM	Grey	FR, XLPO/None	3.861	1.224	16.0	1722.03	274.33	2.383	1.783	0.30	47.159	2KV,Tinned
8-14-8-1	14 AWG	Grey/Black	EPR, FR/ Hypalon	1.667	1.436	83.32	111.8	93.33	0.924	0.162	0.381	18.067	2KV,Tinned
8-1000-8-1	1000 MCM	Black	EPR, FR/ Hypalon	3.496	1.351	19.64	5796.83	1138.33	4.595	3.395	0.60	95.038	2KV,Tinned
9-14-13-1	14 AWG	Grey/Black	EPDM/Hypalon	1.763	1.382	65.67	55.83	36.70	0.635	0.255	0.190	12.235	2KV,Tinned
9-12-13-1	12 AWG	Grey/Black	EPDM/Hypalon	1.942	1.376	57.91	43.33	25.03	0.533	0.229	0.152	10.229	2KV,Tinned
9-2000-14-1	2000 MCM	Orange/Black	EPDM/PO	4.446	1.531	13.22	10655.83	1408.30	5.524	4.124	0.70	113.32	1KV,Tinned
10-12-10-1	12 AWG	Orange/Black	EPR/XLPO,FR, SS	1.952	1.238	53.80	61.25	32.95	0.632	0.246	0.193	12.179	2KV,Tinned
10-500-10-1	500 MCM	Orange/Black	EPR/XLPO,FR, SS	3.824	1.216	16.16	2665.0	430.66	2.979	2.179	0.40	59.695	2KV,Tinned
11-12-1-1	12 AWG	Grey	Mineral filled Teflon/ None	3.733	1.992	43.12	48.33	20.83	0.406	0.178	0.114	7.757	600V,Tinned
11-10-11-1	10AWG	Yellow	Kapton/Teflon film	5.630	2.167	7.33	45.0	3.3	0.319	0.287	0.016	6.028	2KV,Tinned
11-00-1-1	2/0 AWG	Brown	Mineral filled Teflon/	4.427	2.022	17.87	783.3	140.0	1.501	1.101	0.20	28.986	600V,Tinned

TABLE V. SINGLE CONDUCTOR WIRE AND CABLE SAMPLES USED IN THIS STUDY AND THE PREVIOUS STUDY

		AWG											MCM							
Manufacturer	Insulation[a]	20	16	14	12	10	8	6	4	2	2/0	4/0	250	313	444	500	646	1000	1500	2000
Boston Insul.Wire	Silicone/XLPO	x	x		#		x		x				#							
	EPR/XLPO				#								#							
Brand Rex	XLPO				#										#					
Collyer	EPR/XLPO				#											#		#	#	
	EPR/Lead															x				
General Electric	XLPO				#												#			
	GMEX/XLPO				#															
	EPR/Neoprene																#			
	XLPVC						x									x				
Haveg (Champlain Cable)	XLPO	x	x		#		x		x		x	#								
Hi-Temp (Allied Chem)	Halar (ECTFE)				x#							#								
ITT, Surprenant Div	XLPO	x	x		#		x	x			x			#		x				
Kerite	EPR/Hypalon			#														#		
Pirelli	EPR/XLPO				#											#				
Tensolite	PTFE Teflon (filled)	x	x		#				x		#									
	Kapton/FEP	x				#														
	Tefzel (ETFE)	x	x				x			x	x									
	FEP Teflon															x				
Okonite	EPR/Neoprene										x									
	EPDM/Hypalon			#	#															
	EPDM/Polyolefin																			#
Cerro	Asbestos/Teflon/ Glass Braid			x																
	Mica/Silicone/ Glass Braid			x																
Filotex	Tefzel/Polyimide	x					x													
	Kapton	x					x													
	TPFE Teflon/ Kapton/Glass Braid										x									
Harbour	Tefzel (ETFE)	x																		
	Asbestos/PTFE/ Glass Braid		x																	
	Silicone/Glass Braid		x																	

TABLE V. SINGLE CONDUCTOR WIRE AND CABLE SAMPLES USED IN THIS STUDY AND THE PREVIOUS STUDY (CONT.)

		AWG														MCM				
Manufacturer	Insulation[a]	20	16	14	12	10	8	6	4	2	2/0	4/0	250	313	444	500	646	1000	1500	2000
Mili Bride	Tefzel (ETFE)		x																	
Prestolite	Polyester	x	x																	
	Silicone/Glass	x	x				x		x											
Industrial	PTFE Teflon	x																		
	Tefzel (ETFE)		x		x	x														
	Halar (ECTFE				x															
DuPont (Haveg)	Kapton/Polyimide	x	x																	
	Kapton/Nomex Braid						x		x											
Anaconda	Hypalon										x									
Alpha	PVC (XL irrad.)			x																
Unknown (N.Y.C.T.A.)	EPR/Neoprene																			x
British Ins. Cal.	PVC	x																		
	Polyethylene	x																		
	PTFE Teflon	x	x																	
	Silicone/ Terylene/Glass Braid	x	x																	
U.S. Steel	EPR/PVC															x				
Rome Cable	PVC																	x		
Northern Electric	EPR/Hypalon			x																
	EPR			x																
Phillips Cables	XL Polyethylene/ Copper										x									
Canada Wire & Cable	Butyl/Neoprene											x								

a:

XLPVC = Cross-linked polyvinyl chloride
ETFE = Ethylene Trifluoroethylene
PVC = Polyvinyl chloride

x indicates wire and cable samples tested in Ref. 1.
# indicates wire and cable samples tested in this study.

weight and length. The outside diameter and insulation/jacket thickness of the wire and cable sample were obtained by averaging values measured by a vernier slide caliper at four different places along the length of the cable. The effective surface area of the wire and cable sample in the vertical position was calculated by the formula $\frac{\pi}{4}(4 D_o \ell + D_o^2 - D_1^2)$, where D_o and D_1 are the outer diameter of the cable and the diameter of the conductor, respectively, and ℓ is the length of the wire and cable sample used in the experiment.

IV

EXPERIMENTAL RESULTS

4.1 PILOTED IGNITION

In the experiments, the time to sustained piloted ignition of vapors generated from wire and cable samples was measured as a function of the external heat flux. From the data, the critical heat flux and energy required for ignition were calculated (details are given in Appendix B). Critical heat flux is defined as a flux below which ignition is not expected to occur. Ignition energy is defined as the product of time to ignition and external heat flux.

Figure 7 shows the inverse of the product of time to piloted ignition and external heat flux or the inverse of the ignition energy as a function of external heat flux for wire and cable samples. The inverse of ignition energy is defined as the ignition parameters (IP). All the data for IP show similar trends in Figure 7. As external heat flux is decreased, IP decreases and approaches a value of zero. The value of external heat flux at which IP approaches a value of zero is defined as the critical heat flux, which can be obtained from the extrapolation of the data as shown in Figure 7. The data indicate that critical heat flux values are very similar for the wire and cable samples, irrespective of their size or generic nature of the insulation/jacket materials.

As the external heat flux is increased, IP increases and, at higher external heat flux values, IP approaches an asymptotic value, i.e., it becomes a constant. For the wire and cable samples, we have used the asymptotic value of IP to characterize the ignition properties of the samples. The higher the value of IP, the shorter is the ignition time and the higher is the surface flame spread rate expected for the wire and cable samples in fires.

The data in Figure 7 show that as the size of the wire and cable samples increases for the same generic insulation/jacket materials, the value of IP decreases. It is thus expected that with increase in the size of the wire and cable, with the same generic insulation/jacket materials, the ignition times would increase and surface flame spread rate would be reduced, which is a beneficial effect, being dependent on the generic nature of the insulation/jacket materials.

Data for the asymptotic value of the ignition parameter for the wire and cable samples are presented in Table VI, in terms of surface area (m^2) and length (m) of the sample arranged in decreasing order of the parameter, or in

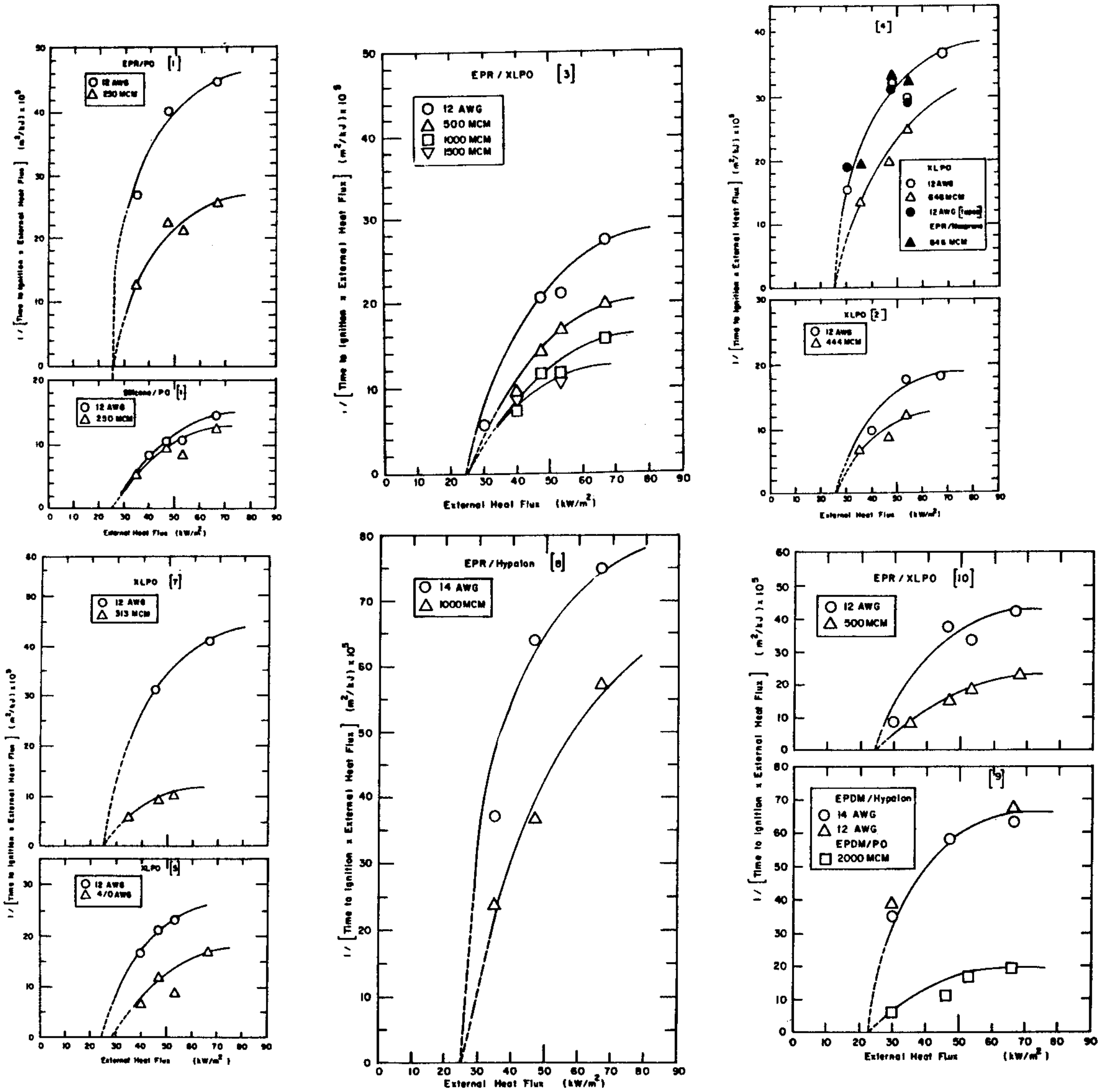


FIGURE 7 1/ (TIME TO PILOTED IGNITION x EXTERNAL HEAT FLUX) AS A FUNCTION OF EXTERNAL HEAT FLUX. Numbers in parentheses are manufacturers' numbers.

terms of expected increasing difficulty of ignition and reduced flame spread rate. In Table VI data for research samples have also been included. The data in Table VI indicate that ignition/surface flame spread characteristics are not only a function of the generic nature of the insulation/jacket materials, but also depend on the additives, size and construction of the wire and cable samples.

The data in Table VI indicate that the surface flame spread rate for wires and cables examined is expected to be significantly smaller than for the flexible polyurethane foam, red oak and Douglas fir. In Table VI, Hypalon jacketed wire and cable samples appear to indicate the highest surface flame spread rate compared to other samples, whereas Teflon and Kapton wire (under simulated flame and external radiation for large-scale fires) and cable samples appear to indicate a low surface flame spread rate compared to other samples. For relative comparisons, the data presented in Table VI may be used as an indicator of relative ranking of the samples for piloted ignition characteristics.

The data for the piloted ignition parameter listed in Table VI can be used to predict the piloted ignition parameter for other wire and cable samples for which time to piloted ignition is known. A careful examination of the piloted ignition parameter obtained in this study under forced air flow conditions, for samples in vertical configurations, and under natural air flow conditions, reported by Boeing(1), for similar wire and cable size samples with same insulation/jacket materials, suggests the following relationship:

$$\text{Asymptotic ignition parameter} \approx \frac{1}{800\ (t_{ig})_{\text{Boeing}}} \tag{1}$$

where asymptotic ignition parameter is in m^2/kJ and $(t_{ig})_{\text{Boeing}}$ is the time to piloted ignition in seconds reported by Boeing(1). The data calculated from Eq (1) for XLPO wire and cable samples are presented in Table VII where asymptotic IP values obtained from this study are also included. A comparison of the asymptotic values of IP calculated from Eq (1) using data reported by Boeing(1) compare reasonably well with the ignition parameter obtained directly from this study. We have thus used Eq (1) to predict ignition parameter for all the single conductor wire and cable samples examined by Boeing(1) for the vertical configuration of the samples, data for which are listed in Table VIII. Data for the asymptotic value of the ignition parameter obtained directly from this study are also included in Table VIII. The predicted ignition parameter for Boeing

TABLE VI. PILOTED IGNITION PARAMETER AND CRITICAL HEAT FLUX FOR WIRE AND CABLE SAMPLES IN VERTICAL CONFIGURATION UNDER FORCED NORMAL AIR FLOW CONDITIONS[a]

Sample No.	Insulation/Jacket Materials	Critical Heat Flux[b] (kW/m^2)	Asymptotic Value of Ignition Parameter (IP) In Terms of Surface Area (m^2/kJ)x10^6	Length (m/kJ)x10^{-3}
Research	Flexible Polyurethane Foam[c]	14	7100	
Research	Red Oak[c]	11	1750	
Research	Douglas Fir[c]	11	1300	
8-14-8-1	EPR/FR/Hypalon	25	770	25.7
9-14-13-1	EPDM/Hypalon	25	670	33.5
9-12-13-1	EPDM/Hypalon	25	670	40.2
8-1000-8-1	EPR/Hypalon	25	630	4.0
7-12-7-1	XLPO,FR/none	25	480	32.0
1-12-15-1	EPR/Low Smoke PO	25	450	22.5
10-12-10-1	EPR/XLPO,FR, Smoke Suppress	25	430	21.5
4-12-4-1	XLPO/none	25	380	25.3
4-12-9-1	Mica-Mat, Gemex Tape/XLPO	25	380	22.8
4-646-6-1	EPR/Neoprene	25	380	3.1
Research	Polymethylmethacrylate[c]	11	330	-
4-646-4-1	XLPO/none	25	330	2.9
3-12-5-1	EPR,FR,Low Smoke/XLPO	25	290	21.75
Research	Polyethylene[c]	15	270	-
1-250-15-1	EPR/Low Smoke PO	25	260	2.6
5-12-4-1	XLPO/none	25	260	19.5
10-500-10-1	EPR/XLPO,FR, Smoke Suppress	25	240	2.4
3-500-5-1	EPR,FR,Low Smoke/XLPO	25	210	2.1
9-2000-14-1	EPDM/PO	25	200	1.06
2-12-3-1	Polyrad XLPO/none	25	180	10.8
5-0000-4-1	XLPO/none	25	180	2.9
3-1000-5-1	EPR,FR, Low Smoke/XLPO	25	170	1.2
1-12-2-1	Silicone Low Smoke/PO	25	150	9.0
7-313-7-1	XLPO,FR/none	25	140	1.8
1-250-2-1	Silicone Low Smoke/PO	25	130	1.7
2-444-3-1	Polyrad XLPO/none	25	130	1.4
3-1500-5-1	EPR,FR,Low Smoke/XLPO	25	130	0.76
6-0000-12-1	Halar (ECTFE)	25	Not sustained 80[d]	
11-00-1-1	Teflon (PTFE)	25	Not sustained 60[d]	
11-10-11-1	Kapton/Teflon (FEP)	25	Not sustained	

---

[a] Ignition parameter is defined as the inverse of ignition energy. Ignition energy is the product of time to ignition and external heat flux (see Figure 7).

[b] Approximate value for wire and cable samples.

[c] Research samples; contain negligible amounts of additives. Samples used in horizontal configuration.

[d] Under combined simulation of flame and external heat flux for large-scale fires. Flame radiation was enhanced by increasing oxygen concentration in the inlet gas well above ambient value in the presence of external heat flux.

TABLE VII

RELATIONSHIP BETWEEN PILOTED IGNITION DATA FROM THIS STUDY AND FROM BOEING STUDY EXPRESSED IN TERMS OF TOTAL CABLE SURFACE AREA[a]

Sample Designation	Insulation/Jacket Material	Asymptotic Value of Ignition Parameter[b] $(m^2/kJ)X10^6$ Predicted From Eq. (1)	Obtained In This Study
6-20-1[c]	XLPO/none	450	-
11-20-1[c]	XLPO/none	630	-
6-16-1[c]	XLPO/none	420	-
11-16-1[c]	XLPO/none	500	-
7-12-7-1[d]	XLPO, FR/none	-	480
4-12-4-1[d]	XLPO/none	-	380
5-12-4-1[d]	XLPO/none	-	260
2-12-3-1[d]	Polyrad XLPO/none	-	180
6-8-1[c]	XLPO/none	280	-
11-8-2[c]	XLPO/none	420	-
11-6-2[c]	XLPO/none	280	-
6-4-1[c]	XLPO/none	250	-
6-00-1[c]	XLPO/none	200	-
11-00-2[c]	XLPO/none	180	-
5-0000-4-1[d]	XLPO/none	-	180
7-313-7-1[d]	XLPO, FR/none	-	140
2-444-3-1[d]	Polyrad XLPO/none	-	130
11-500-1[c]	XLPO/none	200	-
4-646-4-1[d]	XLPO/none	-	330

a = Sample in vertical configuration.

b = Piloted ignition parameter is defined as the inverse of ignition energy.

c = Boeing sample designation, data are given for time to piloted ignition under natural air flow conditions. Ignition parameter predicted from Eq. (1).

d = Sample designation used in this study. Data for asymptotic value of ignition parameter, under forced air flow conditions, taken from Table VI.

