

**NEW YORK POWER AUTHORITY
Indian Point 3 Nuclear Power Plant**

FIRE SEAL EVALUATION

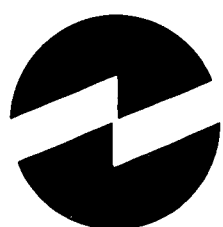
**Self Ignition Temperatures of Cable Insulation as it Relates to the
Design of Fire Seals**

Evaluation Number: IP3-ANAL-FP-01392

Revision 1

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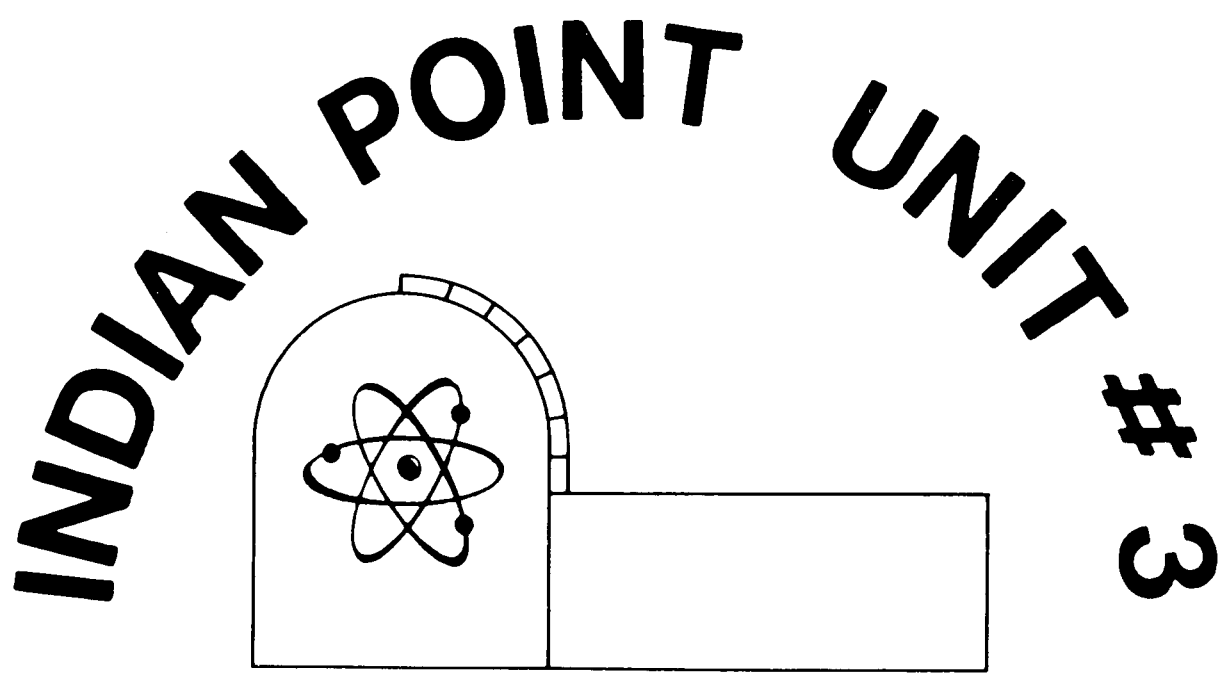
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Evaluation Number: IP3-ANAL-FP-01392, Revision 1

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Record of Revisions

<u>Revision</u>	<u>Reason</u>
0	Initial Issue to respond to NRC Unresolved Item (URI) 286/93-24-03 as documented in NRC Inspection Report 50-286/93-24 (Reference 2.15).
1	Incorporate the review of EPRI report test data anomaly.

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1.0 PURPOSE

This evaluation will review the self-ignition temperatures of Indian Point No. 3 cables that penetrate fire barrier penetration seals. The evaluation will demonstrate that the self ignition temperatures of these cables are sufficiently above 700°F where the fire seal qualification test results indicated an unexposed side temperature of greater than 250°F plus ambient ($\approx 325^\circ\text{F}$), but below 700°F. Seven hundred degrees Fahrenheit (700°F) represents the maximum allowed unexposed side interface and penetrating items temperature identified in the fire test review methodology (ENG-527, Evaluation No. 5, Attachment 6.3). The fire test review methodology was used for reviewing fire seal qualification tests against actual IP3 fire seal designs.

2.0 REFERENCES

- 2.1 ASTM D470-1959T, Tests for Rubber and Thermal Plastic Insulated Wire and Cable.
- 2.2 ASTM E119-1976, Fire Test of Building Construction and Materials.
- 2.3 ASTM E814-1981, Fire Tests of Through-Penetration Fire Stops.
- 2.4 Branch Technical Position (BTP) APCS 9.5-1, Guidelines for Fire Protection for Nuclear Power Plants, dated May 1, 1976.
- 2.5 CASP V; IP3 Conduit & Cable Schedule, report dated November 11, 1994.
- 2.6 EPRI Report NP-1200; Categorization of Cable Flammability Part 1: Laboratory Evaluation of Cable Flammability Parameters, dated October 1979.
- 2.7 EPRI Report NP-1630; Categorization of Cable Flammability, Detection of Smoldering and Flaming Cable Fires, dated November 1980.
- 2.8 EPRI Report NP-1767; A Study of Damageability of Electrical Cables in Simulated Fire Environments, dated May 1981.
- 2.9 EPRI Report NP-1881; Categorization of Cable Flammability, Intermediate-Scale Fire Tests of Cable Tray Installations, dated August 1982.
- 2.10 EPRI Report NP-7332; Design Guide for Fire Protection of Grouped Electrical Cables, dated May 1991.
- 2.11 FMRC Report J.I.OM2E1.RC; Electrical Cables - Evaluation of Fire Propagation Behavior and Development of Small-Scale Test Protocol, dated January 1989.
- 2.12 IEEE Std. 383-1978, IEEE Standard for Type Test of Class IE Electrical Cables, Field Splices, Connections for Nuclear Power

Generating Stations.

- 2.13 IEEE Std. 634-1978, Cable Penetration Firestop Qualification Test.
- 2.14 NRC Letter dated June 1, 1978 regarding Staff Position P4, Cable Penetration Firestops.
- 2.15 NRC letter dated December 14, 1993 transmitting NRC Region I Inspection 50-286/93-24.
- 2.16 Nuclear Regulation (NuReg) 0800; Branch Technical Position (BTP) CMEB 9.5-1, Revision 2, Guidelines for Fire Protection for Nuclear Power Plants, dated July 1981.
- 2.17 National Fire Protection Handbook (NFPA) Fire Protection Handbook, 17th edition.
- 2.18 Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering, 2nd edition. Note: The 2nd edition has not been distributed for public use as of this writing; a copy of the galley proof has been attached to this evaluation.
- 2.19 US Department of Transportation Report No. UMTA-MA-06-0025-83-6; Combustibility of Electrical Wire and Cable for Rail Rapid Transit Systems, Volume 1: Flammability, dated May 1983.
- 2.20 FMRC Report J.I.0G3R9.RC; Small Scale Testing of Flame-Retardant Coated Cables, dated June 1982.
- 2.21 NRC letter dated February 2, 1984 transmitting Appendix R SER.
- 2.22 Fundamentals of Heat and Mass Transfer, John Wiley & Sons, 3rd edition.
- 2.23 Marks Standard Handbook for Mechanical Engineers, 9th edition.
- 2.24 Symposium Series 599, Fire and Polymers II, Materials and Tests for Hazard Prevention, 1995, American Chemical Society, Washington, D.C. Note: This publication has not been distributed for public use as of this writing. A copy of the chapter submitted for publication is attached to this evaluation.

3.0 BACKGROUND

3.1 Initial Fire Seal Qualification

Fire barrier penetration seals are installed with the intent that they remain in place and retain their integrity when subjected to an exposure fire and subsequently, a fire suppression agent. Silicone foam and silicone elastomer comprise the two principal types of penetration fire seals used at IP3. Results of eight separate fire

tests have been used to evaluate the silicone foam and silicone elastomer designs for both electrical and mechanical penetration fire seals. The results of each of these tests are summarized in Attachment 6.5.

The review methodology utilized for comparing IP3 fire seal designs against generic fire seal qualification tests allowed an unexposed side penetrant interface temperature greater than 250°F plus ambient (~325°F) but less than 700°F. If the generic fire seal designs had an unexposed side temperature less than 700°F, the temperatures were assumed to be sufficiently below the self-ignition temperatures of the cables used at IP3. This was based on the qualification fire testing which typically evaluated worst case cable construction in its tested fire seal configurations.

3.2 NRC Inspection 93-24

During NRC Inspection 93-24 (Reference 2.15), an inspector noted that the fire test review methodology (ENG-527, Evaluation No. 5) which was used for reviewing qualification tests for fire seal designs, allowed a maximum unexposed surface temperature of 700°F. The inspector additionally noted that 700°F was considerably higher than the 250°F plus ambient (~325°F) unexposed surface temperature identified by the staff and recognized by fire test standard ASTM E119 (Reference 2.2).

The inspector was informed that the allowance for 700°F was acceptable based on Staff Position P4 (Reference 2.14) and industry standards IEEE 634 (Reference 2.13) and ASTM E814 (Reference 2.3). The inspector stated that the allowance for 700°F in Staff Position P4 was based on self-ignition temperatures. The inspector questioned the IP3 fire test review methodology because it did not consider whether the self-ignition temperatures of IP3 cables are sufficiently above 700°F.

ENG-527, Evaluation No. 5 was revised to document a review of the maximum allowable unexposed side temperature and provide reasonable assurance that the minimum self-ignition temperatures of cables used at IP3 were above 700°F. This assurance was based on the cable testing and the quality assurance requirements that had been imposed at the time of cable purchasing. These requirements included a fire and heat resistance test commonly referred to as the Con Ed Bon-Fire Test (Attachment 6.1).

This qualitative review was performed and made available for the inspector during Inspection 93-24. However, the inspector requested that NYPA obtain the cable insulation ignition temperatures for each of the cable types that penetrate a fire barrier penetration fire seal, where qualification test results indicated an unexposed side temperature greater than 250°F plus ambient. This request was formally issued by the NRC as Unresolved Item (URI) 93-24-03.

3.3 Initial Response to URI 93-24-03

Revision 0 of this evaluation reviewed the self-ignition temperatures of cables used at IP3 by using generic cable flammability test data published in EPRI Reports NP-1200 (Reference 2.6) and NP-7332 (Reference 2.10). The review was performed by comparing cables of similar construction and jacketing to the piloted ignition temperatures of those tested. The reports were based on flammability studies performed by the Factory Mutual Research Corporation (FMRC) of Norwood, MA in the late 1970's and early 1980's.

3.4 EPRI Studies

In 1979, EPRI initiated a study program (EPRI Project 1165-1) to categorize cable flammability in terms of: 1) flammability of cable; 2) detection of combustion in cable tray installations; and 3) fire protection (sprinklers) for cable tray installations. EPRI Report NP-1200 documented the results of the first part of the research. EPRI Reports NP-1630 (Reference 2.7) and NP-1881 (Reference 2.9) documented the results of the second and third parts of the research. The second and third parts of the program referenced the original study (EPRI Report NP-1200) for cable ignition temperatures and relative combustibility of various cable materials. These follow-on studies did not develop completely new flammability data, but did serve to build on earlier results. The studies served to confirm the results of the small scale (laboratory) testing of EPRI Report NP-1200 with regards to the relative combustibility of these materials.

EPRI Report NP-1200 published the results of the behavior of cable samples in terms of individual flammability parameters. As part of these investigations, the ignition/flame spread parameter for various cables was determined. The ignition/flame spread parameter consists of: 1) critical heat flux or temperature at or below which ignition of cable samples cannot be achieved (q^*), and 2) effective energy associated with maintaining a flammable cable sample vapor/air mixture near the surface (E_{eff}). EPRI Report NP-1200, Table 5-1 provides a summary of piloted ignition parameters for various cable test samples.

EPRI Report NP-1200 concluded, in general, high values of critical heat flux (or critical temperature) and effective energy correspond to low values of ignition/flame spread parameter. Correspondingly, the lower the value of ignition/flame spread parameter the more difficult is ignition and the lower is the expected surface flame spread rate. The ignition/flame spread parameter is defined as the ratio of the net heat flux received by the cable sample to the effective energy associated with maintaining a flammable vapor/air mixture near the surface.

EPRI Report NP-1630 published the results of the study of detection of smoldering and flaming cable fires. EPRI Report NP-1881 provides the results of the behavior of cable tray fire (intermediate-scale) during free burn conditions. The laboratory-scale results of EPRI Report NP-1200 were used in the selection of cables used in the intermediate-scale tests. In addition, EPRI Report 1881 published

the results of the application of water (as an extinguishing agent) on cable tray fires.

3.5 NRC Review of Revision 0

During the NRC staff review of Revision 0 of this evaluation, it was noted by the reviewer that the results summarized in EPRI Report NP-1881, Table 3-1, indicated a critical temperature for self-ignition of 545°K (522°F) for Cable Sample #5 (PE/PVC). The reviewer noted that this data appeared to be in conflict with test data that was cited under Section 4.3 of Revision 0 of this evaluation which compared cables used at IP3 to a tested cable of similar construction and jacketing. Section 4.3 of Revision 0 of this evaluation cited test data in EPRI Report NP-7332, Table 3.2 (Reference 2.10) which identified a critical heat flux of 13 kW/m² (critical temperature of approximately 785°F) for Cable Sample #3 (PVC/PVC). In addition, there was contention that cable samples could have a data scatter for ignition temperatures that could vary by as much as 200°F which could question the accuracy of relying on generic test data.

3.6 Disposition of NRC Concern

In NYPA's review of the critical temperatures of the two relatively similar cable samples, it was noted that the data for Sample #5 (EPRI Report NP-1881, Table 3-1) indicated a critical temperature for auto-ignition that was approximately 440°F less than the critical temperature for piloted ignition. Auto-ignition temperature is by definition, the minimum temperature to which a substance must be heated for ignition and self-sustained combustion to occur without a pilot. Whereas, piloted ignition is by definition, the minimum temperature for ignition with the aide of a pilot and self sustained combustion to occur. Based on these definitions, the auto-ignition temperature of any cable should always be equal to or greater than its piloted ignition temperature.

Dr. A. Tewarson of FMRC, the Principal Investigator for the research documented in EPRI Report NP-1200, was contacted to discuss the perceived discrepancy (Attachment 6.4). Dr. Tewarson identified that the critical temperatures were in error due to assumptions and subsequent extrapolation of the test data. He stated that the auto-ignition temperature of a cable sample is not expected to be below its piloted ignition temperature, all things being equal. It was later noted by Dr. A. Terwarson that this is because the oxidative pyrolysis is generally endothermic.

EPRI Report NP-1881, Table 3-1, contains the summary of results from earlier testing which was performed under Part I work of EPRI Project 1165-1. The test methodology and results were previously reported in EPRI Reports NP-1200 and NP-1767. During a review of this critical temperature anomaly and a review of EPRI Reports NP-1200 and NP-1767, NYPA noted the same anomaly with another cable sample. In explaining the anomaly in EPRI Report NP-1767, Mr. Lee, the Principal Investigator of the tests and Dr. Tewarson theorized that the lower

critical flux values could have been as a result of exothermic reactions occurring at the surface of the cable samples. This theory was later discussed with Dr. Terwarson who stated that this theory has since been shown to be not applicable to the cables that were examined (i.e., PE/PVC).

The test methodologies documented in EPRI Reports NP-1200 and NP-1767 which were used to determine the critical heat flux values for piloted ignition and self-ignition, were essentially the same with the exception that the critical heat flux for auto-ignition which was determined without the use of a pilot. In both cases, the time to ignition of a cable sample was measured for several different values of external heat flux. The source of the external heat flux was four (4) tungsten quartz radiative heaters. Interpretation of the test data was accomplished by plotting the external heat flux against the inverse of the times to ignition. External heat flux was plotted along the x-axis and the inverse of the time to ignition was plotted along the y-axis. Refer to Attachment 6.9 for an example of this relationship. The arrangement of data for each sample tested, was fitted as a liner curve. (Note: The behavior of the curve was later found to be the source of inaccuracies as it was later found to be non-linear and follow a power of $\frac{1}{4}$ as the time to ignition approaches infinity. This was later corrected by taking increased data points near the critical heat flux value. This new understanding of the behavior of the curve coupled with a better understanding of the behavior of cables as thermally thick/ thermally thin materials, is discussed below).

In EPRI Reports NP-1200 and NP-1767, the critical heat flux was found by linearly extrapolating the linear curve to the external heat flux intercept (intercept of the x-axis). The critical heat flux is defined as the heat flux at or below which no ignition could occur.

The self-ignition and piloted ignition critical temperatures were then estimated from the critical heat flux by using the Stefan-Boltzmann Law, which relates the radiant heat flux to the surface temperature to the 4th power.

In recent discussions with Dr. Tewarson (Attachment 6.6), NYPA was informed that the test methodology and subsequent interpretation of test data has been considerably refined since the earlier testing documented in EPRI Reports NP-1200 and NP-1767. Electrical cables behave as thermally thin materials close to the critical heat flux value (as time to ignition approaches infinity) and as thermally thick materials away from the critical heat flux value (as time to ignition approaches zero). Therefore, for an accurate determination of critical heat flux, several data points are measured near the x-axis to establish an accurate critical heat flux value. For determination of the Thermal Response Parameter (TRP), which is the ignition resistance of the cable, several data points are measured away from the critical heat flux value. This refined methodology, now in use, provides a technique to accurately measure critical heat flux and TRP.

The principle of thermally thin considers the influence of material density, specific heat and material thickness and assumes a negligible temperature gradient between the surface of the cable sample and its interior. This relationship is expressed as:

$$(1) \quad 1/s \approx (q''_{\text{applied}} - q''_o) / \rho c_p \delta \Delta T_{\text{ig}} \quad (\text{Reference 2.24, Equation 3})$$

Where:

s	= time (sec)
q''_{applied}	= applied radiative heat flux (kW/m ²)
q''_o	= critical heat flux (kW/m ²)
ρ	= material density (g/m ³)
c_p	= specific heat (kJ/g ^o K)
δ	= material thickness (m)
ΔT_{ig}	= difference between ignition temperature and initial surface temperature (°K)

Note that $\rho c_p \delta \Delta T_{\text{ig}}$ is defined as the TRP of a thermally thin material and has been shown by recent research (Reference 2.11) to be satisfied close to the critical heat flux as time to ignition approaches infinity.

The principle of thermally thick considers the influence of thermal conductivity, material density and specific heat which results in a steep temperature gradient between the surface of the cable and its interior. This relationship is expressed as:

$$(2) \quad 1/s^{1/2} \approx (q''_{\text{applied}} - q''_o) / (k \rho c_p)^{1/2} \Delta T_{\text{ig}} \quad (\text{Reference 2.24, Equation 2})$$

Where:

s	= time (sec)
q''_{applied}	= applied radiative heat flux (kW/m ²)
q''_o	= critical heat flux (kW/m ²)
k	= thermal conductivity (kW/m ²)
ρ	= material density (g/m ³)
c_p	= specific heat (kJ/g ^o K)
ΔT_{ig}	= difference between ignition temperature and initial surface temperature (°K)

Note that $(k \rho c_p)^{1/2} \Delta T_{\text{ig}}$ is defined as the TRP of a thermally thick material and has been shown by recent research (Reference 2.11) to be satisfied away from the critical heat flux as time to ignition approaches zero.

The potential influence of surface absorbtivity (α) was also considered to be more important in later research. In accordance with the general theories of radiative heat transfer, the absorbed radiative heat flux is equal to the absorbtivity of the material multiplied by the applied radiative heat flux (i.e., assuming gray colored cable ($\alpha \approx 0.85$, Reference 2.23, Figure 4.3.1) the absorbed heat flux would be approximately 85% of the applied heat flux).

In later testing, the influence of absorbtivity was reduced by painting each cable sample flat black ($\alpha \approx 0.98$, Reference 2.22, Table A.12). Cable jackets were painted flat black so as to more closely simulate the absorbtivity of a black body, which is equal to unity. Because the cable color in early tests, is not known, it is unclear to what extent absorbtivity affected the determined critical heat flux. However, it can be stated that values of absorbtivity of less than unity would render a determined critical heat flux greater than actual.

An FMRC test standard (Attachment 6.2) has since been developed to incorporate this refined methodology so as to ensure consistency of testing. Dr. Tewarson stated that of all the recent testing of more than 300 cable samples that has been performed, he has not seen a critical heat flux for piloted ignition (which is, as previously stated, higher than auto-ignition) for cables of below 10 kW/m^2 (or approximately 707°F).

4.0 EVALUATION

4.1 IP3 Licensing Basis

Licensing Basis for Electrical Cables

The licensing basis for the flame resistant quality of cable covering and insulations is as follows:

1. *Standard Vertical Flame Test - performed in accordance with ASTM-D470-59T [Reference 2.1], Tests for Rubber and Thermal Plastic Insulated Wire and Cable.*
2. *Five-Minute Vertical Flame Test - performed with cable held in vertical position and 1750°F flame applied for five minutes.*
3. *Bonfire Test - Consisting of exposing, for five minutes, bundles of three or six cables to flame produced by igniting transformer oil in a 12-inch pail. The cable was supported horizontally over the center of the pail. The lowest cable was three inches above the top of the pail. The time to ignite the cable and the time the cable continued to flame after the fire was extinguished were noted.*

Discussion

ASTM-D470-1959T, Tests for Rubber and Thermal Plastic Insulated Wire and Cable, was subsequently revised in 1971 (ASTM-D470-1971). While this standard is less restrictive than the requirements of Tests 2 and 3, above, the cable procured by Consolidated Edison after 1971 was qualified in accordance with the more stringent requirements of the Five-Minute Vertical Flame Test and the Bonfire Test.

The licensing basis source for this is in the Consolidated Edison Company of New York, Inc., Indian Point Nuclear Generating Unit No.

3, Final Facility Description and Safety Analysis Report (FSAR), Volume 3, page 8.2-8, dated November 1975. The licensing basis has remained unchanged since the original licensing basis, and appears in the current (1994) Updated FSAR, page 8.2-8.

The NRC's Branch Technical Position APCS 9.5-1, Appendix A, Section 8.46, recommended that electric cable at least passes the current IEEE No. 383 flame test. NYPA's response, submitted December 9, 1976, described the cable tests as presented in the Final Facility Description and Safety Analysis Report, and concluded, with the exception of instrument wires, that the tests performed on the cables are equivalent to the IEEE 383 flame test. The NRC accepted this conclusion in Section 4.8 of the SER to Amendment No. 24, dated March 6, 1979. Section 4.8 states:

"Electrical cables used in the plant were required to pass the ASTM-D470-1959T vertical flame test, as well as certain other tests developed by the licensee. The data indicate that the cables used will not burn vigorously under the test conditions used. We find that retest to the IEEE 383 criteria would not provide information that would change any of our recommendations or conclusions. Accordingly, we find the electrical cables used to be acceptable."

NYPA's justification for excluding the instrument wiring from the IEEE 383 criteria, as explained in the December 9, 1976 submittal, was that they have a low energy producing capability and will not generate high currents capable of igniting wires. The NRC did not object to this conclusion in either their September 29, 1978 response to NYPA's December 9, 1976 submittal discussed above or in the SER to Amendment No. 24.

The licensing basis also appears on page 4-13 of the Fire Protection Reference Manual.

Licensing Basis for Electrical Cable Penetrations

Electrical cable penetrations in critical fire barriers shall be designed to acceptably pass an ASTM E119 exposure fire test. The firestops shall consist of "marinite" collars and sleeves, with "cera-felt" mineral wool blanket or equivalent under the sleeves, and an application of "flamemastic" or equivalent flame retardant coating for a distance of 18 inches from either side of the firestop. Critical fire barriers include those separating the control building from the turbine building and from the diesel generator building, and those separating the diesel generating rooms.

Discussion

The source of this licensing basis is a commitment in NYPA letter IPN-79-2 to the NRC, dated February 6, 1979. This commitment was incorporated into the IP3 Operating License by Amendment No. 24 as a license condition relating to the completion of a facility modification. The modification is stated in section 3.1.2(3) of the

SER accompanying the Amendment. Section 3.1.2(3) states:

"Cable penetration firestops will be upgraded to a design that passes ASTM E119 exposure fire test by the addition of "Marinite" collars and sleeves with "Cera-Felt" or equivalent mineral wool blanket installed under the sleeves and "Flamemastic" flame retardant coating over the firestop and on the cables for a distance of 18 inches on either side of the firestop. Penetrations to be upgraded are those in barriers separating the control building from the turbine building and from the diesel generator building, and those separating diesel generator rooms."

Amendment No. 24 required implementation of this modification by April 1, 1980. While this modification is reflected in the first Updated FSAR in 1982, page 9.6-20, and in the current Updated FSAR, page 9.6-14, many of the specifics of the licensing basis have been deleted from the FSAR description.

4.2 IP3 Fire Seal Design Basis

Fire seals are installed with the intent that they remain in place and retain their integrity when subjected to an exposure fire and subsequently, a fire suppression agent. This will provide reasonable assurance that the effects of a fire are limited to discrete fire areas or zones and that safe shutdown systems will remain available post fire.

Early fire seal design requirements were promulgated by the staff in Branch Technical Position (BTP) APCS 9.5-1 (Reference 2.4). BTP APCS 9.5-1 guidance suggested that cable and cable tray penetrations should be sealed with a designed fire seal which, as a minimum, meets the requirements of ASTM E119, including the hose stream test. The staff also suggested that electrical cable constructions should at least pass the IEEE 383, flame test.

During an NRC site visit in 1978, the staff issued Position 4 regarding the qualification of cable penetration fire seals (Reference 2.14). The staff indicated that fire seal qualification tests should be performed in accordance with ASTM E119 with several noted exceptions as ASTM E119 was not specifically written to address the testing and qualification of fire seals. The standard provides a general test method and acceptance criteria for the testing and qualification of fire barriers such as walls, partitions, floors and roofs.

The design of IP3 fire seals is based on several qualification fire tests that are representative of the worst case configuration including cable loading, cable tray arrangement and anchoring, and penetration fire seal size and design. Tested fire seals also used cables representative of the cable sizes in the facility (i.e., instrumentation verses power). In cases where a fire seal is to be installed in a wall configuration, fire seals were qualified in the worst case configuration (i.e., the worst case of two configurations

180° opposite of each other where the fire seal is not symmetrical).

The review methodology, as outlined in ENG-537, Evaluation 5 (Attachment 6.3) applied to each fire test is:

1. The tested configuration shall be subjected to a 3-hour fire endurance test (or lesser exposure if a lesser fire rating is required) which corresponds to the standard time-temperature curve as specified in ASTM E-119, "Standard Methods of Fire Tests of Building Construction and Materials."
2. The tested configuration has withstood the fire endurance test without the passage of flame or gases hot enough to ignite cable, other penetrating items or seal material on the unexposed side. The maximum temperature is 700°F.
3. The unexposed side field thermocouple temperatures of the tested configuration shall not exceed 250°F plus ambient^[note]. The unexposed side interface and penetrating items thermocouple temperatures of the tested configuration should not exceed 250°F plus ambient. Penetration configurations whose temperatures exceed 250°F plus ambient may be evaluated and qualified on a case-by-case basis as long as all other acceptance criteria has been met and the maximum of temperatures recorded on the unexposed side are sufficiently below the self-ignition temperature of cable, other penetrating items or seal material on the unexposed side. The maximum temperature is 700°F.
4. The tested configuration has withstood an acceptable hose stream test where an acceptable delivery of that hose stream shall be one of the following:
 - a. A 1-1/2 inch nozzle at 30° discharge angle with a nozzle pressure of 75 psi and a minimum discharge of 75 gpm at a maximum distance of 5 feet from the exposed surface.
 - b. A 1-1/2 inch nozzle at 15° discharge angle with a nozzle pressure of 75 psi and a minimum discharge of 75 gpm at a maximum distance of 10 feet from the exposed surface.
 - c. A 2-1/2 inch standard playpipe with a 1-1/8 inch tip with a nozzle pressure of 30 psi at a distance of 20 feet from the exposed surface.
5. The duration of the hose stream test should be 2-1/2 minutes per 100 square foot of exposed surface.
6. The tested configuration shall remain intact without the projection of water beyond the unexposed surface for the duration of the hose stream test.

Note: Temperatures which exceeded 250°F plus ambient have been

evaluated and qualified on a case-by-case basis where the field temperatures are judged to be influenced by placement of the thermocouple adjacent to a penetrating item(s).

A summary of the results of qualification fire testing is presented in Attachment 6.5.

4.3 IP3 Cables

IP3's original cable and raceway schedule (CASP) identifies those cables installed and routed through various areas inside and outside the Containment Building (Reference 2.5).

CASP identifies information regarding specific attributes of each cable including cable number, to and from designations, circuit information and cable information. Data regarding cable cover is identified by an alpha code. The alpha designations are as follows:

A -	Asbestos
B -	Butyl Rubber
C -	Varnish Cambric
D -	Braid
E -	Bare
G -	Glass Braid
I -	Interlock Armor
K -	Kerite
L -	Lead
N -	Neoprene
P -	Polyethylene
R -	Rubber
S -	Shielded
T -	Teflon
U -	Silicone Rubber
V -	PVC
W -	Weatherproof
X -	Cross-linked Polyethylene
Y -	Enamel

An example of a cable cover code is as follows:

VGVA - PVC insulation with glass braid and PVC and an overall asbestos braid jacket

Table 1, page 17, provides a summary of typical cables used at IP3.

4.4 Justification for Acceptance

IP3 cables were reviewed for acceptance based on the data in the following documents; FMRC Report J.I.0M2E1.RC (Reference 2.11), the Society of Fire Protection Engineers Handbook for Fire Protection (Reference 2.18), and the recent testing performed for Rockbestos Co. under FMRC Contract No. J.I.0Y1R9.RC, (Attachment 6.8). Early EPRI/FMRC studies (i.e., EPRI Reports NP-1200, NP-1767 and NP-1881).

will not be relied on to bound IP3 cables due to; (1) the uncertainty of critical heat flux values (or critical temperatures) cited in early EPRI/FMRC reports, (2) questions in the interpretation of the test data and (3) insufficient test data which could render more accurate critical heat flux values.

Since data provided by the latest testing is representative of critical flux values for piloted ignition, and since the auto-ignition temperature of any cable is always greater than or comparable to its piloted ignition temperature, the use of this test data is conservative for bounding self-ignition temperatures of IP3 cables.

The determination of critical heat flux values is based on the principles of radiative heat transfer and the conservation of energy (Reference 2.22, similar to Equation 1.7). The net rate of radiative heat exchange between a cable surface and its surroundings is expressed as:

$$(3) \quad q''_{\text{net}} = q''_{\text{emitted}} - q''_{\text{absorbed}}$$

where:

q''_{net} = net rate of energy (heat flux) absorbed and emitted by a cable sample (kW/m²)

q''_{emitted} = rate of energy emitted by the cable sample due to surface re-radiation (kW/m²)

q''_{absorbed} = rate of energy (heat flux) absorbed by the cable sample (kW/m²)

The Stefan-Boltzmann Law (Reference 2.22, Equation 1.4) which relates radiant heat flux to surface temperature to the 4th power for other than a black body, is written as:

$$(4) \quad q''_{\text{emitted}} = \epsilon \sigma T_{\text{surface}}^4$$

and

$$(5) \quad q''_{\text{absorbed}} = \alpha \sigma T_{\text{ambient}}^4$$

Applying the Stefan-Boltzmann Law to equation (3) gives:

$$(6) \quad q''_{\text{net}} = \epsilon \sigma T_{\text{surface}}^4 - \alpha \sigma T_{\text{ambient}}^4$$

where:

ϵ = emissivity

σ = Stefan-Boltzmann constant
(56.7 EE -12 kW/m²°K⁴)

T_{surface} = cable sample surface temperature (°K)

α = absorptivity

T_{ambient} = surrounding (ambient) temperature ($^{\circ}\text{K}$)

At steady state when as time to ignition approaches infinity, T_{ambient} equals T_{surface} , and q''_{net} equals zero.