TABLE VIII

PILOTED IGNITION PARAMETER FOR SINGLE CONDUCTOR WIRE AND CABLE SAMPLES IN VERTICAL POSITION UNDER FORCED NORMAL AIR FLOW IN TERMS OF TOTAL CABLE SURFACE AREA

Sample No.		Asymptotic Value of	
Boeing Designation[b]	This Study[c]	Ignition Parameter[a] $(m^2/kJ)X10^6$	Jacket Material
		Polyvinyl Chloride Insulation	
14-20-1	-	1250	None
14-20-2	-	1250	None
14-20-3	-	830	None
14-20-4	-	890	None
14-20-6	-	480	None
4-16-1	-	630	None
A1-14-1	-	630	None
4-8-1	-	360	None
4-500-1	-	250	None
A4-1000-3	-	310	None
		Polyester Insulation	
9-20-1	-	740	None
9-16-1	-	1040	None
		Asbestos Insulation	
2-14-1	-	100	Teflon/glass braid
5-16-2	-	130	Teflon/glass braid
		Halar (ECTFE) Insulation	
12-12-4	-	420	None
-	6-0000-12-1	80[d]	None
		Hypalon Insulation	
15-00-1	-	240	None
		Mica Insulation	
2-14-2	-	210	Glass braid silicone
-	4-12-9-1	390	Gemex tapes XLPO
		Thermoplastic Insulation	
A2-14-1	-	420	Nylon
A2-14-2	-	830	None
A2-250-2	-	420	None

TABLE VIII (CONT'D)

Sample No. Boeing Designation[b]	Sample No. This Study[c]	Asymptotic Value of Ignition Parameter[a] $(m^2/kJ)X10^6$	Jacket Material
		Kapton (Polyimide) Insulation	
3-20-2	-	310	Tefzel
10-20-2	-	300	Polyimide
13-20-1	-	280	Polyimide
14-20-9	-	390	Teflon (FEP)
13-16-1	-	160	Polyimide
10-14-2	-	200	Polyimide
-	11-10-11-1		Teflon (FEP)
3-8-2	-	80	None
13-8-1	-	70	Nomex braid
13-4-1	-	120	Nomex braid
3-00-3	-	130	Teflon (PTFE)/ glass braid/ Teflon (PTFE)
		Polyethylene Insulation	
14-20-5	-	250	None
A7-2-1	-	130	None
A5-00-3	-	90	Semi Conductive, Cu armour
		Polyolefin Insulation	
6-20-1	-	450	None
11-20-1	-	630	None
6-16-1	-	420	None
11-16-1	-	500	None
-	7-12-7-1	480	None
-	4-12-4-1	380	None
-	5-12-4-1	260	None
-	2-12-3-1	180	None
6-8-1	-	280	None
11-8-2	-	420	None
11-6-2	-	280	None
6-4-1	-	250	None
6-00-1	-	200	None
11-00-2	-	180	None
-	5-0000-4-1	180	None
-	7-313-7-1	140	None
-	2-444-3-1	130	None
11-500-1	-	200	None
-	4-646-4-1	330	None

TABLE VIII (CONT'D)

Sample No. Boeing Designation[b]	Sample No. This Study[c]	Asymptotic Value of Ignition Parameter[a] $(m^2/kJ)X10^6$	Jacket Material
		Rubber Insulation	
A5-000-4	-	160	Chloroprene
A4-500-1	-	290	Polyvinyl Chloride
A4-500-2	-	20	Lead
A3-2000-3	-	110	Neoprene
		EPDM Insulation	
-	9-14-13-1	670	Hypalon
-	9-12-13-1	670	Hypalon
-	9-2000-14-1	200	Polyolefin
		EPR Insulation	
A5-14-1	-	310	Hypalon
A5-14-2	-	310	None
-	8-14-8-1	770	Hypalon
-	1-12-15-1	450	Polyolefin
-	10-12-10-1	440	Polyolefin
-	3-12-5-1	290	Polyolefin
A7-00-2	-	210	Neoprene
-	1-250-15-1	260	Polyolefin
-	10-500-10-1	240	Polyolefin
-	3-500-5-1	210	Polyolefin
-	4-646-6-1	390	Neoprene
-	3-1000-5-1	170	Polyolefin
-	8-1000-8-1	630	Hypalon
-	3-1500-5-1	130	Polyolefin
		Silicone Rubber Insulation	
1-20-1	-	630	Polyolefin
9-20-2	-	360	Glass braid, lacquer
14-20-8	-	690	Glass braid, Terylene, lacquered
1-16-1	-	460	Polyolefin
5-16-3	-	250	Glass braid
9-16-2	-	208	Glass braid, lacquer
14-16-8	-	830	Glass braid, Terylene, lacquered
14-14-10	-	230	None
-	1-12-2-1	150	Polyolefin
1-8-1	-	310	Polyolefin
9-8-2	-	130	Glass braid, Terylene, lacquered
1-4-1	-	250	Polyolefin
9-4-2	-	250	Glass braid, lacquer
-	1-250-2-1	130	Polyolefin

TABLE VIII (CONCLUDED)

Sample No.		Asymptotic Value of Ignition Parameter[a] $(m^2/kJ) \times 10^6$	Jacket Material
Boeing Designation[b]	This Study[c]		
		Teflon Insulation (PTFE/FEP)	
10-20-1	-	360	None
12-20-1	-	460	None
12-20-2	-	500	None
14-20-7	-	420	None
10-16-1	-	420	None
14-16-7	-	270	None
10-4-1	-	150	None
-	11-00-1-1	60[d]	None
10-500-4	-	80	None
		Tefzel Insulation (ETFE)	
3-20-1	-	570	Polyimide
5-20-1	-	420	None
10-18-3	-	480	None
8-16-1	-	630	None
10-16-3	-	420	None
12-16-3	-	360	None
12-12-3	-	280	None
12-10-3	-	270	None
3-8-1	-	210	Polyimide
10-8-3	-	250	None
10-3-3	-	190	None
10-00-3	-	140	None

a = Ignition parameter is defined as the inverse of ignition energy.

b = Defined in Ref. 1.

c = Defined in Tables I to IV of this report.

d = with oxygen concentration well above ambient value - high flame radiation in the presence of external heat flux samples indicate that as the size of the wire and cable sample is increased, the parameter decreases, i.e., the surface flame spread rate is expected to decrease with increase in the size of the wire and cable. For the selection of the wires and cables, samples with low ignition parameter would be preferable, because in order to initiate fires in wires and cables, the exposure fire would have to be of significant size. The data presented in Table VIII thus can be considered as a relative ranking of wire and cable sample for ignition/flame spread characteristics.

Since almost all of the samples examined by Boeing were small wires and cables, the procedure with the Fisher burner was tested in this study for large wire and cable samples. Table IX lists the data for time to ignition measured in this study for large wire and cable samples using the procedures with the Fisher burner recommended by Boeing(1). Table IX also includes predicted time to piloted ignition using Eq (1) and ignition parameter from Table VI. With the exception of a few samples, the data in Table IX indicate that measured time to ignition, using the Fisher burner technique for large wire and cable samples, is longer than the predicted value and for 2000 MCM cable sample there is no ignition. During the experiments, it was observed that the surface of cable was heated nonuniformly, which one would not expect for smaller wire and cable samples. Because of the nonuniform heating, the time to ignition would be expected to be longer, as indicated by the data in Table IX.

The ignition characteristics of wires and cables indicate that if wires and cables are grouped together, varying in size and generic nature of insulation/jacket materials, varying degrees of ignition characteristics would be expected, depending on the relative numbers of small and large size wires and cables and interactions of the materials. For example, cables with high or low values of IP in Tables VI or VIII, if grouped together with small and large size wires and cables may show only higher IP values than expected from the data based on individual samples. It is thus recommended that experiments be performed with grouped wire and cable samples using a proper combination of small and large size wire and cable samples and generic nature of the insulation/jacket materials.

In order to further examine the size effects of the wire and cable samples, the asymptotic ignition energy is plotted as a function of the ratio of the thermal capacity of the conductor to that of the insulation in Figure 8. Since different types and amounts of additives are added to insulation/jacket materials, the thermal properties of cables may not be the same as their constituents and

TABLE IX

TIME TO PILOTED IGNITION UNDER NATURAL AIR FLOW CONDITIONS FOR LARGE WIRE AND CABLE SAMPLES USING FISHER BURNER TECHNIQUE[a]

Sample Size (AWG/MCM)	Sample Designation	Insulation/ Jacket Materials	Sample Configuration	Time to Piloted Ignition(s)	
				Measured	Predicted[b]
4/0	5-0000-4-1	XLPO/None	Horizontal	10	-
			Vertical	14	7
250	1-250-2-1	Silicone,Low Smoke/PO	Horizontal	40	-
			Vertical	34	10
313	7-313-7-1	XLPO,FR/None	Horizontal	8	-
			Vertical	10	9
500[c]	11-500-1[c]	XLPO/None	Horizontal	6[c]	-
			Vertical	5[c]	6
646	4-646-6-1	EPR/Neoprene	Horizontal	11	-
			Vertical	12	3
1000	8-1000-8-1	EPR/Hypalon	Horizontal	14	-
			Vertical	7	2
1500	3-1500-5-1	EPR,FR,Low Smoke/XLPO	Horizontal	60	-
			Vertical	90	10
2000	9-2000-14-1	EPDM/PO	Horizontal	No ignition	-
			Vertical	No ignition	6

[a] = Technique described in Ref. (1);

[b] = From Eq. (1) and data from Table VI;

[c] = Data given in Ref. (1)

may vary between cables made with the same generic polymer. Because the thermal properties of the insulation/jacket materials were not measured, the values used in Figure 8 were taken from reference 38 for the estimation of thermal capacity.

The data in Figure 8 indicate that, for all three 'families' of insulation/jacket materials, the energy required for ignition increases as the thermal capacity of the materials relative to that of the conductor decreases.

Several heat transfer mechanisms are involved in the transfer of energy into and within the cables - convection to the surface, radiation to and from the surface, radial conduction through the insulation to the conductor and axial conduction along the conductor and insulation. These mechanisms are transient; the time required for the insulation/jacket materials to reach the critical flux is a function of the cable's thermal properties and the dominant mode of heat transfer.

A thorough analysis might collapse the data for ignition energy as a function of a heat transfer parameter. This would be an invaluable tool for quantifying the ignition characteristics of wires and cables. Accurate values of the thermal properties of the insulation and jacket materials would be essential for such an analysis and is recommended for the future studies on cables.

In addition to the size of the wires and cables, IP values are also sensitive to a certain extent to wire and cable configurations and local aerodynamic conditions and flame radiation. Figure 9 is a plot of IP values in horizontal and vertical configurations under natural and forced air flow conditions. (Data taken from Tables VI and XVI.) Horizontal samples under natural air flow conditions were about 0.8 m in length with the middle 0.3 m portion of the sample exposed to the external heat flux (Figure 3). Vertical samples under forced air flow conditions were about 0.06 m in length, with the entire length exposed to the external heat flux. In Figure 9, in some cases vertical samples under forced air flow appear to show higher IP values than horizontal samples under natural air flow. Refinement of IP values thus are recommended for future study.

4.2 GENERATION RATE OF FUEL VAPORS

In the experiments the generation rate of fuel vapors was measured at high external heat flux value (60 kW/m^2) to reduce the influence of flame heat flux (Appendix C). The ratio of the generation rate of fuel vapors to external heat flux applied to the sample is defined as the fuel vapor generation parameter (VP)

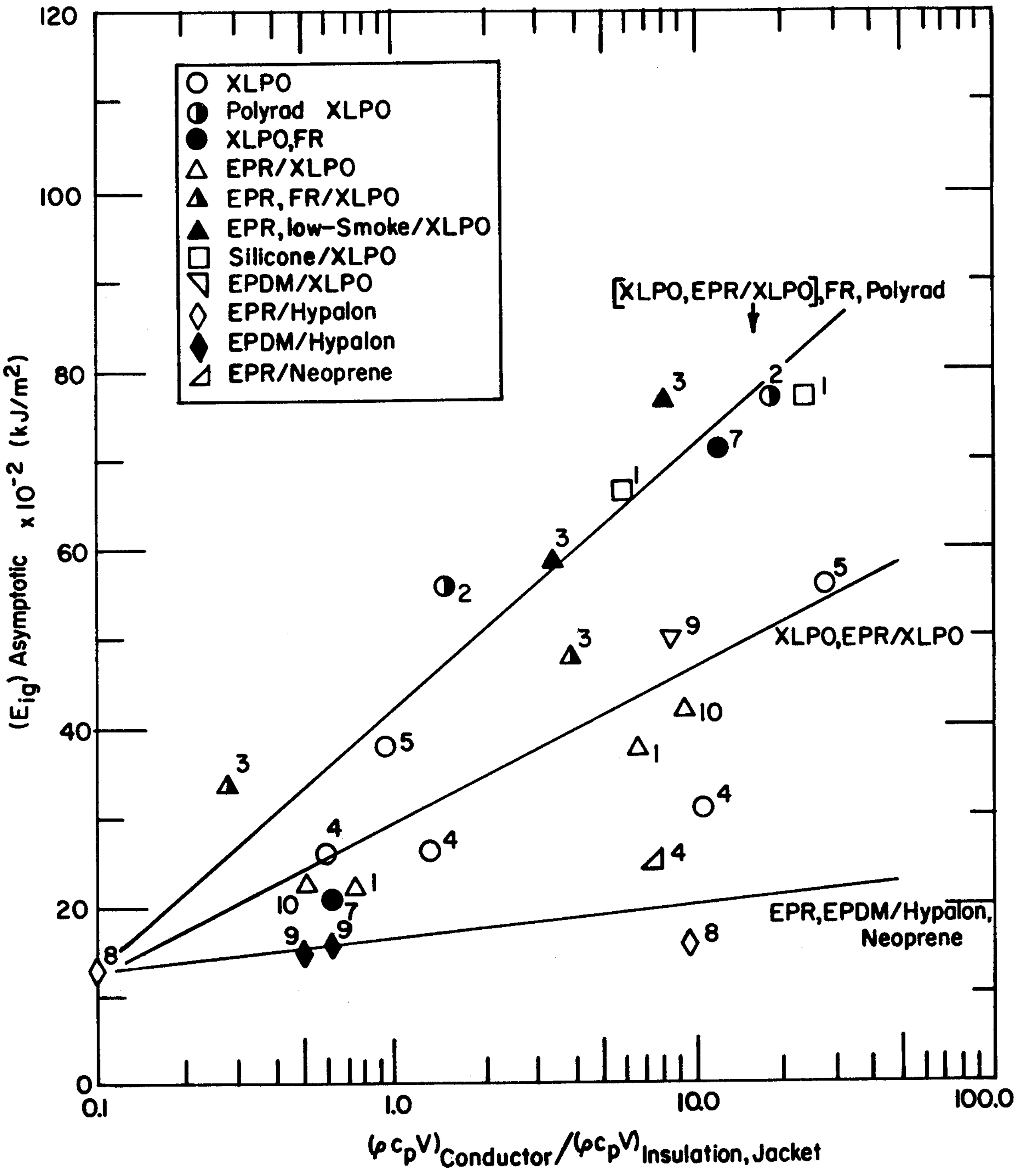


FIGURE 8 ASYMPTOTIC IGNITION ENERGY VERSUS RATIO OF THERMAL CAPACITY OF CONDUCTOR TO THAT OF INSULATION (Numbers 1 to 10 indicate manufacturer listed in Table I.)

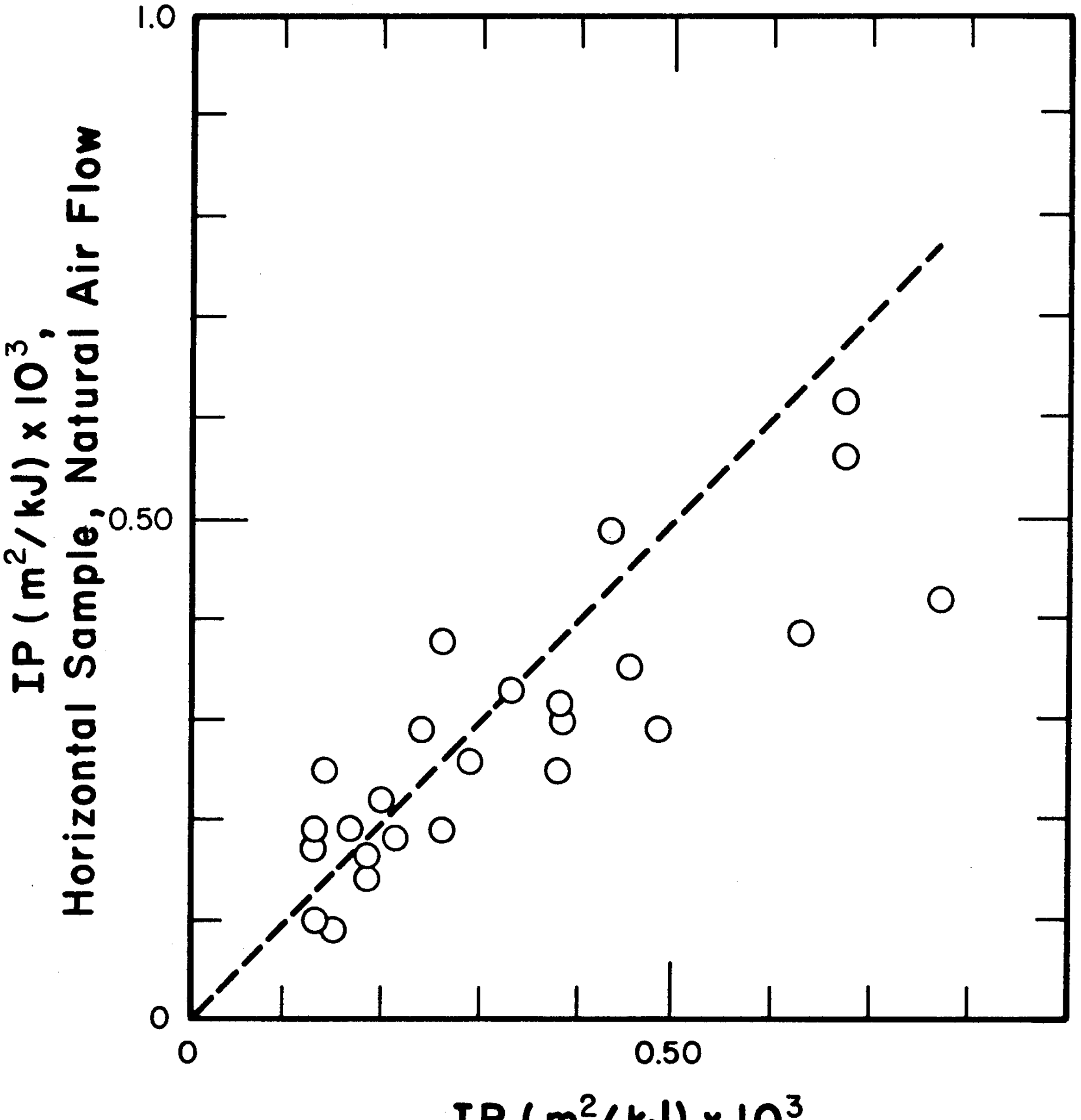


FIGURE 9 PILOTED IGNITION PARAMETER FOR HORIZONTAL AND VERTICAL WIRE AND CABLE SAMPLES UNDER DIFFERENT AIR FLOW CONDITIONS

of wire and cable samples. VP is the amount of fuel vapors generated in grams per unit of heat received by the sample (kJ) (details are given in Appendix C). The higher the value of VP, the higher is the generation rate of fuel vapors expected in fires and thus higher is the fire hazard due to heat, "smoke," toxic or corrosive products. VP thus is an indicator of the relative ranking of wire and cable samples for the fuel vapor generation characteristic.

Table X presents the VP values, arranged in decreasing order for wire and cable samples.

The data in Table X show that VP decreases as the size of the wire and cable increases. In fires, the generation rate of fuel vapors thus is expected to be lower for large wire and cable samples than the small samples, which is a beneficial effect. The decrease in VP values due to increase in the size of the wire and cable sample is the result of increased charring of the surface.

A combined simulation* of flame and external radiation for large-scale fire condition shows higher VP values than the simulation for external radiation only. For example, for EPR/XLPO, VP = 0.55 g/kJ under combined simulation* of flame and external radiation compared with a value of 0.44 g/kJ under simulation of external radiation only in normal air. Teflon and Halar samples are expected to burn when flame radiation is present and show high to intermediate VP values under combined simulation* of flame and external radiation. For simplification and refinement of VP values a combined simulation of flame and external radiation for large-scale fire condition is recommended.

In grouped wires and cables, with small and large sizes and varying insulation/jacket materials, it is not necessary that the VP values listed in Table X would follow. A study is thus needed using systematic variations in the ratio of small and large wires and cables and insulation/jacket materials in order to develop generalized results for grouping the wires and cables for reduced hazard presented by the generation of fuel vapors.

4.3 GENERATION RATE OF FIRE PRODUCTS

Fire products consist of heat and chemical compounds such as "smoke," toxic and corrosive products. In the experiments the generation rate of heat that is actually released or actual heat realease rate and generation rates of

---

*Flame radiation is enhanced by increasing oxygen concentration in the inlet gas well above the ambient value in the presence of external heat flux.

TABLE X

FUEL VAPOR GENERATION PARAMETER FOR WIRE AND CABLE SAMPLES FOR COMBUSTION IN NORMAL AIR[a]

Sample Designation	Insulation/Jacket Materials	Wire/Cable Size	VP[b] (g/kJ)
3-12-5-1	EPR,FR, Low Smoke/XLPO	12 AWG	0.55[c]
3-12-5-1	DPR,FR, Low Smoke/XLPO	12 AWG	0.44
11-00-1-1	Teflon (PTFE)	2/0 AWG	None 0.41[c]
8-14-8-1	EPR,FR/Hypalon	14 AWG	0.37
9-14-13-1	EPDM/Hypalon	14 AWG	0.35
1-250-2-1	Silicone,Low Smoke/PO	250 MCM	0.35
2-444-3-1	Polyrad XLPO/none	444 MCM	0.30
6-0000-12-1	Halar (ECTFE)	4/0 AWG	None 0.24[c]
3-500-5-1	EPR,FR,Low Smoke/XLPO	500 MCM	0.23
3-1000-5-1	EPR,FR,Low Smoke/XLPO	1000 MCM	0.22
8-1000-8-1	EPR/Hypalon	1000 MCM	0.22
10-500-10-1	EPR/XLPO,FR,Smoke Suppress.	500 MCM	0.21
7-313-7-1	XLPO,FR/none	313 MCM	0.17
3-1500-5-1	EPR,FR,Low Smoke/XLPO	1500 MCM	0.17
5-0000-4-1	XLPO/none	4/0 AWG	0.16
4-646-6-1	EPR/Neoprene	646 MCM	0.13

---

[a] Fuel vapor generation parameter (VP) is the ratio of generation rate of fuel vapors to the external heat flux applied to the sample.

[b] Peak value of the generation rate of fuel vapors at 60 kW/m of external heat flux.

[c] Combined simulation of flame and external radiation for very large-scale fire conditions. Flame radiation is enhanced by increasing oxygen concentration in the inlet gas well above the ambient value in the presence of external heat flux.

carbon dioxide, carbon monoxide and total gaseous hydrocarbons were measured at a high external heat flux value (60 kW/m^2)* (see Appendix D). The ratio of actual heat release rate to external heat flux applied to the sample is defined as the heat generation parameter (HP) of the wire and cable samples (details are given in Appendix D). The ratio of the generation rate of the chemical compounds to the external heat flux applied to the sample is defined as chemical compound generation parameter (CP) (details are given in Appendix D). The higher the value of HP and CP, the higher are the heat release rate and generation rates of chemical compounds (such as smoke, toxic and corrosive compounds) and the higher is the hazard expected in fires. HP and CP values thus are indicators of the relative ranking of the wire and cable samples for heat, "smoke," toxic and corrosive compounds generation characteristics.

Tables XI and XII present the data for HP and CP for carbon monoxide (toxic compound) respectively, arranged in decreasing order of HP and CP values for wire and cable samples.

The data in Tables XI and XII indicate that HP and CP values are functions of generic nature of insulation/jacket materials as well as the additives, size and construction of the wires and cables. HP and CP values decrease as the size of the wire and cable increases. The decrease is due to increased surface charring, where increased amounts of carbon are retained in the solid phase. Under combined simulation of flame and external radiation for very large-scale fire, Teflon and Halar samples show low HP values compared to EPR/Hypalon sample; the CP-CO value for Teflon, however, is comparable to the value for EPR/Hypalon sample, whereas the CP-CO value is low for the Halar sample. HP and CP values thus need to be refined for combined simulation of flame and external radiation and this is recommended for future studies. Samples with low HP and CP values would be preferable to samples with high values.

In actual use, wires and cables are grouped together, which may involve varying amounts of small and large sizes as well as varying generic types of insulation/jacket materials. In this situation, the HP and CP values may be much different than expected on the basis of data in Tables XI and XII. It is thus recommended that a careful study be performed with proper variations in the size and materials using grouped wire and cable samples to generalize the results.

---

*Using high external heat flux reduces the effect of flame heat flux (which was not quantified in the study).

TABLE XI

HEAT GENERATION PARAMETER OF WIRE AND CABLE SAMPLES IN NORMAL AIR[a]

Sample Designation	Insulation/Jacket Materials	Wire/Cable Size	HP[b] (kW/kW)
Research	Polyethylene[c]	-	18
3-12-5-1	EPR,FR,Low Smoke/XLPO	12 AWG	17.2[d]
3-12-5-1	EPR,FR,Low Smoke/XLPO	12 AWG	14.1
10-500-10-1	EPR/XLPO,FR,Smoke Suppress.	500 MCM	8.5
2-444-3-1	Polyrad XLPO/none	444 MCM	7.8
3-500-5-1	EPR,FR,Low Smoke/XLPO	500 MCM	7.8
9-14-13-1	EPDM/Hypalon	14 AWG	6.6
8-14-8-1	EPR,FR/Hypalon	14 AWG	6.6
1-250-2-1	Silicone, Low Smoke/PO	250 MCM	6.1
4-646-6-1	EPR/Neoprene	646 MCM	5.9
7-313-7-1	XLPO,FR/none	313 MCM	5.6
3-1000-5-1	EPR,FR,Low Smoke/XLPO	1000 MCM	5.5
5-0000-4-1	XLPO/none	4/0 AWG	5.5
8-1000-8-1	EPR/Hypalon	1000 MCM	4.1
3-1500-5-1	EPR,FR,Low Smoke/XLPO	1500 MCM	3.9
11-00-1-1	Teflon (PTFE)	2/0 AWG	None 3.7[d]
6-0000-12-1	Halar (ECTFE)	4/0 AWG	None 2.3[d]

---

[a] Heat generation parameter (HP) is defined as the ratio of actual heat release rate to the external heat flux applied to the sample (kW/kW)

[b] For peak value of the actual heat release rate at 60 kW/m^2 of external heat flux

[c] Research grade sample

[d] Combined simulation of flame and external radiation for very large-scale fire conditions. Flame radiation is enhanced by increasing oxygen concentration in the inlet gas well above the ambient value in the presence of external heat flux.

TABLE XII

CO GENERATION PARAMETER FOR WIRE AND CABLE SAMPLES IN NORMAL AIR[a]

Sample Designation	Insulation/Jacket Materials	Wire/Cable Size	$(CP)_{CO}$[b]
1-250-2-1	Silicone, Low Smoke/PO	250 MCM	0.053
11-00-1-1	Teflon (PTFE)	2/0 AWG	None 0.043[c]
8-14-8-1	EPR,FR/Hypalon	14 AWG	0.040
3-12-5-1	EPR,FR,Low Smoke/XLPO	12 AWG	0.035[c]
2-444-3-1	Polyrad XLPO/none	444 MCM	0.035
8-1000-8-1	EPR/Hypalon	1000 MCM	0.035
3-12-5-1	EPR,FR,Low Smoke/XLPO	12 AWG	0.016
5-0000-4-1	XLPO/none	4/0 AWG	0.010
3-500-5-1	EPR,FR,Low Smoke/XLPO	500 MCM	0.0083
9-14-13-1	EPDM/Hypalon	14 AWG	0.0076
7-313-7-1	XLPO,FR/none	313 MCM	0.0076
10-500-10-1	EPR/XLPO,FR,Smoke Suppress.	500 MCM	0.0044
3-1000-5-1	EPR,FR,Low Smoke/XLPO	1000 MCM	0.0042
4-646-6-1	EPR/Neoprene	646 MCM	0.0033
3-1500-5-1	EPR,FR,Low Smoke/XLPO	1500 MCM	0.0024
6-0000-12-1	Halar (ECTFE)	4/0 AWG	None 0.0021[c]

---

[a] CO generation parameter is defined as the ratio of the generation rate of the CO to the external heat flux applied to the sample (g/kJ).

[b] For peak values of the generation rate of CO at 60 kW/m^2 of external heat flux.

[c] Combined simulation of flame and external radiation for very large-scale fire conditions. Flame radiation is enhanced by increasing oxygen concentration in the inlet gas to well above the ambient value in the presence of external heat flux.

Since in grouped wires and cables flaming as well as smoldering fires can occur, it is recommended that CP values be quantified for the smoldering fires of wire and cable samples also. In addition, it is recommended that animal experiments be performed in conjunction with the quantification of CP values.

4.4 LIGHT OBSCURATION THROUGH "SMOKE"

The light obscuration through "smoke" is generally measured at a fixed wavelength of light in terms of optical density, expressed as $\log_{10} (I_o/I)$ or $\ln (I_o/I)$ where I_o is the optical transmission in the absence of "smoke" and I is the optical transmission in the presence of "smoke."

In the experiments, the optical density per unit optical path length $\left(\frac{1}{\ell} \ln (I_o/I)\right)$ was measured at three light wavelengths, 0.458μ, 0.624μ and 1.06μ for the selected wire and cable samples at one high value of external heat flux (60 kW/m^2). In addition, the total volumetric flow rate of the fire products air mixture was also measured to account for the dilution of "smoke." The data for the optical density per unit path length multiplied by the total volumetric flow rate of fire product-air mixture and divided by the external heat flux and surface area of the sample was used to calculate the light obscuration parameter (LP) (details are given in Appendix E). LP is the light obscuration property of "smoke" produced per unit amount of energy absorbed by the sample (m^2/kJ). The higher the value of LP, the higher is the light obscuration by "smoke" in fires and thus higher is the hazard due to reduced visibility. LP thus can be used as an indicator of the relative ranking of the wire and cable samples for "smoke" generation characteristics as related to light obscuration.

Table XIII presents the data for LP values. Optical density (at 0.624μ wavelength, which represents visible light) as a function of time for each cable sample listed in Table XIII is shown graphically in Appendix G.

The data in Table XIII indicate that wire and cable samples cannot be rated on the basis of generic natures of the insulation/jacket materials alone. The effects of wire and cable size and construction and the additives are as important as the generic nature of the insulation/jacket materials.

The data in Table XIII indicate that for some samples the additives to reduce smoke, identified as low smoke samples, are effective while for others they are not. Halar and Teflon are very low smoke producing samples under large-scale fire conditions simulated for flame and external radiation.

TABLE XIII

LIGHT OBSCURATION PARAMETER OF "SMOKE" GENERATED FROM WIRE AND CABLE SAMPLES IN NORMAL AIR[a]

Sample Designation	Insulation Jacket Materials	Wire/Cable Size	Light Obscuration Parameter (LP)[b] $(m^2/kJ)x10^3$ Wavelength of Light 1.06μ	0.458μ	0.624μ[d]
3-12-5-1	EPR,FR,Low Smoke/XLPO	12 AWG	8.4	16	20
1-250-2-1	Silicone, Low Smoke/PO	250 MCM	6.5	11	13
9-14-13-1	EPDM/Hypalon	14 AWG	4.8	12	19
2-444-3-1	Polyrad XLPO/none	444 MCM	4.3	8	11
3-12-5-1	EPR,FR,Low Smoke/XLPO	12 AWG	4.0[c]	-	-
8-1000-8-1	EPR/Hypalon	1000 MCM	3.0	6.0	7.8
5-0000-4-1	XLPO/none	4/0 AWG	2.5	4.8	4.5
8-14-8-1	EPR,FR/Hypalon	14 AWG	2.2	6.0	12.0
3-500-5-1	EPR,FR,Low Smoke/XLPO	500 MCM	1.7	3.4	4.8
3-1000-5-1	EPR,FR,Low Smoke/XLPO	1000 MCM	1.6	2.7	3.6
4-646-6-1	EPR/Neoprene	646 MCM	1.3	2.4	3.1
7-313-7-1	XLPO,FR/none	313 MCM	1.1	2.7	3.3
10-500-10-1	EPR/XLPO,FR,Smoke Suppress.	500 MCM	0.92	1.8	2.6
3-1500-5-1	EPR,FR,Low Smoke/XLPO	1500 MCM	0.82	1.5	2.0
6-0000-12-1	Halar (ECTFE)	4/0 AWG	None 0.70[c]	- 1.5[c]	- 2.9[c]
11-00-1-1	Teflon (PTFE)	2/0 AWG	None <0.01[c]	- <0.01[c]	- <0.01[c]

---

[a] Light obscuration parameter (LP) is defined as the light obscuration property of "smoke" produced per unit amount of energy absorbed by the sample (m^2/kJ).

[b] For peak values of optical density for sample exposed to 60 kW/m^2 of external heat flux.

[c] Combined simulation of flame and external radiation for large-scale fire conditions. Flame radiation is enhanced by increasing oxygen concentration in the inlet gas well above the ambient value in the presence of external heat flux.

[d] Wavelength represents visible light.

LP values can be used not only for ranking, but also for estimating light obscuration in various fire scenarios where exposed surface area of the wire and cables, total heat flux received by the wires and cables and volumetric flow rate of fire products are either known or can be estimated. LP values can also be used to quantify the effectiveness of various candidates for suppressing "smoke" from wires and cables.

In order to show correlations between "smoke" data from this study and from the NBS Smoke Chamber, five wire and cable samples were selected and sent to Superpressure, Inc., Silver Spring, Maryland for the measurements of the optical density in the NBS Smoke Chamber using the procedures followed by Boeing in the earlier study on wires and cables(1).

NBS Smoke Chamber data for the wire and cable samples are given in Table XIV. Table XV presents a correlation of the smoke data from NBS Smoke Chamber (a closed system) and FM Combustibility Apparatus (an open system) (see Appendix E). An examination of the NBS data and our data in Table XV show a reasonable correlation considering the uncertainty of the wave length of light, assumption of sample vaporization and uniform mixing of "smoke" and air in the NBS Smoke Chamber.

The smoke emission data presented in the previous report(1) could not be correlated with the smoke data from the FM Combustibility Apparatus because of the unavailability of the data on total weight loss of the samples in the NBS Smoke Chamber used in the previous study.

4.5 ELECTRICAL INTEGRITY

The electrical integrity test method followed in the Boeing program(1) was limited to the single conductor wire and cables of 8 AWG size and smaller. The test method described in Section 2.3.5 was primarily developed for this program with the capability of 1) testing any size of single conductor wire and cable sample, and 2) adapting easily into the FM Combustibility Apparatus.