Under this condition equation (3) becomes:

$$\text{or} \quad (7) \quad 0 = q''_{\text{emitted}} - q''_{\text{absorbed}}$$

$$(8) \quad q''_{\text{absorbed}} = q''_{\text{emitted}}$$

Considering the absorbtivity of the cable surface, the relationship between q''_{absorbed} and q''_{applied} is as follows:

$$(9) \quad \alpha q''_{\text{applied}} = q''_{\text{absorbed}} \quad (\text{Reference 2.22, Equation 1.6})$$

where:

q''_{applied} = rate of energy (heat flux) applied to a cable sample (kW/m^2)

Assuming an absorbtivity of unity (note: cable painted black has an $\alpha \approx 0.98$), equation (9) reduces to:

$$(10) \quad q''_{\text{applied}} \approx q''_{\text{absorbed}}$$

Combining equations (4), (8) and (10), the relationship between the applied heat flux and the cable surface temperature at steady state conditions is:

$$(11) \quad q''_{\text{applied}} \approx q''_{\text{absorbed}} = q''_{\text{emitted}} = \epsilon \sigma T_{\text{surface}}^4$$

or

$$(12) \quad q''_{\text{applied}} \approx \epsilon \sigma T_{\text{surface}}^4$$

By definition, critical heat flux (q''_o) is the temperature at or below which ignition of a cable sample cannot be achieved. This occurs when the energy transfer to the surface of the cable is at steady state. Therefore, the critical heat flux (q''_o) equals the applied heat flux, or

$$(13) \quad q''_o = q''_{\text{applied}}$$

and the temperature of the cable surface is equal to the critical temperature ($T_{\text{surface}} = T$). Equations (12) and (13) can then be rewritten as:

$$(14) \quad q''_o \approx \epsilon \sigma T_{o,K}^4$$

or

$$(15) \quad T_{o,K} \approx (q''_o / \epsilon \sigma)^{1/4}$$

where:

$T_{o,K}$ = temperature at or below which ignition of cable samples cannot be achieved ($^{\circ}$ K).

q''_o = critical heat flux (kW/m^2)

The conversion of $^{\circ}$ K to $^{\circ}$ F is as follows:

$$(16) \quad T_{o,F} = [(T_{o,K} - 273) \times 9/5] + 32$$

By definition, the relationship between T_o and the ignition temperature is:

$$(17) \quad T_{\text{ignition}} \geq T_o$$

where:

$T_{\text{ignition},K}$ = ignition temperature ($^{\circ}$ K)

Assuming an emissivity of unity, equations (15), (16) and (17) reduce to:

$$(18) \quad T_{\text{ignition},F} \approx \{[(q''_o / 56.7 \text{ EE } -12)^{1/4} - 273] \times 9/5\} + 32$$

Where a direct one-to-one correlation between IP3 cables and tested cables could not be made, more conservative test results have been used as the basis for acceptance. Where cables were bounded, two (2) flammability parameters have been reviewed to determine the worst case cable samples. Bounding data is evaluated as follows:

1. The highest Flame Propagation Index (FPI) value of each cable type was evaluated.

In general, high FPI values correlate to lower values of critical heat flux with comparable heat release rates. Also, cables of higher FPI values exhibit greater flame spread characteristics than similar cables of lower FPI values. Therefore, cables which have a higher FPI value will be considered worst case for cables of similar construction and jacketing.

2. The lowest critical heat flux value of each cable type will be evaluated.

Cables which have lower critical heat flux values, by definition, will have lower ignition temperatures. Therefore, cables which have a lower critical heat flux value are considered worst case over cables of similar construction and jacketing.

Where cables have the same jacketing but a different insulation, NYPA cables have been bounded by comparing the worst case of either the

insulation or the jacketing (i.e., a cable of XLPE insulation, lead sheath and PVC jacketing is expected to be no worse than either a cable of PVC or XLPE alone).

Where cables have an asbestos jacket, NYPA cables have been bounded by comparing the worst case of either the insulation or the jacketing (i.e., an asbestos jacketed PVC insulated cable is expected to be no worse than a PVC jacketed cable). No recent test data is available for asbestos jacketed cables. However, the presence of asbestos is expected to significantly dampen fire propagation. This is because asbestos exhibits a higher resistance to flame spread. These cable types were previously reviewed by the NRC staff and documented in NRC SER dated February 2, 1984 (Reference 2.21).

Detailed bounding of each IP3 cable is provided in the table below, where $T_{o,p,p}$ is the temperature at or below which piloted ignition of a cable sample cannot be achieved in degrees Fahrenheit.

Table 1

Summary of Typical Cables used at IP3

Symbol	Description	Bounding Cable Data	Criteria
VSV	Multi-conductor cable. Each conductor is PVC insulated with a shield or an overall shield. Entire assembly is jacketed with PVC.	<p>VSV = (insulation/jacket) = PVC/PVC</p> <p>This cable is bounded by data of the worst case cable construction of PVC insulation and PVC jacketing. The bounding samples are as follows:</p> <p>Sample #1, PVC/PVC, $T_{o,r,p} = 832^{\circ}\text{F}$ & Sample #3, PVC/PVC, $T_{o,r,p} = 786^{\circ}\text{F}$</p> <p>The Samples are from Reference 2.11. Sample #1 chosen for the comparison as it represents a worst case flame spread (FPI = 36) and Sample #3 was used for the comparison as it represents a worst case critical heat flux or critical temperature (= 786°F) for those samples tested. The PVC/PVC values are consistent with the range published in the SFPE Handbook (Reference 2.18) with a range for $T_{o,r,p} = 786$ to 1007°F.</p> <p>The worst case of these two samples is $T_{o,r,p} = 786^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o,r,p}$ above 700°F.</p>	1, 2 & 3
VLV	Single PVC insulated conductors with lead sheath and overall jacket of PVC.	<p>VLV = (insulation/jacket) = PVC/PVC</p> <p>This cable is bounded by data of the worst case cable construction of PVC insulation and PVC jacketing. The bounding samples are as follows:</p> <p>Sample #1, PVC/PVC, $T_{o,r,p} = 832^{\circ}\text{F}$ & Sample #3, PVC/PVC, $T_{o,r,p} = 786^{\circ}\text{F}$</p> <p>The Samples are from Reference 2.11. Sample #1 chosen for the comparison as it represents a worst case flame spread (FPI = 36) and Sample #3 was used for the comparison as it represents a worst case critical heat flux or critical temperature (= 786°F) for those samples tested. The PVC/PVC values are consistent with the range published in the SFPE Handbook (Reference 2.18) with a range for $T_{o,r,p} = 786$ to 1007°F.</p> <p>The worst case of these two samples is $T_{o,r,p} = 786^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o,r,p}$ above 700°F.</p>	1, 2 & 4

<p>VGLV</p>	<p>Multi-conductor PVC insulated with glass braid, lead sheath and overall jacket of PVC</p>	<p>VGLV = (insulation/jacket) = PVC/PVC</p> <p>This cable is bounded by data of the worst case cable construction of PVC insulation and PVC jacketing. The bounding samples are as follows:</p> <p>Sample #1, PVC/PVC, $T_{o.v.p} = 832^{\circ}\text{F}$ & Sample #3, PVC/PVC, $T_{o.v.p} = 786^{\circ}\text{F}$</p> <p>The Samples are from Reference 2.11. Sample #1 chosen for the comparison as it represents a worst case flame spread (FPI = 36) and Sample #3 was used for the comparison as it represents a worst case critical heat flux or critical temperature ($= 786^{\circ}\text{F}$) for those samples tested. The PVC/PVC values are consistent with the range published in the SFPE Handbook (Reference 2.18) with a range for $T_{o.v.p} = 786$ to 1007°F.</p> <p>The worst case of these two samples is $T_{o.v.p} = 786^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o.v.p}$ above 700°F.</p>	<p>1, 2, 4, & 7</p>
<p>XIV</p>	<p>Multi-conductor XLPE insulated with interlocked armor and overall jacket of PVC</p>	<p>XIV = (insulation/jacket) = XLPE/PVC</p> <p>This cable is bounded by selecting the worst case cable sample of PVC jacket (Sample #1) and the worst case cable sample of XLPE insulation (Sample #14). Since each of these worst case samples has the same insulation and jacket type, it is assumed that the insulation will have no effect on the performance of the jacket and vice versa. The bounding samples are as follows:</p> <p>VV = (PVC/PVC) $T_{o.v.p} = 832^{\circ}\text{F}$ XX = (XLPE/XLPE) $T_{o.v.p} = 928^{\circ}\text{F}$</p> <p>Where:</p> <p>Sample #1, PVC/PVC, $T_{o.v.p} = 832^{\circ}\text{F}$, & Sample #14, XLPE/XLPE, $T_{o.v.p} = 928^{\circ}\text{F}$</p> <p>The Samples are from Reference 2.11. The worst case of these two samples is $T_{o.v.p} = 832^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o.v.p}$ above 700°F.</p>	<p>1, 2, & 5</p>
<p>XLV</p>	<p>Multi-conductor XLPE insulated with lead sheath and overall jacket of PVC</p>	<p>XLV = (insulation/jacket) = XLPE/PVC</p> <p>This cable is bounded by selecting the worst case cable sample of PVC jacket (Sample #1) and the worst case cable sample of XLPE insulation (Sample #14). Since each of these worst case samples has the same insulation and jacket type, it is assumed that the insulation will have no effect on the performance of the jacket and vice versa. The bounding samples are as follows:</p> <p>VV = (PVC/PVC) $T_{o.v.p} = 832^{\circ}\text{F}$ XX = (XLPE/XLPE) $T_{o.v.p} = 928^{\circ}\text{F}$</p> <p>Where:</p> <p>Sample #1, PVC/PVC, $T_{o.v.p} = 832^{\circ}\text{F}$, & Sample #14, XLPE/XLPE, $T_{o.v.p} = 928^{\circ}\text{F}$</p> <p>The Samples are from Reference 2.11. The worst case of these two samples is $T_{o.v.p} = 832^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o.v.p}$ above 700°F.</p>	<p>1, 2 & 4</p>

<p>QN</p>	<p>Single or multi-conductor, EPR insulated and overall jacket of Neoprene</p>	<p>QN = (insulation/jacket) = EPR/Neoprene</p> <p>This cable is bounded by selecting the worst case cable sample of Neoprene jacket and the worst case cable Sample of EPR insulation. The insulation is bounded by the worst case sample of EPR (Sample #11). The jacket is bounded by the worst case sample of Neoprene (Sample #21). In comparing the worst case sample of Neoprene the potential affects of a different insulation (XLPE) was also reviewed by looking at Sample #14. The bounding samples are as follows:</p> <p>NX = (XLPE/Neoprene) $T_{o,r,p} = 928^{\circ}\text{F}$</p> <p>XX = (XLPE/XLPE) $T_{o,r,p} = 928^{\circ}\text{F}$</p> <p>QQ = (EPR/EPR) $T_{o,r,p} = 928^{\circ}\text{F}$</p> <p>Where:</p> <p>Sample #21, XLPE/Neoprene, $T_{o,r,p} = 928^{\circ}\text{F}$, Sample #14, XLPE/XLPE $T_{o,r,p} = 928^{\circ}\text{F}$ & Sample #11, EPR/EPR, $T_{o,r,p} = 928^{\circ}\text{F}$</p> <p>The Samples are from Reference 2.11. The worst case of the NX and QQ samples is $T_{o,r,p} = 928^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o,r,p}$ above 700°F.</p>	<p>1 & 2</p>
<p>NX</p>	<p>Single or multi-conductor, XLPE insulated and overall jacket of Neoprene</p>	<p>NX = (insulation/jacket) = XLPE/Neoprene</p> <p>This cable is represented by:</p> <p>Sample #21, XLPE/Neoprene jacket, $T_{o,r,p} = 928^{\circ}\text{F}$ &</p> <p>The sample is from Reference 2.11. This value is higher than the data published in the SFPE Handbook (Reference 2.18) with a value for $T_{o,r,p} = 832^{\circ}\text{F}$. The worst case from the handbook is 832°F. Therefore NYPA's cable when correlated to this sample, has a $T_{o,p}$ above 700°F.</p>	<p>1 & 2</p>
<p>NSX</p>	<p>Multi-conductor cable. Each conductor is XLPE insulated with a shield or an overall shield. Entire assembly is jacketed with Neoprene</p>	<p>NSX = (insulation/jacket) = XLPE/Neoprene</p> <p>This cable is represented by:</p> <p>Sample #21, XLPE/Neoprene jacket, $T_{o,r,p} = 928^{\circ}\text{F}$</p> <p>The sample is from Reference 2.11. This value is higher than the data published in the SFPE Handbook (Reference 2.18) with a range for $T_{o,r,p} = 832^{\circ}\text{F}$. The worst case from the handbook is 832°F. Therefore NYPA's cable when correlated to this sample, has a $T_{o,r,p}$ above 700°F.</p>	<p>1, 2 & 3</p>

QH	Single or multi-conductor, EPR insulated and overall jacket of Hypalon	<p>QH = (insulation/jacket) = EPR/Hypalon</p> <p>This cable is represented by:</p> <p>Sample #35, EPR/Hypalon Jacket, $T_{o,r,p} = 892^{\circ}\text{F}$ Sample #8, EPR/Hypalon Jacket, $T_{o,r,p} = 832^{\circ}\text{F}$</p> <p>The samples are from Reference 2.11 and Attachment 6.8. Sample #35 represents a worst case flame spread (FPI = 13) and Sample #8 represents a worst case critical heat flux or critical temperature (= 832°F) of the test data available. This critical temperature value is higher than the published (Reference 2.22) range which has a low end critical heat flux value of 14 kW/m^2 ($T_{o,r,p} = 809^{\circ}\text{F}$). Therefore NYPA's cable when correlated to this sample, has a $T_{o,r,p}$ above 700°F.</p>	1 & 2
XH	Single or multi-conductor, XLPE insulated and overall jacket of Hypalon	<p>XH = (insulation/jacket) = XLPE/Hypalon</p> <p>This cable is represented by:</p> <p>Sample #4, XLPE/Hypalon Jacket, $T_{o,r,p} = 832^{\circ}\text{F}$</p> <p>The sample is from Attachment 6.8. The worst case test sample is $T_{o,r,p} = 832^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o,r,p}$ above 700°F.</p>	1 & 2
XSH	Single or multi-conductor, XLPE insulated with individual shielding or an overall shield and overall jacket of Hypalon	<p>XSH = (insulation/jacket) = XLPE/Hypalon</p> <p>This cable is bounded by the following cable samples:</p> <p>XX = (XLPE/XLPE) $T_{o,r,p} = 928^{\circ}\text{F}$ QH = (EPR/Hypalon) $T_{o,r,p} = 832^{\circ}\text{F}$</p> <p>Where:</p> <p>Sample #14, XLPE/XLPE $T_{o,r,p} = 928^{\circ}\text{F}$ Sample #35, EPR/Hypalon $T_{o,r,p} = 892^{\circ}\text{F}$ Sample #8, EPR/Hypalon $T_{o,r,p} = 832^{\circ}\text{F}$</p> <p>The samples are from Reference 2.11 and Attachment 6.8. This cable is bounded by selecting the worst case cable sample of Hypalon jacket and the worst case cable sample of XLPE insulation. Sample #14 which represents the XLPE insulation, represents a worst case flame spread (FPI = 17) and critical heat flux or critical temperature (= 928°F) from the available test data. Sample #35 which represents a Hypalon jacket represents a worst case flame spread (FPI = 13) and Sample #8 represents a worst case critical heat flux or critical temperature (= 832°F) from the test data available. In comparing the critical temperatures of these samples against published data (Reference 2.22), the published data has a low end critical heat flux value of 14 kW/m^2 ($T_{o,r,p} = 809^{\circ}\text{F}$).</p> <p>The worst case is the published data which is $T_{o,r,p} = 809^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o,r,p}$ above 700°F.</p>	1, 2 & 3

<p>VA</p>	<p>Single conductor cable with PVC insulated and overall asbestos braid</p>	<p>VA = (insulation) = PVC</p> <p>This cable is bounded by data of the worst case cable construction of PVC insulation and PVC jacketing. The bounding samples are as follows:</p> <p>Sample #1, PVC/PVC, $T_{o,r,p} = 832^{\circ}\text{F}$ & Sample #3, PVC/PVC, $T_{o,r,p} = 786^{\circ}\text{F}$</p> <p>The Samples are from Reference 2.11. Sample #1 was chosen for the comparison as it represents a worst case flame spread (FPI = 36) and Sample #3 was used for the comparison as it represents a worst case critical heat flux or critical temperature (= 786°F) for those samples tested. The PVC/PVC values are consistent with the range published in the SFPE Handbook (Reference 2.18) with a range for $T_{o,r,p} = 786$ to 1007°F.</p> <p>The worst case of these two samples is $T_{o,r,p} = 786^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o,r,p}$ above 700°F.</p>	<p>1,2 & 6</p>
<p>VVA</p>	<p>Multi-conductor cable. Each conductor is PVC insulated with an overall PVC jacket and asbestos braid</p>	<p>VVA = (insulation/jacket) = PVC/PVC</p> <p>This cable is bounded by data of the worst case cable construction of PVC insulation and PVC jacketing. The bounding samples are as follows:</p> <p>Sample #1, PVC/PVC, $T_{o,r,p} = 832^{\circ}\text{F}$ & Sample #3, PVC/PVC, $T_{o,r,p} = 786^{\circ}\text{F}$</p> <p>The Samples are from Reference 2.11. Sample #1 chosen for the comparison as it represents a worst case flame spread (FPI = 36) and Sample #3 was used for the comparison as it represents a worst case critical heat flux or critical temperature (= 786°F) for those samples tested. The PVC/PVC values are consistent with the range published in the SFPE Handbook (Reference 2.18) with a range for $T_{o,r,p} = 786$ to 1007°F.</p> <p>The worst case of these two samples is $T_{o,r,p} = 786^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o,r,p}$ above 700°F.</p>	<p>1, 2 & 6</p>
<p>VGVA</p>	<p>Multi conductor cable PVC insulated with glass braid with an overall PVC jacket and asbestos braid</p>	<p>VGVA = (insulation/jacket) = PVC/PVC</p> <p>This cable is bounded by data of the worst case cable construction of PVC insulation and PVC jacketing. The bounding samples are as follows:</p> <p>Sample #1, PVC/PVC, $T_{o,r,p} = 832^{\circ}\text{F}$ & Sample #3, PVC/PVC, $T_{o,r,p} = 786^{\circ}\text{F}$</p> <p>The Samples are from Reference 2.11. Sample #1 chosen for the comparison as it represents a worst case flame spread (FPI = 36) and Sample #3 was used for the comparison as it represents a worst case critical heat flux or critical temperature (= 786°F) for those samples tested. The PVC/PVC values are consistent with the range published in the SFPE Handbook (Reference 2.18) with a range for $T_{o,r,p} = 786$ to 1007°F.</p> <p>The worst case of these two samples is $T_{o,r,p} = 786^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o,r,p}$ above 700°F.</p>	<p>1,2, 6 & 7</p>

UA	Single conductor cable with silicone rubber and asbestos braid	<p>UA = (insulation) = Silicone Rubber</p> <p>This cable is bounded by data of the worst case cable construction of Silicone Rubber insulation and PVC jacketing. The bounding sample are as follows:</p> <p>Sample #8, Silicone Rubber/PVC, $T_{o.r.p} = 910^{\circ}\text{F}$</p> <p>The sample is from Reference 2.11. Sample #8 was chosen because it represents the worst case construction type (i.e., PVC jacketing). The worst case test sample is $T_{o.r.p} = 910^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o.r.p}$ above 700°F.</p>	1, 2 & 6
UGA	Multi-conductor cables. Each conductor is silicone rubber insulated with glass braid and an overall asbestos jacket	<p>UGA = (insulation) = Silicone Rubber</p> <p>This cable is bounded by data of the worst case cable construction of Silicone Rubber insulation and PVC jacketing. The bounding sample are as follows:</p> <p>Sample #8, Silicone Rubber/PVC, $T_{o.r.p} = 910^{\circ}\text{F}$</p> <p>The sample is from Reference 2.11. Sample #8 was chosen because it represents the worst case construction type (i.e., PVC jacketing). The worst case test sample is $T_{o.r.p} = 910^{\circ}\text{F}$. Therefore NYPA's cable when bounded by this worst case, still has a $T_{o.r.p}$ above 700°F.</p>	1, 2, 6 & 7

The following criterion has been applied in bounding cables:

1. Each IP3 cable sample is compared to two (2) worst case, flammability parameters to determine the bounding cable sample. The two flammability parameters are the Flame Propagation Index (FPI) and the critical heat flux.
2. **Differences in conductor cable size, conductor number and cable insulation and jacket size are expected to have a negligible effect on the critical heat flux.** An increase in the conductor size and number is not expected to influence the critical heat flux because a cable sample is expected to behave per the principles of a thermally thin polymer as time to ignition approaches infinity. An increase in the cross-sectional area of the insulation (i.e., a thicker insulation or jacket) is not expected to effect the ignition temperature only the time to ignition. This is because critical heat flux is a property of the material.

These differences are expected to influence the thermal response parameter (TRP) and the flame propagation characteristics. In general, cables of increasing conductor size and number will exhibit decreasing TRP values and better flame propagation characteristics. This is due to their behavior per the principles of thermally thick, as time to ignition approaches zero.

3. **Internal cable shielding is expected to have a negligible effect on the critical heat flux** and a negligible effect on the Thermal Response Parameter (TRP) value. This is due to the increase in density, thermal conductivity and thickness of the overall cable assembly which is expected to be negligible.
4. **The presence of an internal lead sheath is expected to have a negligible effect on the critical heat flux.** This is because lead is an inert material. The change of state of the lead (i.e., from a solid to a liquid) is expected to increase the TRP value and improved flame propagation characteristics. The melting point of lead is 622°F (Reference 2.22, Table 8.1)
5. **The presence of an interlocked armor beneath the overall jacket is expected to have a negligible effect on the critical heat flux.** The combined effect of an increase in density and specific heat and decrease in thermal conductivity is expected to increase the Thermal Response Parameter (TRP) value.
6. **The presence of an overall asbestos braid is not expected to have an effect on the critical heat flux** but is expected to significantly dampen fire propagation. This is because asbestos is an inert material and in the configuration that it has been used, the cable is expected to exhibit a high resistance to flame spread. The asbestos braid is typically constructed of woven fibers saturated with a flame and moisture resistance lacquer which, by inspection, is not expected to encapsulate the off gasses of the material beneath the woven asbestos braid jacket.

7. **The presence of an glass braid is not expected to have an effect on the critical heat flux nor is it expected to have an effect on the fire propagation characteristics. This is because glass is typically used internal to the jacket. The glass braid is typically constructed of woven fibers saturated with a flame and moisture resistance lacquer.**

5.0 CONCLUSION

NYPA compared the cables installed at Indian Point 3 to tested cable samples of similar construction and jacketing. This review shows that it is reasonable to conclude that the self-ignition temperatures of cables that penetrate a fire seal (where the qualification test results indicated an unexposed side temperature greater than 250°F above ambient), are sufficiently above 700°F. This conclusion is based on a cable type-by-cable type comparison to new test data and the following:

1. Auto-ignition temperature by definition, would be comparable to or greater than the critical temperatures for piloted ignition reviewed for comparison.
2. Penetration fire seal qualification tests were typically performed using maximum cable loading and worst case cable construction and jacketing (i.e. PVC jacketed cables of 600V rating). Mixtures typically included single conductor cables, multi-conductor cables and large diameter cables.
3. Of all the generic test data discussed in Section 4.4 of this evaluation and presented in Attachments 6.8 and 6.10, none of the cable samples of construction and jacketing similar to those used at IP3 have a critical piloted ignition temperature less than 786°F (13kW/m²).

6.0 ATTACHMENTS

- 6.1 Con Ed Specification E-6068-3; Fire and Heat Resistance Tests on 600V Power and Control Cable and Switch Board Wires.
- 6.2 FMRC Specification Test Standard, Class Number 3972; Cable Flame Propagation.
- 6.3 ENG-527, Evaluation No. 5, Revision 1, Penetration Fire Seal Program.
- 6.4 Record of Conversation between A. Tewarson of FMRC and S. Wilkie of NYPA on March 3, 1995 regarding EPRI Reports NP-1200, NP-1767 and 1881.
- 6.5 Summary of Penetration Fire Seal Test Reviews.

- 6.6 FMRC letter to EPRI, dated May 10, 1995.
- 6.7 Licensing Attachments.
- 6.8 Rockbestos cable testing, FMRC Contract No. J.I. OY1R9.RC.
- 6.9 Typical Plot of the Inverse of Time verses External Heat Flux.
- 6.10 Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering, 2nd edition, Section 3, Chapter 4, copy of the galley proof.
- 6.11 Symposium Series 599, Fire and Polymers II, Materials and Tests for Hazard Prevention, Chapter 30, 1995, American Chemical Society, Washington, D.C., copy of chapter submitted by Dr. A. Tewarson for publication.

ATTACHMENT 6.1

Con Ed Specification E-6068-3

Fire and Heat Resistance Test on

600V Power and Control Cable and Switch Board Wires

SURPLUS



Consolidated Edison Company of New York, Inc.
4 Irving Place, New York, N Y 10003

Purchase and Test Manual No. 6-Sect. 1
All Districts

Page 1
EO-6068-3
DEC 27 1978

FIRE AND HEAT RESISTANCE TESTS ON
600V POWER AND CONTROL CABLE
AND SWITCHBOARD WIRES

DSR # 164114
OF PAGES _____

SCOPE

1. This specification covers the fire and heat resistance tests to be performed on 600V power and control cable, switchboard wires and multiconductor cable as a requirement for Company acceptance in various cable specifications.

DEFINITION OF TERMS

2. The following are definitions of terms relating to this specification.

- a. Power Cable - Stranded conductors, completely covered with the type of insulation suitable for 600 volt power applications. The cable may or may not be lead covered or jacketed depending on the applicable specification.
- b. Control Cable - (Cable Systems). Cable which is usually applied at relatively low current levels or used for intermittent operation to change the operating status of a utilization device of the plant auxiliary system. This could be considered a special type of multiconductor cable.
- c. Switchboard Wire - Wire of a single strand properly insulated and utilized for a large single panel, frame, or assembly of panels, on which are mounted, on the face or the back or both, switches, overcurrent and other protective devices, buses, and usually instruments.
- d. Multiconductor Cables - A combination of two or more conductors cabled together and insulated from one another and from sheath or armor where used. Note: Specific cables are referred to as 3-conductor cable, 7 conductor cable, and multiples thereof, or grouped in pairs.

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GENERAL

3. When performing any of the tests outlined in Paragraphs 5 and 6 of this specification on a sample of wire or cable, an approved wire or cable shall be submitted to the same test(s) at the same time so that a performance level is established for the test sample under the same test conditions.

4. The Transmission and Distribution Engineer will review the results of all testing and determine the suitability of the sample construction for use.

5. The following flame tests shall be performed on all 600V power and control cables and switchboard wires, except where specified. All cables shall be meggered at 1000V before and after the test. All cables which do not meet paragraph 5a and 5b shall be considered to have failed and are not to be submitted to any additional testing.

a. A.S.T.M. Vertical Flame Test

As a preliminary test, the A.S.T.M. vertical flame test, designation D-2633 shall be performed only on 600V control cable and switchboard wires. All cables which do not meet this test shall be considered to have failed and shall not be submitted to any additional testing.

b. Con Edison Vertical Flame Test

With the cable in a vertical position a burner flame with the tip of the inner cone of the flame at the outer surface of the cable covering, is held on the cable for five (5) minutes. The time to ignite the cable is noted and after removing the flame, the time that the cable continued to flame and the extent of the burning are noted.

The flame shall be supplied by a Fischer Burner No. 3-902, 40mm. diameter head, using natural gas with the tip of the flame adjusted for 1900 degrees F.

c. Con Edison Bonfire Test

This test shall be performed on 600V power and multi-conductor cable. The test shall be performed three times and if two out of three show indications of short circuit conditions during the test, it shall be considered to have failed. All multi-conductor cables with an overall diameter of less than 1/2 inch shall not be subjected to this test.

c. Con Edison Bonfire Test (Cont'd)

Several cables to be tested, the number depending on service conditions, shall be three feet in length each. The cables to be tested shall be grouped in a bundle and exposed to an oil flame produced by igniting transformer oil in a 12 inch diameter pail. At the start of each test the oil level is adjusted to 2-inches below the rim of the pail. The grouped cables shall be placed horizontally over the center of the pail, with the lowest conductor 3 inches above the top of the pail. The flame is applied for five minutes.

All cables shall be meggered at 1,000V before and after the test.

1. Throughout the test a voltage shall be applied to the cables as shown in figure I attached.
2. The cables shall be grouped in such a way that each cable is in contact with the others as shown in figure II attached.
3. Should there be more than three cables, they shall be grouped as shown in figure III attached.

d. Flame Test

Section 2.5 of the Latest Revision of I.E.E.E. 383 under "Flame Test".

HEAT TESTS

6. The following heat tests shall be performed on all 600V network power cables which pass the flame tests mentioned previously:

a. Oven Test

A sample of cable approximately one foot in length is placed in an oven and heated at 260°C for four hours. The sample is then examined for damage. There shall be no signs of blistering, cracking, etc. All cables which do not meet the requirements of this test shall be considered to have failed and are not to be submitted to any additional testing.

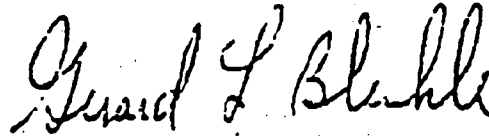
b. Roasting Test

Several cables to be tested, the number depending on service conditions, each approximately twenty (20) feet

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b. Roasting Test (Cont'd)

in length are grouped in a bundle and placed in a four inch duct. Current, as determined by the Transmission and Distribution Engineer, is applied to raise the temperature of the conductor to 260°C in two hours. Immediately after this temperature is reached, the cable is removed from the duct and the insulation is examined for damage. There shall be no visible signs of blistering, cracking, etc.



Gerard L. Blenkle
Transmission and Distribution Engineer
Electrical Engineering Department

Paul Cordero/bc

<p>REVISION: 3 Added definitions, set criteria of Bonfire Test & Clarified 5d requirements. Review by 11/80</p>	<p><u>FILE</u> Purchase and Test Manual No. 6 Sect. 1, Acceptance Testing</p>
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OPEN
CIRCUIT
TEST
CABLES

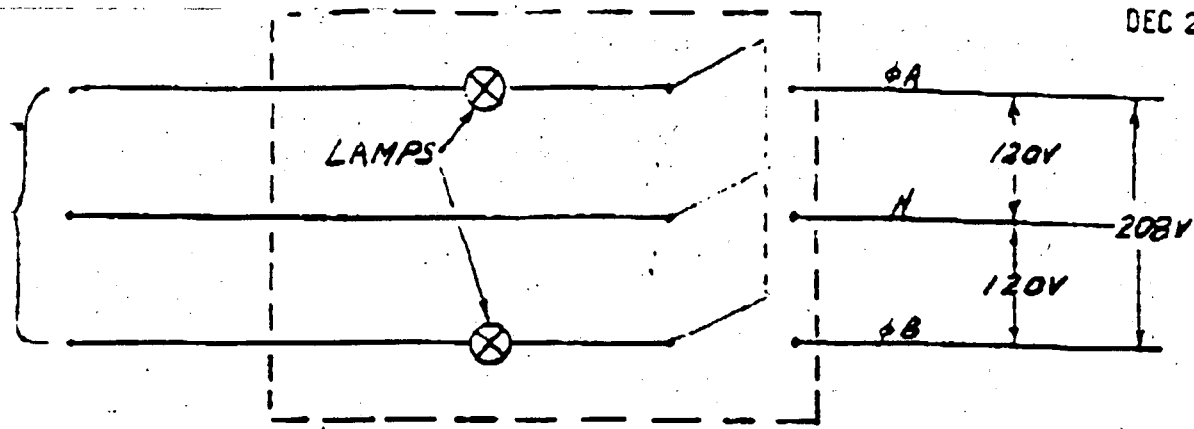


FIG I

THE CABLES SHALL BE GROUPED IN SUCH A WAY THAT EACH CABLE IS IN CONTACT WITH THE OTHERS AS SHOWN BELOW:

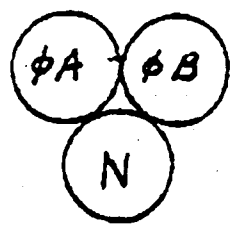


FIG II

SHOULD THERE BE MORE THAN THREE CABLES, THEY SHALL BE GROUPED AS SHOWN BELOW:

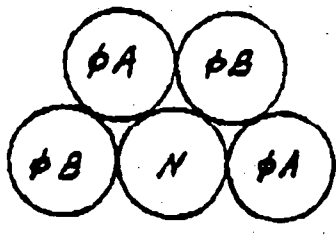


FIG III

CABLE ARRANGEMENT FOR
BON-FIRE TEST.
THIS DRAWING IS PART OF

ATTACHMENT 6.2

FMRC Specification Test Standard, Class Number 3972

Cable and Flame Propagation

Specification Test Standard

Cable Fire Propagation

Class Number 3972

March 1994



Factory Mutual Research

**SPECIFICATION TEST STANDARD
FOR
CABLE FIRE PROPAGATION**

Class No. 3972

March 1994

(Replaces July 1989)



Factory Mutual Research

1151 Boston-Providence Turnpike
Norwood, Massachusetts 02062

Class 3972

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March 1994

SPECIFICATION TEST STANDARD FOR CABLE FIRE PROPAGATION

1. INTRODUCTION

1.1 PURPOSE

This standard describes Factory Mutual Research Corporation (FMRC) requirements for establishing the classification for cable fire propagation. Cables covered by this standard include electrical and optical cables, herein called cables. The classification rating established in this Specification Test Standard may be used to determine acceptable fire protection techniques applicable to a given field installation.

1.2 SCOPE

This standard is applicable, but not limited, to various types of electrical cables such as communications cables (including fiber optic cables), power distribution cables, feeder branch circuit wiring, etc., having outer insulating coverings or metallic sheath, which may be used for commercial and industrial purposes.

1.3 BASIS FOR FACTORY MUTUAL RESEARCH LISTING

Factory Mutual Research Corporation Listing is based on satisfactory evaluation of the product and manufacturer in the following major areas:

- 1.3.1 Examination and tests shall be performed on production samples to evaluate flammability characteristics of product formulation; and
- 1.3.2 An examination of the manufacturing facilities and audit of quality control procedures shall be made to evaluate the manufacturer's ability to produce the product which is examined and tested, and the marking procedures used to identify the product. These examinations are repeated as part of FMRC's Product Follow-Up program.

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1.4 BASIS FOR CONTINUED LISTING

Continued Listing is based upon:

- production or availability of the product as currently Listed;
- the continued use of acceptable quality control procedures;
- satisfactory field experience;
- compliance with the terms stipulated in the Specification Tested Product Agreement and
- re-examination of production samples for continued conformity to requirements.

1.5 BASIS FOR REQUIREMENTS

1.5.1 The requirements of this standard are based on experience, research and testing. The advice of manufacturers, users, trade associations and loss control specialists was also considered.

1.5.2 Subjecting cables to the tests described by this standard will result in their classification as described in Section 5.1 of this standard. The classification is based on the fire propagation (flame spread) characteristics of a cable. Listing requirements prohibit substitution of components in the cable construction without prior authorization.

1.6 EFFECTIVE DATE

The effective date of a Specification Test Standard mandates that all products tested for Listing after the effective date shall satisfy the requirements of that standard. Products Listed under a previous edition shall comply with the new version by the effective date or else forfeit Listing. The effective date shall apply to the entire specification test standard, or, where so indicated, only to specific paragraphs of the standard.

The effective date of this standard is the issue date.

1.7 SYSTEM OF UNITS

Units of measurement are U.S. customary units. These are followed by their arithmetic equivalents in International System (SI) units, enclosed in parentheses. Appendix E lists the selected units for quantities dealt with in testing these products; conversions to SI units are included. Conversion of the U.S. customary units is in accordance with ASTM E 380.

2. GENERAL INFORMATION**2.1 PRODUCT INFORMATION**

The cables covered by this standard may be supplied as insulated single- or multiple-conductor having a metallic or non-metallic sheath. The conductor is usually manufactured of electrically conductive materials such as copper or aluminum, or may be a fiber optic material. Various combinations of polymeric materials, modified by additives, are used for insulations and jackets.

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2.2 FLAMMABILITY CLASSIFICATION

The flammability characteristics of the cable will fall within the ranges specified in this standard when tested according to the Piloted Ignition and Fire Propagation Test Methods described in Appendixes B and C of this standard.

3. APPLICABLE DOCUMENTS AND GLOSSARY

3.1 DOCUMENTS

The flammability requirements are a result of Factory Mutual Research Corporation efforts summarized in the Factory Mutual Research Technical Report J.I. 0M2E1RC "Electrical Cables - Evaluation of Fire Propagation Behavior and Development of Small-Scale Test Protocol."

3.2 GLOSSARY

CABLE - a conductor (electrical or optical) with or without insulation and other coverings (single conductor cable) or a combination of conductors insulated from one another (multi-conductor cable).

CRITICAL HEAT FLUX - the minimum heat flux at or below which there is no ignition.

CHEMICAL HEAT RELEASE - the heat release during the fire propagation process and determined from the generation rates of carbon monoxide and carbon dioxide

HEAT FLUX - the rate of heat flow measured across a given surface.

INSULATED WIRE - a slender rod or filament of drawn metal with an insulating cover.

FIRE PROPAGATION INDEX - a measure of the fire propagation tendency of the cable and is the ratio of the radiant heat flux provided by the flame and the thermal response parameter of the cable.

SELF-SUSTAINED FLAME PROPAGATION - a cable flame propagation assisted by the flame heat flux from the burning cable only and not by other heat sources.

THERMAL RESPONSE PARAMETER - a property of material describing its reaction to heat in terms of ignition temperature, thermal conductivity, density and specific heat.

3.3 COMPLIANCE

Compliance with the flammability requirements is verified by conducting the required testing and obtaining satisfactory performance for requirements outlined in the Test Methods described in Appendixes B and C of this standard.

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4. GENERAL REQUIREMENTS**4.1 MARKING**

- 4.1.1** The marking, to be placed along the length of the cable, shall be repeated at intervals not exceeding 24 inches (610 mm) and shall bear a classification marking shown below:

FMRC GP-1 (or -2 or -3)

NOTE: THE MARKING SHALL BE OF A CONTRASTING COLOR WITH RESPECT TO
THE BACKGROUND (E.G., WHITE MARKING ON BLACK BACKGROUND).

- 4.1.2** The classification marking (FMRC GP-1,-2 or -3) shall be used in conjunction with the products which have been tested by FMRC. The classification marking shall not be used in a manner (including advertising, sales, or promotional purposes) that suggests or implies FMRC endorsement of a specific manufacturer or distributor. Also, it shall not be implied that Listing extends to a product not covered by specific written agreement with FMRC. The classification mark signifies only that the product has met certain requirements as reported by FMRC.

4.2 DRAWINGS, FORMULATIONS AND SPECIFICATIONS

- 4.2.1** Drawing(s), formulation(s) and specifications identifying materials, formulations and construction details shall be provided to FMRC for each configuration tested (i.e., itemized percentage of combustible material types per unit length). Information submitted to FMRC by the manufacturer with their cables shall include notification of any insulation/jacket materials having very high halogen contents (>60%) in their structures.
- 4.2.2** A drawing(s) shall be provided to FMRC indicating the size and location of the Factory Mutual Research Corporation marking as it will be shown on the product.
- 4.2.3** The manufacturer shall also provide to FMRC copies of all brochures, sales literature and specification sheets relating to the cable(s) submitted for test.

4.3 MANUFACTURERS RESPONSIBILITIES

- 4.3.1** The manufacturer shall furnish a total minimum cable length of 20 ft (6 m) from its standard production line of each different cable type to be tested. For ease of shipment, the cable may be cut into segments of lengths not less than 3 ft (0.91 m) each. A "different cable type" is defined for purposes of this standard, as variations in overall cable diameter and combustible materials (types and quantities) used in its construction. The cable, as supplied by the manufacturer, shall be cleaned of all foreign materials. The samples shall be labeled so as to properly identify each sample so that they correspond to the documentation provided.
- 4.3.2** Cable construction of the samples tested shall be representative of production samples and shall conform to the specifications and drawings provided by the manufacturer.

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5. FLAMMABILITY CHARACTERISTICS**5.1 CLASSIFICATION REQUIREMENTS FOR GROUPS 1, 2 OR 3 CABLE**

To be classified as either Group 1, 2, or 3 cable, the test results of samples subjected to the Piloted Ignition and Fire Propagation Test Methods shall exhibit one of the following patterns of fire propagation and a corresponding Fire Propagation Index (see Graph 1).

GROUP 1 - Non-self-sustained flame propagation having a Fire Propagation Index less than 10.

GROUP 2 - Self-sustained flame propagation having a Fire Propagation Index of 10 or greater, but less than 20.

GROUP 3 - Rapid self-sustained flame propagation having a Fire Propagation Index of 20 or greater.

NOTE 1: THE FIRE PROPAGATION INDEX IS GIVEN AS THE RATIO OF THE RADIANT FRACTION OF CHEMICAL HEAT RELEASE RATE OF THE CABLE TO THE THERMAL RESPONSE PARAMETER OF THE CABLE.

NOTE 2: THE PILOTED IGNITION TEST METHOD IS CONDUCTED TO DETERMINE THE THERMAL RESPONSE PARAMETER OF THE CABLE AND IS USED IN DETERMINING THE FIRE PROPAGATION INDEX.

NOTE 3: THE FIRE PROPAGATION TEST METHOD IS CONDUCTED TO DETERMINE THE CHEMICAL HEAT RELEASE RATE OF THE CABLE AND IS USED IN DETERMINING THE FIRE PROPAGATION INDEX.

5.2 DETERMINING FIRE PROPAGATION INDEX

The determination of the Fire Propagation Index (FPI) is explained in Appendix A. This Appendix references equations and terms used to obtain the Thermal Response Parameter as a result of the data collected from the Piloted Ignition Test Method and to obtain the Chemical Heat Release Rate as a result of the data collected from the Fire Propagation Test Method. It also shows how these terms are interrelated in determining FPI.

5.2.1 PILOTED IGNITION AND THERMAL RESPONSE PARAMETER

The Piloted Ignition Test Method is described in Appendix B. This Appendix states how to conduct the test, obtain the required data and calculate the Thermal Response Parameter referencing the equation stated in Appendix A.

5.2.2 FIRE PROPAGATION AND CHEMICAL HEAT RELEASE RATE

The Fire Propagation Test Method is described in Appendix C. This Appendix states how to conduct the test, obtain the required data and calculate the Chemical Heat Release Rate referencing the equations stated in Appendix A.

5.3 TEST REPRESENTATION

The following cable representation is allowed provided that the only difference in cable construction is the overall diameter of the cable.

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- 5.3.1 The larger cables, employing the same construction and material as the smaller cables, shall be acceptable for the same group marking as the smallest cable satisfactorily tested.
- 5.3.2 The larger cables, employing the same construction and material as the smaller cables, may be acceptable for a lower group marking (e.g., from Group 3 to 2, and 2 to 1) provided the smallest cable tested has been determined to be a Group 3 or 2 cable. However, this can only be verified by subjecting the larger sample sizes to tests.

6. OPERATIONS REQUIREMENTS

6.1 DEMONSTRATED QUALITY CONTROL PROGRAM

- 6.1.1 A Quality Control Program is required to assure that each subsequent cable produced by the manufacturer shall present the same product uniformity and construction as the specific cable samples examined. Design quality, conformance to design, and performance are the areas of primary concern.

Design quality is determined during the examination and tests.

Conformance to design is verified by control quality in the following areas:

- existence of corporate quality control guidelines
- incoming assurance, including testing
- in-process assurance, including testing
- final inspection and test
- equipment calibration
- drawing and change control
- packing and shipping
- handling discrepant materials.

Quality of performance is determined by field performance and by re-examination and test.

- 6.1.2 The manufacturer shall establish a system of product configuration control to prevent unauthorized changes, including, as appropriate:

- engineering drawings
- engineering change request
- engineering orders
- change notices.

These shall be executed in conformance with a written policy and detailed procedures. Records of all revisions to all Listed products shall be kept.

- 6.1.3 The manufacture shall assign an appropriate person or group to be responsible to obtain Factory Mutual Research Corporation authorization of all changes applicable to Listed products. FMRC Form 797, Product Revision Report or Address/Contact Change Notice, is provided to notify FMRC of pending changes.

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6.2 FACILITIES AND PROCEDURES AUDIT (F&PA)

- 6.2.1 An inspection of the product manufacturing facility shall be part of the specification tested product investigation. Its purpose shall be to determine that equipment, procedures, and the manufacturer's controls are properly maintained to produce a product of the same quality as initially tested.
- 6.2.2 Unannounced follow-up inspections shall be conducted to assure continued quality control and product uniformity.
- 6.2.3 Follow-Up Verification - During the follow-up audit, a random, representative production cable test sample shall be provided to Factory Mutual Research Corporation for testing. Verification of proper manufacturing shall be indicated by no significant change in the Fire Propagation Index Curve when compared to that which is on file at Factory Mutual Research Corporation.

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APPENDIX A

APPENDIX A

DETERMINATION OF FIRE PROPAGATION INDEX

In order to determine FPI for a cable, tests are conducted in two phases: first, the Piloted Ignition Test, and second, the Fire Propagation Test. The Factory Mutual Research Corporation 50kW Flammability Apparatus is used for this purpose. See Figure B-1.

I PHASE I - PILOTED IGNITION TEST

The details of the piloted ignition test method are described in Appendix B. In the tests, cable samples are exposed to different external radiant heat flux, q_c'' , values and time to ignition, t_{ig} , is recorded for each sample. Figure A-1 shows the relationship between the inverse of square root of time to ignition and external radiant heat flux values.

The Thermal Response Parameter of the cable is expressed as the inverse of the slope of the line obtained by plotting $t_{ig}^{-1/2}$ versus q_c'' and performing regression analysis in the linear portion of the curve.

The equation of the linear portion of the curve in Figure A-1 is given by:

$$t_{ig}^{-1/2} = q_c'' / \Delta T (k \rho c_p)^{1/2} - a$$

where t_{ig} is time to ignition, q_c'' is the external heat flux, $\Delta T (k \rho c_p)^{1/2}$ is the Thermal Response Parameter, and a is the intercept.

The Thermal Response Parameter of the cable is obtained experimentally by subjecting the cable to various external heat flux values, q_c'' , and recording the time it takes to obtain sustained pilot ignition of the combustible cable vapors, given as t_{ig} . Derived from the time to ignition is, $t_{ig}^{-1/2}$, i.e., the inverse of its square root. For each increment in the heat flux, q_c'' , the corresponding $t_{ig}^{-1/2}$ increases. The inverse of the slope is the Thermal Response Parameter of the cable.

The Thermal Response Parameter will be required for determining the Fire Propagation Index for cable.

II PHASE 2 - FIRE PROPAGATION TEST

The fire propagation test detailed in terms of test apparatus and procedure is given in Appendix C. Fire propagation test for cable is conducted in the apparatus shown in Figure C-1 in Appendix C. During the fire propagation test, all fire products along with the ambient air are captured in the sampling duct. Fire products-air mixture in the measurement section of the sampling duct is well mixed, where concentrations of CO and CO₂ (using gas analyzers) and total volumetric flow rate, \dot{v} (using pressure transducers across a calibrated orifice plate), and gas temperature in the sampling duct and ambient temperature, are measured as a function of time. The gas analyzers (both CO and CO₂) are pre-calibrated using standard gas-nitrogen mixtures in the concentration range expected in the test. Typically for cables, CO analyzer range between 0 and 1000 ppm by volume, and CO₂ analyzer range between 0 and 1.5% by volume, are used. The generation rates of CO and CO₂ during the fire propagation as a function of time are computed from:

$$\dot{G}_i = \dot{v} c_i p_i$$

where \dot{G}_i is the generation rate of compound i (where i is either CO or CO₂) in g/s, \dot{v} is the volumetric flow rate in m³/s, c_i is the measured concentration of compound i (CO or CO₂), and p_i is the density of compound i (CO or CO₂) in g/m³.

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APPENDIX A

APPENDIX A

The Chemical Heat Release rate, \dot{Q}_{chem} , in kW as a function of time is calculated from the generation rates of CO and CO₂ as follows:

For cables with very high halogen content in the structure (>60%) of the insulation/jacket materials:

$$\dot{Q}_{chem} = 5.4 \dot{G}_{CO_2}$$

For all other cable insulation/jacket materials:

$$\dot{Q}_{chem} = 11.08 \dot{G}_{CO_2} + 7.02 \dot{G}_{CO}$$

where constants 11.08 and 7.02 are average values for cable sample, \dot{G}_{CO_2} is the generation rate of CO₂ in g/s, and \dot{G}_{CO} is the generation rate of CO in g/s.

The Fire Propagation Index (FPI) as a function of time is expressed as:

$$FPI = \frac{[0.40(\dot{Q}_{chem})/\pi D]^2}{\text{Thermal Response Parameter}} \times 10^3$$

where 0.40 is a value for radiative fraction, \dot{Q}_{chem} in kW, D is the outer diameter of the cable in meters (not just the conductor) and Thermal Response Parameter is in (kW/m²)^{1/2} (sec)^{1/2} which was determined in the piloted ignition test as described above.

Finally, FPI is plotted as a function of time as shown in Graph D-1 in Appendix D.

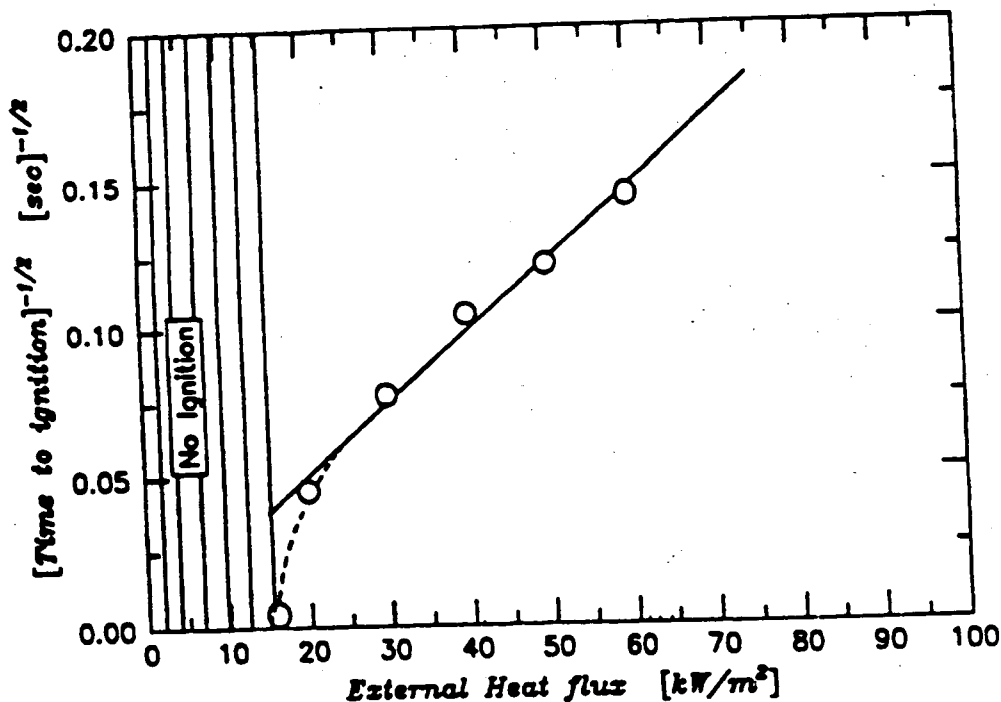


Figure A-1. Relationship between Time to Ignition and External Heat Flux

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APPENDIX B

APPENDIX B

PILOTED IGNITION TEST METHOD

I GENERAL

The objective of the piloted ignition test procedure is to determine the Thermal Response Parameter of cables for the evaluation of fire propagation behavior. Testing is conducted in the Factory Mutual Research Corporation 50kW Flammability Apparatus.

II TEST APPARATUS

The Factory Mutual Research Corporation 50kW Flammability Apparatus is shown in Figures B-1 and B-2. Figure B-1 shows an overall sketch of the apparatus, whereas Figure B-2 shows the lower part of the apparatus used for the piloted ignition testing.

For the piloted ignition testing, a 5-inch (127 mm) horizontal cable sample with 0.5 inch (12.7 mm) at both ends tightly covered with heavy duty aluminum foil and placed on a holder/platform is used, as shown in Figure B-2. In the test, the sample is surrounded by four high density tungsten-quartz radiant heaters. The radiant heaters are used to expose the sample to various external heat flux values. In the test, the combustible vapors generated from the cable sample as a result of exposure to external heat flux, are ignited with a pilot flame. The pilot flame, adjusted to provide a blue-white flame, consists of a horizontal premixed ethylene-air flame, established at the ceramic tip of a 0.25 inch (6 mm) diameter metallic tube attached to ethylene and air cylinders. The pilot flame is about 0.4 inch (10 mm) long and is located within 0.4 inch (10 mm) from the cable surface as indicated in Figure B-2.

In the test, the cable sample is exposed to external heat flux, q'' , using the test sequence given in Table 1, ranging from 158 to 317 Btu/ft²/min (30 to 60 kW/m²). The test are performed in the open under normal air flow conditions.

III TEST PROCEDURE

The radiant heater test sequence and calibration procedure of the Factory Mutual Research Corporation Flammability Laboratory shall be used.

The test shall be performed in the test sequence as specified in Table 1.

TABLE 1.
Radiant Heater Test Sequence for Ignition Testing

Test Sequence	Heat Flux	
	Btu/ft ² /min	kW/m ²
1	158	30
2	211	40
3	264	50
4	317	60

NOTE: If the piloted ignition data is graphically plotted and exhibits clear curvilinear behavior between the heat fluxes of 158 to 211 Btu/ft²/min (30 to 40 kW/m²), the Test Sequence 1 data point shall be discarded and Test Sequence 5 added with a heat flux of either 238 or 291 Btu/ft²/min (45 to 55 kW/m²). Additionally, if a determination of the critical heat flux for the particular cable is required, one or more further tests at heat fluxes below 158 Btu/ft²/min (30 kW/m²) might be necessary.

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The length of the cable sample shall be 5 inches (127 mm). The cable, as supplied by the manufacturer, shall be clean of all foreign materials. If not supplied clean by the manufacturer, the sample length of cable shall be cleaned with a warm, soap solution to remove any surface deposits, film or residue that may have some impact on ignition. Should any oil, grease or other foreign residue remain on the surface of the cable, it shall be removed by the use of methyl, ethyl or isopropyl alcohol. Care should be taken not to wet the insulating or filler materials of the cable. The cable shall then be towel-dried and allowed to stand at room temperature until the cable is completely dry. The surface of the cable shall be painted using "Krylon 1602 Ultra-Flat Black" paint. After applying the paint, all cable sample surfaces shall be allowed to dry at room temperature (approximately 75° F [24° C]) for a minimum of 24 hours. In the test, the sample shall be placed on the holder/platform which is positioned such that the height of the centerline of the sample is located at the point of maximum heat flux intensity determined during calibration of the Flammability Apparatus. 0.5 inch (12.7 mm) of both cable ends shall be covered with heavy duty aluminum foil. The pilot flame shall be 0.4 inch (10 mm) long established by adjusting the flow of ethylene and air, and placed 0.4 inch (10 mm) from the cable surface. The centerline of the test cable sample shall be located at the point of maximum heat flux intensity as determined during calibration of the Flammability Apparatus. After the sample has been placed on the holder/platform in the Apparatus, the water-cooled radiant heater shield shall be raised and power to the radiant heaters shall be turned on and the voltage increased to produce the initial test sequence setting of 158 Btu/ft²/min (30 kW/m²). After one minute the shield shall be lowered and a stop watch shall be started. The elapsed time on the stopwatch reading shall be defined as time to ignition, t_{ig} . A split/lap stopwatch shall be used to record flash (entire sample ignites briefly but fails to support combustion) time(s) as well as sustained ignition time. The flash time(s) and the sustained ignition time are then added and averaged; this average value is designated the "time to ignition." Higher heat flux settings may eliminate flash events. An individual piloted ignition test shall be terminated if the cable sample fails to ignite after a full 15 minutes, and the test result shall be reported as: NO IGNITION. This procedure shall be repeated for each of the radiant heater test sequence given in Table 1. The measured data for time to ignition, t_{ig} , and corresponding external heat flux, q_{ext} , shall be recorded for each of the four samples.

Derived from the time to ignition is $t_{ig}^{-1/2}$, i.e., the inverse of its square root. For each increment in the heat flux, e.g., 158, 211, 264 and 317 Btu/ft²/min (30, 40, 50 and 60 kW/m²) the corresponding $t_{ig}^{-1/2}$ increases. Thermal Response Parameter shall be determined from the slope of the best fitted line formed by plotting $t_{ig}^{-1/2}$ versus q_{ext} on the y-axis and x-axis, respectively. The ignition data may be plotted as each piloted ignition test is completed to check the dispersion of the data points from the best-fit line. An individual ignition test may be run only if a problem occurred during the initial test that might invalidate the result, e.g., a power surge occurred, the pilot flame flickered, the stopwatch used to record elapsed time during the test malfunctioned, the water-cooled radiant heater shield was not raised when the quartz radiant heaters were first turned on, etc. The Thermal Response Parameter shall be determined using a programmable hand-held calculator, a calculator with a built-in function that ascertains the best-fit line for a given set of data using the least-mean square procedure, or the computer data acquisition data system of the flammability apparatus such as is used at FMRC. Regression analysis of the data shall be performed and shall indicate the least-mean square correlation coefficient to be at least 0.996, in accordance with the regression analysis such as used at FMRC. This will assure no more than a 5 percent error in determining the Thermal Response Parameter of a cable. When ignition occurs at all heat fluxes, but the correlation coefficient is determined to be less than 0.996, the data shall be plotted as shown in Appendix A, Figure A-1. If the plot clearly indicates that the 30 kW/m² data point is outside the linear range, it shall be discarded and a substitute ignition test conducted at a heat flux of either 45 or 55 kW/m². The correlation coefficient of the resulting four points shall then be calculated; should it be found to be less than 0.996, four additional piloted ignition tests at the heat fluxes normally selected between 40 and 60 kW/m² shall be conducted. If the ignition plot does not suggest curvilinear behavior at the 30 kW/m² heat flux, four additional ignition tests shall be performed at different heat flux settings.

If ignition of the test sample does not occur at 30 kW/m² after a full 15 minutes, and the correlation coefficient for the remaining three ignition points is greater than or equal to 0.996, the Thermal Response Parameter of the sample shall be determined from these three points; should the correlation coefficient be less than 0.996, five additional ignition tests at elevated heat fluxes are required. Experience has also shown that it is not uncommon for certain cables to fail to ignite at both 30 and 40 kW/m². In such a situation, six additional ignition tests shall be conducted with the heat fluxes selected so that the eight total data points are distributed with three each at 60

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and 55 kW/m^2 , and the remaining two points at 50 kW/m^2 . Although it is unlikely that such added tests will significantly improve the correlation coefficient, the confidence level in the best-fit line drawn through the eight data points will clearly be higher. Statistically, the best-fit line through the eight points (rather than through only two or three) more closely represents the mean average of the total population of the manufactured cable.

Some cable samples, especially those which are manufactured with fluoropolymer jacket, fail to ignite at the heat fluxes of 30, 40 or even 50 kW/m^2 . In such cases, the cable shall be assigned a Thermal Response Parameter of $500 \text{ kW}^{1/2}/\text{m}^2$.

After the tests for piloted ignition have been completed, tests following the Fire Propagation Test Method described in Appendix C shall be performed.

**WARNING: WEAR SAFETY GLASSES AND EAR PROTECTORS. HANDLE SAMPLES WITH PROTECTIVE GLOVES.
DO NOT REMOVE HOT CABLE SAMPLES FROM THE APPARATUS AFTER THE TEST; WAIT UNTIL THEY
ARE COOLED. AFTER THE TEST, DISCARD THE COLD RESIDUE IN SPECIAL CONTAINERS.**

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APPENDIX B

APPENDIX B

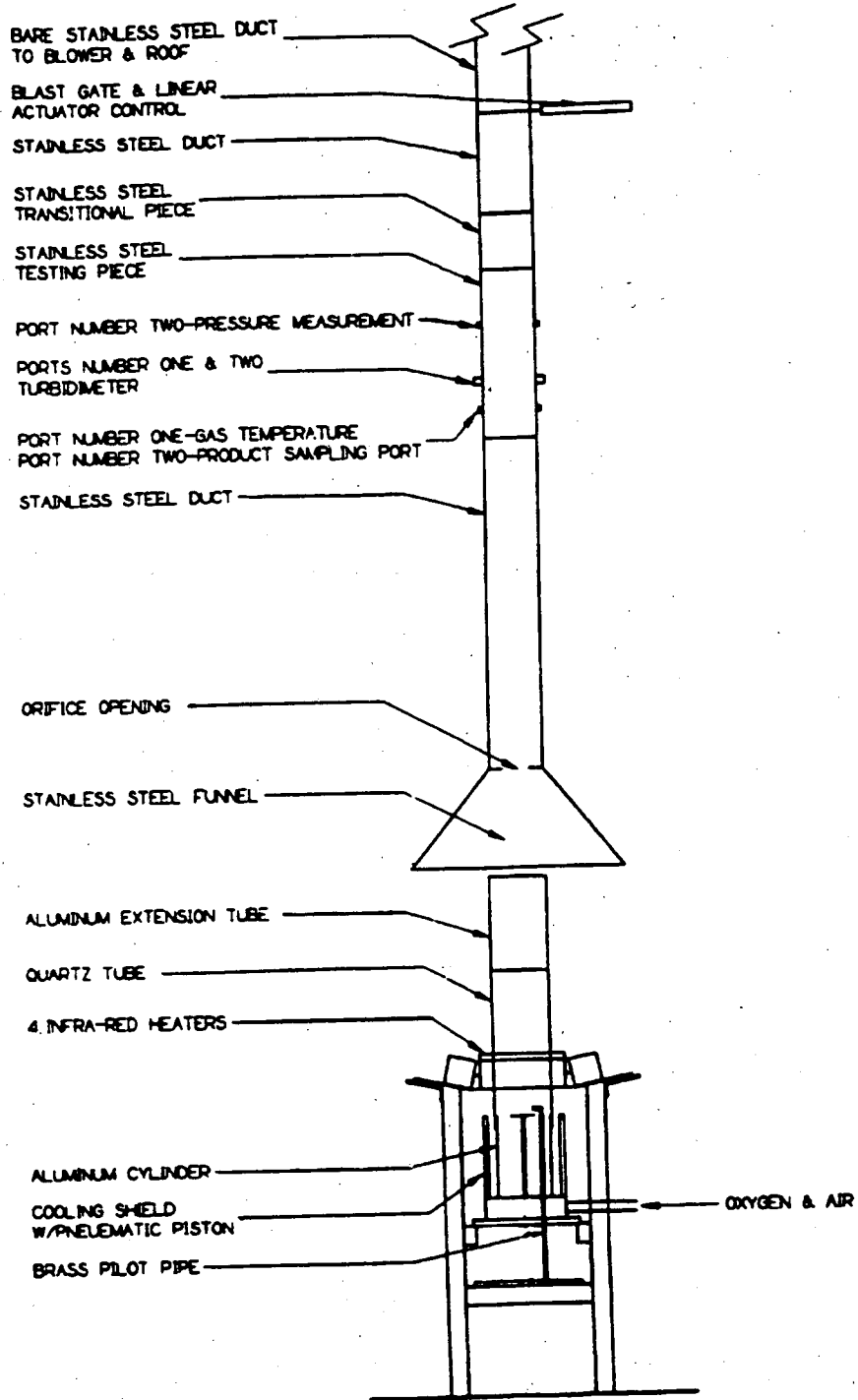


Figure B-1. Factory Mutual Research 50 kW Flammability Apparatus

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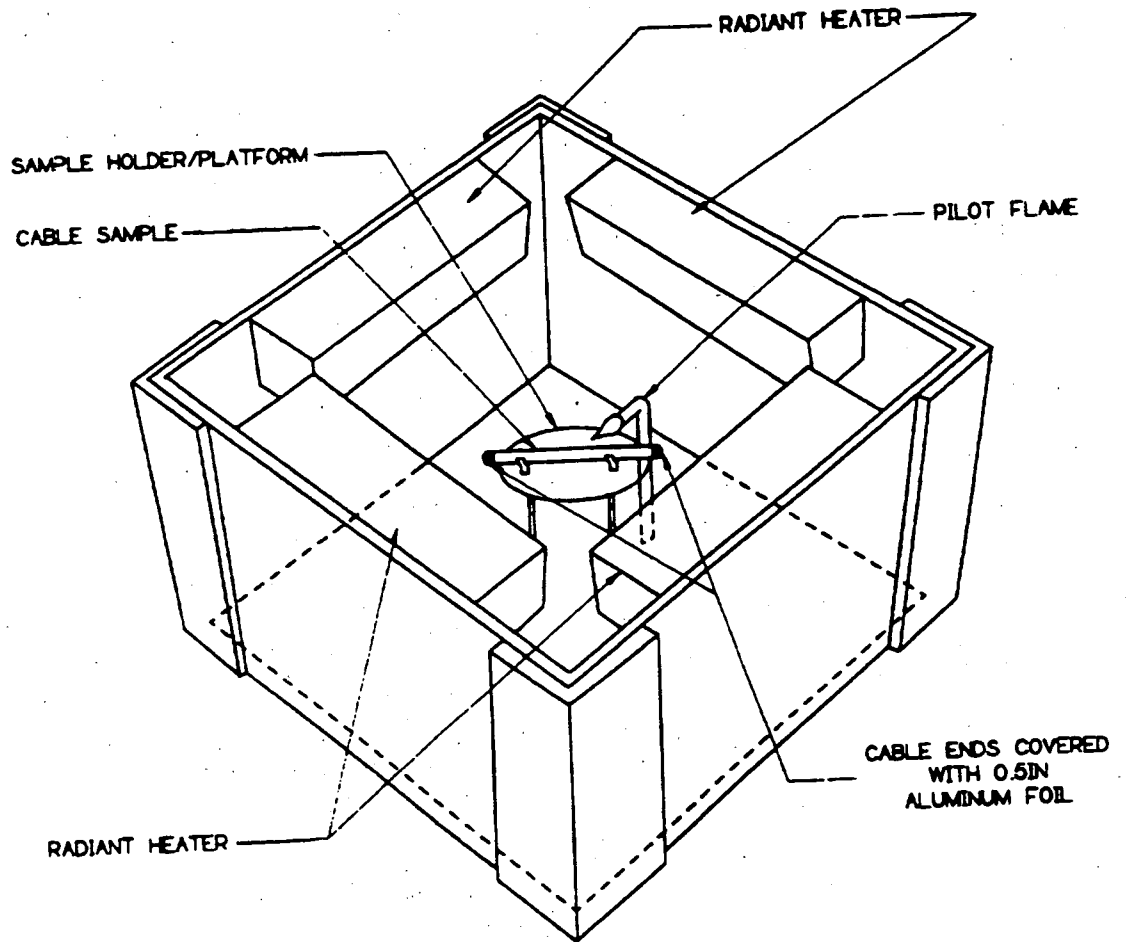


Figure B-2. Piloted Ignition Test Method Setup

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APPENDIX C

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FIRE PROPAGATION TEST METHOD**I GENERAL**

The objective of the fire propagation test method is to obtain the generation rates for CO and CO₂ for determining the Chemical Heat Release Rate for the evaluation of fire propagation behavior and for determining the Fire Propagation Index. Testing is conducted in the Factory Mutual Research Corporation Flammability 50kW Apparatus.