The electrical integrity failure in a wire and cable was defined as the electrical shorting between conductor to ground or as loss of insulation with exposure of the conductor. The time at which the electrical integrity failure in a wire and cable occurred as a function of external heat flux was measured in the experiments. The product of time to electrical failure and external heat flux was defined as the energy for electrical failure, very similar to ignition energy. The inverse of the energy for electrical failure was defined as

TABLE XIV. NBS SMOKE CHAMBER DATA FOR THE FLAMING FIRES OF WIRES AND CABLE SAMPLE[a]

Sample Designation	Insulation/Jacket Materials	Initial Wt. of the Sample (g)	Wt. of Sample Vaporized[b] (g)	Transmittance		Specific optical Density (D_s)[c]					
				Time to Reach Minimum (s)	Minimum Value (%)	at 90s	at 240s	Maximum Value, Dm	Time to attain(s)		dD_s/dt (s^{-1})
									D_s=16	90% of Max. D_s	
1-250-2-1	Silicone, Low Smoke/Po	30	11	1080	0.14	0	94	378	96	804	0.82
5-0000-4-1	XLPO/None	15	14	480	0.12	116	302	389	54	288	1.9
4-646-6-1	EPR/Neoprene	44	27	300	0.014	57	480	510	72	228	3.3
8-1000-8-1	EPR/Hypalon	60	53	420	0.019	20	377	497	78	294	2.6
3-1500-5-1	EPR, FR, Low Smoke/XLPO	59	42	1020	4.2	0	16	206	234	876	0.58

a: Measured by Superpressure Inc. Silver Spring, Maryland; External heat flux = 25 kw/m^2; Sample Surface area (A) = 0.00424 m^2; optical path length (l) = 0.92 m; range of Wave-Length of Light ≈ 0.4 to 0.7μ ; Volume of the chamber (V) = 0.51 m^3;

b: Calculated on the basis of char yields measured in our study.

c: Specific optical density (D_s) = DV/Aℓ; D = $\log_{10}$ (I_0/I); I/I_0 = transmittance.

TABLE XV. COMPARISON OF "SMOKE" DATA FROM THE NBS SMOKE CHAMBER AND FROM THE FM SMALL-SCALE APPARATUS[a]

		σy_s (m^2/g)[b]				
Sample Designation	Insulation/Jacket Materials	NBS Smoke Chamber [c]	FM Small-Scale Apparatus[d] Wave Length of Light			
			0.458μ	0.624μ	1.06μ	Average
1-250-2-1	Silicone, Low Smoke/PO	0.14	0.16	0.13	0.083	0.12
5-0000-4-1	XLPO/None	0.12	0.12	0.13	0.069	0.11
4-646-6-1	EPR/Neoprene	0.083	0.10	0.078	0.043	0.074
8-1000-8-1	EPR/Hypalon	0.040	0.15	0.12	0.061	0.11
3-1500-5-1	EPR, FR, Low Smoke/XLPO	0.021	0.096	0.065	0.033	0.065

a: Using maximum values of D_s from NBS Smoke Chamber and $1/\ell \ \ell n \ (I_0/I)$ converted to $1/\ell \ \log_{10} (I_0/I)$ from the FM Small-Scale apparatus and Eqs (E-7) and (E-4) in the Appendix.

b: σ = mass attenuation coefficient of "Smoke"; y_s = Yield of "Smoke" (g/g)

c: From data in Table XIV; range of wave length of light ~ 0.4 to 0.7μ.

d: From data in Tables X and XIII.

the electrical failure parameter (EP). The data listed in Table XVI are arranged according to the size of the samples. Data for the ignition parameter are also included in the table. The larger the value of EP, the faster is the electrical failure expected in fires. Electrical failure follows ignition, except for Teflon and Halar as shown in Figure 10, where EP is plotted as a function of IP. Electrical failure for Teflon and Halar samples is due to melting and softening of the samples.

EP decreases as the size of wire and cable sample is increased. For 500 MCM and larger sizes of wire and cable samples, no electrical failure was observed because of increased charring of the surface.

Small samples which show high EP values are: EPDM/Hypalon (9-14-13-1); XLPO/XLPO (7-12-7-1); XLPO (5-12-4-1) and Halar (6-12-12-1). Kapton/Teflon (11-10-11-1) shows no electrical failure, although it is a small size wire and cable sample.

The time to electrical integrity failure measured by this method depends on several variables, such as size and tension of the Nichrome wire, external heat flux, and the applied voltage to the cable. Further, tests of this kind and the one described in Boeing program(1) are not reproducible because of local char formation.

The general intent of an electrical integrity test method is to measure the time a cable will remain serviceable in the event of a fire situation. A more practical test method is being developed at FMRC which will use 240 or 120 volts and scan every 5s or less on each conductor (in the case of a multiconductor cable) or on a group of conductors (in the case of grouped single conductor cable). The other ends of the conductors will be connected to a minicomputer through a suitable failure detector circuit so that a short between conductors or conductor to ground during a fire situation can be detected as a function of time and the measurements will be reproducible.

4.6 CORROSIVITY OF FIRE PRODUCTS

The corrosivity of the water soluble fire products generated from the wire and cable samples was measured with a mild steel probe connected to a corrosionmeter. Similarly, the corrosivity of a standard chloride ion solution (0.1 mole/litre of HCl) was also measured in order to express the corrosivity of the fire products of wire and cable samples relative to the corrosivity of HCl to the mild steel. Detail measurement technique and calculation for the evaluation

TABLE XVI

ELECTRICAL FAILURE AND IGNITION PARAMETERS OF WIRE AND CABLE SAMPLES UNDER NATURAL AIR FLOW

Sample No.	Insulation/Jacket Material	Parameter (m^2/kJ) x 10^6 Ignition	Parameter (m^2/kJ) x 10^6 Electrical Failure
14 AWG			
8-14-8-1	EPR, FR/Hypalon	420	100
9-14-3-1	EPDM/Hypalon	560	160
12 AWG			
11-12-1-1	Teflon (filled)/None	0(NI)	50
1-12-2-1	Silicone/PO	90	80
2-12-3-1	Poly Rad. XPO/None	140	110
4-12-9-1	Gemex Tape/XLPO	300	160
3-12-5-1	EPR/XLPO	260	160
1-12-15-1	EPR/PO	350	210
10-12-10-1	EPR/XLPO, FR, SS	490	220
6-12-12-1	Halar	0(NI)	240
9-12-13-1	EPDM/Hypalon	620	250
4-12-4-1	XLPO/None	250	250
7-12-7-1	FR, XLPO/None	290	260
5-12-4-1	XLPO/None4	380	290
10 AWG			
11-10-11-1	Kapton/Teflon Film	0(NI)	0(NF)

TABLE XVI (CONT'D.)

Sample No.	Insulation/Jacket Material	Parameter $(m^2/kJ) \times 10^6$	
		Ignition	Electrical Failure
2/0 AWG			
11-00-1-1	Teflon (filled)/None	0(NI)	50
4/0 AWG			
5-0000-4-1	XLPO/None	160	40
6-0000-12-1	Halar	0(NI)	110
250 MCM			
1-250-15-1	EPR/PO	190	30
1-250-2-1	Silicone/PO	100	50
313 MCM			
7-313-7-1	FR, XLPO/None	250	30
444 MCM			
2-444-3-1	Poly Rad. XPO/None	190	40

TABLE XVI (CONT'D.)

	Insulation/Jacket	Parameter $(m^2/kJ) \times 10^6$	
Sample #	Material	Ignition	Electrical Failure
500 MCM			
3-500-5-1	EPR/XLPO	180	0(NF)
10-500-10-1	EPR/XLPO, FR, SS	290	0(NF)
646 MCM			
4-646-4-1	XLPO/None	300	0(NF)
4-646-6-1	EPR/Neoprene	330	30
1000 MCM			
3-1000-5-1	EPR/XLPO	190	0(NF)
8-1000-8-1	EPR, FR/Hypalon	390	0(NF)
1500 MCM			
3-1500-5-1	EPR/XLPO	170	0(NF)
2000 MCM			
9-2000-14-1	EPDM/PO	220	0(NF)

---

a: External heat flux 60 kw/M^2; ∿ 0.8 m long sample in horizontal configuration with middle section (∿ 0.3 m long) exposed to the flux under natural air flow conditions.

NI: No ignition; NF : No electrical failure up to 10 minutes

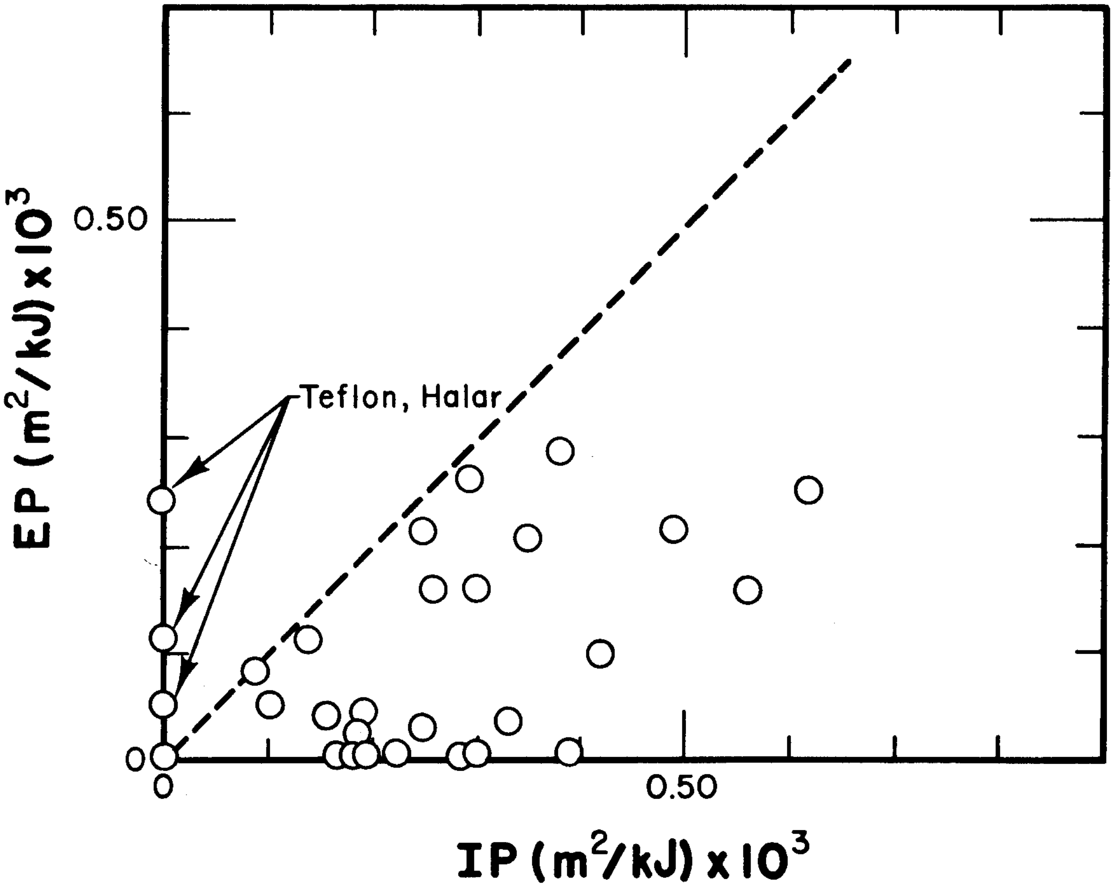


FIGURE 10 ELECTRICAL FAILURE PARAMETER AS A FUNCTION OF PILOTED IGNITION PARAMETER

of corrosivity of wire and cable samples are given in Section 2.3.6 and Appendix F. The raw data are listed in Table XVII. Table XVIII and Figure 11 present data for cumulative corrosion (micron) per unit concentration* expressed as ppm of fire products of wire and cable samples as a function of probe exposure time.

Table XVIII also includes corrosion data for research grade powdered polyvinyl chloride (PVC) and polymethyl methacrylate (PMMA) for evaluating the accuracy of the corrosivity measurements of wire and cable fire products. Corrosion data calculated on the basis of HCl present in PVC (i.e., 58% of the weight loss of PVC) were slightly lower than the data for the standard chloride ion solution. The difference indicates that there was a slight loss of HCl in the sampling line of the corrosive products collecting apparatus, as described in Section 2.3.6. As expected, the corrosion from PMMA fire products was negligibly small, because research grade PMMA contains negligible amounts of corrosive products.

The degree of corrosiveness of fire products from the various insulation/jacket materials of wire and cable samples relative to the degree of corrosiveness of HCl on mild steel are presented in Table XIX as a ratio of corrosion rate of wire and cable fire products to the corrosion rate of HCl (standard chloride ion solution). The corrosion rates (in micron/ppm-hour) of wire and cable fire products and HCl on mild steel were determined from the respective slopes of the corrosion (micron) per ppm of cable fire products versus probe exposure time (hours) curves of Figure 11. The slopes were determined from the respective least square fits. Table XIX also includes the corrosion potentials of PMMA and PVC as compared to HCl. PMMA, as expected, shows a negligible amount of corrosion compared to HCl. The corrosion potential of PVC expressed in terms of HCl generated from PVC (i.e., 58% of weight loss of PVC) was found to be 0.90 relative to standard chloride ion solution (HCl).

Data in Table XIX represent relative rankings of wire and cable samples in terms of the corrosivity of the fire products. It can be noted that Zero Hal cable sample (12-12-16-1, unspecified insulation/jacket materials) had the lowest corrosion potential under combustion conditions and cable samples 5-12-12-1 and 11-12-1-1 (ECTFE and PTFE) had the highest corrosion potential under pyrolysis

---

*For corrosion, normalization of the measurements by the concentration of the fire products is useful for generalization of the results.

TABLE XVII. CUMULATIVE CORRISION (IN MICRON) OF WIRE AND CABLE SAMPLE FIRE PRODUCTS ON MILD STEEL AS A FUNCTION OF EXPOSURE TIME (HOUR)

Sample Number	Insulation/ Jacket Materials	Decomposition Mode	Total Weight Loss of Insulation/ Jacket Materials (g)	Cumulative Corrosion (Micron) on Mild Steel Probe due to Wire and Cable Fire Products[a] Hours of Exposure					
				5	10	15	20	25	30
1-12-2-1	Silicone/XLPO	Combustion	0.39	0.078	0.176	0.273	0.39	0.507	0.660
2-12-3-1	Poly Rad XLPO	Combustion	0.89	0.267	0.578	0.890	1.246	1.558	1.870
3-12-5-1	EPR/XLPO	Combustion	1.60	0.160	0.480	0.80	1.120	1.440	1.680
4-12-4-1	XLPO	Combustion	0.74	0.148	0.444	0.740	1.036	1.332	1.665
5-12-4-1	XLPO	Combustion	0.60	0.240	0.540	0.810	1.140	1.440	1.80
6-12-12-1	ECTFE	Pyrolysis	0.25	0.312	0.625	0.950	1.275	1.587	1.90
7-12-7-1	XLPO	Combustion	0.72	0.504	0.828	1.152	1.512	1.872	2.160
8-14-8-1	EPR	Combustion	1.15	0.345	0.690	1.035	1.380	1.840	2.588
9-14-13-1	EPDM	Combustion	1.28	0.384	0.768	1.152	1.60	2.176	3.264
10-12-10-1	EPR/XLPO	Combustion	1.06	0.318	0.530	0.742	0.954	1.166	1.380
11-12-1-1	Min. Filled Teflon	Pyrolysis	0.22	0.352	0.616	0.913	1.210	1.50	1.782
12-12-16-1	Zero Hal	Combustion	0.30	0.006	0.012	0.018	0.039	0.051	0.075

---

[a] All fire products (from 0.06 m length of wire and cable sample) were collected in 100 mℓ of distilled water. The measurements of cumulative corrosion were made at room temperature.

TABLE XVIII. CUMULATIVE CORROSION (MICRON) PER PPM OF WIRE AND CABLE SAMPLE FIRE PRODUCTS ON MILD STEEL AS A FUNCTION OF EXPOSURE TIME (HOUR)

Sample Number	Insulation/Jacket Materials	Decomposition Mode	Total Weight Loss of Insulation/Jacket Materials g	Cumulative Corrosion on Mild Steel Probe (Micron/PPM of Fire Products x 10^4) Hours of Exposure 5	10	15	20	25	30
1-12-2-1	Silicone/XLPO	Combustion	0.39	0.20	0.45	0.70	1.0	1.30	1.70
2-12-3-1	Poly Rad. XLPO	Combustion	0.89	0.30	0.65	1.0	1.40	1.75	2.10
3-12-5-1	EPR/XLPO	Combustion	1.60	0.10	0.30	0.50	0.70	0.90	1.05
4-12-4-1	XLPO	Combustion	0.74	0.20	0.60	1.0	1.40	1.80	2.25
5-12-4-1	XLPO	Combustion	0.60	0.40	0.90	1.35	1.90	2.40	3.0
6-12-12-1	Halar	Pyrolysis	0.25	1.25	2.50	3.80	5.10	6.35	7.60
7-12-7-1	XLPO	Combustion	0.72	0.70	1.15	1.60	2.10	2.60	3.0
8-14-8-1	EPR	Combustion	1.15	0.30	0.60	0.90	1.20	1.60	2.25
9-14-13-1	EPDM	Combustion	1.28	0.30	0.60	0.90	1.25	1.70	2.55
10-12-10-1	EPR/XLPO	Combustion	1.06	0.30	0.50	0.70	0.90	1.10	1.30
11-12-1-1	Min. Filled Teflon	Pyrolysis	0.22	1.60	2.80	4.15	5.50	6.80	8.10
12-12-16-1[c]	Zero Hal	Combustion	0.30	0.02	0.04	0.06	0.13	0.17	0.25
PVC[a]		Pyrolysis	1.37[d]	0.40	0.80	1.10	1.50	1.90	2.25
HCℓ[b] Standard Solution		-	-	0.40	0.90	1.30	1.70	2.10	2.20
PMMA[a]		Pyrolysis	8.60	0	0.0025	0.0030	0.0059	0.0088	0.012

a: Research Grade Powder, from Aldrich Chemical Company

b: A Standard Solution of chloride ions, from Orion Research Inc.

c: This cable was tested for corrosivity measurement only.

d: Cumulative corrosion data is calculated on the basis of HCl present in PVC (i.e., 58% of weight loss of PVC).