II TEST APPARATUS

The Factory Mutual Research Corporation 50 kW Flammability Apparatus is shown in Figure B-1. An overall sketch of the Apparatus in Figure C-1 shows the lower part of the Apparatus where the cable sample is placed for fire propagation testing.

For fire propagation testing, a minimum cable sample length of 32 inches (0.81 m) with a diameter not exceeding 2.0 in. (5.08 cm) is required. Except for jacketed metallic-armored cables, where the top 6 inches (0.15 m) of the jacket shall be removed, the exterior surface of the cable sample shall not be coated, cut, or otherwise changed or modified. Using the FMRC test sample holder as an example, the cable is inserted into the holder until it rests upon the base, is centered, then fastened near its bottom by three set screws in the base of the holder, and finally held firmly near its upper end by #24 gauge nichrome wire attached to the two upright supports. If other sample holder designs are used, the cable sample shall also be positioned so that it is centered and rests upon the base of the holder. In the test, the sample is surrounded by a quartz or Pyrex tube, 6 inches (152 mm) in diameter approximately 17 inches (432 mm) in length. Placed on top of the quartz or Pyrex tube is a 6 inch (152 mm) diameter stainless steel extension tube approximately 10 inches (254 mm) in length which directs all gases and particulates into the collection funnel. Holes 3/8 inch (9.5 mm) in diameter are drilled through the tube, vertically, for observation purposes. The cable height is adjusted so that 3.0 inches (76 mm) above the top edge of the base of the sample holder corresponds to the peak level of the directed external heat flux. The maximum heat flux location is determined during calibration testing of the instrument. The total vertical cable length above the base of the sample holder shall be 2 ft (0.61 m), and the cable length below this point shall be a minimum of 8 inches (0.20 m). The purpose of this lower, shielded end of the cable sample is to provide an adequate "cool" zone to minimize the likelihood that the sample will burn completely down to its bottom end and ignite any pooled liquid and/or gaseous cable decomposition products that may be present, creating a "pool fire" that is unrepresentative of actual cable fires.

The cable sample is surrounded by four radiant heaters and is exposed to 264 Btu/ft²/min (50 kW/m²) of external heat flux. For the ignition of the combustible cable vapors, a pilot flame located 3.5 inches (88.9 mm) above the bottom end of the cable is used. The pilot flame, adjusted to produce a blue-white flame, consists of a horizontal ethylene-air premixed flame, established at the ceramic tip of a 0.25 inch (6 mm) diameter metallic tube attached to ethylene and air cylinders. The pilot flame is about 0.4 inch (10 mm) long and is located within 0.4 inch (10 mm) from the cable surface as indicated in Figure C-1.

In the fire propagation test, for the simulation of large scale flame radiation conditions, air with an oxygen concentration of 40% is introduced at the air distribution chamber inlet and travels upward through the quartz (Pyrex) tube at a flow rate of 7 cfm (200 l/min) as shown in Figure C-1. The oxygen concentration of air is monitored by an oxygen analyzer and an air flow meter.

The fire products generated during fire propagation are captured in the sampling duct of the Apparatus as shown in Figure C-1. In the sampling duct, fire products and air are allowed to mix well before measurements are made for the concentrations of carbon monoxide (CO), carbon dioxide (CO₂), and volumetric flow rate (\dot{v}).

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The detailed description of the analyzers, calibration procedures and calculation formulas are described in the Factory Mutual Research Corporation Technical Report J.I. 0M2E1.RC "Electrical Cables - Evaluation of Fire Propagation Behavior and Development of a Small-Scale Test Protocol".

III TEST PROCEDURE

The equipment calibration procedures of the Factory Mutual Research Corporation Flammability Laboratory shall be used. The cable outer diameter shall be measured (the volume by displacement method, with the ends of the cable sealed with tape, is most accurate and is preferred) and recorded. An example of a typical test data sheet is shown in Appendix D. The cable diameter, along with the other test data requested by the data sheet, shall be entered into the computer.

The length of the cable sample shall be 32 inches (0.81 m). The cable, as supplied by the manufacturer, shall be clean of all foreign materials. If not supplied clean by the manufacturer, the sample length of cable shall be cleaned with a warm, soapy solution to remove any surface deposits, film or residue that may have some impact on ignition. Should any oil, grease or other foreign residue remain on the surface of the cable, it shall be removed by the use of methyl, ethyl or isopropyl alcohol. Care should be taken not to wet the insulation or filler materials of the cable. The cable shall then be towel-dried and allowed to stand at room temperature until the cable is completely dry. For jacketed metallic-armored cables, the top 6 inches (0.15 m) of the jacket shall be removed, preferably with a sharp utility knife. Jacketed metallic-armored cables are susceptible to "torching" behavior when the jacket covers the entire length of the sample. The vaporous decomposition products of the cable material within the armor that routinely exit the top of this type of cable during the test can be ignited by the burning external jacket. Such "torching" is unrepresentative of actual cable fires, and the removal of the top 6 inches of the jacket creates a "buffer zone" to minimize the likelihood of this behavior occurring. The sample shall be secured to the cable sample holder, both of which are then inserted into the central bore of the air distribution chamber.

The exhaust stack blast gate shall then be opened. The data acquisition system used shall be turned on to facilitate the monitoring of the calibration process. The exhaust stack's pressure transducer shall be adjusted to its reference zero value with the exhaust blower off. The exhaust blower shall be turned on. The CO₂, CO and O₂ analyzers shall be calibrated.

The pilot flame shall be lit and the ethylene and air mixture adjusted to produce a flame cone length of 0.4 inch (10 mm). The horizontal flame shall then be directed to within 0.4 inch (10 mm) of the cable's outer diameter surface. The quartz (Pyrex) tube shall be placed over the sample. The stainless steel extension tube shall be placed on top of the quartz (Pyrex) tube. The air flow into the bottom of the quartz (Pyrex) tube shall be set at 7 cfm (200 l/min). The oxygen concentration in the air entering the quartz (Pyrex) tube shall be increased to 40±1% by adding a metered concentration of 100% oxygen while also maintaining the proper apparatus air flow of approximately 7 cfm (200 l/min).

A test parameter file shall be created in the computer data acquisition system of the flammability apparatus. Upon completion of the parameter file, the test program shall be initiated to compile three minutes of background data (ambient conditions). The pilot flame shall be lit. The cable sample cooling shield shall be raised and its cooling water supply turned on for both the shield and the infrared radiant heaters. The infrared radiant heater's cooling air shall be turned on. The infrared radiant heater's power controller shall be turned on and adjusted to the 264 Btu/ft²/min (50 kW/m²) setting, which should be stabilized within 30 seconds. An additional 30 seconds shall be allowed, but not exceeded, before the start of the test is initiated. This protocol prevents re-radiated heat from affecting the cable above the protective cooling shield.

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The test shall now be started and a hand-held split/lap stopwatch immediately activated. The stopwatch shall be utilized to record event times, such as time to ignition. The cooling shield shall be dropped at the 30 second mark of the test. Observations of events and their times shall be noted. As the cable is exposed to the energy produced by the infrared radiant heaters, vapors will be generated. When they reach a combustible concentration, the vapors will be ignited by the pilot flame. Following the cable ignition, the pilot flame shall be turned off to prevent degradation of the quartz (Pyrex) tube. During the course of the test, exhaust gases are drawn from the exhaust stack and analyzed, and their concentrations of carbon monoxide (CO) and carbon dioxide (CO₂) recorded. The volumetric flow rate (v) shall be measured and recorded using the exhaust stack-mounted pitot tube. The cable shall be allowed to burn until it self-extinguishes. The program shall continue compiling data for three additional minutes following the extinguishment of the cable. After the three minutes have elapsed, the test program shall be terminated and the infrared radiant heaters and the supplementary oxygen supply shall be turned off. The cooling water and the air supply shall remain on until the end plates of the infrared radiant heaters reach a temperature which is cool to the touch. It is also advisable that the exhaust blower be left on to aid the quartz tube in its cooling-down process. The quartz tube should not be handled until it reaches ambient temperature; otherwise, the tube is very susceptible to cracking if disturbed while it is at an elevated temperature. Normally, 30 minutes are required for the tube to reach ambient temperature. The exhaust blower shall then be turned off.

Following completion of the test, the computer data acquisition system of the flammability apparatus shall process and format the accumulated data before the test results are printed. The computer software shall include an averaging program to "smooth out" the calculated FPI data generated over the length of the test. The program shall compute the 5--point rolling average of the Fire Propagation Index (the average of the CO and the CO₂ generation rate over 15 seconds, converted to FPI values, at the typical scan rate of the one scan every three seconds) and store the average peak FPI for the duration of the test. Such an averaging program is required to prevent an unrepresentative, transient fire "spike" from unduly influencing the peak FPI value that is reported and upon which the FMRC Group Number is based. Subsequently, a computer plot of the successive changes in the average Fire Propagation Index (0-30) versus time. A sample plot is shown in Appendix D. The Fire Propagation Index scale is divided into three Group Classifications identified as Group 1 (<10), Group 2 (≥10, <20), and Group 3 (≥20). If a group boundary is reached or crossed at any time, it shall be rated by the next higher Group classification.

For FMRC Specification Tested Products Listing, three individual fire propagation tests are required for each cable submitted for Listing. The three FPI peak values determined shall also be subjected to a statistical evaluation to determine their mean and standard deviation values. These calculated values shall then be substituted into the equation below. The FPI value thus obtained shall be the average peak value of the sample population, which shall be the basis of the FMRC Group Number classification of the cable sample.

$$FPI = 1.1 S_x + \bar{x}$$

where 1.1 = 90% confidence level factor for the sample size of three

S_x = Standard deviation

\bar{x} = Mean (average) value.

WARNING: WEAR SAFETY GLASSES AND EAR PROTECTORS. HANDLE SAMPLES WITH PROTECTIVE GLOVES. DO NOT REMOVE HOT CABLE SAMPLES FROM THE APPARATUS AFTER THE TEST; WAIT UNTIL THEY HAVE COOLED. AFTER THE TEST, DISCARD THE COLD RESIDUE IN SPECIAL CONTAINERS.

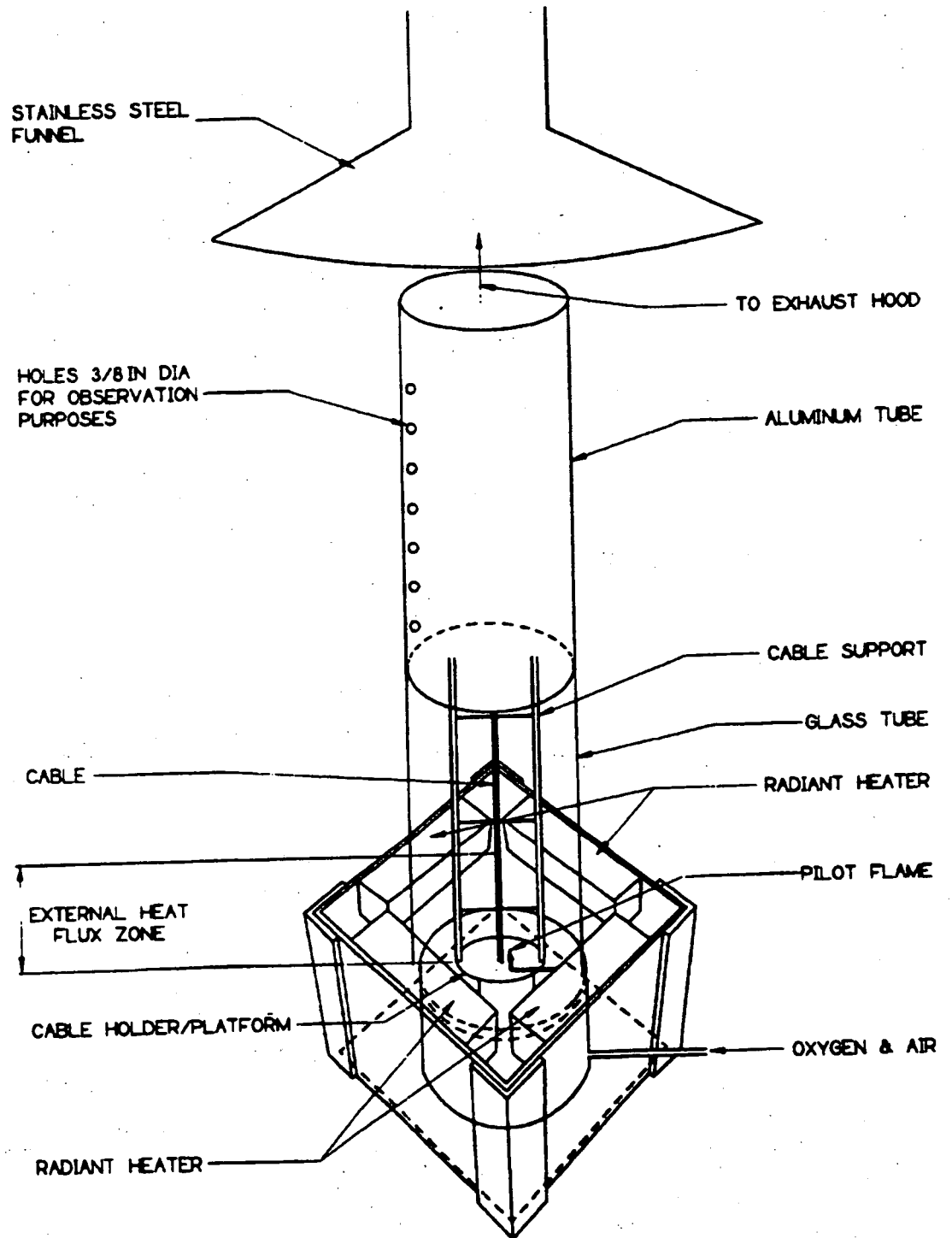


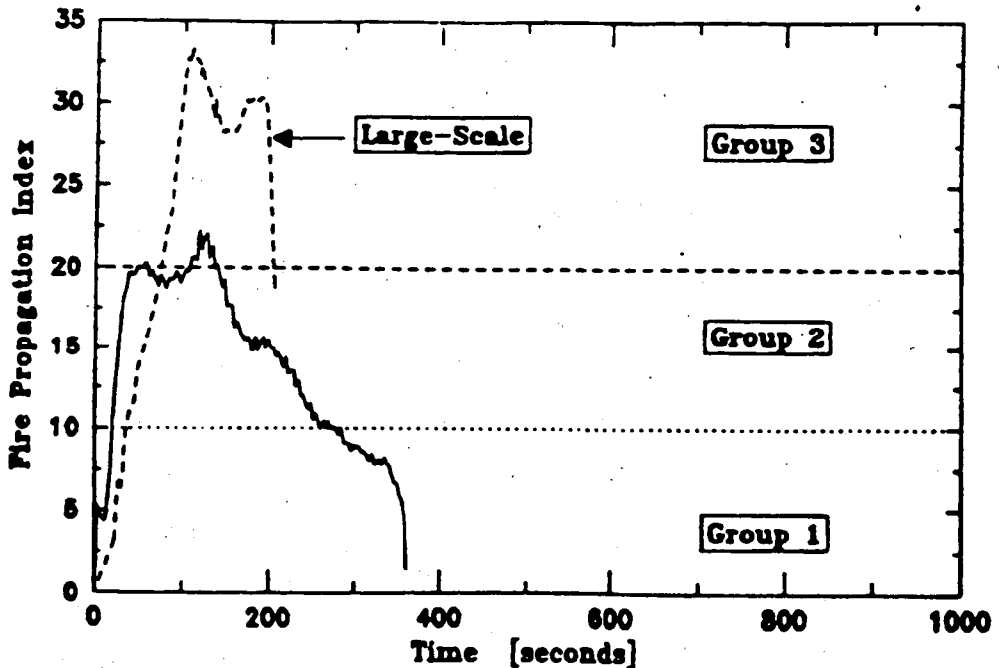
Figure C-1. FMRC (50 kW Scale) Flammability Apparatus, Lower Part

TEST DATA SHEET (An Example)

Sample Number:	RS 0001 (3-22-88)
Sample:	EPRI (FMRC #6)
Cable Type:	Not Known
Manufacturer/Supplier:	Not Known
Cable Insulation:	Polyethylene (PE)
Cable Jacket:	Polyvinyl Chloride (PVC)
Conductor Size:	12 AWG.
Number of Conductors/Volts:	3 / Not known
Diameter:	0.011 m.
Critical Heat Flux:	10 kW/m ²
Chemical Heat of Combustion:	Not Determined

Fire Propagation Test Conditions

Apparatus:	50 kW-Scale
Cable Length:	0.508 m
Ignition Flux:	50 kW/m ²
Oxygen Concentration:	40%
Factory Mutual Classification:	Group 3



Graph D-1. Fire Propagation Index Curves

UNITS OF MEASUREMENT

LENGTH:

in. - "inches"
(mm - "millimeters")

$$\text{mm} = \text{in.} \times 25.4$$

ft - "feet"
(m - "meters")

$$\text{m} = \text{ft} \times 0.3048$$

VOLUME:

ft³/min - "cubic feet per minute"
(l/min - "liters per minute")

$$\text{l/min} = \text{ft}^3/\text{min} \times 28.32$$

TEMPERATURE: °F - "degrees Fahrenheit"
(°C - "degrees Celsius")

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) \times 5/9$$

ENERGY:

Btu/ft²/min - "British thermal units per
square foot per minute"
(kW/m² - "kilowatts per square meter")

$$\text{kW/m}^2 = \text{Btu/ft}^2/\text{min} \times 0.1891$$

ATTACHMENT 6.3

Evaluation No. 5, Revision 1 of ENG-527

Penetration Fire Seal Program

ENG-527, Fire Barrier Inspections

Penetration Fire Seal Program
Evaluation No. 5, Rev. 1

1.0 PURPOSE

To establish criteria which will be used to evaluate those fire test reports referenced as qualification fire tests of typical design details of fire barrier penetration seals at Indian Point 3.

2.0 REFERENCES

- 2.1 Report titled "Review of the Indian Point Station Fire Protection Program", dated December 1976, revised April 1977
- 2.2 NRC Letter to the Authority dated April 26, 1978 regarding Request for Additional Information.
- 2.3 NRC Letter to the Authority dated June 1, 1978 regarding Staff Position P4, Cable Penetration Firestops.
- 2.4 Authority Letter IPO-125 to the NRC dated June 29, 1978 regarding response to RfAI requested April 26.
- 2.5 Authority Letter IPO-163 to the NRC dated October 23, 1978 regarding Staff Position P4, Cable Penetration Firestops.
- 2.6 NRC Letter to the Authority dated March 6, 1979 regarding the issuance of Amendment 24 to the facility operating license. Reference Section 4.9.
- 2.7 Authority Letter (JAF, JPN-80-53) to the NRC dated November 20, 1980 regarding License Amendment 47, Open Item 3.1.20, Electrical Cable Penetration Qualification.
- 2.8 NRC Letter to the Authority (JAF) dated February 13, 1981 regarding supplemental review and evaluation of Open Item 3.1.20, Electrical Cable Penetration Qualification.
- 2.9 NUREG 75/087; Branch Technical Position (BTP) APCS 9.5-1, Appendix A, "Guidelines for Fire Protection for Nuclear Power Plants Docketed Prior to July 1, 1976", dated August 23, 1976

Prepared By / Date: STWIKIE / 10/16/93

Reviewed By / Date: J. W. KENDRICK FOR J.M. TER TELEKON / 10/26/93

Approved By / Date: [Signature] / 10/26/93

- 2.10 NUREG 0800; Branch Technical Position CMEB 9.5-1, Revision 2, "Guidelines for Fire Protection for Nuclear Power Plants", dated July 1981
- 2.11 ASTM E-119, "Standard Test Method for Fire Tests of Building Construction and Materials"
- 2.12 ASTM E-814, "Standard Test Method for Fire Tests of Through-Penetration Fire Stops"
- 2.13 IEEE-634, "IEEE Standard Cable Penetration Fire Stop Qualification Test"
- 2.14 Information Notice 88-04 including Supplement 1, "Inadequate Qualification and Documentation of Fire Barrier Penetration Seals", dated February 5, 1988 and August 9, 1988 respectively.
- 2.15 NRC Generic Letter 86-10, "Implementation of Fire Protection Requirements", dated April 24, 1986
- 2.16 Con Ed Specification E-6068-3; "Fire and Heat Resistance Tests on 600V Power and Control Cable and Switch Board Wires" (refer to Attachment 1).
- 2.17 EPRI Report NP-1200; "Categorization of Cable Flammability Part 1: Laboratory Evaluation of Cable Flammability Parameters", dated October 1979.

3.0 DISCUSSION

Fire barrier penetration seals are installed with the intent that they will remain in place and retain their integrity when subjected to an exposure fire and subsequently, a fire suppression agent. In return, this will provide reasonable assurance that the effects of a fire are limited to discrete fire areas or zones and that one division of safe shutdown system will remain free of fire damage.

3.1 Historical Guidance

Branch Technical Position 9.5-1, Appendix A, Section D.1.(j) discusses design parameters for the installation of fire seals and electrical penetrations to the extent that:

Penetrations in these fire barriers including conduit and piping should be sealed or closed to provide a fire resistance rating at least equal to that of the barrier itself.

If barrier fire resistance cannot be made adequate, fire detection and suppression should be provided, such as:

- (i) Water curtain in case of fire,*
- (ii) Flame retardant coatings,*
- (iii) additional fire barriers*

Cable and cable tray penetrations of fire barriers (vertical and horizontal) should be sealed to give protection at least equivalent to that of the fire barrier. The design of fire barriers for horizontal and vertical cable trays should, as a minimum, meet the requirements of ASTM E-119, "Fire Test of Building Construction and Materials," including the hose stream test.

This position was later revised to include both clarification and expansion of the guidance regarding: testing and qualification of penetration seals, and to address the concern of internal conduit seals and smoke and hot gas seals. This guidance is not specifically applicable to Indian Point 3 due to the age of the plant and other specific commitments made relative to Amendment 24 to the facility operating license. However, the guidance has been included in this evaluation as a matter of completeness. Per NUREG 0800 (BTP CMEB 9.5-1), Section 5.a.(3):

Openings through fire barriers for pipe, conduit and cable trays which separate fire areas should be sealed or closed to provide a fire resistance rating at least equal to that of the barrier itself. Openings inside conduit larger than 4 inches in diameter should be sealed at the fire barrier penetration. Openings inside conduit 4 inches or less in diameter should be sealed at the fire barrier unless the conduit extends at least 5 feet on each side of the fire barrier and is sealed either at both ends or at the fire barrier with non-combustible material to prevent the passage of smoke and hot gases.

Penetration designs should utilize only noncombustible materials and should be qualified by tests. The penetration qualification tests should use the time-temperature exposure curve specified by ASTM E-119, "Fire Test of Building Construction and Materials." The acceptance criteria for the test should require that:

- (a) The fire barrier penetration has withstood the fire endurance test without the passage of flame or ignition of cables on the unexposed side for a period of time equivalent to the fire resistance rating required of the barrier.
- (b) The temperature levels recorded for the unexposed side are analyzed and demonstrate that the maximum temperature does not exceed 325°F.
- (c) The fire barrier penetration remains intact and does not allow projection of water beyond the unexposed surface during the hose stream test. The stream shall be delivered through a 1-1/2 inch nozzle set at a discharge angle of 30% with a nozzle pressure of 75 psi and a minimum discharge of 75 gpm with the tip of the nozzle a maximum of 5 ft from the exposed face; or the stream shall be delivered through a 1-1/2 inch nozzle set at a discharge angle of 15% with a nozzle pressure of 75 psi and a minimum discharge of 75 gpm with the tip of the nozzle a maximum of 10 ft from the exposed face; or the stream shall be delivered through a 2-1/2 inch national standard playpipe equipped with 1-1/8 inch tip, nozzle pressure of 30 psi, located 20 ft from the exposed face.

3.2 IP3 Related Commitments

During a site visit, the NRC promulgated a staff position regarding the qualification of cable penetration firestops to the extent that:

Staff Position P4

Cable Penetration Firestops should be qualified to a rating equal to the rating of the fire barriers. Firestop qualification may be accomplished by performing tests of the IP-3 firestop design to show conformance with the following position and provide the results of tests on equivalent design which have already been qualified and the basis for the equivalency. The tests should be performed in accordance with ASTM E-119, with the following exceptions:

- a. The cable used in the test should include the cable insulation material used in the facility.
- b. The test sample should be representative of the worst case configuration or cable loading, cable tray arrangement and anchoring, and penetration firestop size and design. The test sample should also be representative of the cable sizes in the facility. Testing of the firestop in the floor configuration will qualify the firestop for use in the wall configuration also.
- c. Cables penetrating the firestop should extend at least three feet on the unexposed side and at least one foot on the exposed side.
- d. The firestop should be tested in both directions unless the firestop is symmetrical.

- e. *The firestop should be tested with pressure differential across it that is equivalent to the maximum pressure differential a firestop in the plant is expected to experience.*
- f. *Temperature levels of the cable insulation, cable conductor, cable tray or conduit, and firestop material should be recorded for the unexposed side of the firestop.*
- g. *Acceptance criteria - the test is successful if:*
 - 1. *The cable penetration firestop has withstood the fire endurance test without passage of flame or ignition of cable on the unexposed side for a period equal to the required fire rating, and*
 - 2. *The temperature levels recorded for the unexposed side are analyzed and demonstrate that the maximum temperatures are sufficiently below the cable insulation ignition temperature, and*
 - 3. *The firestop remains intact and does not allow projection or water beyond the exposed surface during the hose stream test.*

3.3 General Test Method and Acceptance Criteria of ASTM E-119

Although not specifically written to address the testing and qualification of fire seals, ASTM E-119 was reviewed for its general test method and acceptance criteria. Conditions of acceptance and qualification of a test assembly (fire wall) shall be based on the following:

- *The [test assembly] shall have withstood the fire and hose stream test... without passage of flame, of hot gases hot enough to ignite cotton waste, or of the hose stream. The assembly shall be considered to have failed the hose stream test if an opening develops that permits a projection of water from the stream beyond the unexposed surface during the time of the hose stream test.*
- *Transmission of heat through the [test assembly] shall not have been such as to raise the temperature on its unexposed surface more than 250°F above its initial temperature.*

The conditions of acceptance and qualification are intended to demonstrate the limiting heat transmission capability of a test assembly and structural integrity. During the construction of the test assembly, the standard recognizes that thermocouple placement on the unexposed side is important in providing a representative average temperature rise so that the review and qualification can be consistently applied to each assembly tested. Per Section 6.2:

... None of the thermocouples shall be located opposite or on top of beams, girders, pilasters, or other structural members if temperatures at such points will obviously be lower than at more representative locations. None of the thermocouples shall be located over fasteners such as screws, nails or staples that will be obviously higher or lower in temperature than at a more representative location if the aggregate area of any part of such fasteners on the unexposed surface is less than 1% of the area within any 6 inch (152mm) diameter circle, unless the fasteners extend through the assembly.

The standard provides further discussion regarding the construction of the test assembly as it relates to "service or through-penetrations". Section X.5.7.4 states that:

Although the standard does not contain specific criteria for judging the impact of through joints nor "poke-through" devices such as electrical or telephone outlets, it should be recognized that these components should be evaluated with respect to structural performance and temperature rise criteria if they constitute a significant part of the test assembly.

3.4 Other Industry Standards and Guidance

IEEE 634

IEEE-634 which does address the testing and qualification of electrical fire seals was also reviewed for general test method and acceptance criteria. Conditions of acceptance and qualification of a test assembly (firestop) shall be based on the following:

- *The cable penetration fire stop shall have withstood the fire endurance test as specified without passage of flame or gases hot enough to ignite the cable or other fire stop material on the unexposed side for a period equal to the required fire rating.*
- *Transmission of heat through the cable penetration fire stop shall not raise the temperature on its unexposed surface above the self-ignition temperature as determined in ANSI K65.111-1971 of the outer cable covering, the cable penetration fire stop material, or material in contact with the cable penetration fire stop, when measured in accordance with 5.3.10 and 5.3.11. For power generating station, the maximum temperature is 700°F.*
- *The fire stop shall have withstood the hose stream test without the hose stream causing an opening through the test specimen.*

ASTM E-814

ASTM E-814 which also addresses the testing and qualification of electrical fire seals was reviewed for general test method and acceptance criteria. Conditions of review leading to acceptance and qualification of a test assembly (firestop) shall be based the appropriateness of either of two separate rating criteria. The first being an "F Rating" and the second being a "T rating". The F rating is based on the observation of the passage of flame and the T rating is based on the both the observation of the passage of flame and a temperature limitation of 325°F above ambient. Conditions of acceptance and qualification of both rating criteria shall be based on the following:

F Rating:

A fire stop shall be considered as meeting the requirements of an F rating when it remains in the opening during the fire test and hose stream test within the following limitations:

- *The fire stop shall have withstood the fire test for the rating period without permitting the passage of flame through openings, or the occurrence of flaming on any element of the unexposed side of the fire stops.*
- *During the Hose stream test, the fire stop shall not develop any opening that would permit a projection of water from the stream beyond the unexposed side.*

T Rating:

A fire stop shall be considered as meeting the requirements of a T rating when it remains in the opening during the fire test and hose stream test within the following limitations:

- *The transmission of heat through the fire stops during the rating period shall not have been such as to raise the temperature of any thermocouple on the unexposed surface of the fire stop or on any penetrating item more than 325°F (181°F) above its initial temperature. Also, the fire stop shall have withstood the fire test for the rating period without permitting the passage of flame through openings, or the occurrence of flaming on any element of the unexposed side of the fire stops.*
- *During the Hose stream test, the fire stop shall not develop any opening that would permit a projection of water from the stream beyond the unexposed side.*

It should be noted that the standard recognizes the validity of two separate arguments regarding the use of the temperatures of the unexposed surface to determine the performance of the fire stop to the extent that the authority having jurisdiction may choose either of the rating criteria depending of construction and the particular needs of the building.