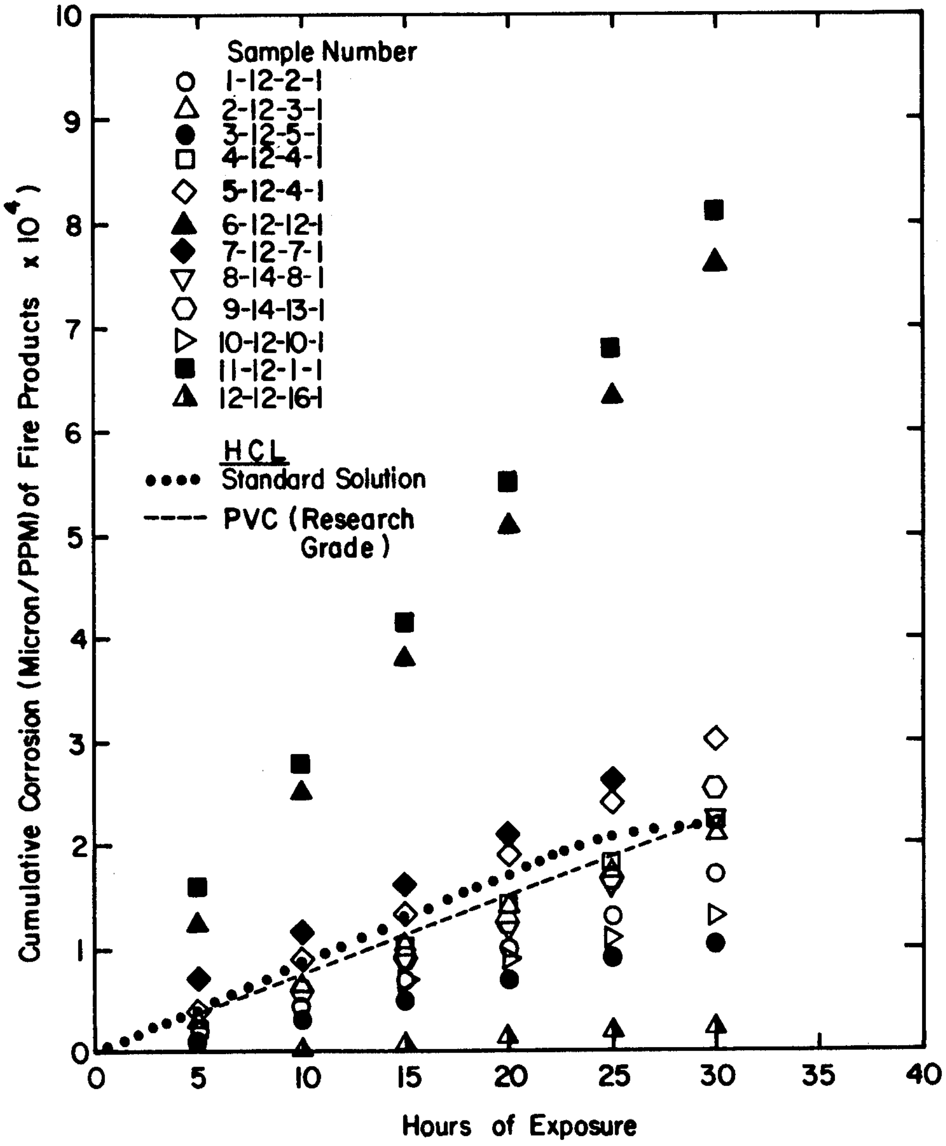


FIGURE 11 CUMULATIVE CORROSION (Microns) PER PPM OF CABLE FIRE PRODUCTS ON MILD STEEL AS A FUNCTION OF EXPOSURE TIME (Hr)

TABLE XIX

CORROSION POTENTIAL OF FIRE PRODUCTS OF WIRE AND CABLE SAMPLES RELATIVE TO THE CORROSION POTENTIAL OF HCl ON MILD STEEL

Sample Number	Materials	Decomposition Mode	$\{(R_{Corr.})\ \text{Sample}/(R_{Corr.})\ \text{HC}\ell\}^a$
Research Grade	PMMA (Powder)	Pyrolysis	0.005
12-12-16-1	Zero Hal	Combustion	0.08
3-12-5-1	EPR/XLPO	Combustion	0.45
10-12-10-1	EPR/XLPO	Combustion	0.48
1-12-2-1	Silicone/XLPO	Combustion	0.70
2-12-3-1	Poly Rad. XLPO	Combustion	0.86
8-14-8-1	EPR/Hypalon	Combustion	0.89
Research Grade	PVC (Powder)[b]	Pyrolysis	0.90[b]
4-12-4-1	XLPO	Combustion	0.97
9-14-13-1	EPDM/Hypalon	Combustion	1.01
7-12-7-1	XLPO	Combustion	1.11
5-12-4-1	XLPO	Combustion	1.23
6-12-12-1	ECTFE	Pyrolysis	3.0
11-12-1-1	Min. Filled PTFE	Pyrolysis	3.12

a: R_{Corr} = Corrosion per ppm of cable fire products or HCl per unit time.

b: Calculated on the basis of HCl present in PVC (i.e., 58% of the weight loss of PVC) conditions. About six out of twelve cable samples under combustion conditions showed corrosion potential similar to HCl, in spite of the fact that only two samples had Hypalon jacket (Hypalon contains chlorine and sulfur, both of which are corrosive compounds). It thus appears that additives in the wires and cables are responsible for the corrosion.

Instead of expressing corrosivity per unit concentration of the fire products, if one expresses corrosivity per unit length of the wire and cable sample, the following results are obtained using data from Table XVIII for time of exposure of 30 hr:

Sample	Cumulative Corrosion (micron/m)
EPDM (9-14-13-1)	54
EPR (8-14-8-1)	43
XLPO (7-12-7-1)	36
ECTFE (6-12-12-1)*	32
Poly Rad XLPO (2-12-3-1)	31
XLPO (5-12-4-1)	30
Min Filled Teflon (11-12-1-1)*	30
EPR/XLPO (3-12-5-1)	28
XLPO (4-12-4-1)	28
EPR/XLPO (10-12-10-1)	23
Silicone/XLPO (1-12-2-1)	11
Zero Hal (12-12-16-1)	1

---

*Pyrolysis

The above data are indicative of the amounts of corrosive products produced per unit length of the wire and cable sample.

In real fires, corrosivity of the fire products is expected to depend on the generation rates of the corrosive products, surface areas of the objects expected to come in contact with the products, environmental conditions (humidity, temperature, etc.), and exposure time duration of the objects as well as their physical and chemical properties, for example, coated or uncoated metals, types of metals, etc. For further simplification and refinement of the technique developed in this study, it is recommended that a generalized relationship be established between the generation rates of the corrosive products and the quantified corrosivity ranking as used in this study where, in addition to mild steel, other metals should also be used. Also, functional dependency of the corrosion rate to the concentration of the fire products needs to be established by performing experiments with varying concentration of fire products. Since CO_2, CO, and hydrocarbons are noncorrosive to mild steel, the corrosivity data may be combined with HP and CP values to estimate the fraction of fuel vapors present as a mixture of corrosive products.

V

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1) It has been shown that flammability characteristics of wires and cables exposed to external heat flux can be evaluated in a systematic manner using the FM Small-Scale Combustibility Apparatus.

2) The following parameters were successfully used to rank wire and cable samples: a) Ignition Parameter (IP); b) Electrical Failure Parameter (EP); c) Corrosivity of the fire products generated from wire and cable samples; d) Fuel Vapor Generation Parameter (VP); e) Heat Generation Parameter (HP); f) "Smoke", Toxic and Corrosive Compounds Generation Parameter (CP); and g) Ligh Obscuration Parameter (LP).

3) It is possible to translate the ignition data measured in the previous study(1) into asymptotic IP values, and to establish a general ranking for ignition/flame spread characteristics for all single-conductor wires and cables tested in this and in the previous study(1).

4) The Fisher burner technique recommended in the previous study(1) is not suitable for testing ignition/flame spread characteristics of large size wires and cables because of nonuniform heating.

5) It is found that with an increase in the size of the wire and cable, having the same generic insulation/jacket materials, the value of IP decreases, i.e., the ignition times increase and the expected surface flame spread rates decrease.

6) EP value decreases as the size of wire and cable sample is increased. For 500 MCM and larger sizes of wire and cable samples, no electrical failure was observed because of increased charring of the surface. However, the time to electrical integrity failure measured in this study depends on several variables, such as size and tension of the Nichrome wire, external heat flux, the applied voltage to the cables, and the extent of local char formation.

7) VP, HP and CP values decrease as the size of the wire and cable increases because of increased surface charring. Data indicate that VP, HP and CP values are functions of the generic nature of insulation/jacket materials as well as the additives, size, constructions of the wires and cables.

8) LP values can reasonably be used to correlate data from various kinds of "smoke" test apparatus, such as the FM Combustibility Apparatus (an open

system) and the NBS Smoke Chamber (a closed system), etc., provided accurate values of wavelength of the light source, amount of combustible vapors produced, and the dilution of the vapors by air are known. Because of the lack of total sample weight loss data in the "smoke" tests, the "smoke" data presented in the previous study(1) could not be correlated with the data from the FM Combustibility Apparatus.

9) A new and simple technique was developed for the measurements of the corrosivity of fire products generated from the wire and cable samples. The corrosivity was defined in terms of the cumulative corrosion in mild steel as a function of time per unit concentration of the water soluble corrosive compounds. The corrosivity data were used for ranking wires and cables and was expressed as relative to the corrosivity of a standard HCl (0.1 mole/liter) solution to mild steel.

10) A complete data sheet for wires and cables which may include all the flammability parameters (as described above) along with the electrical and mechanical data by the manufacturers may be useful tools for users for selecting wires and cables for particular application. The parameters may be expressed in terms of per unit length of the cable.

11) For the estimation of generation rates of fuel vapors, heat, "smoke," toxic and corrosive products and light obscuration in large-scale fires, flammability parameters in conjunction with the expected heat flux and dilution can be used. For example, the heat release rate expected in large-scale cable fires would be equal to HP x heat flux received by the cable in the large-scale fire.

5.2 RECOMMENDATIONS

On the basis of the results of this program the following are recommended for future studies:

1) Range of variations in the IP values are needed for variations in an air flow (natural and forced), flame radiation, cable configurations (horizontal and vertical).

2) Quantification of thermal properties (e.g., thermal conductivity and specific heat) in conjunction with IP values is needed to simplify the testing of wires and cables of all sizes and constructions.

3) A radiation-scaling technique(21-23,31) for combined simulation of flame and external radiation for large-scale fires is needed to further refine and simplify IP, EP, VP, HP, CP and LP to predict the values representative of large-scale fires. The simulation involves increasing oxygen concentration in the inlet gas well above the ambient value in the presence of external heat flux.

4) In grouped wires and cables with varying sizes, packing and insulation/jacket materials, predictions based on quantified ranking (using IP, EP, VP, HP CP and LP values) should be confirmed.

5) Since the electrical-carrying properties of wires and cables are strong functions of the electrical properties of the insulation materials, a change in material property, such as charring (chars have high temperature electrical conductivity), is expected to affect the electrical properties, even though there may not be an actual contact between the conductors or conductor to ground. It thus appears that EP should be quantified by a test method which will be able to detect the failure of the cable in actual use conditions, due to the change in the electrical resistance of the insulation/jacket materials during a fire situation. Such a test method is being developed at FMRC which is described briefly in Section 4.5.

6) In real fires, corrosivity of the fire products is expected to depend on the generation rates of the corrosive products, surface areas of the objects expected to come in contact with the products, environmental conditions (humidity, temperature, etc.) and exposure time duration of the objects as well as their physical and chemical properties, for example, coated or uncoated metal. For further simplification and refinement of the technique developed in this study, it is thus recommended that a generalized relationship be established between the generation rates of the corrosive products and the quantified corrosivity ranking as used in this study. Also, in addition to mild steel, a few other metals such as copper and aluminum, should be used in testing to quantify corrosivity.

APPENDIX A

TOTAL VOLUMETRIC AND MASS FLOW RATES OF PRODUCT-AIR MIXTURE THROUGH THE SAMPLING DUCT

The flow rates are calculated from measurements of: 1) pressure drop across the measuring orifice plate, Δp_m; 2) pressure inside the sampling duct p_d; and 3) bulk gas temperature in the duct, T_d. Using these measurements, the flow rates are calculated from the following relationship:

$$\dot{m} = 34.783 \; K \; y \; d^2 \; F_a (\Delta p_m \rho)^{1/2} \qquad \text{(A-1)}$$

where $\dot{m}$ is the mass flow rate (g/s); K = flow coefficient of the orifice in the duct; y = expansion factor (assumed to be unity); d = orifice opening diamter (cm); F_a = thermal expansion factor of metal (assumed to be unity); Δp_m = pressure drop across the orifice (g/cm^2); and ρ = density of the gaseous mixture flowing through the duct (g/cm^3).

The density of the gaseous mixture, assumed to be ideal, can be expressed as follows:

$$\rho = 11.798 \; (p_d/T_d) \; MW \qquad \text{(A-2)}$$

where p_d = pressure of the gaseous mixtures in the duct (g/cm^2); T_d = bulk gas temperature (K); and MW = molecular weight of the gaseous mixture.

From Eqs. (A-1) and (A-2)

$$\dot{m} = 119.48 \; K \; d^2 \; [\Delta p_m \; (p_d/T_d) \; MW]^{1/2} \qquad \text{(A-3)}$$

If the products are diluted by large amounts of air, the molecular weight is approximately equal to 28.93 (i.e., the molecular weight of air) and Eq. (A-3) can be written as:

$$\dot{m}\ (\mathrm{kg/s}) = 0.6426\ Kd^2\ [\Delta p_m\ (p_d/T_d)]^{1/2}. \tag{A-4}$$

In the FM Small-Scale Apparatus the orifice plate diameter, d, is 5.08 cm. To determine the value of the flow coefficient K, the funnel (see Figure 2) was replaced by a calibration orifice plate. Experiments were performed with ambient air to measure the pressure drop across both plates (the calibration orifice plate and the orifice plate in the duct) simultaneously. The flow coefficient was calculated using the following equation:

$$K_m = K_c d_c{}^2\ (\Delta p_c)^{1/2}/d_m{}^2(\Delta p_m)^{1/2} \tag{A-5}$$

where the subscript c refers to the calibration orifice plate and the subscript m refers to the measuring orifice plate in the duct. For this calculation, K_c was assumed to be equal to 0.61 and d_c was 4.06 cm. Using d_m equal to 5.08 cm, the average value of K_m was 0.62.

In the experiments, Δp_m is measured in cm H_2O and p_d is measured in kg/cm^2. Using these units and the values of K_m and d_m in Eq. (A-4), the mass flow rate can be expressed as:

$$\dot{m}\ (\mathrm{kg/s}) = 0.02032\ K_m d_m{}^2\ (\Delta p_m)^{1/2}\ (p_d/T_d)^{1/2} \tag{A-6}$$

and the volumetric flow rate from Eqs. (A-2) and (A-6) is:

$$\dot{v}\ (\mathrm{m^3/s}) = \dot{m}/\rho = 0.00005953\ K_m d_m{}^2\ (\Delta p_m{}^{1/2}(T_d/p_d)^{1/2}. \tag{A-7}$$

In the experiments, Δp_m, p_d and T_d are measured at one second (or longer) intervals. The mass and volumetric flow rates are calculated by substituting measured values into Eqs. (A-6) and (A-7), together with the values of K_m and d_m.

APPENDIX B
IGNITION

The time to ignition (t_{ig}) as a function of external heat flux ($\dot{q}''_e$) can be expressed as:

$$E_{ig} = \alpha\, t_{ig}\, \dot{q}''_e \qquad \text{(B-1)}$$

where E_{ig} = ignition energy (kJ/m^2), defined as the energy required to maintain a combustible vapor-air mixture near the surface; α = surface absorptivity; Figure B-1 shows $1/E_{ig}$ as a function of $\alpha\dot{q}''_e$ for piloted ignition of research grade polymers under forced air flow, with samples in a horizontal pool-like configuration,contained in a sample dish made from two sheets of heavy duty aluminum foil. It can be noted in Figure B-1 that $1/E_{ig}$ is not a linear function of $\alpha\dot{q}''_e$ or t_{ig} is not a linear function of $(1/\dot{q}''_e)^2$. From the data shown in Figure B-1, the functional relationship between t_{ig} and $\dot{q}''_e$ can be derived. Also by data extrapolation, it is possible to obtain: 1) a value of $\dot{q}''_e$ at which $1/E_{ig}$ approaches zero, which can be defined as the critical heat flux ($\dot{q}''_{cr}$), which is a flux at or below which ignition is not expected to occur; and 2) the asymptotic value of $1/E_{ig}$ at higher external heat flux values where $1/E_{ig}$ is a constant or where t_{ig} is proportional to $1/\dot{q}''_e$. The larger the value of $1/E_{ig}$, the shorter is the ignition time and higher is the surface flame spread rate expected in fires. $1/E_{ig}$ thus can be defined as the ignition parameter (IP). In Figure B-1, the data indicate that IP for flexible polyurethane foam >>IP for polymethylmethacrylate >IP for polyethylene. Thus, in fires the surface flame spread rate is expected to be much faster for the flexible polyurethane foam than for polymethylmethacrylate; the rate for polymethylmethacrylate is expected to be faster than for polyethylene.

IP is a function of generic nature of the sample, sample orientation, local aerodynamic conditions (forced or natural air flow), mode of ignition (piloted or autoignition), and surface absorptivity.