IN 88-04

Information Notice 88-04 provides guidance with regard to conditions of acceptance when reviewing through penetrations to the extent that higher temperatures at through penetrations are permitted when justified in terms of cable ignitability.

3.5 Review of Maximum Temperature on the Unexposed Surface

The guidance and acceptance criteria of Staff Position 4 provides a means to evaluate the maximum temperature levels recorded on the unexposed surface to the extent that "...the maximum temperatures are sufficiently below the cable insulation ignition temperature". For the purpose of this evaluation, cable insulation ignition temperature has been defined as the minimum temperature to which a cable must be heated to in order to initiate or cause self-sustained combustion independently of the heating or heating source.

Since data regarding the cable insulation ignition temperature of cable used at IP3 is not readily available nor practical to obtain, the cable insulation ignition temperatures were evaluated based on past and current quality assurance requirements imposed at the time of purchasing.

As part of the past as well as the current quality assurance requirements imposed at the time of purchasing, samples of the cables types to be purchased were submitted to what has been commonly referred to as the Con Ed "Bon-fire Test". The Con Ed "Bon-fire Test" consists of exposing for 5 minutes, bundles of three to six cables to a flame produced by igniting transformer oil in a 12 inch pail. The cable are supported horizontally over the center of the pail with the lowest cable 3 inches above the top of the pail. The time to ignite the cable and the time the cable continued to flame after the fire extinguished were noted (refer to Attachment 1).

While the test did not specifically record the temperatures at which the cable ignited, it is conservative to assume that the initial temperature of the flame at the point of impingement at time zero of the test was approximately 1000-1200°F and was maintained for a period of 5 minutes as the transformer oil continued to burn. It is also recognized and implied as part of the conditions of acceptance and qualifications, that the cable would not self-sustain combustion independent of the transformer oil, pail fire as the time period the cable continued to burn was recorded. Therefore, based on a review of the test conditions under which the cables were subjected and the relative small mass of the cables verses the temperature and duration of the fire, a minimum self-ignition temperature of 700°F has been established for the purpose of this evaluation.

4.0 CONCLUSION

Based on the previous discussion, the general test method and acceptance criteria which will be used to evaluate the fire test reports which support the qualification of an approved seal design at Indian Point 3, is as follows:

1. The tested configuration shall be subjected to a 3-hour fire endurance test (or lesser exposure if a lesser fire rating is required) which corresponds to the standard time-temperature curve as specified in ASTM E-119, "Standard Methods of Fire Tests of Building Construction and Materials".
2. The tested configuration has withstood the fire endurance test without the passage of flame or gases hot enough to ignite cable, other penetrating items or seal material on the unexposed side. The maximum temperature is 700°F.
3. The unexposed side field thermocouple temperatures of the tested configuration shall not exceed 250°F plus ambient. The unexposed side interface and penetrating items thermocouple temperatures of the tested configuration should not exceed 250°F plus ambient. Penetration configurations whose temperatures exceed 250°F plus ambient may be evaluated and qualified on a case-by-case basis as long as all other acceptance criteria has been met and the maximum of temperatures recorded on the unexposed side are sufficiently below the self-ignition temperature of cable, other penetrating items or seal material on the unexposed side. The maximum temperature is 700°F.
4. The tested configuration has withstood an acceptable hose stream test where an acceptable delivery of that hose stream shall be one of the following:
 - a. A 1-1/2 inch nozzle at 30° discharge angle with a nozzle pressure of 75 psi and a minimum discharge of 75 gpm at a maximum distance of 5 feet from the exposed surface.
 - b. A 1-1/2 inch nozzle at 15° discharge angle with a nozzle pressure of 75 psi and a minimum discharge of 75 gpm at a maximum distance of 10 feet from the exposed surface.
 - c. A 2-1/2 inch standard playpipe with a 1-1/8 inch tip with a nozzle pressure of 30 psi at a distance of 20 feet from the exposed surface.

5. The duration of the hose stream test should be 2-1/2 minutes per 100 square foot of exposed surface.
6. The tested configuration shall remain intact without the projection of water beyond the unexposed surface for the duration of the hose stream test.

Attachment 1

Con Ed Specification E-6068-3; "Fire and Heat Resistance Tests on
600V Power and Control Cable and Switch Board Wires"

(see following pages)

ATTACHMENT 6.4

Record of Conversation
between A. Tewarson (FMRC) and S. Wilke (NYPA)
March 3, 1995



Memorandum

Record of Conversation

Participants: Steven Wilkie - NYPA Fire Protection Engineer
Dr. Archibald Tewarson - Factory Mutual Research Corp. (FMRC) Manager, Flammability Section

Date: March 3, 1995

Re: To discuss a perceived discrepancy between EPRI Report NP-1200, Table 5-1, and EPRI Report NP-1881, Table 3-1.

Ref.:
1. EPRI Report NP-1200 ; "Categorization of Cable Flammability Part 1: Laboratory Evaluation of Cable Flammability Parameters", dated October 1979
2. EPRI Report NP-1881, "Categorization of Cable Flammability, Intermediate-Scale Fire Tests of Cable Tray Installations", dated August 1982

Dr. A. Tewarson was contacted because he was one of the FMRC principal investigators for the tests conducted under EPRI Project 1165-1. These tests were subsequently documented in EPRI Report NP-1200 and others.

During the conversation, I pointed out that I believed an anomaly exists in Table 3-1 of EPRI Report NP-1881. I indicated that the Table identified the self-ignition temperature for a PE/PVC cable sample (Sample #5) is cited as 545°K and its piloted ignition temperature is cited as 789°K. I indicated that this conflicts with my understanding of the definitions of auto- and piloted ignition. I further pointed out that this information is identified as coming from earlier; Part I work which is identified as being documented in EPRI Report NP-1200.

Dr. Tewarson indicated that in his earlier work the critical temperatures were determined by interpretation and subsequent extrapolation of the test data. He briefly discussed some of the assumptions that were made which would question the accuracy of those determinations. He indicated that he would send me more accurate and up-to-date information which address the assumptions and refined testing methodology. Dr. Tewarson agreed that the cable sample's auto-ignition temperature would not be less than its piloted ignition temperature, all things being equal. He further indicated that the cable's auto-ignition temperature would be equal to or greater than its piloted ignition temperature.

ATTACHMENT 6.5

Summary of Penetration Fire Seal Test Reviews

Attachment 6.5

Summary of Fire Test Reviews

Electrical penetration fire seal tests are typically performed using maximum cable loading and worst case cable construction and jacketing (i.e. PVC jacketed cables of 600V rating). Mixtures typically included single conductor cables, multi-conductor cables and large diameter (power) cables. This Attachment summarizes qualifying test data on the two principle designs used to qualify the penetration seals at IP3. (Additional tests have been used to qualify unique parameters but the methodology remains the same.) These test details show that penetration seal unexposed surface (field) temperatures exceeded 325°F in only three of the eight tests. Only one of these three tests was of an electrical penetration, and that field temperature was only 330°F, achieved in the final eight minutes of the test. The other examples where 325°F was exceeded were of mechanical penetration seal designs where the maximum field temperatures were 357°F and 398°F.

For each qualifying seal configuration tested of the seals tested no flame or ignition of cables occurred on the unexposed side for the period equal to the rating and the fire seal remained intact and did not allow water projection beyond the unexposed surface during the hose stream test. In the fire tests, the maximum temperatures that were be reached on the unexposed side are generally due to large diameter (power) cable or metallic penetrating items.

This Attachment represents a summary review of the qualifying tests. For details regarding penetrations and testing method as well as post-test observations, refer to the actual test reports.

Attachment 6.5

Design Detail: E-1, Silicone Elastomer Typical Electrical Penetration Seals, (Walls & Floors)

1.0 Summary of Detail:

- | | | |
|-----|----------------------------|--|
| 1.1 | Maximum Opening Size: | 19-1/2 sq.ft. ¹ |
| 1.2 | Penetrants Allowed: | Cable trays
Conduit ² |
| 1.3 | Orientation: | wall or floor |
| 1.4 | Minimum Barrier Thickness: | 6", concrete |
| 1.5 | Seal Depth & Material: | 6" silicone elastomer with
no ceramic damming |
| 1.6 | Notes: | |
- 1) The maximum opening size is also limited by the maximum unsupport area (maximum free rectangular area) of 7-1/2" sq.ft.
 - 2) Internal conduit seals (i.e., fire seal, smoke & hot gas seal or no seal) is based on criteria discussed in Evaluation No. 3 of ENG-527.

2.0 Qualifying Fire Tests:

TS-TP-0018

TS-TP-0084

Attachment 6.5

E-1 (Continued)

2.1 Fire Test: TS-TP-0018

- 2.1.1 Performed at: Construction Technology Laboratories
of the Portland Cement Association
- 2.1.2 For: Tech-Sil, Inc.
- 2.1.3 Date: August, 1979
- 2.1.4 Qualifying Seal Configuration: single opening (blockout)
- 2.1.4.1 Opening Size: 32" x 32" opening¹
- 2.1.4.2 Penetrants: Two solid bottom cable trays²
Three 4" rigid steel conduits³
One 2" PVC coated flex conduit
One ground cable⁴
- 2.1.4.3 Comb. Penetrant & Material: Cable⁵ & PVC coated
flex conduit
- 2.1.4.4 Orientation: Slab
- 2.1.4.5 Slab or Wall Thickness: 12", concrete
- 2.1.4.6 Seal Depth & Material: 6" silicone elastomer
no ceramic damming
- 2.1.4.7 Max. Unexposed Surface Temp.: 240°F³ in the field,
~550°F⁶ on the jacket
of a 500 MCM cable in
the power cable tray
- 2.1.4.8 Notes:

- 1) A ¼" thick steel plate was provided on two sides of the opening (at right angle to each other) to simulate a lined or sleeved opening.
- 2) One cable trays was a 24" x 4" cable tray filled with typical power cables (cable fill approx. 58%, actual), and the other was a 24" x 6" cable tray filled with typical control cables (fill approx. 43% actual).

Attachment 6.5

E-1 (Continued)

2.1 Fire Test: TS-TP-0018(Continued)

- 3) The three rigid conduits internally sealed with silicone elastomer were investigated as part of the fire test, but was not reviewed as part on this review. Internal conduit seals (i.e., fire seal, smoke & hot gas seal or no seal) is based on criteria discussed in Evaluation No. 3 of ENG-527.
- 4) The Ground cable was fabricated by stripping a 1/C 1/0 cable.
- 5) Cables used were representative of those used at W.H.Zimmer NPP. They were primarily cables of EPR insulation and Hypalon jacketing.
- 6) A temperature of ~750°F was noted on the conductor of the 500 MCM cable in the power cable tray. This temperature is considered acceptable as the cable jacket temperature did not exceed 700°F. It is believed that the temperature gradient between the cable conductor and the outside jacket exists due to the insulating properties of the insulation and jacket material.
- 7) The test was conducted using the standard time temperature curve for 3-hours (ASTM E119); fire did not propagate to the unexposed side nor did any cable ignite on the unexposed side during the 3-hour exposure period. Two hose stream tests were performed. One in accordance with the requirements of ASTM E119 and the other with IEEE 634-1978. The duration of each hose stream was 24 seconds. Water did not project beyond the unexposed surface for the hose stream test period.

Attachment 6.5

E-1 (Continued)

2.2 Fire Test: TS-TP-0084

- 2.2.1 Performed at: Construction Technology Laboratories
of the Portland Cement Association
- 2.2.2 For: Tech-Sil, Inc.
- 2.2.3 Date: April, 1982
- 2.2.4 Qualifying Seal Configuration: single opening (blockout)
- 2.2.4.1 Opening Size: 53" x 53" opening¹
- 2.2.4.2 Penetrants: Two cable trays²
Other³
- 2.2.4.3 Comb. Penetrant & Material: Cable, (PVC jacketing)
- 2.2.4.4 Orientation: Slab
- 2.2.4.5 Slab or Wall Thickness: 6", concrete
- 2.2.4.6 Seal Depth & Material: 6" silicone elastomer
no ceramic damming
- 2.2.4.7 Max. Unexposed Surface Temp.: 130°F in the field,
413°F at the cable
tray-to-seal interface
- 2.2.4.8 Notes:

- 1) A ¼" thick steel plate was provided on two sides of the opening (at right angle to each other) to simulate a lined or sleeved opening.
- 2) A 24" x 4" cable tray was filled approx. 110%, visual, and a 30" x 4" cable tray was filled with approx. 105%, visual.

Attachment 6.5

E-1 (Continued)

2.2 Fire Test: TS-TP-0084 (Continued)

- 3) A piece of unistrut was embedded in the fire seal 3" below the unexposed surface. The unistrut was divided the fire seal in half. The unistrut was welded to the $\frac{1}{4}$ " thick steel plate on one side of the opening and anchored to the concrete on the other side. Post test observations indicated that the unistrut had warped during the exposure fire test.
- 4) The test was conducted using the standard time temperature curve for 3-hours (ASTM E119); fire did not propagate to the unexposed side nor did any cable ignite on the unexposed side during the 3-hour exposure period. Two hose stream tests were performed. One in accordance with the requirements of ANI test criteria and the other in accordance with IEEE 634-1978. The duration of each hose stream was 4 minutes and 48 seconds. Water did not project beyond the unexposed surface for the hose stream test period.

Attachment 6.5

Design Detail: E-4, Silicone Foam, Typical Electrical Penetration Seals, (Walls & Floors)

1.0 Summary of Detail:

1. Maximum Opening Size: Not limited
2. Penetrants Allowed: Cable trays
Conduit¹
3. Orientation: wall or floor
4. Minimum Barrier Thickness: unspecified², concrete
5. Seal Depth & Material: 10" silicone foam with 1" ceramic damming
6. Notes:

- 1) Internal conduit seals (i.e., fire seal, smoke & hot gas seal or no seal) is based on criteria discussed in Evaluation No. 3 of ENG-527.
- 2) Where walls or floors are less than the required 12" to support installation of the fire seal within the plane of the barrier, the seal can be "boxed-out" exterior to the wall plane.

2.0 Qualifying Fire Tests:

2.0.1 TS-TP-0004

Attachment 6.5

E-4 (Continued)

2.1 Fire Test: TS-TP-0004

- 2.1.1 Performed at: Southwest Reseach Institute
- 2.1.2 For: Tech-Sil, Inc.
- 2.1.3 Date: January, 1977
- 2.1.4 Qualifying Seal Configuration: Penetration No. 1
- 2.1.4.1 Opening Size: 48" x 48" opening
- 2.1.4.2 Penetrants: Four 18" wide solid bottom cable trays
Four 18" wide ladder bottom cable trays
- 2.1.4.3 Comb. Penetrant & Material: Cable¹
- 2.1.4.4 Orientation: Slab
- 2.1.4.5 Slab or Wall Thickness: 12", concrete
- 2.1.4.6 Seal Depth & Material: 10" silicone foam²
with 1" ceramic damming
- 2.1.4.7 Max. Unexposed Surface Temp.: -330°F³ in the field
- 2.1.4.8 Notes:

- 1) Each cable tray was filled with 5 cable bundles. Each cable bundle consisted of 6-250 MCM cables, 9-7/C #12 cables and 16-2/C #14 cables. All cable was constructed wuith PVC insulation and PVC jacketing.
- 2) The fire seal was installed such that the damming was flush with the exposed side and exposed to the furnace and the silicone foam was present of the unexposed side of the test slab.
- 3) Exact thermalcouple location was not cited. It is assumed that the location was in the field on the unexposed side seal surface.

Attachment 6.5

E-4 (Continued)

2.1 Fire Test: TS-TP-0004 (Continued)

- 4) The test was conducted using the standard time temperature curve for 3-hours (ASTM E119); fire did not propagate to the unexposed side nor did any cable ignite on the unexposed side during the 3-hour exposure period. Cable ignition did occur for a brief period after the endurance test enroute to the hose stream test area. A hose stream test was performed in accordance with the requirements of ASTM E-119. The duration of the hose stream was 82 seconds. Water did not project beyond the unexposed surface for the hose stream test period.

Attachment 6.5

Design Detail: M-1, Silicone Elastomer, Typical Mechanical Penetration Seals, (Walls & Floors)

1.0 Summary of Detail:

1. Maximum Opening Size: Sleeved or unsleeved, maximum opening dependant on annular gap¹.
2. Penetrants Allowed: piping with or without insulation
3. Orientation: wall or floor
4. Minimum Barrier Thickness: 6", concrete
5. Seal Depth & Material: 6" silicone elastomer with no ceramic damming
6. Notes:

1) Maximum annular gap shall be 11-1/4" and the minimum annular gap shall be 1/8". Annular gaps less than 1/8" are allowed if the affected area is stuffed with 2" of ceramic fiber and covered with a bead of silicone adhesive caulk.

2.0 Qualifying Fire Tests:

TS-TP-0048C

TS-TP-0073B

TS-TP-0075B

Attachment 6.5

M-1 (Continued)

2.1 Fire Test: TS-TP-0048C

- 2.1.1 Performed at: Construction Technology Laboratories
of the Portland Cement Association
- 2.1.2 For: Tech-Sil, Inc.
- 2.1.3 Date: August, 1980
- 2.1.4 Qualifying Seal Configuration: single opening (corebore)
- 2.1.4.1 Opening Size: 14" diameter unsleeved opening
- 2.1.4.2 Penetrants: Two 2" diameter steel pipes. (1-pipe
was insulated with 1" thick thermal
insulation and aluminum jacket
- 2.1.4.3 Comb. Penetrant & Material: None
- 2.1.4.4 Orientation: Slab
- 2.1.4.5 Slab or Wall Thickness: 12", concrete
- 2.1.4.6 Seal Depth & Material: 6" silicone elastomer¹ no
ceramic damming
- 2.1.4.7 Max. Unexposed Surface Temp.: 249°F in the field, 690°F on
the uninsulated pipe
- 2.1.4.8 Notes:
- 1) The fire seal was installed such that the seal was
flush with the exposed side and exposed to the furnace.

Attachment 6.5

M-1 (Continued)

2.1 Fire Test: TS-TP-0048C

- 2) The test was conducted using the standard time temperature curve for 3-hours (ASTM E119); fire did not propagate to the unexposed side nor did any cable ignite on the unexposed side during the 3-hour exposure period. Two hose stream tests were performed. One in accordance with the requirements of IEEE 634-1978 and the other in accordance with the requirements of ASTM E119. The duration of each hose stream was 12 seconds. Water did not project beyond the unexposed surface for the hose stream test period.

Attachment 6.5

M-1 (Continued)

2.2 Fire Test: TS-TP-0073B

- 2.2.1 Performed at: Construction Technology Laboratories
of the Portland Cement Association
- 2.2.2 For: Tech-Sil, Inc.
- 2.2.3 Date: April, 1981
- 2.2.4 Qualifying Seal Configuration: single opening (sleeve)
- 2.2.4.1 Opening Size: 12" diameter sleeved
opening
- 2.2.4.2 Penetrants: Two 2" diameter steel pipes. (1-
pipe was insulated with 1-1/2"
thick calcium silicate insulation
and aluminum jacket
- 2.2.4.3 Comb. Penetrant & Material: None
- 2.2.4.4 Orientation: Slab
- 2.2.4.5 Slab or Wall Thickness: 12", concrete
- 2.2.4.6 Seal Depth & Material: 5" silicone elastomer¹ no
ceramic damming
- 2.2.4.7 Max. Unexposed Surface Temp.: 398°F in the field, 717°F³ at
the interface
- 2.2.4.8 Notes:
- 1) The fire seal was installed such that the seal was
flush with the exposed side and exposed to the furnace.
 - 2) The depth of the test fire seal configuration was 5"
with no ceramic damming, if the seal depth had been
increased to 6", it is expected that the resulting
maximum unexposed surface temperatures would be similar
to those experienced in Fire Test TS-TP-0048C.

Attachment 6.5

M-1 (Continued)

2.2 Fire Test: TS-TP-0073B(Continued)

- 3) The test was conducted using the standard time temperature curve for 3-hours (ASTM E119); fire did not propagate to the unexposed side nor did any cable ignite on the unexposed side during the 3-hour exposure period. Three hose stream tests were performed. One in accordance with the requirements of IEE 634-1978, one in accordance with ANI test criteria and the last in accordance with ASTM E119. The duration of each hose stream was 12 seconds. Water did not project beyond the unexposed surface for the hose stream test period.

Attachment 6.5

M-1 (Continued)

2.3 Fire Test: TS-TP-0075B

- 2.2.1 Performed at: Construction Technology Laboratories
of the Portland Cement Association
- 2.2.2 For: Tech-Sil, Inc.
- 2.2.3 Date: August, 1981
- 2.2.4 Qualifying Seal Configuration: Penetration H
- 2.2.4.1 Opening Size: 12" x 12" sleeved opening¹
- 2.2.4.2 Penetrants: 5- $\frac{1}{4}$ " diameter copper tubes
1-2 $\frac{5}{8}$ " diameter pipe with $\frac{1}{2}$ "
thick insulation with an
aluminum jacket
- 2.2.4.3 Comb. Penetrant & Material: none
- 2.2.4.4 Orientation: Slab
- 2.2.4.5 Slab or Wall Thickness: 12", concrete
- 2.2.4.6 Seal Depth & Material: 5" silicone elastomer²
no ceramic damming
- 2.2.4.7 Max. Unexposed Surface Temp.: 316°F in the field,
603°F at the sleeve-
to-seal interface²
- 2.2.4.8 Notes:

- 1) A $\frac{1}{4}$ " thick steel plate was provided on four sides of the opening to simulate a sleeved opening. The steel plate extended 6" above and 12" below (exposed side) the test slab. An 1/8" gap sealed with silicone adhesive caulk was also investigated as part of the fire test, but was not reviewed as part of this review. This type of seal was not reviewed as part of the qualifying seal configuration.
- 2) The fire seal was installed flush with the exposed side of the test slab.

Attachment 6.5

M-1 (Continued)

2.3 Fire Test: TS-TP-0075B

- 3) A higher temperature was experienced at the 5/32" gap. However, this temperature was not considered in this review as it is associated with a fire seal of silicone adhesive caulk; refer to Note 1.
- 4) The depth of the qualifying seal configuration was 5" with no ceramic damming, if the seal depth is increased to 6", it is expected that the resulting maximum unexposed surface temperatures would be similar to those experienced in Fire Test TS-TP-0048C.
- 5) The test was conducted using the standard time temperature curve for 3-hours (ASTM E119); fire did not propagate to the unexposed side nor did any cable ignite on the unexposed side during the 3-hour exposure period. Three hose stream tests were performed. One in accordance with the requirements of IEE 634-1978, one in accordance with ANI Fire Seal Test Criteria and the last in accordance with ASTM E119. The duration of each hose stream was 12 seconds. Water did not project beyond the unexposed surface for the hose stream test period.

Attachment 6.5

Design Detail: M-8, "Silicone Foam, Typical Mechanical Penetration Seals, Walls & Floors"

1.0 Summary of Detail:

- 1.1 Maximum Opening Size: Sleeved or unsleeved, maximum opening dependant on annular gap¹.
- 1.2 Penetrants Allowed: Piping with or without insulation
- 1.3 Orientation: wall or floor
- 1.4 Minimum Barrier Thickness: 12", concrete
- 1.5 Seal Depth & Material: 10" silicone foam with 1" ceramic damming
- 1.6 Notes:

1) Maximum annular gap shall be 11-5/8" and the minimum annular gap shall be 1/16".

2.0 Qualifying Fire Tests:

TS-TP-0075A

TS-TP-0050D

Attachment 6.5

M-8 (Continued)

2.1 Fire Test: TS-TP-0075A

- 2.1.1 Performed at: Construction Technology Laboratories of the Portland Cement Association
- 2.1.2 For: Tech-Sil, Inc.
- 2.1.3 Date: July, 1981
- 2.1.4 Qualifying Seal Configuration: Penetration F
- 2.1.4.1 Opening Size: 12" x 12" opening¹
- 2.1.4.2 Penetrants: One 2-5/8" diameter steel pipe insulated with 1/2" thick thermal insulation and aluminum jacket
Five 1/4" diameter copper tubes
- 2.1.4.3 Comb. Penet. & Material: None
- 2.1.4.4 Orientation: Slab
- 2.1.4.5 Slab or Wall Thickness: 12", concrete
- 2.1.4.6 Seal Depth & Material: 9" silicone foam² with 1" ceramic damming/M-board
- 2.1.4.7 Max. Unexposed Surface Temp.: 357°F³ in the field, 391°F on the uninsulated pipe
- 2.1.4.8 Notes:
- 1) A 1/4" thick steel plate was provided on three sides of the opening to simulate a sleeved opening. The steel plate extended 6" above and 12" below (exposed side) the test slab. An 1/8" gap sealed with silicone foam and no damming material was also investigated as part of the fire test, but was not reviewed as part of this review.
 - 2) The fire seal was installed with the damming material flush with the exposed surface and 9" silicone foam installed over the 1" thick damming material.

Attachment 6.5

M-8 (Continued)

2.1 Fire Test: TS-TP-0075A(Continued)

- 3) If seal depth is increased to 6" it is expected that the resulting maximum unexposed surface temperatures would be similar to those experienced in Fire Test TS-TP-0050D
- 4) The test was conducted using the standard time temperature curve for 3-hours (ASTM E119); fire did not propagate to the unexposed side nor did any cable ignite on the unexposed side during the 3-hour exposure period. Two hose stream tests were performed. One in accordance with the requirements of ASTM E119 and the other with IEEE 634-1978. The duration of each hose stream was 12 seconds. Water did not project beyond the unexposed surface for the hose stream test period.

Attachment 6.5

M-8 (Continued)

2.2 Fire Test: TS-TP-0050D

- 2.2.1 Performed at: Construction Technology Laboratories
of the Portland Cement Association
- 2.2.2 For: Tech-Sil, Inc.
- 2.2.3 Date: August, 1980
- 2.2.4 Qualifying Seal Configuration: single opening
- 2.2.4.1 Opening Size: 12" diameter unsleeved opening
- 2.2.4.2 Penetrants: Two 2" diameter steel pipes (One
pipe was insulated with 1" thick
thermal insulation and aluminum
jacket)
- 2.2.4.3 Comb. Penetrant & Material: none
- 2.2.4.4 Orientation: Slab
- 2.2.4.5 Slab or Wall Thickness: 12", concrete
- 2.2.4.6 Seal Depth & Material: 10" silicone foam¹
with 1" ceramic
damming
- 2.2.4.7 Max. Unexposed Surface Temp.: 277°F in the field,
647°F at the seal-to-
pipe interface
- 2.2.4.8 Notes:
- 1) The fire seal was installed such that the silicone foam was flush with the exposed side and exposed to the furnace and the damming material was present on the unexposed side of the test slab.

Attachment 6.5

M-8 (Continued)

2.2 Fire Test: TS-TP-0050D(Continued)

- 2) The test was conducted using the standard time temperature curve for 3-hours (ASTM E119); fire did not propagate to the unexposed side nor did any cable ignite on the unexposed side during the 3-hour exposure period. Two hose stream tests were performed. One in accordance with the requirements of IEEE 634-1978 and the other in accordance with ASTM E119. The duration of each hose stream was 12 seconds. Water did not project beyond the unexposed surface for the hose stream test period.

ATTACHMENT 6.6

FMRC Letter to EPRI, Dated May 10, 1995



Factory Mutual Research

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May 10, 1995

Mr. Robert Kassawara
Manager Nuclear Power
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304

Reference: EPRI Interim Reports EPRI NP-1200 and 1767, Project 1165-1 and 1165-1-1, October 1979 and March 1981

Dear Mr. Kassawara:

It has come to my attention that utilities are using the Critical Heat Flux data from these reports for the assessment of fire risks associated with cable penetration. The data presented in these reports, however, are in error due to the following reasons:

As you know, the EPRI project was the first project to utilize the fundamental knowledge of polymer combustion science developed at the Factory Mutual Research Corporation to electrical cables. Several assumptions had to be made due to lack of understanding of the cable combustion. Two critical assumption applicable to ignition were: 1) surface absorptivities of cables are unity, and 2) cables behave as thermally thin, because the jacket as well as the insulation are physically thin.

Since the issuance of the reports, we have been studying the fundamental aspects of the combustion of the cables and have developed an extensive data base on the ignition and fire propagation of the cables. In fact, the research has led to the development of the Specification Standard for Cable Fire Propagation, Class No. 3972 by the Factory Mutual Research Corporation. The Standard utilizes the Fire Propagation Index (FPI) concept, where the fire propagation behavior is assessed by quantifying the FPI value. The quantification takes into account ignition as well as the heat release rate (flame heat flux transferred back to the surface). *An FPI value of less than 7 would be needed for the cables used in the nuclear reactors.* The FPI value based electrical cable standard is being used extensively in our plants throughout the world for fire protection needs.

The FPI value based concept has recently been used for the conveyor belts and a standard is to be issued shortly. The U.S. Mine Safety and Health Administration is interested in adopting it as a standard test method for conveyor belts to be used in mines. EPRI is in a very good position to encourage utilities to adopt the FPI value based standard for cable specifications.

We now have a data base for the Critical Heat Flux, Thermal Response Parameter, and Fire Propagation Index values for over 300 cables. We have not found any cable with Critical Heat Flux less than 10 kW/m². We have also performed correlations with the existing IEEE and other cable standard test results. We find that the electric cable standards currently in use do not

provide consistent results and no quantitative data are reported. We will be happy to compile the data for EPRI for the use of the utilities on a contract basis.

I will be happy to talk to you and discuss the matter further. My telephone number is 617-255-4940 and my fax number is 617-255-4024.

With best wishes.

Sincerely,

A handwritten signature in black ink, appearing to read 'A. Tewarson', written in a cursive style.

A. Tewarson, Ph.D.
Manager, Flammability Section

cc C. Yao, FMRC

cc R.L. Alpert, FMRC

cc A. Ettliger, New York Power Authority

ATTACHMENT 6.7

Licensing Attachments

- Attachment 1 - Exerpt from original FSAR
- Attachment 2 - Exerpt from current FSAR
- Attachment 3 - Exerpt from BTP 9.5.1 response
- Attachment 4 - Exerpt from Amendment 24
- Attachment 5 - Exerpt from FPRM
- Attachment 6 - Exerpt from NYPA Letter IPN-79-2
- Attachment 7 - Exerpt from Amendment 24
- Attachment 8 - Exerpt from first update to IP3 FSAR
- Attachment 9 - Exerpt from current FSAR
- Attachment 10 - Exerpt from FPRM

Attachment 1 - From original FSAR

Cables which do not require channeling may be run in any tray or conduit; however, once it has entered a tray or raceway containing a channeled cable, it shall not leave this channel and enter another tray containing a cable from a different channel.

To assure that only fire retardant cables are used throughout the plant, a careful study of cable insulation systems was undertaken early in the design. Insulation systems that have superior flame retardant capability were selected and manufacturers were invited to submit cable samples for testing. An extensive flame testing program took place which included ASTM vertical flame testing and Consolidated Edison Company vertical flame and bonfire tests as described below. These flame tests were used as one of the means of qualifying cables and specifications were written on the basis of the results from the tests.

The following tests were made to determine the flame resistant qualities of the covering and insulations of various types of cables for Indian Point #2 and #3.

- 32
- 1) Standard Vertical Flame Test - made in accordance with ASTM-D-470-59T, "Tests for Rubber and Thermalplastic Insulated Wire and Cable".*
 - 2) Five-Minute Vertical Flame Test - made with cable held in vertical position and 1750°F flame applied for five minutes.
 - 3) Bonfire Test - Consisting of exposing, for five minutes, bundles of three or six cables to flame produced by igniting transformer oil in 12-inch pail. The cable was supported horizontally over the center of the pail, the lowest cable three inches above the top of the pail. The time to ignite the cable and the time the cable continued to flame after the fire was extinguished were noted.

On the basis of these tests, the cables were selected for the reactor containment vessel for both Unit #2 and Unit #3.

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* This Standard has since been revised and the provisions of the currently approved version [ASTM-D-470-71] are less restrictive than the requirements of Tests 2) and 3). Therefore, cable procured by Consolidated Edison after 1971 is qualified in accordance with the more stringent requirements of the Five-Minute Vertical Flame Test and the Bonfire Test.