In this study, we have used the above concept for the wire and cable samples where samples are used in a vertical configuration under forced air flow conditions

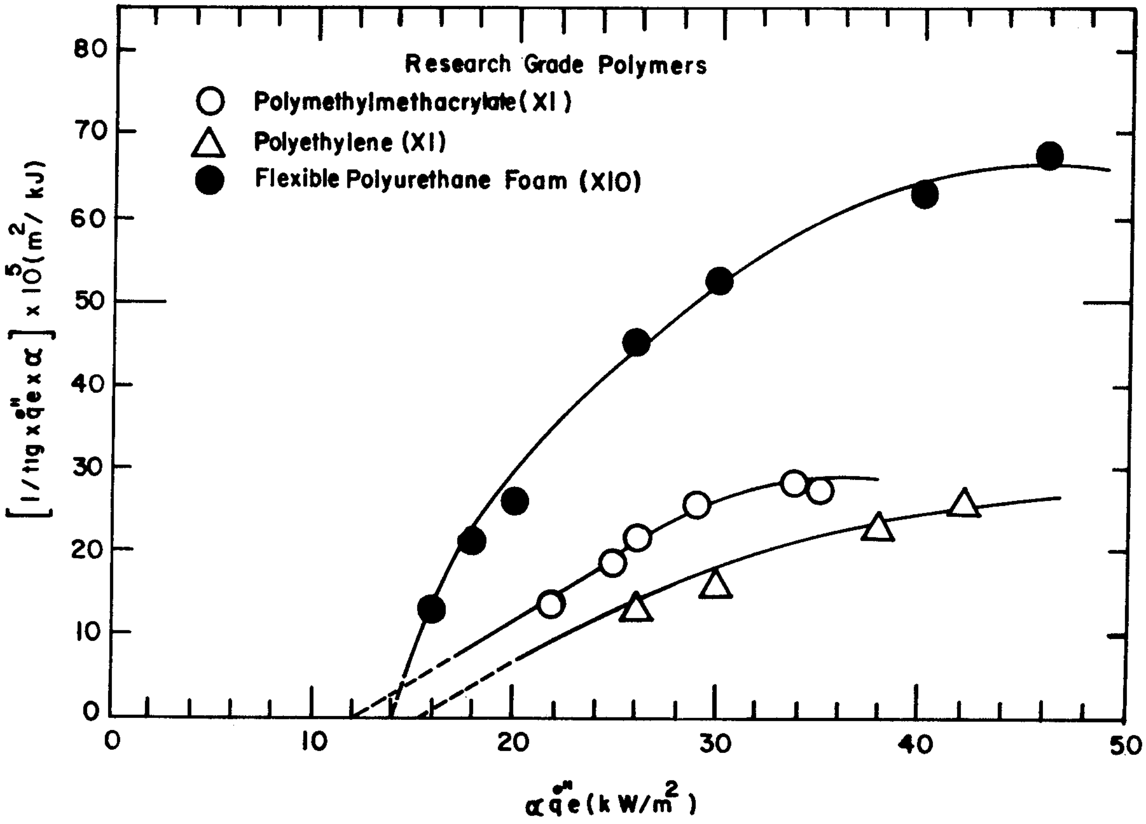


FIGURE B-1 PILOTED IGNITION PARAMETER AS A FUNCTION OF EXTERNAL HEAT FLUX assuming surface absorptivity to be unity for the piloted ignition. By measuring the IP values in this fashion, their differences would be expected to show differences in the surface flame spread rate expected in fires.

In order to evaluate the self propagating surface flame characteristics of the wires and cables, the heat flux from the burning wires and cables needs to be quantified. In this study no attempt was made to quantify the flame heat flux from wire and cable samples but this is recommended for future studies.

APPENDIX C

GENERATION RATE OF COMBUSTIBLE VAPORS PER UNIT SAMPLE SURFACE AREA

The generation rate of fuel vapors per unit sample surface area in flaming fires, $\dot{G}''_{comb}$, can be expressed as follows:

$$\dot{G}''_{Comb} = (\dot{q}''_e + \dot{q}''_{fs} - \dot{q}''_{rr})/L \tag{C-1}$$

where $\dot{G}''_{comb}$ is in g/m^2s; $\dot{q}''_e$ = external heat flux (kW/m^2); $\dot{q}''_{fs}$ = flame heat flux received by the sample (kW/m^2); $\dot{q}''_{rr}$ = surface reradiation loss (kW/m^2); and L = heat of gasification of the sample (kJ/g). In large fires, $\dot{q}''_{fs}$ is predominately due to flame radiation and in small fires $\dot{q}''_{fs}$ is predominantly due to flame convection. For small samples thus oxygen concentration in the inlet air is increased for radiation-scaling(3-6). In this study for wires and cables, radiation-scaling was not performed, but is recommended for future studies.

Dividing Eq. (C-1) by $\dot{q}''_e$,

$$\dot{G}''_{comb}/\dot{q}''_e = [1 + (\dot{q}''_{fs} - \dot{q}''_{rr})/\dot{q}''_e]/L \tag{C-2}$$

For higher $\dot{q}''_e$ values, for small samples, in normal air, $(\dot{q}''_{fs} - \dot{q}''_{rr})/\dot{q}''_e << 1.0$ and hence:

$$\dot{G}''_{comb}/\dot{q}''_e \approx 1/L \tag{C-3}$$

The larger the value of 1/L, the higher is the generation rate of the fuel vapors and thus 1/L can be defined as the fuel vapor generation parameter (VP) for wire and cable samples; VP (g/kJ) is the amount of fuel vapors generated per unit of heat received by the sample.

This concept has been used to determine VP values for the wire and cable samples.

For better definition of VP, it is necessary to include the heat flux from the flame, especially the flame radiation heat flux for simulating large-scale fires.

If the flame heat flux is quantified, it would also be possible to better define the ignition parameter (IP) discussed in Appendix B, especially for the self propagating fires in wires and cables. It is thus recommended that, for wires and cables, $\dot{q}''_{fs}$ be quantified using radiation-scaling techniques$^{(21,22,31)}$.

In the experiments, the generation rate of **fuel vapors is** measured by a load-cell assembly. When the fuel vapors are generated from the sample the load-cell plate deflects a strainguage, which forms one leg of a wheatstone bridge. The voltage required to balance the bridge circuit is proprtional to the change of the mass of the sample. This voltage is monitored at one (or longer) second intervals by the MINC data acquisition system.

The generation rate of the **fuel vapors is the instantaneous slope** or the derivative of the voltage (or mass) versus time curve. Because the electrical signal is somewhat noisy, a moving average is used by summing a specified number of points (p) adjacent to each other and dividing the sum by the total number of points involved. The average mass $\dot{m}_i$ (in volts) at scan, i is thus:

$$\bar{m}_i = \left(\sum_{j=-p}^{p} m_{i+j} \right) / n \qquad \text{(C-4)}$$

where n = number of points to the regression set (2p+1).

Early scan (i.e., scans before p+1) and late scans (i.e., scans after s-(p+1), where s is the total number of scans are treated separately, since data cannot be averaged before or after the test. Early values of the mass loss are set equal to m_p, and late values are set equal to m_{s-p}.

The slope, a, then is calculated as follows:

$$a = \frac{n \sum_{i=1}^{n} t_i \, \bar{m}(t_i) - \sum_{i=1}^{n} t_i \sum_{i=1}^{n} \bar{m}\,(t_i)}{n \sum_{i=1}^{n} t_i^{2} - \sum_{i=1}^{n} t_i \sum_{i=1}^{n} t_i} \qquad \text{(C-5)}$$

where, t is the time in seconds.

The generation rate of fuel vapors per unit surface area of the combustible at time, t, thus is:

$$\dot{G}''_{comb}(t) = a\ K/A \qquad \text{(C-6)}$$

where K = calibration constant of the load-cell assembly determined before each experiment (g/volt); and A = surface area of the sample (m^2).

APPENDIX D

GENERATION RATES OF FIRE PRODUCTS - HEAT AND CHEMICAL COMPOUNDS

D.1 GENERATION RATES OF FIRE PRODUCTS

Fire products consist of heat and various chemical compounds such as "smoke" toxic and corrosive products. The generation rate of heat actually released in flaming fires is defined as the actual heat release rate per unit sample surface area, $\dot{Q}''_A$, and can be expressed as:

$$\dot{Q}''_A = \dot{Q}''_c + \dot{Q}''_R \tag{D-1}$$

where $\dot{Q}''_A$ is in kW/m^2; $\dot{Q}''_c$ = convective heat release rate per unit sample surface area (kW/m^2); and $\dot{Q}''_R$ = radiative heat release per unit sample surface area (kW/m^2).

The chemical compounds can be generated in both nonflaming and flaming fires. In this study the mass generation rates per unit sample surface area of only CO, CO_2, and total gaseous hydrocarbons were determined in flaming fires of wire and cable samples.

D.2 MASS GENERATION RATES OF CHEMICAL COMPOUNDS PER UNIT SAMPLE SURFACE AREA

The mass generation rate of a chemical compound per unit sample surface area, $\dot{G}''_j$, can be expressed as:

$$\dot{G}''_j = \dot{v} c_j \, \rho_j / A \tag{D-2}$$

where $\dot{G}''_j$ is in g/m^{2}s; $\dot{v}$ is given by Eq. (A-7); c_j is the measured concentration of compound, j; and ρ_j is the density of the compound, j, given by Eq. (A-2); and A is the surface area of the sample (m^2).

From Eqs. (A-2), (A-7) and (D-2), if c_j is expressed in ppm,

$$\dot{G}''_j = 0.07025 \times 10^{-5} \, K_m (d_m)^2 \;\; c_j \; (MW)(\Delta p_m)^{1/2} (p_d/T_d)^{1/2} \tag{D-3}$$

The molecular weights for CO_2, CO, and total gaseous hydrocarbons (assumed to be CH_4) are 44, 28 and 16 respectively.

In the experiments, concentrations of CO_2, CO, and total gaseous hydrocarbons, as well as Δp_m, p_d and T_d, are monitored at one second interval (or longer). The generation rates are calculated from Eq. (D-3). The data for the generate rates are time shifted to account for delays with the gas sampling lines and respective instrument response. The generation rates of chemical compounds are functions of the generation rate of fuel vapors:

$$\dot{G}''_j = y_j \, \dot{G}''_{comb} \tag{D-4}$$

where Y_j is the yield of compound j (g/g). From Eqs. (C-1) and (D-4):

$$\dot{G}''_j = y_j \, (\dot{q}''_e + \dot{q}''_{fs} - \dot{q}''_{rr})/L \ . \tag{D-5}$$

Dividing Eq. (D-5) by $\dot{q}''_e$,

$$\dot{G}''_j/\dot{q}''_e = (y_j/L)\left(1 + \frac{\dot{q}''_{fs} - \dot{q}''_{rr}}{\dot{q}''_e}\right) . \tag{D-6}$$

For higher $\dot{q}''_e$ values for small samples in normal air, $(\dot{q}''_{fs} - \dot{q}''_{rr})/\dot{q}''_e << 1$, hence,

$$\dot{G}''_j/\dot{q}''_e \approx y_j/L \ . \tag{D-7}$$

y_j/L is the amount of compound j produced per unit amount of heat received by the sample; y_j/L thus can be defined as the chemical compound generation parameter (CP) of the wire and cable samples.

D.3 HEAT RELEASE RATES

In the experiments, actual heat release rate, $\dot{Q}''_A$, and convective heat release rate, $\dot{Q}''_C$, per unit sample surface area are obtained directly from the measured data. The difference between $\dot{Q}''_A$ and $\dot{Q}''_C$, from Eq. (D-1), is the radiative heat release rate, $\dot{Q}''_R$.

D.4 ACTUAL HEAT RELEASE RATE PER UNIT SAMPLE SURFACE AREA

The actual heat release rate per unit sample surface area, $\dot{Q}''_A$, is calculated from the following equation:

$$\dot{Q}''_A = (H_T/k_{CO_2})\,\dot{G}''_{CO_2} + \left(\frac{H_T - H_{CO}}{k_{CO}}\right)\dot{G}''_{CO} \qquad \text{(D-8)}$$

where H_T is the net heat of complete combustion (kJ/g); H_{CO} is the heat of combustion of CO (10.1 kJ/g); and k_{CO} and k_{CO_2} are the maximum yields of CO and CO_2, calculated on the basis of complete conversion of carbon in the sample to CO without any CO_2 and CO_2 without any CO, respectively. $\dot{G}''_{CO_2}$ and $\dot{G}''_{CO}$ are calculated from Eq. (D-3). From the data for a variety of common combustibles with known H_T, k_{CO} and k_{CO_2}, it has been shown(22) that H_T/k_{CO_2} and $(H_T - H_{CO})/k_{CO}$ are approximately constant (average values 15 and 16 kJ/g respectively). Thus for wire and cable samples the average values of H_T/k_{CO_2} and $(H_T - H_{CO})/k_{CO}$ were used to calculate $\dot{Q}''_A$.

D.5 CONVECTIVE HEAT RELEASE RATE PER UNIT SAMPLE SURFACE AREA

The convective heat release rate per unit sample surface are, $\dot{Q}''_{conv}$, is calculated from the following equation:

$$\dot{Q}''_C = 4.184\,\frac{\dot{m}}{A}\,c_p\,(T_d - T_a) \qquad \text{(D-9)}$$

where $\dot{m}$ is the total mass flow rate of the gaseous mixture flowing through the sampling duct (calculated from Eq. (A-6) as a function of time by the MINC); c_p is the specific heat of air (cal/g K); T_d is the gas temperature in the duct (K) and T_a is the ambient temperature (K). The specific heat, c_p, is corrected for temperature:

$$c_p = 0.2392 + 3.19 \times 10^{-5}\,T_d - 619/T_d^2 \qquad \text{(D-10)}$$

In the experiments, T_a and T_d are recorded at one second intervals (or longer) by the MINC and $\dot{Q}''_C$ is calculated from Eq. (D-9) and (D-10) using values of T_a and T_d and Eq. (A-6).

D.6 RADIATIVE HEAT RELEASE RATE PER UNIT SAMPLE SURFACE AREA

The radiative heat release rate, $\dot{Q}''_R$, is calculated as a function of time by the MINC by using Eqs. (D-1), (D-8) and (D-9) and stored in the disc for analysis.

$\dot{Q}''_A$, $\dot{Q}''_C$ and $\dot{Q}''_R$ are functions of the generation rate of the combustible vapors, $\dot{G}''_{comb}$,

$$\dot{Q}''_A = H_A \dot{G}''_{comb} \tag{D-11}$$

$$\dot{Q}''_C = H_C \dot{G}''_{comb} \tag{D-12}$$

$$\dot{Q}''_R = H_R \dot{G}''_{comb} \tag{D-13}$$

where H_A, H_C and H_R are the actual, convective, and radiative heat of combustion respectively in kJ/g. From Eqs. (C-1) and (D-11 to 13),

$$\dot{Q}''_A = (H_A/L)\ (\dot{q}''_e + \dot{q}''_{fs} - \dot{q}''_{rr}) \tag{D-14}$$

$$\dot{Q}''_C = (H_C/L)\ (\dot{q}''_e + \dot{q}''_{fs} - \dot{q}''_{rr}) \tag{D-15}$$

$$\dot{Q}''_R = (H_R/L)\ (\dot{q}''_e + \dot{q}''_{fs} - \dot{q}''_{rr}) \tag{D-16}$$

and,

$$\frac{H_A}{L} = \frac{H_C}{L} + \frac{H_R}{L}\ . \tag{D-17}$$

Dividing Eq. (D-14) by $\dot{q}''_e$

$$\dot{Q}''_A/\dot{q}''_e = (H_A/L) \left[1 + \frac{\dot{q}''_{fs} - \dot{q}''_{rr}}{\dot{q}''_e} \right] \tag{D-18}$$

For higher $\dot{q}''_e$ values for small samples in normal air, $(\dot{q}''_{fs} - \dot{q}''_{rr})/\dot{q}''_e << 1$, and

$$\dot{Q}''_A/\dot{q}''_e \approx H_A/L\ . \tag{D-19}$$

In a similar fashion, it can be shown that

$$\dot{Q}''_C/\dot{q}''_e \approx H_C/L \quad \text{and} \tag{D-20}$$

$$\dot{Q}''_R/\dot{q}''_e \approx H_R/L \quad . \tag{D-21}$$

H_A/L, H_C/L and H_R/L are the amounts of actual, convective and radiative heat produced per unit amount of heat received by the sample respectively and, thus, can be defined as the heat generation parameter (HP) of the wire and cable samples (actual, convective or radiative).

The higher the values of the chemical compound and heat generation parameters, (CP and HP respectively), the higher are the generation rates of chemical compounds and heat expected in fires; thus, CP and HP can be used as indicators of the relative rankings of the combustibles. We have used these concepts for the wires and cables.

For better definition of CP and HP, the contribution of flame heat flux, especially flame radiation simulated for large-scale fires, should be considered. It is recommended that flame heat flux be quantified by using the radiation-scaling technique(21,22,31) on future studies on wires and cables.

APPENDIX E

OPTICAL PROPERTIES OF SMOKE

E.1 OPTICAL TRANSMISSION THROUGH "SMOKE"

The fraction of light transmitted through "smoke", I/I_o, can be expressed as,

$$\ell n(I_o/I) = \ell \sigma c \tag{E-1}$$

where ℓ is the optical path length (m); σ is the mass attenuation coefficient of "smoke" (m^2/g); and c is the mass concentration of "smoke" (g/m^3). $\ell n(I_o/I)$ is defined as the optical density, D (also expressed as log rather than ℓn).

In the experiments, I and I_o are recorded by the MINC at 1-s intervals (or longer) and D is calculated, for 0.10 m optical path length, by the MINC as a function of time for the three wavelengths: 0.458, 0.624, and 1.06 μ.

The concentration of "smoke" in Eq. (E-1) can be expressed as:

$$c = y_{smoke} \dot{G}''_{comb} A/\dot{v} \quad , \tag{E-2}$$

where $\dot{G}''_{comb}$ = generation rate of fuel vapors per unit sample surface area (g/m^2s); A = sample surface area (m^2); y_{smoke} = yield of "smoke" (g/g); and $\dot{v}$ = volumetric flow rate of fire product-air mixture (m^3/s, calculated from Eq. (A-7) as a function of time by the MINC).