Attachment 2

From current FSAR

IP3 FSAR UPDATE

For physical loading of trays, the following criteria was followed: 6.9 kV power, one horizontal row of cables with spacing was allowed in a tray; 480 volt power, two horizontal rows of cables were allowed in a tray (if derating requirements did not dictate less); for control and instrumentation, the tray was filled to a point just below the top (the total cable area for this configuration is 60% of tray cross-sectional area). A computer program was used to monitor cable routing and tray loading.

Cables which do not require channeling may be run in any tray or conduit; however, once it entered a tray or raceway containing a channeled cable, it does not leave this channel and enter another tray containing a cable from a different channel.

To assure that only fire retardant cables were used throughout the plant, a careful study of cable insulation systems was undertaken early in the design. Insulation systems that have superior flame retardant capability were selected and manufacturers were invited to submit cable sample for testing. An extensive flame testing program took place which included ASTM vertical flame testing and Consolidated Edison Company vertical flame and bonfire tests as described below. These flame tests were used as one of the means of qualifying cables and specifications were written on the basis of the results from the tests.

The following tests were made to determine the flame resistant qualities of the covering and insulations of various types of cables for Indian Point 3:

- 1) Standard Vertical Flame Test - made in accordance with ASTM-D-470-59T, "Test for Rubber and Thermalplastic Insulated Wire and Cable".*
- 2) Five-Minute Vertical Flame Test - made with cable held in vertical position and 1750 F flame applied for five minutes.
- 3) Bonfire Test - Consisting of exposing, for five minutes, bundles of three or six cables to flame produced by igniting transformer oil in 12-inch pail. The cable was supported horizontally over the center of the pail, the lowest cable three inches above the top of the pail. The time to ignite the cable and the time the cable continued to flame after the fire was extinguished were noted.

On the basis of these tests, the cables were selected for the Reactor Containment Building for Indian Point 3.

This Standard has since been revised and the provisions of the currently approved version (ASTM-D-470-71) are less restrictive than the requirements of Tests 2) and 3). Therefore, cable procured by Consolidated Edison and the Authority after 1971 is qualified in accordance with the more stringent requirements of the Five-Minute Vertical Flame Test and the Bonfire Test.

Attachment 3 (page 1 of 2)

8.45 Branch Technical Position

From 12/9/76 submittal

D.3(e) Fire Breaks - Fire breaks should be provided as deemed necessary by the fire hazards analysis. Flame or flame retardant coatings may be used as a fire break for grouped electrical cables to limit spread of fire in cable ventings. (Possible cable derating owing to use of such coating materials must be considered during design.)

Conformance With Guidelines

The fire retardant construction and non-propagating properties of the cables used at Indian Point, as described in Paragraph 8.46, provide the equivalent of fire breaks between areas. This, in conjunction with the firestops described in Paragraph 8.44 effectively prevents any fire spread through "chimney" effects.

Non-Conformance With Guidelines

None.

Proposed Change

None.

8.46 Branch Technical Position

D.3(f) Electric Cable Construction - Electric cable construction should at least pass the current IEEE No. 383 flame test. (This does not infer that cables passing this test will not require additional fire protection).

For cable installation in operating plants and plants under construction that do not meet the IEEE No. 383 flame test requirements, all cables must be covered with an approved flame retardant coating and properly derated.

Description

All cables used in Units 2 and 3 are of three general types (1) PVC insulated with a closely woven glass braid and overall covering of lapped mylar tape and closely woven asbestos braid saturated with a flame and moisture resistant finish; (2) EPR insulated with a neoprene or lead jacket; (3) Silicone rubber insulated with a lapped mylar tape separator and an overall braid of closely woven asbestos and finished with a flame and moisture resistant saturant.

Attachment 3 (page 2 of 2)

Samples of cable types used in Units 2 and 3 were submitted to the following tests: (1) Standard Vertical Flame Test - in accordance with ASTM-D-470-59T, "Tests for Rubber and Thermalplastic Insulated Wire and Cable". (2) Five minute Vertical Flame-made with cable held in vertical position and a 1750°F flame applied for 5 minutes. (3) Bon-Fire Test - consisting of exposing for 5 minutes, bundles of three of six cables to a flame produced by igniting transformer oil in a 12 inch pail. The cable was supported horizontally over the center of the pail with the lowest cable 3 inches above the top of the pail. The time to ignite the cable and the time the cable continued to flame after the fire extinguished were noted. Some low voltage instrument wires will not meet IEEE No. 383 flame test requirements. However, since they're used exclusively for instrumentation purposes, they have a low energy producing capability and will not generate high currents capable of igniting the wires.

In November 1971, during the construction of Unit 2, a temporary wooden shanty caught fire. As reported to the then AEC, the shanty and the large quantities of combustibles it contained produced a fire of sufficient intensity to damage building structural members, electrical equipment and cables.

In spite of the size of this fire, the cables did not burn beyond the confines of the fire area nor did they re-ignite once the external sources of combustion had been eliminated. This experience demonstrated the excellent fire resistant, non-propogating properties of the cable construction used at Indian Point.

Conformance With Guidelines

The tests performed on the Units 2 and 3 cables are equivalent to the IEEE 383 flame test.

Non-Conformance With Guidelines

The instrument wires previously noted do not meet the IEEE 383 flame test.

Proposed Changes

None. The instrument wires are not safety related nor would they add much of a fuel loading to any one area.

Attachment 4

IP3 Amendment No. 24, 3/6/79

4.5 Floor Drains

The oil hazards in the turbine building and the diesel generator building are provided with curbs or trenches to direct any spills to the floor drain system, preventing the spread of oil to other areas. This floor drain system is not connected to other safety-related areas. The diesel generator rooms drain separately to an oil-water separator and are arranged so that a fire would not spread between rooms via the drain system.

We find that the floor drain system contains adequate measures to prevent spread of oil to safety-related areas and satisfies the objectives of Section 2.2 of this report. We, therefore, find the drain system acceptable.

4.6 Lighting Systems

The plant is provided with a normal and emergency lighting system. Lighting in critical plant areas can be supplied by the emergency diesel generators. However, a fire could cause loss of all lighting in certain areas providing access for fire fighting in safety-related areas or where lighting is required to achieve safe shutdown. The licensee has proposed to install 8-hour battery operated lighting units in areas providing access to safety-related areas where a fire in the area may cause loss of lighting. The licensee has also proposed to provide electric hand lanterns for use by the fire brigade.

We find that, subject to the implementation of these modifications, the lighting systems satisfy the objectives in Section 2.2 of this report and are, therefore, acceptable.

4.7 Communication Systems

In addition to the normal in-plant telephone communications system, voice powered head sets are available for emergency communications. However, these are hardwired systems and as such are subject to damage in a fire. The licensee has proposed to provide portable radio sets for use by the fire brigade should the fixed systems be damaged in a fire.

We find that the communications systems satisfy the objectives stated in Section 2.2 of this report and are, therefore, acceptable.

4.8 Electrical Cable Combustibility

Electrical cables used in the plant were required to pass the ASTM-D-470-59T vertical flame test, as well as certain other tests developed by the licensee. The data indicate that the cables used will not burn vigorously under the test conditions used. We find that retest to the IEEE 383 criteria would not provide information that would change any of our recommendations or conclusions. Accordingly, we find the electrical cables used to be acceptable.

Attachment 5
From Fire Protection Reference Manual

manufacturers were invited to submit cable sample for testing. An extensive flame testing program took place which included ASTM vertical flame testing and Consolidated Edison Company vertical flame and bonfire tests as described below. These flame tests were used as one of means of qualifying cables and specifications were written on the basis of the results from the tests.

The following tests were made to determine the flame resistant qualities of the covering and insulations of various type of cables for Indian Point 3:

- (1) Standard Vertical Flame Test - made in accordance with ASTM-D-470-59T, "Test for Rubber and Thermalplastic Insulated Wire and Cable".
- (2) Five-Minute Vertical Flame Test - made with cable held in vertical position and 1750°F flame applied for five minutes.
- (3) Bonfire Test - Consisting of exposing, for five minutes, bundles of three or six cables to flame produced by igniting transformer oil in 12-inch pail. The cable was supported horizontally over the center of the pail, the lowest cable three inches above the top of the pail. The time to ignite the cable and the time the cable continued to flame after the fire was extinguished were noted.

The cable types specified for IP3 are as follows:

- (1) Silicone rubber insulated cable with a lapped mylar tape separator and an overall braid of closely woven asbestos and finished with a flame and moisture resistant saturant.
- (2) EPR insulated cable with a neoprene or lead jacket.
- (3) PVC insulated cable with a closely woven glass braid and overall covering of lapped mylar tape and closely woven asbestos braid saturated with a flame and moisture resistant finish.

With these types of fire resistant cable, a fire should not propagate along the cable.

The areas of high cable concentration where safe shutdown and essential device cables are installed at IP3 include the Cable Spreading Room, the Electrical Tunnels and the Switchgear Room. Cable trays in these areas are of non-combustible metallic construction with channel for support. No PVC conduits or conduits made from other combustible materials are used. Fire loadings in these areas are low and there is no storage or accumulation of combustible materials present. It is, therefore, most improbable that a fire could occur which could generate the

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February 6, 1979
IPN-79-2

Director, Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Attention: Mr. Albert Schwencer, Chief.
Operating Reactors Branch No. 1
Division of Operating Reactors

Subject: Indian Point 3 Nuclear Power Plant
Docket No. 50-286
Fire Protection Program Review

Dear Sir:

Enclosed please find ten (10) copies of Attachment 1 which contains responses to your request for additional information on the Power Authority's October 23, 1978 (IPO-163) submittal to the NRC on the subject item. The request was telecopied to us on November 28, 1978 by your Mr. L. Olshan.

In the April 15, 1977 submittal to the NRC containing Revision 1 to the report entitled, "Review of Indian Point Station Fire Protection Program", commitments were made to the NRC with respect to the hydrogen trailer located outside the Primary Auxiliary Building (Pg 8-9) and the air intake louvers on the Battery Room Doors (Pgs 8-100, 10-35).

Please be advised that the hydrogen trailer will be removed. Instead, a bulk hydrogen storage facility located at the river front will provide hydrogen to the plant through a buried line to the Primary Auxiliary Building.

The air intake louvers on the Battery Room doors will not be closed off with fire dampers. In a phone conversation on January 22, 1979 between the Authority's staff and your Mr. L. Olshan and Mr. H. George it was concluded that such modification is not required.

Very truly yours,

Paul J. Early
Assistant Chief Engineer-
Projects

GMW:gs

Attachment 6 (page 2 of 2)

7. (P4) (a) Cable penetration fire stops should be upgraded to 3-hour fire rated in the following fire barriers; barriers between the diesel generator building and control building; barriers between diesel generator rooms; and barriers between the turbine building and control building.
- (b) To conform to the referenced design tested by Florida Power and Light Company, the IP-3 firestops that will be upgraded by the addition of "Marinite" collars and sleeves should also include "Cera-Felt" blanket or equivalent under the sleeves and application of "Flame-mastic" or equivalent flame retardant coating for a distance of 18 inches from either side of the firestop.

Response

(a) and (b) The Power Authority will conform to the above requirements for firestops.

Attachment 7 (page 1 of 2)

IP3 Amendment No. 24, 3/6/79

- 2 -

2. Accordingly, operating license DPR-64 is amended by adding paragraph 2.I to read as follows:

2.I) The licensee may proceed with and is required to complete the modifications identified in Paragraphs 3.1.1 through 3.1.14 of the NRC's Fire Protection Safety Evaluation (SE), dated March 6, 1979 for the facility. These modifications will be completed in accordance with the schedule in Table 3.1 of the SE and supplements thereto.

In addition, the licensee shall submit the additional information identified in Table 3.2 of this SE in accordance with the schedule contained therein. In the event these dates for submittal cannot be met, the licensee shall submit a report, explaining the circumstances, together with a revised schedule.

3. This license amendment is effective as of the date of its issuance.

FOR THE NUCLEAR REGULATORY COMMISSION



A. Schwencer, Chief
Operating Reactors Branch
Division of Operating Reactors

Date of Issuance: March 6, 1979

3.0 SUMMARY OF MODIFICATIONS AND INCOMPLETE ITEMS

3.1 Modifications

The licensee plans to make certain plant modifications to improve the fire protection program as a result of both his and the staff's evaluations. Such proposed modifications are summarized below. The sections of this report which discuss the modifications are noted in parentheses following each item. Further detail is contained in the licensee submittals. All modifications will be completed in accordance with the scheduled dates given in Table 3.1. Certain items listed below are marked with an asterisk to indicate that the NRC staff will require additional information in the form of design details to assure that the design is acceptable prior to actual implementation of these modifications. The balance of the other modifications has been described in an acceptable level of detail.

3.1.1 Hydrogen Line

The hydrogen trailer outside the primary auxiliary building containing H₂ cylinders will be removed and replaced with a buried H₂ line routed to H₂ bottles located at least 50 feet from the primary auxiliary building.

3.1.2 Fire Barriers and Penetrations

- (1) Three-hour fire-rated doors and frames will be provided in barriers separating the diesel generator rooms from each other and from the control building, separating the control building and turbine building, and separating the control building and primary auxiliary building from the transformer yard area where the doors are within 50 feet of the transformers with the exception that the door between the control room and turbine building will be a three-hour equivalent fire door (see 3.1.14) (4.9.1).
- (2) Three-hour fire-rated dampers will be provided in ventilation openings or ductwork penetrations in barriers separating the turbine building from the control building, and separating the cable tunnel from the transformer yard area (4.9.2).
- (3) Cable penetration firestops will be upgraded to a design that passes an ASTM-E-119 exposure fire test by the addition of "Marinite" collars and sleeves with "Cera-Felt" or equivalent mineral wool blanket installed under the sleeves and "Flamemastic" flame retardant coating over the firestop and on the cables for a distance of 18 inches on either side of the firestop. Penetrations to be upgraded are those in barriers separating the control building from the turbine building and from the diesel generator building, and those separating diesel generator rooms (4.9.3).

From First Update FSAR

curtain, in conformance with NFPA 15, "Water Spray Fixed Systems", protects this opening.

Six fire doors are provided between diesel generator cubicles and between cubicles and the Control Building. The fire doors are labeled and have passed the Underwriter's Laboratories Fire Door Test for 3 hours "A" Classification in accordance with the testing procedure of ASTM E-152. Although only the six doors mentioned above have the Class "A" label, the hollow metal doors used throughout the site meet the UL Class "A" requirements.

Ventilation Duct Penetrations

Dampers which are rated for three hours of fire resistance to damage have been installed in HVAC openings and duct work to maintain the integrity of fire rated barriers. These barriers separate fire zones in the Control Building, Diesel Generator Building, Primary Auxiliary Building, and the Fan House. Fuse links on the fire dampers will melt at a predetermined temperature which will cause automatic closure of these dampers.

Other ventilation ducts throughout the plant do not have fire dampers where the ducts penetrate fire barriers. Fire protection measures provide 3-hour fire rated dampers in ducts:

- 1) Between the Switchgear Room and the Turbine Building
- 2) Between the Cable Spreading Room and the Turbine Building.

Electrical Cable Penetrations

Electrical cable penetrations in fire barriers are sealed with three types of construction utilizing ceramic fiber, asbestos sheet, glass fiber, and sprayed mastic. Cable penetrations in critical fire barriers have been upgraded to a design that acceptably passed an ASTM-E-119 exposure fire test. Modifications consisted of addition of "marinite" collars and sleeves at the penetrations, installation of a "Cera-Felt" mineral wool blanket under the sleeves, and application of a flame retardant coating on the fire stop. Critical fire barriers include those separating the Control Building from the Turbine Building and from the Diesel Generator Building, and those separating Diesel Generator Rooms.

Combustible Material Control in Structures

All structures on Indian Point 3 were constructed of reinforced concrete, concrete block, structural steel and metal partitions, metal wall siding sandwich panels (consisting of 20GA galvanized steel backup liner panels, 1-1/2" fiberglass insulation and protected metal face sheets) and/or built-up roofing (over 1" hard board insulation on 15 lb felt vapor barrier on metal decking). These are all noncombustible materials.

From Current FSAR

IP3
FSAR UPDATE

Where penetrations have been created in fire doors, fire door frames or transoms, appropriately related penetration seals have been installed which maintain the rating of the fire door assembly.

Fire Dampers

Dampers which are rated for three hours of fire resistance have been installed in HVAC openings and duct work to maintain the integrity of fire rated barriers. These barriers separate fire zones in the Control Building, Diesel Generator Building, Primary Auxiliary Building, and the Fan House. Fuse links on the fire dampers will melt at a predetermined temperature which will cause automatic closure of these dampers.

Electrical Cable and Mechanical Penetration Seals

Electrical cable and mechanical penetrations in fire barriers are sealed with several types of construction utilizing ceramic fiber, asbestos sheet, glass fiber, sprayed mastic and silicon elastomer and foam. Cable penetrations in fire barriers providing area separation for Appendix R have been installed to a design that passed an ASTM-E-119 3 hour fire test.

Fire Wraps and Radiant Energy Shields

One hour rated fire wraps and radiant energy shields have been installed on various cable trays and conduits in the Containment, Electrical Tunnels and PAB. The wraps consist of high temperature mineral wool blankets. The blankets have been tested satisfactorily and qualified as a one hour barrier in accordance with ASTM-E 119. Additional testing has qualified the wraps for three hour water repellency, radiation resistance and water leachable chlorides and fluorides. The radiant energy shields are comprised of marinite or transite fire board.

These protective features were added to Safe Shutdown related instrumentation in the Containment to establish compliance with Section III.G.2.f of Appendix R. One hour wraps have been installed to protect:

1. Wide range RCS pressure transmitter PT-402 conduit from the transmitter to the electrical penetration inside containment.
2. Source Range neutron flux N-31 conduit from its preamp box to the electrical penetration inside containment.
3. Wide Range RCS temperature elements and cabling for TE 413 A and B at the electrical penetrations.
4. Steam Generator wide range level instrument LT-417D at the penetrations.
5. Steam Generator wide range level instrument LT-447D at Rack 21.

Attachment 10

From Fire Protection Reference Manual

equivalent to the required rating of the fire barrier, as delineated in Table 2-2." [NYPA-064-017]

3.2.3.2 Licensing Conditions (Penetration Seals)

The following is a condition of the IP3 facility operating license established by NRC SER, Amendment 24, dated March 6, 1979. [NRC-019]

"3.1.2 Fire Barriers and Penetrations

- (3) Cable penetration firestops will be upgraded to a design that passes an ASTM-E-119 exposure fire test by the addition of "Marinite" collars and sleeves with "Cera-Felt" or equivalent mineral wool blanket installed under the sleeves and "Flamemastic" flame retardant coating over the firestop and on the cables for a distance of 18 inches on either side of the firestop. Penetrations to be upgraded are those in barriers separating the control building from the turbine building and from the diesel generator building, and those separating diesel generator rooms (4.9.3)." [NRC-019-004]

3.3 FIRE DOORS

3.3.1 General

Doors located in fire barriers (Appendix A and Appendix R) must have a rating equivalent to that of the barrier except where specifically evaluated as acceptable with a lesser rating in an approved exemption to the requirements of Appendix R or in an engineering evaluation.

The fire doors, frames and construction are generally constructed as 3-hour fire rated and are provided with either fire actuated release devices, locks, or alarms such that the Control Room is alerted if the door is left open.

Table 3-1 provides a complete listing of fire doors in Appendix A and Appendix R fire barriers along with their respective locations and the fire areas/zones on either side of the door.

The doorway between the Control Room and Turbine Building operating floor is a three-hour equivalent fire door which consists of a metal plate which falls over a window on the door in the event of fire.

The door between the Electrical Tunnel and the Cable Spreading Room at Elevation 33'-0" is normally left open, but has a fusible link and actuation device for automatic closure.

In lieu of a 3-hour fire-rated door in the barrier separating the Primary Auxiliary Building from the Transformer Yard, an

ATTACHMENT 6.8

Rockbestos Cable Testing

FMRC Contract No. J.I. OY1R9.RC



Memorandum

Record of Conversation

Participants: Steven Wilkie - NYPA Fire Protection Engineer
Mr. Mohammed Khan - Factory Mutual Research Corporation (FMRC) Research Scientist, Flammability Section

Date: May 5, 1995

Re: To discuss the testing of Rockbestos cables.

Ref.: FMRC Report J.I.0Z0Q3.AE, "Fire Propagation Results for Control Power and Instrumentation Cable", dated April 3, 1995

Mr. M. Khan was referred to me by Dr. A. Tewarson - Manager, Flammability Section of FMRC as he was one of the scientists that was involved in the recent testing of cable samples for the Rockbestos Co.

During the conversation, I indicated to Mr. Khan that I had received a copy of the referenced report, however it did not identify critical heat flux values for the cable samples tested. Mr. Khan stated that the subject testing was performed in order to categorize cables into one of three categories per their Fire Propagation Index (FPI) values. He stated that the only values that were reported when the test was done were the FPI and Thermal Response Parameter (TRP) values.

Mr. Khan further stated that he would send me a copy of the actual test data that was taken to support the calculated FPI and TRP values. (Note: a copy has since been attached to this record of conversation for completeness)



Memorandum

Addendum
to
Record of Conversation

Participants: Steven Wilke - NYPA Fire Protection Engineer
Mohammed Khan - FMRC Research Scientist,
Flammability Section
Donald Major - FMRC Assistant Manager, Electrical
Section

Date: May 18, 1995

Re: To discuss the testing of Rockbestos cables.

Ref.: 1. FMRC Report J.I.0Z0Q3.AE, "Fire Propagation
Results for Control Power and Instrumentation
Cable", dated April 3, 1995
2. Actual Test Data performed under FMRC Contract
No. J.I.0Y1R9.RC to support FMRC Report
J.I.0Z0Q3.AE

During a discussion about the subject data (which was sent to me by Mr. Khan of FMRC), I asked Mr. Major why the subject report did not identify all FPI and TRP values for cables tested. Mr. Major indicated that the results of testing on the worst case cable samples were reported as they were considered to be the bounding cases for cables of that particular cable construction.

I asked why the description of Samples #1 and #2 in the report did not match the description given for Samples #1 and #2 as documented in the actual test data. Mr. Major stated that since the report identified the two bounding cable samples using a description and catalog no., the actual data could be traced back to the actual test data. He stated that since the report only cited the FPI and TRP values for two cable samples, the use of designations Samples #1 and #2 was more appropriate from a report standpoint. Mr. Major stated that Samples #1 and #2 of the report corresponded to Samples #5 and #11, respectively of the actual test data. He further noted that the TRP value for Sample #2 in the report was taken from the test results from Sample #1 from the actual test data which did not use a polypropylene filler.

ROCKBESTOS CABLE DESCRIPTION

	SAMPLE 1	SAMPLE 2	SAMPLE 3
NUMBER OF CONDUCTORS	2	2	2
GAUGE AWG	14	18	14
OVERALL DIAMETER	.340"	.335"	.310"
VOLTAGE RATING	600	600	600
INSULATION			
TYPE	XLPE	XLPE	XLPE
THICKNESS	.020"	.025"	.020"
LOI	30	30	30
BINDER TAPE 1			
TYPE	MYLAR(polyester)	NOMEX (Aramid)	MYLAR(polyester)
THICKNESS	.001"	.002"	.001"
LOI	21	45	21
BINDER TAPE 2			
TYPE	NONE	ALUMINUM/MYLAR	NONE
THICKNESS		.004"	
LOI		N/A	
FILLER			
TYPE	NONE	POLYPROPYLENE	NONE
LOI		27	
OUTER JACKET			
TYPE	XLPO	CSPE	XLPO
THICKNESS	.035"	.045"	.035"
LOI	38	38	45

TRP	384	320	370
FPI	8.7	10.6	—

ROCKBESTOS CABLE DESCRIPTION

	SAMPLE 4
NUMBER OF CONDUCTORS	2
GAUGE AWG	14
OVERALL DIAMETER	.370"
VOLTAGE RATING	600
INSULATION	
TYPE	XLPE
THICKNESS	.030"
LOI	30
BINDER TAPE 1	
TYPE	MYLAR(polyester)
THICKNESS	.001"
LOI	21
BINDER TAPE 2	
TYPE	NONE
THICKNESS	
LOI	
FILLER	
TYPE	POLYPROPYLENE
LOI	27
OUTER JACKET	
TYPE	CHLORINATED POLYETHYLENE
THICKNESS	.045"
LOI	31

TRP 294

FPI 13.5

ROCKBESTOS CABLE DESCRIPTION

PRODUCT NAME	X-LINK TC	FIREWALL III	GSIA TC	FIREWALL EP	FIREWALL III SOL JX
PRODUCT CODE	I 83-0021	I 46-0021	S 32-3876	P 68-0140	I 67-3423
NUMBER OF CONDUCTORS	#5 2	#6 2	#7 3	#8 1	#9 2
GAUGE AWG	16	16	8	14	16 SOLID JX
OVERALL DIAMETER	.279"	.321"	.804"	.180"	.307"
VOLTAGE RATING	600	600	600	600	600
INSULATION					
TYPE	XLPE	XLPE	XLPE	EPR	XLPE
THICKNESS	.020"	.025"	.045"	.030"	.025"
LOI	30	30	25	18	30
GROUND WIRE					
NUMBER OF CONDUCTORS	1	1	3	NONE	1
GAUGE AWG	18	18	14		18
INSULATION	NONE	NONE	NONE		NONE
BINDER TAPE 1					
TYPE	ALUMINUM/MYLAR	ALUMINUM/MYLAR	MYLAR	NONE	ALUMINUM/MYLAR
THICKNESS	.002"	.002"	.002"		.002"
LOI	N/A	N/A	22		N/A
ARMOR					
TYPE	NONE	NONE	GALVANIZED STEEL	NONE	NONE
THICKNESS			.025"		
LOI			N/A		
FILLER/RIP CORD					
TYPE	RIP CORD POLYESTER	FILLER POLYPROPYLENE	FILLER POLYPROPYLENE	NONE	FILLER POLYPROPYLENE
LOI	18	27	27		27
OUTER JACKET					
TYPE	XLPO	CSPE	CSPE	CSPE	CSPE
THICKNESS	.035"	.045"	.050"	.015"	.045"
LOI	38	38	35	38	35
TRP	424	294	319	332	351
FPI	8.5	12.0	>10	12.4	9.8

ROCKBESTOS CABLE DESCRIPTION

	SAMPLE 1	SAMPLE 11
NUMBER OF CONDUCTORS	2	5
GAUGE AWG	14	14
OVERALL DIAMETER	.340"	.405"
VOLTAGE RATING	600	600
INSULATION		
TYPE	XLPE	XLPE
THICKNESS	.020"	.020"
LOI	30	30
BINDER TAPE 1		
TYPE	MYLAR(polyester)	MYLAR(polyester)
THICKNESS	.001"	.001"
LOI	21	21
BINDER TAPE 2		
TYPE	NONE	NONE
THICKNESS		
LOI		
FILLER		
TYPE	NONE	POLYPROPYLENE
LOI		27
OUTER JACKET		
TYPE	XLPO	XLPO
THICKNESS	.035"	.035"
LOI	38	38

TRP 384 385.5

FPI 8.7 8.2

IGNITION DATA FILE

Date of Test: 11oct94
 Apparatus: 50 kW
 Manufacturer: Rockbestos Cables
 Number of samples: 3
 Sample name(s): See below
 Sample description:
 Surface area: 1.0

Ends sealed with aluminum foil
 Dish: Ignition cable holder
 Free Convection

ALL samples were painted with Thermalox 250 spray paint
 Pilot 1 cm. over the sample

Flam. Sec. Scientist: M. M. Khan

Sample(1) Rockbestos 2 Cond. x 14 AWG X-link
 Type TC Dir. Bur. Sun Res. 600V
 Insulation: XLPE Binder #1: Mylar (polyester)
 Binder #2: None Filler : None
 Outer Jacket: XLPO

R² value: 0.9973948 TRF: 383.73
 y Int.: 0.001930 Slope: 0.002606
 Calc. y @60kW/m²: 0.1583

Heat Flux (kW/m ²)	T(ign.)s	1/sqrt Tig(s)	1/Tig(s)
30(94.87 VAC)	152.59	0.0809	0.0065
40(112.1 VAC)	93.26	0.1035	0.0107
50(127.6 VAC)	54.72	0.1352	0.0183
60(141.8 VAC)	40.45	0.1572	0.0247
<i>critical heat flux</i> → 20(75.17 VAC)	Did not ignite (900 s)		

q" / q" / q" / q" / q" Sample(2) Rockbestos 2 Cond. x 18 AWG
 Insulation: XLPE Binder #1: Nomex (Aramid)
 Binder #2: Aluminum/Mylar
 Filler : Polypropylene
 Outer Jacket: CSPE

R² value: 0.996118 TRF: 320.51
 y Int.: 0.017050 Slope: 0.003120
 Calc. y @60kW/m²: 0.2042

Heat Flux (kW/m ²)	T(ign.)s	1/sqrt Tig(s)	1/Tig(s)
30(94.87 VAC)	86.69	0.1074	0.0115
40(112.1 VAC)	47.26	0.1455	0.0216
50(127.6 VAC)	32.48	0.1755	0.0308
60(141.8 VAC)	24.64	0.2014	0.0406

q" / q" / q" / q" / q" → 20(75.17 VAC) Sample swelled to 2 1/2 times its original size
 and generated a lot of vapors in the first 4 minutes. but the sample

Sample(3) Rockbestos 2 Cond. x 14 AWG

Insulation: XLPE Binder #1: Mylar (polyester)
 Binder #2: None Filler : None
 Outer Jacket: XLPO

R² value: 0.9967503 TRP: 369.55
 y Int.: -0.003520 Slope: 0.002706
 Calc. y @60kW/m²: 0.1588

Heat Flux (kW/m ²)	T(ign.)s	1/sqrt Tig(s)	1/Tig(s)
30(94.87 VAC)	170.52	0.0766	0.0059
40(112.1 VAC)	91.83	0.1043	0.0109
50(127.6 VAC)	54.21	0.1358	0.0184
60(141.8 VAC)	40.91	0.1563	0.0244
$\dot{q}_{cr}'' \rightarrow$ 20(75.17 VAC)	Did not ignite (900 s)		

Sample(4) Rockbestos 2 Cond. x 14 AWG

Insulation: XLPE Binder #1: Mylar (polyester)
 Binder #2: None Filler : Polypropylene
 Outer Jacket: Chlorinated Polyethylene

R² value: 0.9983622 TRP: 293.68
 y Int.: -0.011550 Slope: 0.0034050
 Calc. y @60kW/m²: 0.1927

Heat Flux (kW/m ²)	T(ign.)s	1/sqrt Tig(s)	1/Tig(s)
30(94.87 VAC)	119.50	0.0915	0.0084
40(112.1 VAC)	63.93	0.1251	0.0156
50(127.6 VAC)	41.56	0.1551	0.0241
60(141.8 VAC)	26.29	0.1950	0.0380
20(75.17 VAC)	670.90	0.0386	0.0015

$\dot{q}_{cr}'' \approx 15$

IGNITION DATA FILE

Date of Test: 20dec94
 Apparatus: 50 kW
 Manufacturer: Rockbestos Cables
 Number of samples: 4
 Sample name(s): See below
 Sample description:
 Surface area: 1.0
 Ends sealed with aluminum foil
 Dish: Ignition cable holder
 Free Convection
 ALL samples were painted with Krylon Ultra Flat Black spray paint
 Pilot 1 cm. over the sample
 Flam. Sec. Scientist: M. M. Khan

Sample(5) Rockbestos 2 Cond x 16AWG X-link TC Prod Code: I-83-0021
 Type XLPE 600V (Black)
 Insulation: XLPE Binder Tape: Aluminum/Mylar
 Armor: None Filler/Rip Cord : Rip Cord Polyester
 Outer Jacket: XLPO

R² value: 0.9972567 TRP: 424.27
 y Int.: 0.016060 Slope: 0.002357
 Calc. y @60kW/m²: 0.1575

Heat Flux (kW/m ²)	T(ign.)s	1/sqrt Tig(s)	1/Tig(s)
30(94.87 VAC)	138.48	0.0850	0.0072
40(112.1 VAC)	79.93	0.1118	0.0125
50(127.6 VAC)	53.82	0.1363	0.0186
60(141.8 VAC)	41.43	0.1554	0.0241
$\dot{q}_{cr} \rightarrow$ 20(75.17 VAC)	Did not ignite (900 s)		

Sample(6) Rockbestos 2 Cond. x 16 AWG Firewall III Prod Code I46-0021
 Insulation: XLPE Binder Tape: Aluminum/Mylar
 Armor: None
 Filler : Polypropylene
 Outer Jacket: CSPE

R² value: 0.9947893 TRP: 294.38
 y Int.: 0.023610 Slope: 0.0033970
 Calc. y @60kW/m²: 0.2274

Heat Flux (kW/m ²)	T(ign.)s	1/sqrt Tig(s)	1/Tig(s)
30(94.87 VAC)	66.80	0.1223	0.0150
40(112.1 VAC)	38.24	0.1617	0.0261
50(127.6 VAC)	25.33	0.1987	0.0395
60(141.8 VAC)	20.08	0.2232	0.0498
20(75.17 VAC)	176.86	0.0752	0.0056
$\dot{q}_{cr} \rightarrow$ 15(63.98 VAC)	Did not ignite (900 s)		

Sample(7) Rockbestos 3 Cond. x 8 AWG GSIA TC (Black)

Product Code: S-32-3876

Insulation: XLPE Binder Tape: Mylar

Armor: Galviniuzed Steel Filler : Polypropylene

Outer Jacket: CSPE

R² value: 0.9917383

TRP: 319.28

y Int.: 0.001910

Slope: 0.003132

Calc. y @60kW/m²: 0.1898

Heat Flux (kW/m ²)	T(ign.)s	1/sqrt Tig(s)	1/Tig(s)
30(94.87 VAC)	98.72	0.1006	0.0101
40(112.1 VAC)	67.19	0.1220	0.0149
50(127.6 VAC)	41.78	0.1547	0.0239
60(141.8 VAC)	23.54	0.1941	0.0377
20(75.17 VAC)	231.55	0.0657	0.0043

Sample(8) Rockbestos 1 Cond. x 14 AWG FIREWALL EP (Black)

Product Code: P-68-0140

Insulation: EFR Binder Tape: None

Armor: None Filler : None

Outer Jacket: CSPE

R² value: 0.9982653

TRP: 332.34

y Int.: 0.057920

Slope: 0.003009

Calc. y @60kW/m²: 0.2385

Heat Flux (kW/m ²)	T(ign.)s	1/sqrt Tig(s)	1/Tig(s)
30(94.87 VAC)	46.74	0.1463	0.0214
40(112.1 VAC)	30.31	0.1816	0.0330
50(127.6 VAC)	23.24	0.2074	0.0430
60(141.8 VAC)	17.65	0.2380	0.0567
20(75.17 VAC)	94.21	0.1030	0.0106
15(63.98 VAC)	Did not ignite (900 s)		

Sample(9) Rockbestos 2 Cond. x 16 AWG Firewall III SOL JX (Purple)
 Product Code: I-67-3423 (Solid 16AWG JX)
 Insulation: XLPE Binder Tape: Aluminum/Mylar
 Armor: None Filler : Polypropylene
 Outer Jacket: CSPE

R² value: 0.9949082 TRF: 351.12
 y Int.: 0.027590 Slope: 0.002848
 Calc. y @60kW/m²: 0.1985

Heat Flux(kW/m ²)	T(ign.)s	1/sqrt Tig(s)	1/Tig(s)
30(94.87 VAC)	74.92	0.1155	0.0133
40(112.1 VAC)	50.96	0.1401	0.0196
50(127.6 VAC)	36.55	0.1654	0.0273
60(141.8 VAC)	24.50	0.2020	0.0408
20(75.17 VAC)	147.38	0.0824	0.0068
$\frac{q''}{kcs} \rightarrow$ 15(63.98 VAC)	Did not ignite (900 s)		

IGNITION DATA FILE

Date of Test: 15feb95
 Apparatus: 50 kW
 Manufacturer: Rockbestos Cables
 Number of samples: 1
 Sample name(s): See below
 Sample description:
 Surface area: 1.0
 Ends sealed with aluminum foil
 Dish: Ignition cable holder
 Free Convection
 ALL samples were painted with Krylon Ultra Flat Black spray paint
 Pilot 1 cm. over the sample
 Flam. Sec. Scientist: M. M. Khan

Sample ~~(8)~~ (11) Rockbestos 5 Cond x 14AWG (Rcvd 03-feb-95)
 Type XLPE 600V (Black)
 Insulation: XLPE Binder Tape: Mylar/Polyester
 Armor: None Filler: Polypropylene
 Outer Jacket: XLPO

R² value: 0.9934382 TRP: 385.50
 y Int.: -0.002980 Slope: 0.0025940
 Calc. y @60kW/m²: 0.1527

Heat Flux	T(ign.)s	1/sqrt Tig(s)	1/Tig(s)
30(94.87 VAC)	197.15	0.0712	0.0051
40(112.1 VAC)	89.14	0.1059	0.0112
50(127.6 VAC)	61.57	0.1274	0.0162
60(141.8 VAC)	44.17	0.1505	0.0226
20(75.17 VAC)	Did not ignite (900 s)		

NOT to be distributed outside the FACTORY MUTUAL SYSTEM, except by CLIENT.