From Eqs. (E-1) and (E-2):

$$D = \sigma y_{smoke} \dot{G}''_{comb} A\ell/\dot{v} \tag{E-3}$$

Converting D from $\ell n(I_o/I)$ to $\log_{10}(I_o/I)$ and rearranging Eq. (E-3),

$$\sigma y_{smoke} = \frac{D}{2.303} \frac{\dot{v}}{\dot{G}''_{comb} A\ell} \tag{E-4}$$

For a closed system, such as the NBS Smoke Chamber, Eq. (E-4) can be expressed as:

$$\sigma y_{smoke} = \frac{DV}{W\ell} \tag{E-5}$$

where D is expressed as $\log_{10}(I_o/I)$, V is the volume of the chamber (m^3); and W is the weight of sample vaporized (g). The specific optical density, D_s, in the NBS Smoke Chamber is defined as:

$$D_s = DV/A\ell \tag{E-6}$$

From Eqs. (E-5) and (E-6),

$$\sigma \, y_{smoke} = D_s A/W \quad . \tag{E-7}$$

The mass attenuation coefficient, σ, is a function of the chemical and physical properties of the "smoke"; y_{smoke} is a function of the chemical and physical properties of the combustible. Thus, the value of $\sigma \, y_{smoke}$ for a material is expected to be similar in different types of experiments, as long as the combustion/pyrolysis chemistry remains invariant.

From Eqs. (C-1) and (E-3),

$$D = \left[\frac{\sigma y_{smoke}}{L}\right] \left[\frac{A\ell}{\dot{v}}\right] (\dot{q}''_e + \dot{q}''_{fs} - \dot{q}''_{rr}) \quad . \tag{E-8}$$

Dividing Eq. (E-8) by $\dot{q}''_e$

$$D/\dot{q}''_e = \left[\frac{\sigma y_{smoke}}{L}\right] \left[\frac{A\ell}{\dot{v}}\right] \left[1 + \frac{\dot{q}''_{fs} - \dot{q}''_{rr}}{\dot{q}''_e}\right] \quad . \tag{E-9}$$

For higher $\dot{q}''_e$ values for small samples in normal air, $(\dot{q}''_{fs} - \dot{q}''_{rr})/\dot{q}''_e << 1$ and from Eq. (E-9)

$$D/\dot{q}''_e \approx \left[\frac{\sigma y_{smoke}}{L}\right] (A\ell/\dot{v} \quad . \tag{E-10}$$

Since A, ℓ, and $\dot{v}$ are known, from $D/\dot{q}''_e$ values, $\sigma y_{smoke}/L$ can be calculated. σ is a characteristic property of the "smoke"; y_{smoke}/L is the amount of "smoke" in grams generated per unit of heat received by the sample. $\sigma y_{smoke}/L$ thus can be defined as the light obscuration parameter (LP) of "smoke".

E.2 CORRELATION BETWEEN DIFFERENT KINDS OF "SMOKE" APPARATUS OR DIFFERENT FIRE SIZES

There are basically two kinds of apparatus used for the measurement of light obscuration by "smoke": 1) a closed system such as the NBS Smoke Chamber, where light obscuration measurement is cumulative; and 2) an open system such as the FM Small-Scale Combustibility Apparatus, where light obscuration measurement is noncumulative. For correlation of the data between open and closed systems the following techniques can be used.

E.2.1 Data Correlation Based On "Smoke" Properties

From Eqs. (E-4) and (E-7), σy_{smoke} can be calculated for the open and closed systems respectively. Since σy_{smoke} is the property of "smoke," it is expected to remain invariant for a material irrespective of the type of apparatus used, as long as chemistry remains invariant. Thus, σy_{smoke} can be used to correlate "smoke" data from different kinds of apparatus or different fire sizes. We have used this technique in this study to correlate the "smoke" data obtained from the NBS Smoke Chamber, which is a closed system and from the FM Small-Scale Apparatus, which is an open system.

E.2.2 Data Correlation Based On Cumulative Light Obscuration

The specific optical density, D_s in Eq. (E-6), in the NBS Smoke Chamber is cumulative. The cumulative specific optical density, D_s, for an open system such as the FM Small-Scale Apparatus can be defined as:

$$D_s = \left[\int_o^t \frac{D}{2.303}\, dt\right] \dot{v}/A\ell \quad , \tag{E-11}$$

where $D = \ell n(I_o/I)$, is the optical density. D_s is thus equal to the area of the D versus time curve at any time, t, multiplied by the volumetric flow rate and divided by the sample surface area and optical path length. Figure E-1 shows the data from the FM Small-Scale Apparatus, where optical density per unit path length is plotted as a function of time.

From Eqs. (E-4) and (E-11), the maximum value of D_s, expressed as D_m for the FM Small-Scale Apparatus is:

$$(D_m)_{FM} = \sigma y_{\text{smoke}} \left[\int_o^t \dot{G}''_{\text{Comb}}\, dt\right]_{FM} \tag{E-12}$$

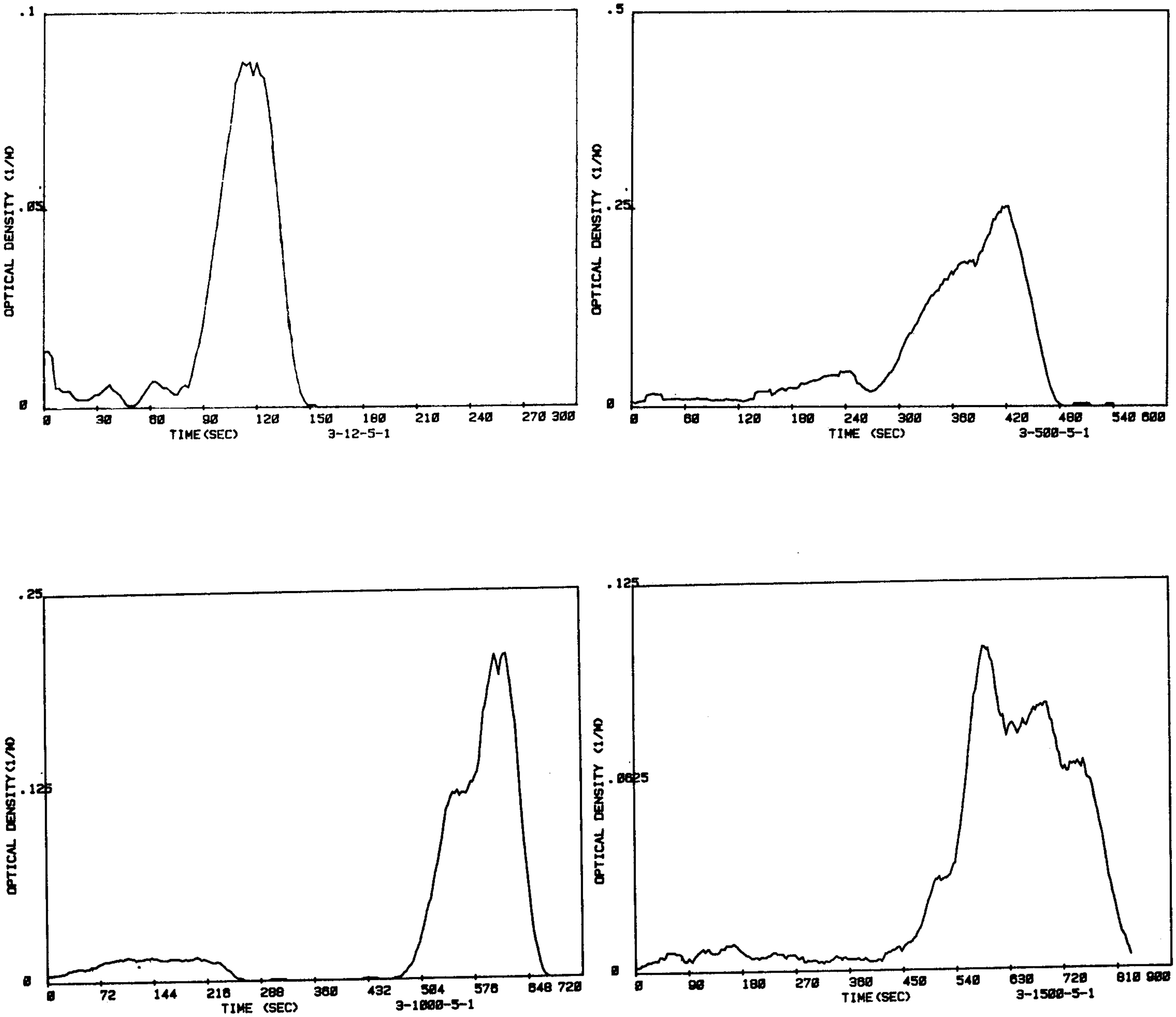


FIGURE E-1 OPTICAL DENSITY PER UNIT PATH LENGTH AS A FUNCTION OF TIME FOR CABLE SAMPLES EXPOSED TO 60kW/m^2 OF EXTERNAL HEAT FLUX (Sample numbers are identified along the time axis; areas under the curves and cable sample areas are listed in Table E-1.)

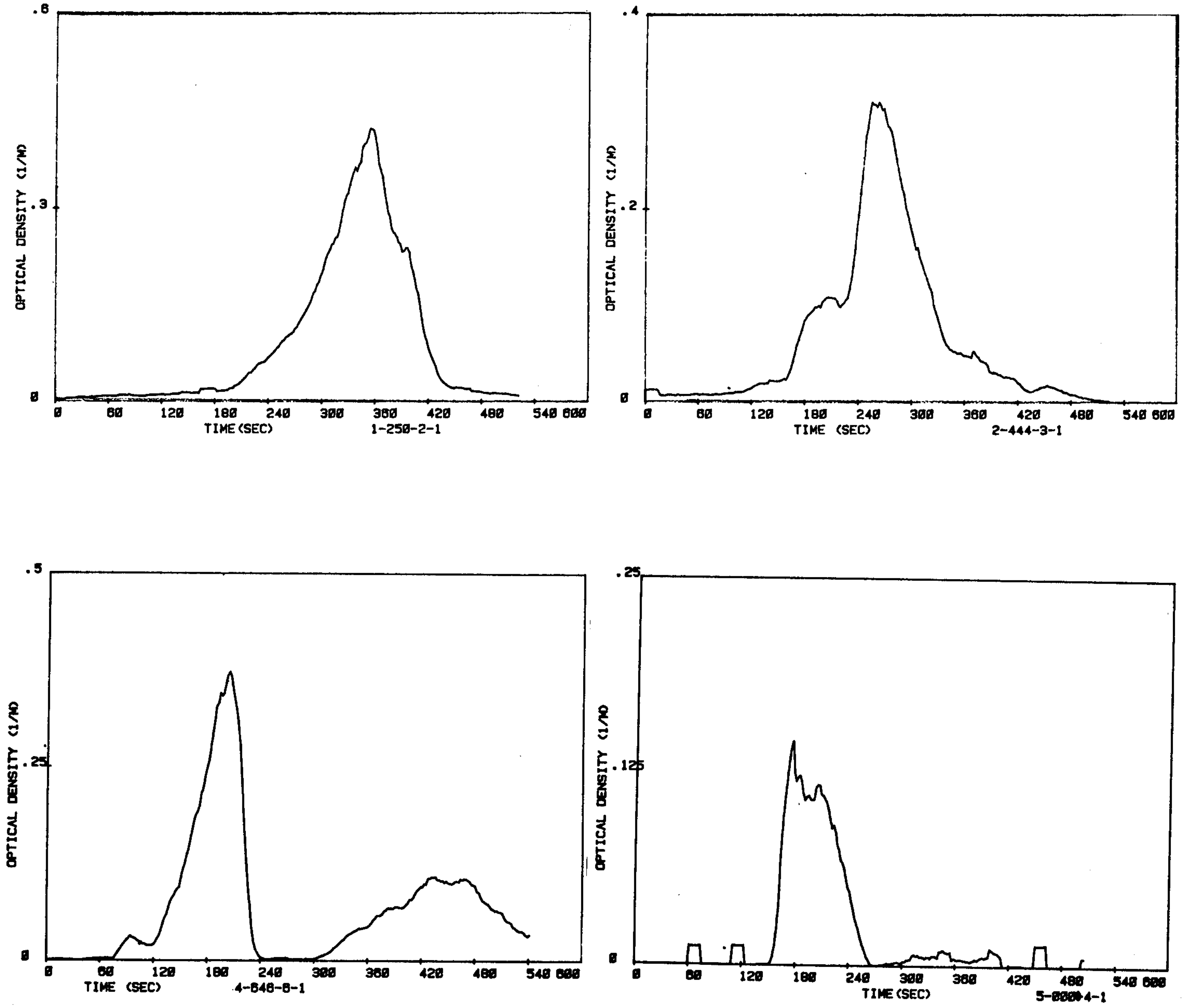


FIGURE E-1 (Continued)

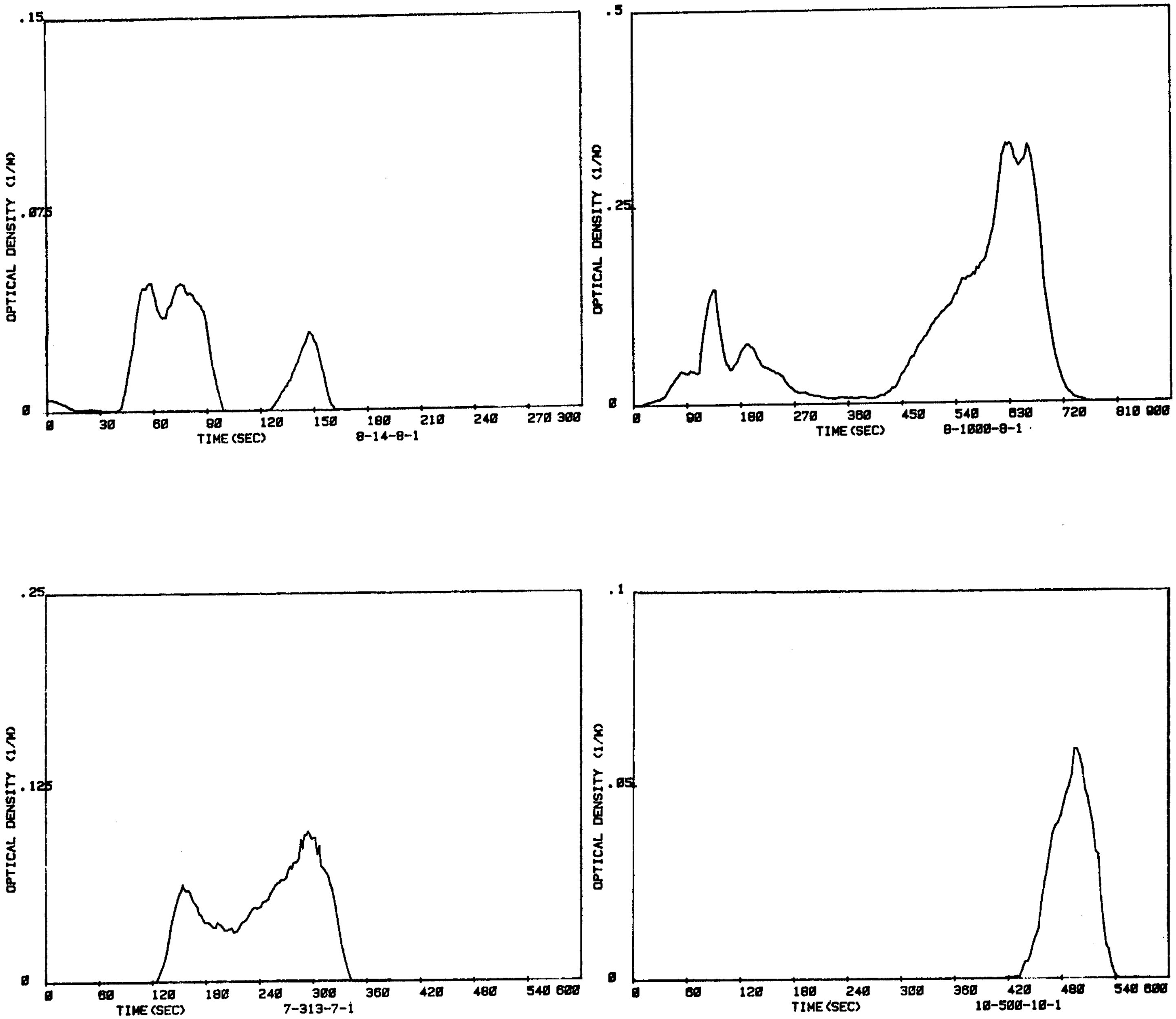


FIGURE E-1 (Continued)