SPECIFICATION TESTED CABLE REPORT

FIRE PROPAGATION RESULTS FOR CONTROL, POWER AND INSTRUMENTATION CABLE

Prepared For:

The Rockbestos Company
20 Bradley Park Rd.
East Granby, CT. 06026

J.I. 0Z0Q3.AE
(3972)
April 3, 1995



Factory Mutual Research

1151 Boston-Providence Turnpike
P.O. Box 9102
Norwood, Massachusetts 02062



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(3972)

April 3, 1995

FIRE PROPAGATION RESULTS FOR CONTROL, POWER AND INSTRUMENTATION CABLE

Prepared For

The Rockbestos Company
20 Bradley Park Rd.
East Granby, CT. 06026

I INTRODUCTION

1.1 The Rockbestos Company (manufacturer) requested that Factory Mutual Research Corporation (FMRC) perform tests on their cable product type identified as X-Link TC® in accordance with the Factory Mutual Research Corporation's Specification Test Standard for "Cable Fire Propagation", Class 3972. This report describes the tests performed, the results obtained and the cable products covered.

1.2 The product described by this report was initially tested under Project J.I. 0Y1R9.RC. This project, J.I. 0Z0Q3.AE, was opened to complete the testing of the cable in accordance with the FMRC Standard Class 3972.

1.3 The specific cable products described by this report will appear in the Factory Mutual Research Corporation's Specification Tested Products Guide as follows:

The following cables are Classified Group 1 having a Fire Propagation Index (FPI) less than 10.

Control Cable

<u>Product Code</u>	<u>Construction Conductor&Size</u>	<u>Insulation & Thickness</u>	<u>Jacket & Thickness</u>
I83-0020	2/C 16 AWG	FR XLPE 20 Mils	XLPO 35 Mils
I83-0030	2/C 16 AWG	FR XLPE 20 Mils	XLPO 35 Mils
I83-0040	4/C 16 AWG	FR XLPE 20 Mils	XLPO 35 Mils
I83-0070	7/C 16 AWG	FR XLPE 20 Mils	XLPO 35 Mils
I83-0120	12/C 16 AWG	FR XLPE 20 Mils	XLPO 35 Mils
I83-0190	19/C 16 AWG	FR XLPE 20 Mils	XLPO 45 Mils
C10-0020	2/C 10 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C10-0030	3/C 10 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C10-0040	4/C 10 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C10-3006	3/C 10 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C10-3007	4/C 10 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C12-0020	2/C 12 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C12-0030	3/C 12 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C12-0040	4/C 12 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C12-0050	5/C 12 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C12-0070	7/C 12 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C12-0090	9/C 12 AWG	FR XLPE 20 Mils	XLPO 45 Mils
C12-3011	3/C 12 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C12-3015	4/C 12 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C12-0120	12/C 12 AWG	FR XLPE 20 Mils	XLPO 45 Mils
C12-0190	19/C 12 AWG	FR XLPE 20 Mils	XLPO 45 Mils
C14-0020	2/C 14 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C14-0030	3/C 14 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C14-0040	4/C 14 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C14-0050	5/C 14 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C14-0070	7/C 14 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C14-0090	9/C 14 AWG	FR XLPE 20 Mils	XLPO 35 Mils
C14-0120	12/C 14 AWG	FR XLPE 20 Mils	XLPO 45 Mils
C14-0190	19/C 14 AWG	FR XLPE 20 Mils	XLPO 60 Mils
C14-3012	3/C 14 AWG	FR XLPE 20 Mils	XLPO 35 Mils

Power Cable

<u>Product Code</u>	<u>Construction Conductor&Size</u>	<u>Insulation & Thickness</u>	<u>Jacket & Thickness</u>
P92-0023	3/C 2 AWG	FR XLPE 35 Mils	XLPO 65 Mils
P92-0043	3/C 4 AWG	FR XLPE 35 Mils	XLPO 45 Mils
P92-0063	3/C 6 AWG	FR XLPE 30 Mils	XLPO 45 Mils
P92-0083	3/C 8 AWG	FR XLPE 30 Mils	XLPO 45 Mils
P92-0103	3/C 1/0 AWG	FR XLPE 45 Mils	XLPO 65 Mils
P92-0203	3/C 2/0 AWG	FR XLPE 45 Mils	XLPO 65 Mils
P92-0403	3/C 4/0 AWG	FR XLPE 45 Mils	XLPO 65 Mils
P92-0024	4/C 2 AWG	FR XLPE 35 Mils	XLPO 65 Mils
P92-0064	4/C 6 AWG	FR XLPE 35 Mils	XLPO 45 Mils

Instrumentation Cable

<u>Product Code</u>	<u>Construction Conductor&Size</u>	<u>Insulation & Thickness</u>	<u>Jacket & Thickness</u>
I83-0021	2/C 16 AWG	FR XLPE 20 Mils	XLPO 35 Mils
I83-0031	3/C 16 AWG	FR XLPE 20 Mils	XLPO 35 Mils
I83-0024	2 STP 16 AWG	FR XLPE 20 Mils	XLPO 35 Mils
I83-0044	4 STP 16 AWG	FR XLPE 20 Mils	XLPO 45 Mils
I83-0084	8 STP 16 AWG	FR XLPE 20 Mils	XLPO 45 Mils
I83-0124	12 STP 16 AWG	FR XLPE 20 Mils	XLPO 65 Mils
I84-0021	2/C 18 AWG	FR XLPE 20 Mils	XLPO 35 Mils
I84-0031	3/C 18 AWG	FR XLPE 20 Mils	XLPO 35 Mils
I84-0024	2 STP 18 AWG	FR XLPE 20 Mils	XLPO 35 Mils
I84-0044	3 STP 18 AWG	FR XLPE 20 Mils	XLPO 45 Mils
I84-0084	8 STP 18 AWG	FR XLPE 20 Mils	XLPO 45 Mils
I84-0124	12 STP 18 AWG	FR XLPE 20 Mils	XLPO 65 Mils

1.4 This report describes representative cable test result values for the Thermal Response Parameter, Chemical Heat Release Rate, and Fire Propagation Index. Testing procedures are described in the Specification Test Standard for Cable Fire Propagation, Class No. 3972, by FMRC. These cable characteristics are to be used for determining the suitability of a cable installation from the fire protection standpoint; the cable electrical/mechanical construction characteristics were not considered. The construction of cables listed in Report Section 1.2 have been found, by examination, to be acceptable for the Group classification rating determined as a result of testing representative samples. An audit of the manufacturer's facility has shown a demonstrated Quality Control Program exists, in compliance with the referenced standard. Installation must be in accordance with the National and Local Codes.

II DESCRIPTION

2.1 General Product Description - The cable types included in this test program are of the control, power and instrumentation type. These cables are of various materials of construction differing in; their quantity and gauge size (AWG or MCM) of conductors (C), insulation material thickness, jacket material thickness and whether or not separating tape (used in construction of shielded twisted pairs (STP) of conductors) or filler material is included. All of these variations result in determining the cables diameter. Visual differences such as color of insulation or jacket material does not have an affect on product flammability performance.

2.2 Product Traceability - Product traceability is accomplished by use of the Product Code number printed on the cable as part of the overall marking. The manufacturer's Document No. I-13 entitled, "Factory Mutual Research Listing Traceability" Attachments 5, 6 and 7 identifies the X-Link TC® Product Codes and materials used in the cable's construction. Reference Section VII of this report.

2.3 Material Specifications - Document No. I-13 entitled, "Factory Mutual Research Listing Traceability" Attachments 6, describes the material specification for the combustible materials of construction used by Rockbestos as follows. Rockbestos uses the identification "KXL-760" as their specific designation for the insulation material used, which is more generically known as a type of flame retardant cross linked polyethylene, or FR XLPE. The identification "KZH-400" as their specific designation for the jacket material, which is more generically known as a type of cross linked polyolyfin, or XLPO. The identification "VFPP FR" is used as their specific designation for the filler material (not used in all cable constructions), which is more generically known as a type of flame retardant polypropylene, or FR PP. The aluminum/mylar tape, mylar tape and polyester rip cord material due to their small volume amounts used in the construction of the cable does not contribute significantly to the cables flammability characteristic.

Documentation regarding these materials and their traceability through the manufacturing process are on file at FMRC as listed in the Documentation List given in Section VII of this report. The following table lists the manufacturer's combustible materials of construction, identification numbers (I.D.) and limiting oxygen index (LOI) for the cable samples tested. The LOI is based on testing conducted in accordance with ASTM Standard D-2863.

MATERIAL SPECIFICATIONS				
<u>CABLE USE</u>	<u>DOCUMENT NO.</u>	<u>MATERIAL TYPE</u>	<u>I.D.</u>	<u>LOI</u>
Insulation	I-13	XLPE	KXL-760	30%
Jacket	I-13	XLPO	KZH-400	38%
Filler	I-13	FR PP	VFPP FR	27%
Rip Cord	I-13	Polyester	Polyester	18%
Tape	none	Aluminum/Mylar	Aluminum/Mylar	none

2.4 Test Sample Description - Two cable samples were submitted for the purpose of conducting tests, product code I83-0021 and C14-0050. The significant difference in the construction of these two cables samples is the affect the filler material has on the test results. Product code C14-0050 is the cable sample which included the filler material. The two cable samples are described in Section III of this report.

III EXAMINATION AND TESTS

3.1 Test Samples - The cable sample was provided, for testing purposes, in the following sample quantities and lengths: 5 - Five inch lengths and 3 - 32 inch lengths. The five inch samples were used to conduct the Piloted Ignition Tests and the three 32 inch samples were used to conduct the Fire Propagation Tests. All testing was conducted at the FMRC facilities located in Norwood, MA.

3.1.1 Test Sample #1 - is identified as product code I83-0021. This sample is a 2 conductor, 16 AWG each, with 20 mil thick of the insulation compound KXL-760 (flame retardant cross linked polyethylene, FR XLPE), one bare 18 AWG ground wire is included. An aluminum/mylar binder tape is used to wrap the conductors and a rip cord made of polyester is provided. The overall jacket is a nominal 35 mil thick compound XLPO (KZH-400, flame retardant cross linked polyolyfin) jacket. All cable is rated at 600 volts.

3.1.2 Test Sample #2 - is identified as product code C14-0050. This sample is a 5 conductor, 14 AWG each, with 20 mil thick of the insulation compound KXL-760 (flame retardant cross linked polyethylene, FR XLPE), without a ground wire. A mylar binder tape is used to wrap the conductors and a rip cord made of polyester is provided. A polypropylene filler material is included to round out the cable's diameter. The overall jacket is a nominal 35 mil thick XLPO compound (KZH-400, flame retardant cross linked polyolyfin) jacket. All cable is rated at 600 volts.

3.2 Test Methods - The test methods used to obtain the data and determined the results of the following items are described in Appendices A, B and C of the "Specification Test Standard for Cable Fire Propagation", Class 3972. Only a brief description of the test set-up is given below.

3.3 Piloted Ignition Test Method - The piloted ignition test is used to obtain data to calculate the Thermal Response Parameter. For this test, five-5 inch, samples of the cable described in Sections 3.2 were exposed to increasing heat flux levels of 132, 158, 211, 264, 317 BTU/ft²/min. (25, 30, 40, 50 and 60 kW/m²). A pilot flame was used to ignite the combustible cable vapors. The cable test sample was exposed to the heat flux and the time to ignition was recorded. In accord with the standard the Thermal Response Parameter was determined to be as follows.

<u>Test Sample Number</u>	<u>Thermal Response Parameter</u>
1	424 kW/m ² · s ^{-1/2}
2	384 kW/m ² · s ^{-1/2}

3.4 Fire Propagation Tests Method - The fire propagation test is used to obtain data to calculate the Chemical Heat Release Rate. For this test, three-32 inch, samples of each cable type were individually set up vertically in the test apparatus, within a glass cylinder. The bottom portion of each cable sample, 8 inches (0.2m), is surrounded by four radiant quartz heaters and exposed to 264 Btu/ft²/min. (50 kW/m²) of external heat flux. A pilot flame was used to ignite the combustible cable vapors. The test was continued until the cable sample was completely consumed. In accord with the standard the Chemical Heat Release Rate was determined to be:

<u>Test Sample Number</u>	<u>Chemical Heat Release Rate</u>
1	2.6 kW
2	3.01 kW

3.5 Fire Propagation Index - The results of conducting both tests have determined that the X-Link TC® cable products listed in Section I of this report are all Group I cable, although their constructions may or may not include the ground wire or filler material. The following is in agreement with the requirements of Section 5.3 of the Class 3972 Standard "Cable Fire Propagation", March 1994.

- Group 1 cables are those cables constructed having a diameter equal to or greater than 0.279 inches (0.708 cm) and have conductors with a cross sectional area equal or greater than 2 conductors of 16 AWG each.

3.6 Documentation Review - The manufacturer's documentation was reviewed with satisfactory results. It was determined that the products, as listed in Section I, are represented by the cable samples which were subjected to tests, and are manufactured using the same construction and materials as described by Section II. The documentation required for this review is tabulated in Section VII.

3.7 Product Acceptance - The larger diameter cables employing the same construction and material as the samples tested were determined acceptable for the same Group marking, based on the only difference in cable construction being the overall diameter of the cable and that diameter increase is based on an increase in number and size of conductors and thickness of combustible materials. Based on these factors, the cable products listed in Section 1.3 of this report were concluded to be represented by the tests conducted on the cable samples #1 and #2 described herein.

IV FACILITIES AND PROCEDURES AUDIT

The manufacturer's design and manufacturing facilities in East Granby, CT., were examined, as part of this project, to determine the Quality Control Program assured each cable produced presents the same product uniformity and construction as the cable samples described in Section 1.3 of this report. The facility is subject to follow-up audits. The facilities and procedures were satisfactory.

V MANUFACTURER'S RESPONSIBILITIES

The manufacturer shall advise FMRC of all proposed changes to the documents and cable construction identified by this report. The documentation is listed in Section VII, which affect the cables listed in Section I and cable construction described in Section II.

VI CONCLUSION

6.1 The cable products described in Section 1.3 of this report have been assigned a Classification of Group 1 based on test and examination results reflected in Sections 3.3, 3.4, 3.5 and 3.6 of this report.

6.2 After the Product Listing Agreement (Form 1281) is signed and returned to FMRC, the product shall be listed and the manufacturer is permitted to mark the cable with "FMRC GP 1". NOTE: To be repeated at intervals not to exceed 24 inches.

6.3 The Group Classification only specifies a relative fire propagation characteristic for the cable and does not define other hazards presented by the cable or any other material under actual fire conditions.

6.4 The FMRC makes no judgement of product suitability for its intended end-use solely as a result of the tests described herein. This decision is usually the responsibility of the local authority having jurisdiction.

VII DOCUMENTATION FILE

The following documentation is applicable to this equipment and is on file at FMRC. No changes of any nature shall be made unless notice of the proposed change has been submitted and written authorization obtained from FMRC. The Revision Report, FMRC Form 797, shall be forwarded to FMRC as notice of proposed changes.

<u>Document Number</u>	<u>Title</u>	<u>Rev./Date</u>
I-13	FMR LISTING TRACEABILITY	2
The following documents are on file under J.I. 0Y7Q8.AE and are listed for report completeness.		
I-12	FMR LABEL PROCESS	01-31-95
Q-4	IN-PROCESS INSPECTION	1
Q-5	IN-PROCESS INSPECTION	0
Q-6	PROCEDURE FOR CONTROL OF TDA's & TDB's	14
Q-7	RECEIVING INSPECTION PROCEDURE	1
Q-9	DOCUMENT CONTROL PROCEDURE	9
Q-10	TRACEABILITY	1
Q-13	CORRECTIVE ACTION PROCEDURE	5
Q-15	PROCEDURE FOR RELEASE OF CABLE FOR SHIPMENT	14
Q-16	FINAL INSPECTION PROCEDURE	14
Q-19	LAB SAMPLE TESTING OF PRODUCTION ORDER AND LOTS	1
Q-21	MIT CONTROL	3
Q-31	CONTROLLED STAMPS	5
Q-32	RAW MATERIAL REJECTION PROCEDURE	4

J.I. 020Q3.AE

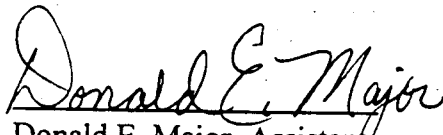
TESTS AND RESULTS BY: S. D. Ogden and John Kelliher, Jr.

EXAMINATION BY: D. E. Major.

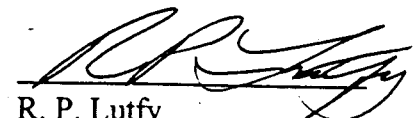
ORIGINAL DATA: PDR located in Blueprint File of FMRC's TIC.

ATTACHMENTS: -Sales Literature

REPORT BY:


Donald E. Major, Assistant
Electrical Section Manager

REVIEWED BY:


R. P. Lutfy
Electrical Section Manager

	Binder Tape	Conductor
	Non-hygroscopic and non-wicking	Tin-coated copper, Class "B" strand
	Jacket (Reduced wall)	Insulation (Reduced wall)
	Flame retardant, low smoke, zero halogen, crosslinked polyolefin (XLPO)	Flame retardant, crosslinked polyolefin (XLPO)

X-Link TC

Control Cable

(XLPO/XLPO)

90°C*, 600 Volt
NEC Type TC
UL Listed

Spec. RSS-3-089

Scope

X-Link[®]TC is the smallest diameter, thermoset, UL listed, Type TC control cable available in the industry today. X-Link TC is 30% to 40% smaller in diameter than standard control cable. It may be installed in wet and dry locations, indoors and

outdoors, in metal trays, conduits, ducts, or in direct burial applications. It is ideal for applications in substations, cogeneration, waste/energy and industrial facilities to perform a variety of control and related functions.

Features

- Thermoset insulation and jacket for enhanced thermal stability
- Small diameter
- Economical
- More cables per tray or conduit
- Flame retardant
- Light weight
- Flexible
- Heat, sunlight, moisture and abrasion resistant
- Easily pulled (low friction jacket)
- Tin-coated conductors for improved terminations and corrosion resistance
- Jackets have printed sequential footage markers for improved inventory control
- Jacket strippability facilitates termination
- Reduced halogen design
- Low smoke jacket
- Lead free jacket

Performance Standards

- UL listed, Type TC (UL 1277)
- UL listed for direct burial and sunlight
- Passes ICEA 210.000 BTU/hr vertical tray flame test
- Passes IEEE-383 70.000 BTU/hr vertical tray flame test
- Single conductors pass UL VW-1 flame test
- In accordance with the National Electrical Code - Article 340
- Single conductors in accordance with performance requirements of ICEA S-66-524 and UL 44, Class XL
- Single conductors in accordance with AWM style No. 3502
- Jacket exceeds the requirements of UL Class XL/90°C
- UL approved for 90°C operation in both wet and dry locations

Construction

Construction:

Annealed tin-coated copper, Class "B" strand (ASTM B-8 & B-33)

Insulation:

20 mils of flame retardant crosslinked polyolefin meeting performance requirements of ICEA S-66-524 and UL 44 Class XL

Circuit Identification:

Colored insulation per ICEA Method 1, Table K-2

Fillers:

When required, non-hygroscopic and non-wicking

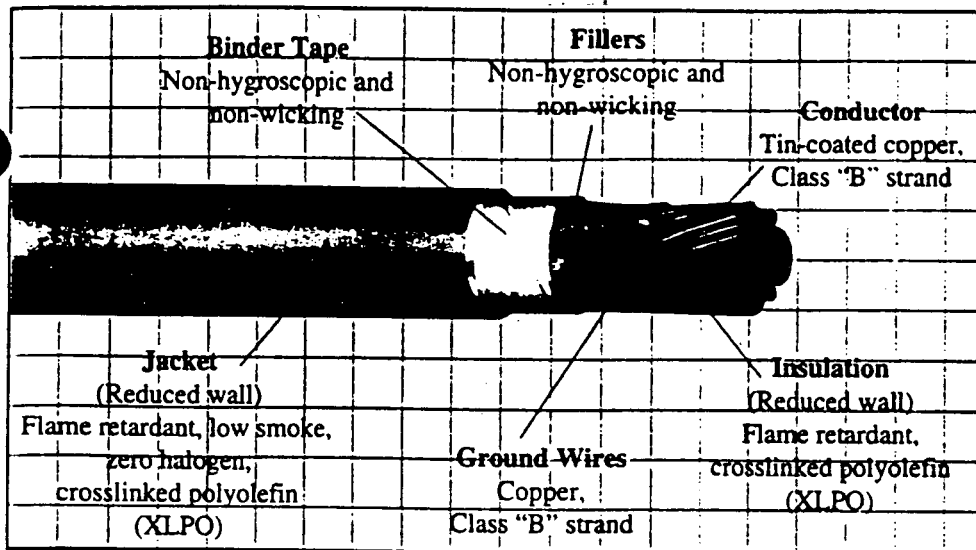
Binder Tape:

Non-hygroscopic and non-wicking tape

Jacket:

Reduced wall, black flame retardant, low smoke, zero halogen, crosslinked polyolefin jacket

*Rated 90°C for normal operation in wet and dry locations, 130°C for emergency overload conditions, and 250°C for short circuit conditions.



X-Link TC Power Cable (XLPO/XLPO)

90°C, 600 Volt
NEC Type TC
UL Listed

Spec. RSS-3-089

Scope

X-Link[®]TC is the smallest diameter, thermoset, UL listed, Type TC power cable available in the industry today. X-Link TC is 20% to 30% smaller in diameter than standard power cable. It may be installed in wet and dry locations, indoors and

outdoors, in metal trays, conduits, ducts, or in direct burial applications. It is ideal for applications in substations, cogeneration, waste/energy and industrial facilities to perform a variety of low voltage power, lighting and related functions.

Features

- Thermoset insulation and jacket for enhanced thermal stability
- Small diameter
- Economical
- More cables per tray or conduit
- Flame retardant
- Light weight
- Flexible
- Heat, sunlight, moisture and abrasion resistant
- Easily pulled (low friction jacket)
- Tin-coated conductors for improved terminations and corrosion resistance
- Jackets have printed sequential footage markers for improved inventory control
- Jacket strippability facilitates termination
- Reduced halogen design
- Low smoke jacket
- Lead free jacket

Performance Standards

- UL listed, Type TC (UL 1277)
- UL listed for direct burial and sunlight
- Passes ICEA 210,000 BTU/hr vertical tray flame test
- Passes IEEE-383 70,000 BTU/hr vertical tray flame test
- Single conductors pass UL VW-1 flame test
- In accordance with the National Electrical Code - Article 340
- Single conductors in accordance with performance requirements of ICEA
- S-66-524 and UL 44, Class XL
- Jacket exceeds the requirements of UL Class XL/90°C
- UL approved for 90°C operation in both wet and dry locations

Construction

Conductor:

Annealed, tin-coated copper, Class "B" strand (ASTM B-8 & B-33)

Insulation:

Flame retardant crosslinked polyolefin, meeting performance requirements of ICEA S-66-524 and UL 44 Class XL

Circuit Identification:

Printed numbers per ICEA Method 4

Ground Wire(s):

Annealed copper, Class "B" strand, sized to comply with UL 1277 requirements

Fillers:

When required, non-hygroscopic and non-wicking

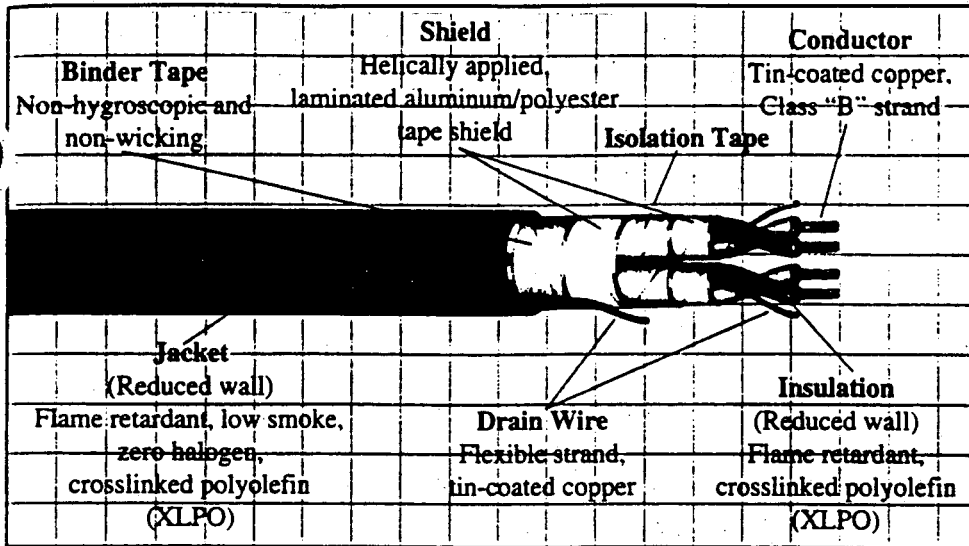
Binder Tape:

Non-hygroscopic and non-wicking

Jacket:

Reduced wall, black flame retardant, low smoke, zero halogen, crosslinked polyolefin jacket

*Rated 90°C for normal operation in wet and dry locations, 130°C for emergency overload conditions, and 250°C for short circuit conditions.



X-Link TC Instrumentation Cable

Multi-Shielded Pairs
With Overall Shield

(XLPO/XLPO)

90°C, 600 Volt
NEC Type TC
UL Listed

Spec. RSS-3-089

Scope

X-Link[®]TC is the smallest thermoset, UL listed, Type TC Instrumentation Cable available in the industry today. X-Link[®]TC is 30% to 40% smaller in diameter than standard 600 volt cable. It may be installed in wet or dry locations, indoors and outdoors, in metal trays, ducts, conduits or in direct burial applications. It is ideal for applications in substations, cogeneration, waste/energy and industrial facilities to perform a variety of signaling, data acquisition and monitoring functions. *Designed for use on circuits where complete isolation is required between pairs and from external interference.*

Construction

Conductor:

Tin-coated copper conductors, Class "B" strand (ASTM B-8 & B-33)

Insulation:

20 mils of flame retardant crosslinked polyolefin

Pair Assembly:

Two insulated conductors twisted with a flexible strand, tin-coated copper drain wire, a helically applied aluminum/polyester laminated tape shield and an isolation tape

Cabling:

Required number of pairs cabled

Circuit Identification:

One black & one red insulated single conductor in each pair with printed pair numbers on both singles for pair identification (alternate methods also available)

Fillers:

When required, non-hygroscopic and non-wicking

Overall Shield System:

Helically applied aluminum/polyester laminated tape shield in continuous contact with a flexible strand, tin-coated copper drain wire

Binder Tape:

Non-hygroscopic and non-wicking

Jacket:

Reduced wall, black flame retardant, low smoke, zero halogen, crosslinked polyolefin jacket

* Rated 90°C for normal operation in wet and dry locations, 130°C for emergency overload conditions, and 250°C for short circuit conditions.