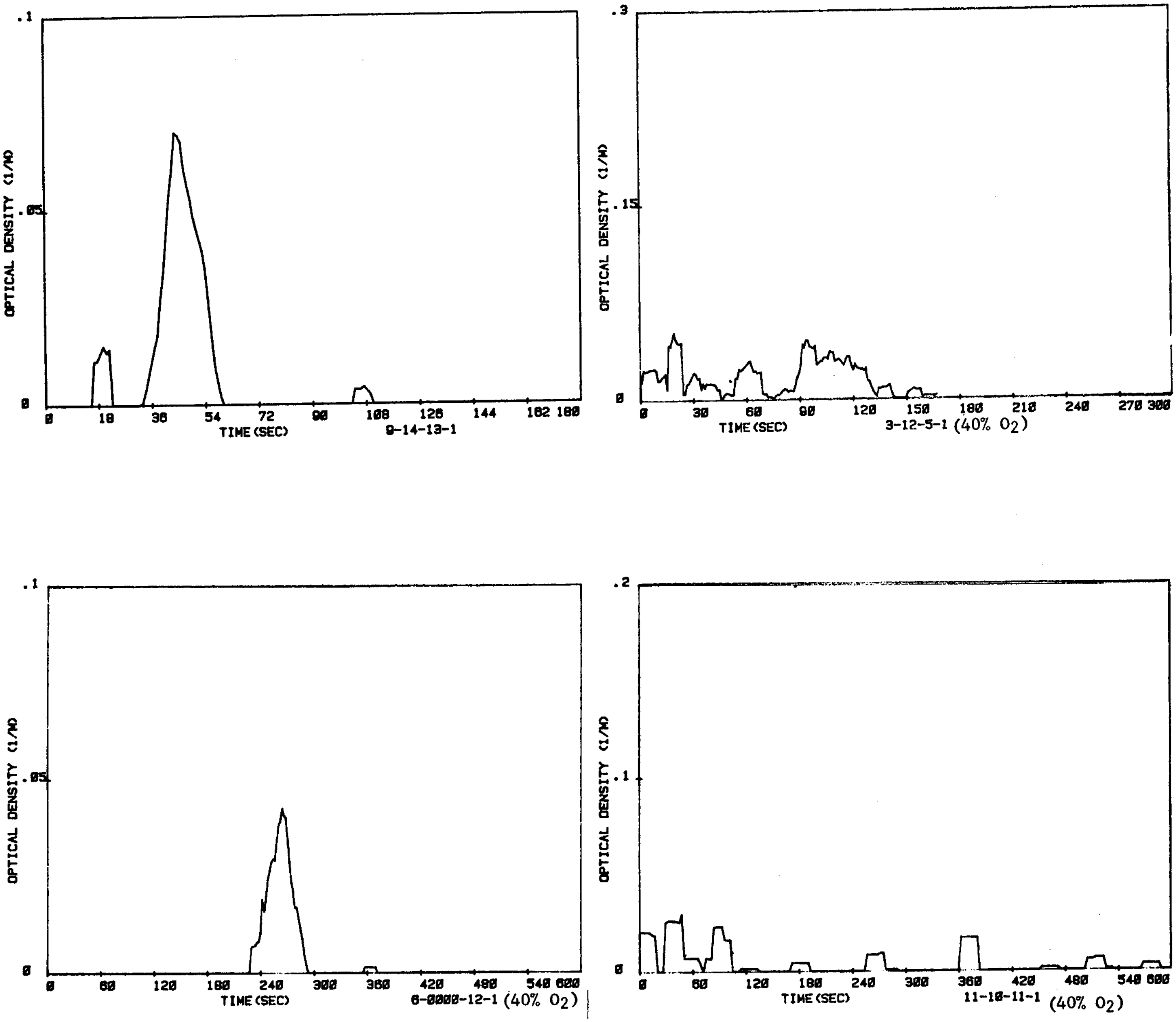


FIGURE E-1 (Concluded)

where $\int_0^t \dot{G}''_{Comb}\,dt$ is the total area under the curve for the generation rate of fuel vapors per unit sample area versus time curve. For The NBS Smoke Chamber from Eq. (E-7),

$$(D_m)_{NBS} = \sigma y_{smoke}\,(W/A)_{NBS} \quad . \tag{E-13}$$

where $(W/A)_{NBS}$ is the total amount of fuel vapors generated in the NBS Smoke Chamber per unit surface area of the sample.

If we assume that "smoke" properties are the same in the open and closed systems, then σy_{smoke} will be the same in both systems, and

$$\frac{(D_m)_{NBS}}{(D_m)_{FM}} \approx \frac{(W/A)_{NBS}}{\left[\int_0^t \dot{G}''_{Comb}\,dt\right]_{FM}} \tag{E-14}$$

Thus, the differences in D_m values from the NBS Smoke Chamber and from the FM Small-Scale Combustibility Apparatus are expected to be due to differences in the amounts of fuel vapor generated in the two systems, as long as "smoke" properties do not change. (In the NBS Smoke Chamber combustion could change toward underventilated conditions, because it is a closed system.)

The "smoke" data are listed in Table E-1 from both the FM Small-Scale Combustibility Apparatus and the NBS Smoke Chamber. The last two columns in the table compare the data from the two apparatuses. The values of $(D_m)_{NBS}/(D_m)_{FM}$ expected on the basis of $(W/A)_{NBS}/\left[\int_0^t \dot{G}''_{Comb}dt\right]_{FM}$ are about four times higher. It thus appears that either the combustion conditions in the two apparatuses are different or the estimated values of $(W/A)_{NBS}$ are not accurate.

TABLE E-1. COMPARISON OF OPTICAL DENSITY PER UNIT PATH LENGTH FROM THE FM SMALL-SCALE APPARATUS AND NBS SMOKE CHAMBER[a]

Sample No.	Cable Sample Surface Area $(m^2)\times10^4$	$\left(\int_o^t (D/\ell)dt\right)_{FM}$ (s/m)	$\left(\int_o^t \dot{G}''_{Comb}dt\right)_{FM}$ (g/m^2)	$(D_m)_{FM}$	$(W/A)^b_{NBS}$ (g/m^2)	$(D_m)_{NBS}$	$(W/A)_{NBS}/\left(\int_o^t \dot{G}''_{Comb}dt\right)_{FM}$	$(D_m)_{NBS}/(D_m)_{FM}$
3-12-5-1	8.1	3.4	-	55	-	-	-	-
3-500-5-1	59.6	33	-	72	-	-	-	-
3-1000-5-1	83.9	23	-	36	-	-	-	-
3-1500-5-1	101.8	23	4840	29	9906	206	2.0	7.1
1-250-2-1	47.4	45	3705	124	2594	378	0.70	3.0
2-444-3-1	57.0	33	-	75	-	-	-	-
4-646-6-1	73.4	38	2870	67	6368	510	2.2	7.6
5-0000-4-1	37.4	8.8	1601	31	3302	389	2.1	12.5
8-14-8-1	18.1	2.4	-	17	-	-	-	-
8-1000-8-1	95.0	60.0	5027	82	12,500	497	2.5	6.06
7-313-7-1	47.2	11	-	30	-	-	-	-
10-500-10-1	59.7	3.2	-	7	-	-	-	-
9-14-13-1	12.2	1.0	-	11	-	-	-	-
3-12-5-1(40% O_2)	8.1	2.9	-	47	-	-	-	-
6-0000-12-1 (40% O_2)	34.1	1.4	-	5	-	-	-	-
11-10-11-1 (40% O_2)	6.0	1.8	-	39	-	-	-	-

---

[a] FM Small-Scale Apparatus - open system, wavelength of light source, 0.624μ; $\dot{V} = 0.03\ m^3/s$; NBS Smoke Chamber - closed system, wavelength of light ~0.4 to 0.7μ

[b] $(W/A)_{NBS}$ - estimated

APPENDIX F

CORROSIVITY OF FIRE PRODUCTS OF WIRE AND CABLE SAMPLES

Fire products generated from various combustibles containing halogens, sulfur, etc., are corrosive in nature. The degree of corrosion to buildings, equipments, instrumentation, etc., depends on the generation rate of the corrosive products and environmental conditions. Quantitative predictions of corrosivity to various components of buildings, equipments, instrumentations, etc., based on generation rates of individual corrosive products generated in fires are difficult, because corrosion is a slow process depending on the environmental conditions and properties of the materials which come in contact with the corrosive products.

In this study, we have used a simple technique, where corrosivity of fire products to mild steel is evaluated on a relative basis using hydrogen chloride as a reference.

If w is the total mass of the fuel vapors produced when a sample is heated and if all the vapors are captured and passed through a known volume of distilled water, v, then the concentration, c, of the water soluble corrosive compounds present in the fuel vapors is,

$$c = x_{corr} \, w/v \tag{F-1}$$

where c is in g/mℓ; x_{corr} is the fraction of water-soluble corrosive compounds present in the combustible vapors; w is the mass of vapors in g; and v is in mℓ.

If Y is the cumulative corrosion as a function of time measured by the corrosometer in micro-inches of metal loss, then Y x 0.0254 is corrosion in microns (μ). The cumulative corrosion per unit concentration of the corrosive compounds (in ppm) is then given as follows:

$$Z = \frac{Y \times 0.0254 \cdot v \cdot \rho_{H_2O}}{x_{corr} \, w \times 10^6} \tag{F-2}$$

where Z is the cumulative corrosion per unit concentration of the water-soluble corrosive compounds (micron/ppm) as a function of time. The density of water, ρ_{H_2O} at 293 K is 0.998 g/mℓ. Thus

$$Z = \left(\frac{Y.v}{w}\right)\left(\frac{2.53 \times 10^{-8}}{x_{corr}}\right) \qquad \text{(F-3)}$$

where Y is measured in micro-inches by the corrosometer, v is the volume of distilled water in mℓ used in the tests; and w is the total mass of the combustible vapors produced from the sample in g (difference between initial weight of the sample and weight of the residue).

If Z is a linear function of time, then the cumulative corrosion rate is given as:

$$R_{corr} = \Delta Z/\Delta t \qquad \text{(F-4)}$$

where R_{corr} is micron/ppm/hr.

The corrosivity of the fire products of wire and cable samples relative to the corrosivity of the standard solution of HCl then can be expressed as follows:

$$\frac{(R_{corr})\ \text{sample}}{(R_{corr})\ \text{HCl}} = \frac{(\Delta Z/\Delta t)\ \text{sample}}{(\Delta Z/\Delta t)\ \text{HCl}} \qquad \text{(F-5)}$$

The rate of corrosion of the mild steel due to fire products can be the same , slower than, or faster than the rate due to HCl, depending on the properties of the corrosive products. Thus, $(R_{corr})_{sample}/(R_{corr})$HCl can be less than, equal to or greater than unity.

APPENDIX G

REPORT OF NEW TECHNOLOGY

A review of the work performed under this contract discloses no new invention or discovery. However, a great deal of new data was generated concerning the combustibility of electrical wire and cable for rail rapid transit systems.

REFERENCES

1. Meyer, L.E., Taylor, A.M., and York, J.A., "Electrical Insulation Fire Characteristics Volume I Flammability Tests," Report UMTA-MA-06-0025-79-1, I, U.S. Dept. of Transportation Report No. DOT-USC-UMTA-78-48, I, Washington, D.C., March 1979.
2. Hathway, W.T., and Flores, A.L., "Identification of The Fire Threat in Urban Transit Vehicles," Report No. UMTA-MA-06-0051-80-1, U.S. Dept. of Transportation, Washington, D.C., June 1980.
3. Tewarson, A., "The Effects of Fire-Exposed Electrical Wiring Systems on Escape Potential from Buildings - Part I, A Literature Review of Pyrolysis/Combustion Products and Toxicities - Poly (vinyl chloride)," Factory Mutual Research Corporation, Norwood, Mass., Technical Report RC75-T-47, December 1975, prepared for National Electrical Manufacturers Assoc., Washington, D.C.
4. Tewarson, A., "Fire Toxicology - A Literature Review for Poly (vinyl chloride)," Factory Mutual Research Corporation, Norwood, Mass., Technical Report RC79-T-41, August 1979, prepared for National Electrical Manufacturers Assoc., Washington, D.C.
5. Tewarson, A., Lee, J.L., and Pion, R.F., "Categorization of Cable Flammability, Part I. Laboratory Evaluation of Cable Flammability Parameters," Interim Report EPRI NP-1200, Part I, Research Project 1165-1 Electric Power Research Institute, Palo Alto, Calif., October 1979.
6. Delichatsios, M.A., "Categorization of Cable Flammability: Detection of Smoldering and Flaming Cable Fires," Interim Report EPRI NP-1630, Research Project 1165-1, Electric Power Research Institute, Palo Alto, Calif., October 1979.
7. Sumitra, P.S., "Categorization of the Cable Flammability Part III Intermediate-Scale Fire Tests of Cable Tray Installations," EPRI Project 1165-1, Electric Power Research Institute, Palo Alto, Calif., (to be published).
8. Modak, A., "Ignitability of High-Fire-Point Liquid Spills," Final Report EPRI NP-1731, Research Project 1165-1, Electric Power Research Institute, Palo Alto, Calif., March 1981.
9. Newman, J.S., and Hill, J., "Assessment of Exposure Fire Hazards to Cable Trays," Interim Report NP-1675, Research Project 1165-1-1, Electric Power Research Institute, Palo Alto, Calif., January 1981.

10. Lee, J.L., "A Study of Damageability of Electrical Cables in Simulated Fire Environments," Final Report, EPRI NP-1767, Research Project 1165-1-1, Electric Power Research Institute, Palo Alto, Calif., March 1981.

11. Khan, M.M., Steciak, J., and Tewarson, A., "Small-Scale Testing of Flame-Retardant Coated Cables," Factory Mutual Research Corporation, Norwood, Mass., Technical Report 0G3R9.RC, June 1982, prepared for Florida Power & Light Co., Juno Beach, Fla.

12. Newman, J.S., "Fire Environments in Ventilated Rooms, Part I. Detection of Cable/Exposure Fires," Final Report, EPRI Research Project 1165-1-1, Electric Power Research Institute, Palo Alto, Calif. (to be published).

13. Hill, J.P., "Fire Environments in Ventilated Rooms, Part II. Extinguishment of Fires in Grouped Cable Trays," Final Report, EPRI Research Project 1165-1-1, Electric Power Research Insitute, Palo Alto, Calif. (to be published).

14. Gouldson, E.J., Woollerton, G.R., and Checkland, J.A., "Fire Hazard Evaluation of Cables and Materials," Proc. of 24th International Wire and Cable Symp., U.S. Army Electronics Command, Cherry Hill, N.J., p. 26, November 1975.

15. Przybyla, L.J., Coffey, E.J., Kaufman, S., Yocum, M.M., Reed, J.C., and Allen, D.B., J. Fire & Flammability 12, 177, 1981.

16. Mikado, T., and Akita, K., J. Fire & Flammability 12, 143, 1981.

17. Jaluria, Y., J. Of Heat Transfer, Transactions of the ASME, 127, 1976.

18. Lee, J.L., Tewarson, A., and Pion, R.F., "Indexing Method for Cable Classification Using the FM Laboratory-Scale Combustibility Apparatus," Proc. of the 29th International Wire & Cable Symp. U.S. Army Communications R&D Command, Cherry Hill, N.J., p. 236, 1980.

19. "Performance Specification for Development of Electric Wire and Cable with Improved Fire Characteristics for Use in Underground Transit Systems," American Public Transit Association (APTA)/International Union of Public Transports (UITP), Washington, D.C., July 1981.

20. Klamerus, "Fire Protection Research Quarterly Progress Reports," Sandia Laboratories, Albuquerque, N.M., NUREG/CR-0366, SAND 78-0477, SAND 78-0518, SAND 78-1456, SAND 78-2238, SAND 77-1424, 1977-1978.

21. Tewarson, A., Lee, J.L., and Pion, R.F., Eighteenth Symposium (International) on Combustion, The Combustion Institute, 1981, p. 563.

22. Tewarson, A., "Physico-Chemical and Combustion/Pyrolysis Properties of Polymeric Materials," Report NBS-GCR-80-295, U.S. National Bureau of Standards, Washington, D.C., (National Technical Information Service, Springfield, VA 22161), November, 1980.
23. Tewarson, A., "Combustibility Evaluations Using FM Small-, Intermediate-, and Large-Scale Combustibility Apparatuses," Technical Report J.I. 1A7E4.RC, Factory Mutual Research Corporation, Norwood, Mass., June 1982.
24. Tewarson, A., Fire and Materials, 4:185 (1980).
25. Tewarson, A., Flame Retardant Polymeric Materials, (E.M.Pearce, Ed.) Plenum Publishing Corporation, New York, NY, Vol. 3, p. 97 (1982).
26. Tewarson, A., Lee, J., and Pion, R.F., "Fuel Parameters for Evaluation of the Fire Hazard of Red Oak," Technical Report J.I. 0C3R1.RC, Factory Mutual Research Corporation, Norwood, Mass., December 1979.
27. Tewarson, A., Lee, J.L., and Pion, R.F., "Fire Behavior of Transformer Dielectric Insulating Fluids," Report No. DOT TSC-1703, Project No. 332-0021-FLB, U.S. Department of Transportation, National Technical Information Service, Springfield, VA, September 1979.
28. Tewarson, A., and Pion, R.F., "Evaluation of the Flammability Parameters of a Glass Fiber-Reinforced Epoxy Resin Material," Technical Report, Serial No. J.I. 0C2N8.RC, Factory Mutual Research Corporation, Norwood, Mass., October 1978.
29. Tewarson, A., "Analysis of Full-Scale Timber Fire Tests in a Simulated Mine Gallery," Technical Report J.I. 0E0N1.RC/0F0N3.RA, Factory Mutual Research Corporation, Norwood, Mass., January 1982, prepared for U.S. Bureau of Mines, Pittsburgh, Pa.
31. Tewarson, A., "Quantification of Fire Properties of Fuels and Interaction with Fire Environment," Factory Mutual Research Corporation, Norwood, Mass, Technical Report J.I. 0E0N6.RC, April 1982, prepared for National Bureau of Standards, Washington, D.C.
32. Quintiere, J.G., McCaffrey, B.J., and Den Braven, K., Seventeenth Symposium (International) on Combustion, The Combustion Institute, 1978, p. 1125.
33. Emmons, H.W., Seventeenth Symposium (International) on Combustion, The Combustion Institute, 1978, p. 1101.

34. Thomas, P.H., Eighteenth Symposium (International) on Combustion, The Combustion Institute, 1981, p. 503.

35. Friedman, R., "Status of Mathematical Modeling of Fires," Technical Report RC81-BT-5, Factory Mutual Research Corporation, Norwood, Mass., April 1981.

36. Heskestad, G., "Generalized Characterization of Smoke Entry and Response for Products-of-Combustion Detectors," Proceedings, Fire Detection for Life Safety, National Academy of Sciences, Washington, D.C., 1977, p. 93.

37. Yao, C., "Application of Sprinkler Technology," Proceedings Engineering Application of Fire Technology, National Bureau of Standards, Washington, D.C. (in press).

38. "Guide to Plastics: Properties and Specifications Charts," Modern Plastics Encyclopedia, McGraw-Hill, New York, N.Y. (1975).

☆ U. S. GOVERNMENT PRINTING OFFICE: 1983--601-632--75

350 copies