Features

- Thermoset insulation and jacket for enhanced thermal stability
- Small diameter
- Economical
- More cables per tray or conduit
- 600 volt rating allows cables to be run in trays without separation (300 vs 600 volt)
- Flame retardant
- Light weight
- Flexible
- Heat, moisture, abrasion and crush resistant
- Easily pulled (low friction jacket)
- Tin-coated conductors for improved terminations and corrosion resistance
- Jackets have printed sequential footage markers for improved inventory control
- Jacket strippability facilitates termination
- Shield to shield isolation system provided and verified by electrical testing
- Reduced halogen design
- Low smoke jacket
- Lead free jacket

Performance Standards

- UL listed, Type TC (UL 1277)
- UL listed for sunlight resistance
- Passes ICEA 210.000 BTU/hr vertical tray flame test
- Passes IEEE-383 70.000 BTU/hr vertical tray flame test
- Single conductors pass UL VW-1 flame test
- In accordance with the National Electrical Code - Article 340
- Insulation in accordance with performance requirements of ICEA S-66-524 and UL 44, Class XL
- Single conductors in accordance with AWM style No. 3502
- Jacket exceeds the requirements of UL Class XL/90°C
- UL approved for 90°C operation in both wet and dry locations

ATTACHMENT 6.9

Typical Plot of the Inverse of Time verses External Heat Flux

(Exerpt from EPRI Report NP-1200)

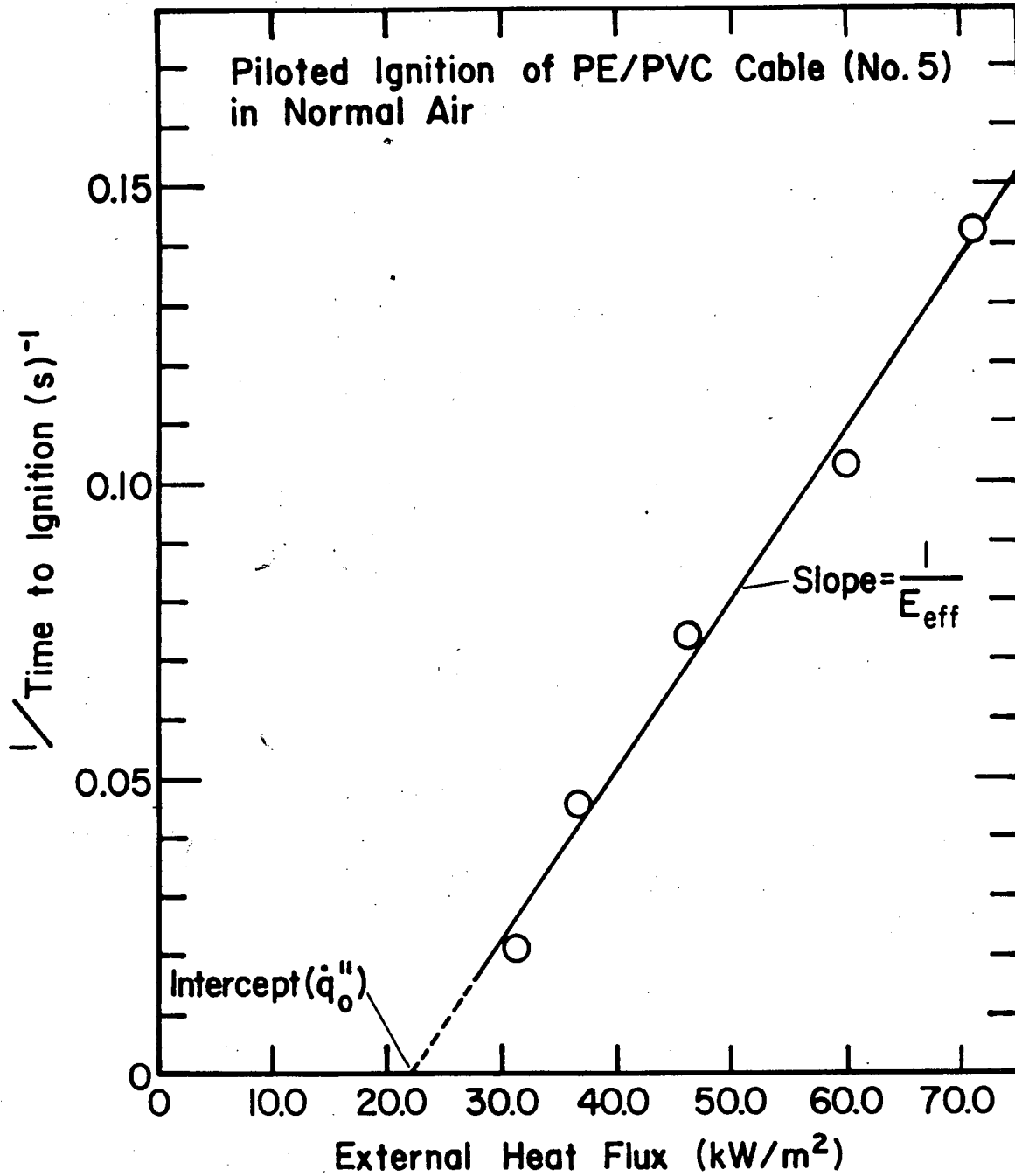


Figure 4-1. Piloted Ignition of Cable Sample Vapor/Air Mixture

ATTACHMENT 6.10

Society of Fire Protection Engineers (SFPE)
Handbook of Fire Protection Engineering, 2nd edition.

Section 3, Chapter 4

(copy of the galley proof)

GENERATION OF HEAT AND CHEMICAL COMPOUNDS IN FIRES

Archibald Tewarson

INTRODUCTION

Fire hazard is characterized by the generation of calorific energy and products, per unit of time, as a result of the chemical reactions between surfaces and vapors of materials and oxygen from air. If heat is the major contributor to hazard, it is defined as thermal hazard.¹ If fire products (smoke, toxic, corrosive, and odorous compounds) are the major contributors to hazard, it is defined as nonthermal hazard.¹ Various tests are used to determine the generation per unit of time of: (1) the calorific energy, defined as the heat release rate; and (2) fire products. The heat release rate and generation rates of fire products normalized by the generation rate of material vapors, airflow, etc., defined as fire properties, are used in models to predict: (1) heat release rate to assess the thermal hazard and fire protection needs; and (2) generation rates of fire products to assess the nonthermal hazard due to reduced visibility, and smoke damage, toxicity, corrosivity, and protection needs.

The region where vapors are generated is defined as the pyrolysis region and its leading edge as the pyrolysis front. The initiation of flaming fire is defined as ignition. Ignition is a process where vapors generated by heating the surface of a material mix with air, form a combustible mixture, ignite, and a fire is initiated. The region where the ignition process occurs is defined as the *ignition zone*. Minimum heat flux at or below which a material cannot generate the combustible mixture is defined as the *Critical Heat Flux (CHF)*.¹⁻⁴ The resistance of a material to generate a combustible mixture is defined as the *Thermal Response Parameter (TRP)*.¹⁻⁴ The higher the CHF and TRP values, the longer it takes for the material to heat up, ignite, and initiate a fire, and thus lower the fire propagation rate.

Depending on the magnitude of the heat flux provided by external sources and the flame of the material burning in the ignition zone, the pyrolysis front and flame can move beyond the ignition zone. The movement of the pyrolysis

front is defined as fire propagation. The rate of movement of the pyrolysis front on the surface is defined as the fire propagation rate.

Heat and chemical compounds are generated as a result of the chemical reactions between: (1) pyrolyzing material vapors and oxygen in the gas phase, and (2) pyrolyzing material surface and oxygen in the solid phase. Heat generated in chemical reactions is defined as the *chemical heat*.²⁻⁴ The rate of generation of chemical heat is defined as the *chemical heat release rate*. The chemical heat release rate distributes itself into a convective component, defined as the *convective heat release rate*, and into a radiative component, defined as the *radiative heat release rate*.²⁻⁴ Convective heat release is associated with the flow of a hot products-air mixture, and radiative heat release is associated with the electromagnetic emission from the flame.

In a majority of cases, hazards to life and property are due to fires in enclosed spaces, such as in buildings. In general, fires in enclosed spaces are characterized by an upper and a lower layer. The main constituents of the upper layer are the hot fire products, and the main constituent of the lower layer is fresh air. In early stages, a building fire is well-ventilated, and is easy to control and extinguish. However, if the fire is allowed to grow, especially with limited enclosure ventilation and large material surface area, the chemical reactions between oxygen from air and products of incomplete combustion (smoke, CO, hydrocarbons, and other intermediate products) remain incomplete, resulting in an increase in nonthermal hazard. Rapid increase in the generation rates of products of incomplete combustion and growth rate of the fire, due to sudden and dramatic involvement of most of the exposed material surfaces, is termed flashover. Flashover is the most dangerous condition in a fire.

Heat release rate and generation rates of fire products as well as their nature are governed by: (1) fire initiation within the ignition zone; (2) fire propagation rate beyond the ignition zone; (3) fire ventilation; (4) external heat sources; (5) presence or absence of the fire suppression/extinguishing agents; and (6) materials: (a) their shapes, sizes, and arrangements; (b) their chemical natures; (c) types of additives mixed in; and (d) presence of other materials. In this handbook most of these areas have been discussed from a fundamental as well as applied views. For example, the mechanisms of thermal decomposition of polymers, which govern

Dr. Archibald Tewarson is Senior Research Specialist and Manager, Flammability Section, Factory Mutual Research Corporation. His research has focused on chemical kinetics, chemiluminescence, and chemical aspects of fires.

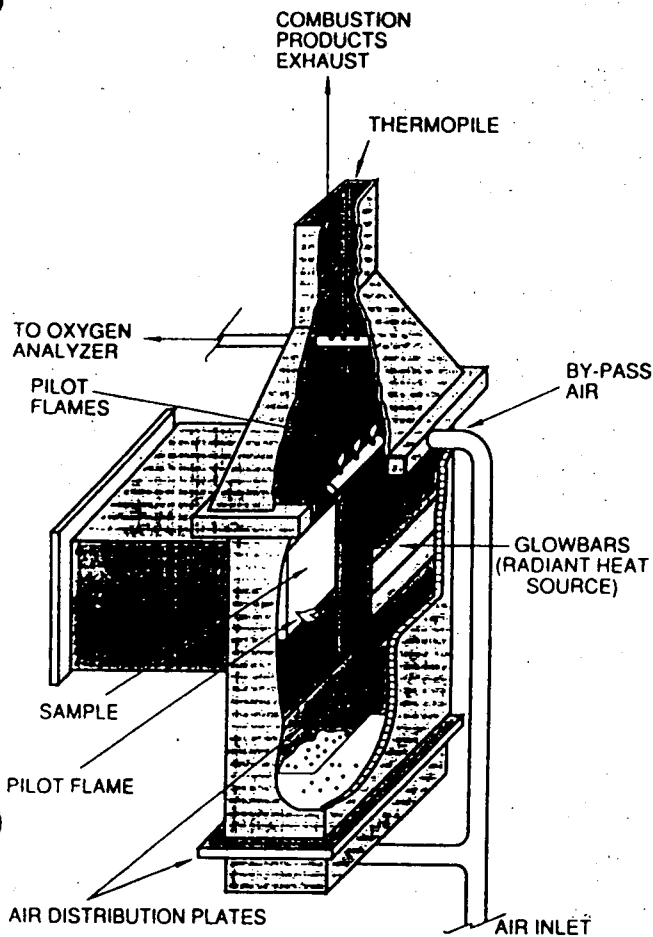


Fig. 3-4.1. Ohio State University's (OSU) heat release rate apparatus.⁵⁻⁸

the generation rates of material vapors, is discussed by Beyler in Section 1, Chapter 7; generation rate of heat (or heat release rate) from the viewpoint of thermochemistry is discussed by Drysdale in Section 1, Chapter 5; and its relationship with flame height by McCaffrey in Section 2, Chapter 1. Flaming ignition of the mixture of material vapors and air is discussed by Kanury in Section 2, Chapter 13; and surface flame spread by Quintiere in Section 2, Chapter 14.

This chapter presents the applications of the principles discussed in several chapters in this handbook to determine the fire properties of materials. Simple calculations have been included in the chapter to show how the properties can be used for various applications.

CONCEPTS GOVERNING GENERATION OF HEAT AND CHEMICAL COMPOUNDS IN FIRES

Fire Initiation (Ignition)

The fundamental ignition principles are described in detail by Kanury in Section 2, Chapter 13. The principles suggest that, for fire initiation, a material has to be heated above its CHF value (CHF value is related to the fire point). The CHF value can be determined in one of the several heat release rate apparatuses, e.g., the Ohio State University's (OSU)

heat release rate apparatus,⁵⁻⁸ shown in Figure 3-4.1; the Flammability Apparatus,^{1-4,9-16} shown in Figures 3-4.2, parts (a) and (b); and in the Cone Calorimeter,¹⁷⁻¹⁹ shown in Figure 3-4.3. The design features, test conditions, and types of measurements for the three apparatuses are listed in Table 3-4.1.

Typically the CHF values are determined by exposing the horizontal sample (e.g., about 100-mm diameter or about 100 × 100-mm square and up to about 100-mm in thickness with blackened surface in the Flammability Apparatus) to various external heat flux values until a value is found at which there is no ignition for about 15 min.

As the surface is exposed to heat flux, initially most of the heat is transferred to the interior of the material. The ignition principles suggest that the rate with which heat is transferred depends on the ignition temperature (T_{ig}), ambient temperature (T_a), material thermal conductivity (k), material specific heat (c_p), and the material density (ρ). (See Section 2, Chapter 13.) The combined effects are expressed by a parameter defined as the Thermal Response Parameter (TRP) of the material^{1-4,9-15}

$$TRP = \Delta T_{ig} \sqrt{kp c_p} \quad (1)$$

where $\Delta T_{ig} (= T_{ig} - T_a)$ is the ignition temperature above ambient (K), k is in kW/m-K, ρ is in g/m³, c_p is in kJ/g-K, and

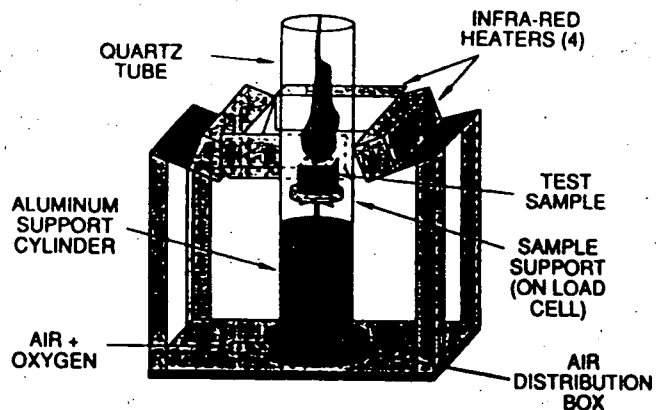
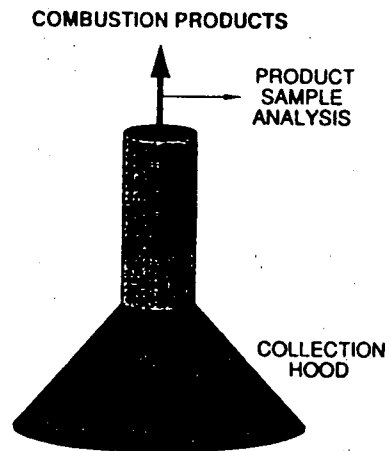


Fig. 3-4.2(a). Flammability Apparatus designed by the Factory Mutual Research Corporation (FMRC). Sample configuration for ignition, pyrolysis, and combustion tests.^{1-4, 8-18}

TRP is in $\text{kW}\cdot\text{s}^{1/2}/\text{m}^2$. TRP is a very useful parameter for the engineering calculations to assess resistance to ignition and fire propagation.

The ignition principles (see Section 2, Chapter 13) suggest that, for thermally thick materials, the inverse of the square root of time to ignition is expected to be a linear function of the external heat flux away from the CHF value

$$\sqrt{\frac{1}{t_{ig}}} = \frac{\sqrt{4/\pi}(\dot{q}_c^* - \text{CHF})}{\text{TRP}} \quad (2)$$

where t_{ig} is time to ignition (sec), \dot{q}_c^* is the external heat flux (kW/m^2), and CHF is in kW/m^2 . Most commonly used materials behave as thermally thick materials and satisfy Equation 2, such as shown by the data in Figures 3-4.4 for polymethylmethacrylate (PMMA); in Figure 3-4.5 for heavy corrugated paper sheets, measured in the Flammability Apparatus; and in Figure 3-4.6 for non-blackened samples, measured in the Cone Calorimeter. The Cone Calorimeter data are taken from reference 20.

The value of the Thermal Response Parameter is determined, for example, in the Flammability Apparatus, by: (1) measuring the time to ignition for 100×100 -mm square or 100-mm diameter and up to 25-mm-thick samples at differ-

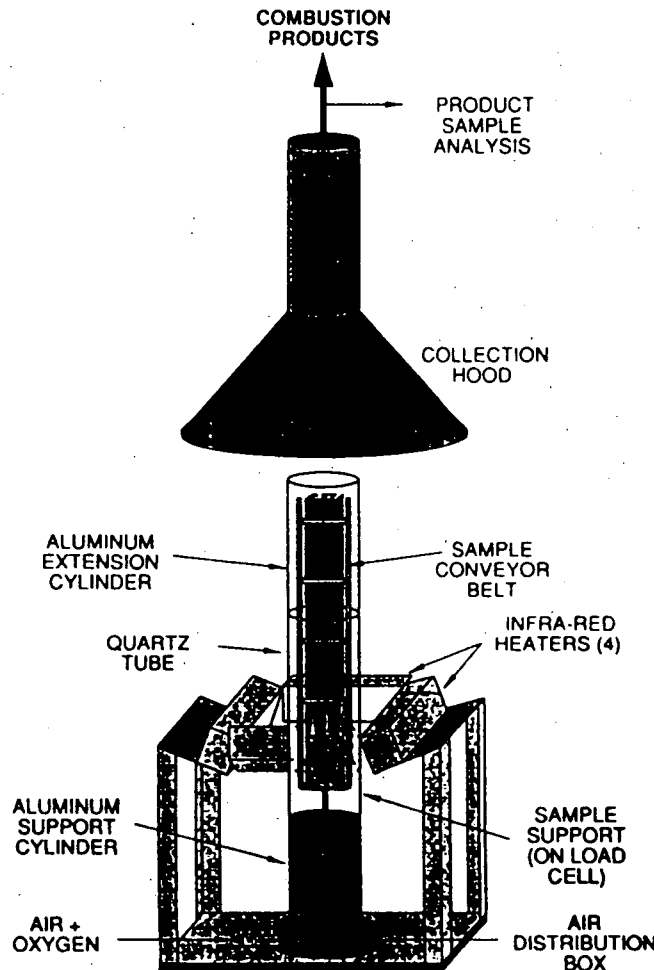


Fig. 3-4.2(b). Flammability Apparatus designed by the Factory Mutual Research Corporation (FMRC). Sample configuration for fire propagation tests.^{1-4,9-18} A conveyor belt sample is shown.

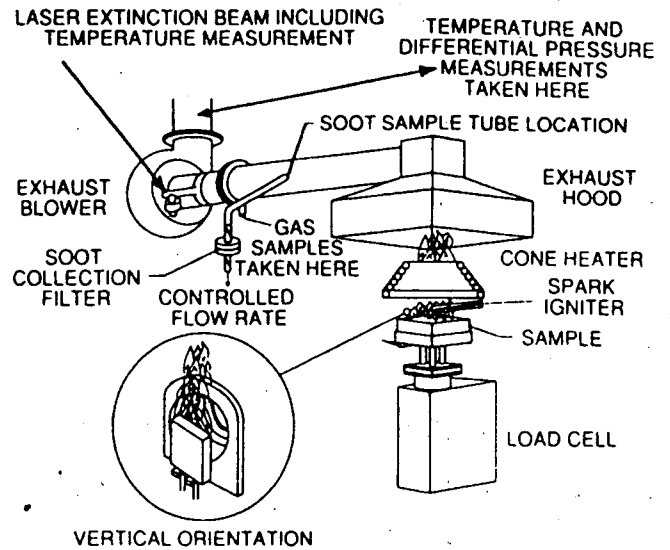


Fig. 3-4.3. The Cone Calorimeter designed at the National Institute of Standards and Technology (NIST).¹⁷⁻¹⁹

ent external heat flux values for samples with surfaces blackened with a very thin layer of black paint or fine graphite powder to avoid errors due to differences in the radiation absorption characteristics of the materials, and (2) performing a linear regression analysis of the data away from critical heat flux, following Equation 2, and recording the inverse of the slope of the line.

The value of the Thermal Response Parameter for a surface that is not blackened is higher than the value for the blackened surface. For example, for non-blackened and blackened surfaces of polymethylmethacrylate (PMMA), $\text{TRP} = 383$ and $274 \text{ kW}\cdot\text{s}^{1/2}/\text{m}^2$, respectively, from the Flammability Apparatus.² The value for the Thermal Response Parameter for a blackened surface of PMMA is close

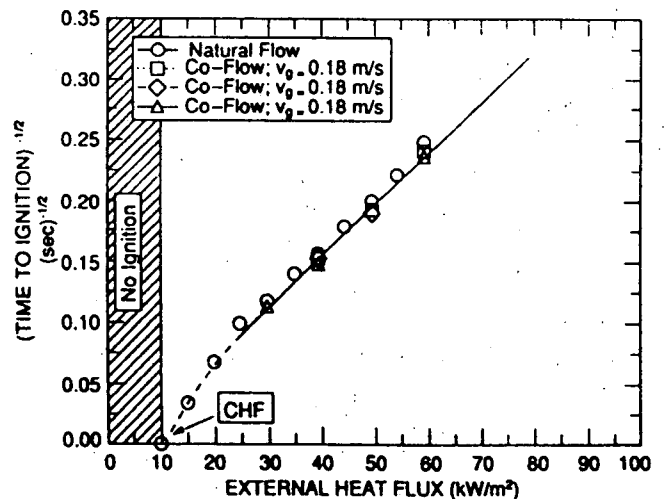


Fig. 3-4.4. Square root of the inverse of time to ignition vs external heat flux for $100 \times 100 \times 25$ -mm-thick polymethylmethacrylate (PMMA) slab with blackened surface. Data measured in Flammability Apparatus and reported in reference 2 are shown.

3-56 DESIGN CALCULATIONS

TABLE 3-4.1 Design Features, Test Conditions, and Types of Measurements for OSU and Flammability Apparatuses, and NIST Cone Calorimeter

Design and Test Conditions	OSU*	Flammability Apparatus	Cone [†]
Inlet gas flow	Co-flow	Co-flow/natural	Natural
Oxygen concentration (%)	21	0 to 60	21
Co-flow gas velocity (m/s)	0.49	0 to 0.146	NA
External heaters	Silicon Carbide	Tungsten-Quartz	Electrical Coils
External heat flux (kW/m ²)	0 to 100	0 to 65	0 to 100
Exhaust product flow (m ³ /s)	0.04	0.035 to 0.364	0.012 to 0.035
Horizontal sample dimensions (mm)	110 x 150	100 x 100	100 x 100
Vertical sample dimensions (mm)	150 x 150	100 x 600	100 x 100
Ignition source	Pilot flame	Pilot flame	Spark plug
Heat release rate capacity (kW)	8	50	8
Measurements			
Time to ignition	yes	yes	yes
Material gasification rate	no	yes	yes
Fire propagation rate	no	yes	no
Generation rates of fire products	yes	yes	yes
Light obscuration by smoke	yes	yes	yes
Optical properties of smoke	no	yes	no
Electrical properties of smoke	no	yes	no
Gas-phase corrosion	no	yes	no
Chemical heat release rate	yes	yes	yes
Convective heat release rate	yes	yes	no
Radiative heat release rate	no	yes	no
Flame extinction			
By water	no	yes	no
By halon	no	yes	no
By halon alternates	no	yes	no

*As specified in ASTM E 906-83⁷ and by DOT/FAA⁸

[†]As specified in ASTM E 1354-90¹⁹

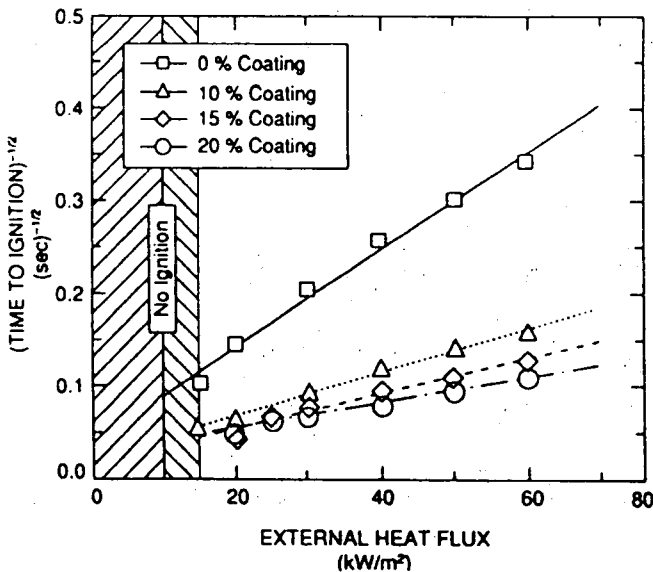


Fig. 3-4.5. Square root of the inverse of time to ignition vs external heat flux for two 100 x 100 x 11-mm-thick sheets of heavy corrugated paper with blackened surface. Data measured in Flammability Apparatus.

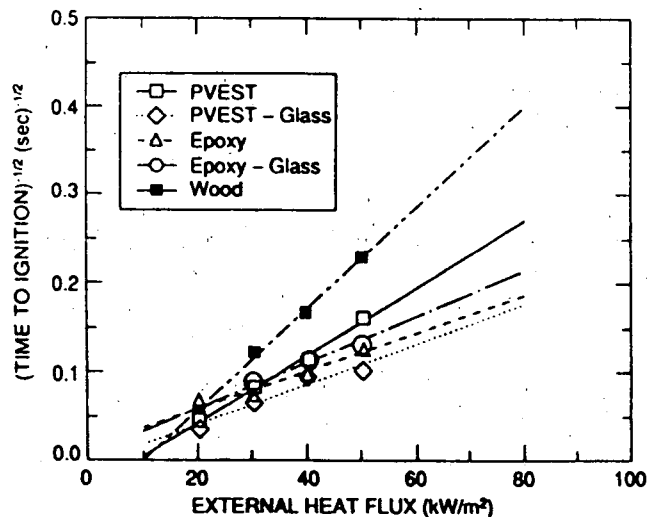


Fig. 3-4.6. Square root of the inverse of time to ignition vs external heat flux for 100 x 100-mm non-blackened surfaces of: 10- x 11-mm-thick polyvinyl ester (PVEST), 11-mm-thick epoxy, and 6-mm-thick wood (hemlock). Data measured in the Cone Calorimeter as reported in reference 20 are shown.

to the value calculated from the known T_{ig} , k , ρ , and c_p values for PMMA.²

The Thermal Response Parameter depends on the chemical as well as the physical properties of materials, such as the chemical structure, fire retardants, thickness, etc. For example, Figure 3-4.7 shows that the Thermal Response Parameter increases with sample thickness and increases in the amount of passive fire protection agent used, such as provided by a surface coating to a heavy corrugated paper sheet.

The Critical Heat Flux and the Thermal Response Parameter values for materials derived from the ignition data measured in the Flammability Apparatus and the Cone Calorimeter (as reported in reference 20) are listed in Table 3-4.2. In the Cone Calorimeter, the surface was not blackened, and thus the values of the Thermal Response Parameter may be somewhat higher than expected from the T_{ig} , k , ρ , and c_p values.

EXAMPLE 1:

In a fire, newspaper and polypropylene are exposed to a heat flux value of 50 kW/m². Estimate which material will ignite first, assuming physical conditions to be very similar for both the materials.

SOLUTION:

From Table 3-4.2, for newspaper and polypropylene, CHF = 10 and 15 kW/m², respectively, and TRP = 108 and 193 kW-s^{1/2}/m², respectively. Substituting these values in Equation 2 with $\dot{q}_c^* = 50$ kW/m², the times to ignition are calculated to be 6 and 24 sec for newspaper and polypropylene, respectively. Thus, newspaper will ignite first.

EXAMPLE 2:

Halogenated materials are obtained by replacing hydrogen atoms by halogen atoms in the chemical structures of the materials. For example, a unit in polyethylene (PE) consists of C₂H₄. If a hydrogen atom (H) is replaced by a chlorine atom (Cl) in a PE unit, it becomes a unit of rigid polyvinylchloride (PVC), i.e., C₂H₃Cl. If two H atoms are replaced by two fluorine atoms (F) in a PE unit, it becomes a unit of Tefzel™ (ethylene tetrafluoroethylene), i.e., C₂H₂F₂. If all the hydrogen atoms are replaced by four F atoms in a PE unit, it becomes a unit of Teflon™ (polytetrafluoroethylene), i.e., C₂F₄. Show how the replacement of hydrogen atoms by the halogen atoms affects the ignitability of the materials.

SOLUTION:

From Table 3-4.2, for PE (high density), PVC (rigid), Tefzel™, and Teflon™, the CHF values are 15, 15, 27, and 38 kW/m², respectively, and the TRP values are 321, 406, 356, and 682 kW-s^{1/2}/m², respectively. In the calculations, it is assumed that these materials are exposed to a uniform heat flux of 60 kW/m² in a fire under very similar physical conditions. From Equation 2, using $\dot{q}_c^* = 60$ kW/m², the times to ignition for PE (high density), PVC (rigid), Tefzel™, and Teflon™ are calculated to be 40, 64, 91, and 755 sec, respectively. Thus, resistance to ignition increases as the hydrogen atom is replaced by the halogen atom in the chemical structure of PE. The higher the number of hydrogen atoms replaced by the halogen atoms in the structure, the higher the resistance to ignition. When all the hydrogen atoms are replaced by the fluorine atoms, the material becomes highly resistant to ignition.

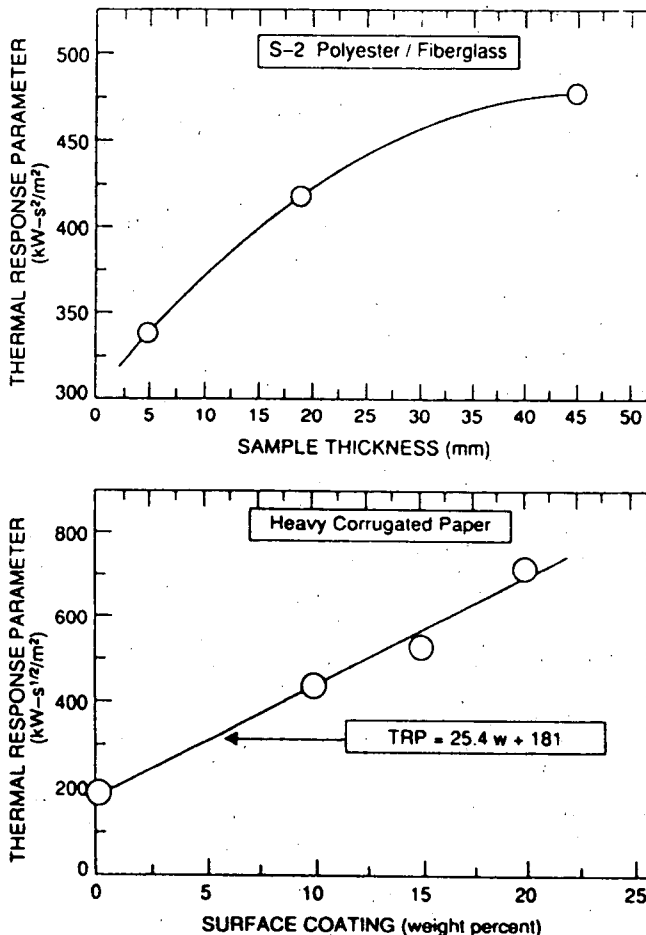


Fig. 3-4.7. Thermal Response Parameter vs thickness for S-2 polyester/fiberglass sample and weight percent of surface coating for the heavy corrugated paper. Data measured in the Flammability Apparatus. w is weight %.

Fire Propagation

The fundamental surface flame spread principles are described by Quintiere in Section 2, Chapter 14. According to these principles, the fire propagation process, as indicated by surface flame spread, can be explained as follows.

As a material is exposed to heat flux from internal and/or external heat sources, a combustible mixture is formed that ignites, and a flame anchors itself on the surface in the ignition zone. As the vapors of the material burn in the flame, they release heat with a certain rate, defined as the chemical heat release rate.* Part of the chemical heat release rate is transferred beyond the ignition zone as conductive heat flux through the solid and as convective and radiative heat fluxes from the flame. If the heat flux transferred beyond the ignition zone satisfies the Critical Heat Flux, Thermal Response Parameter, and gasification requirements of the material, the pyrolysis and flame fronts move beyond the ignition zone and the flame anchors itself over additional surface. Due to increase in the burning surface area, flame

*In earlier papers, it was defined as the actual heat release rate, \dot{Q}_A .

TABLE 3-4.2 Critical Heat Flux and Thermal Response Parameter of Materials

Materials	CHF (kW/m ²) Flammability Apparatus	TRP (kW·s ^{1/2} /m ²)	
		Flammability Apparatus	Cone Calorimeter*
<i>Natural Materials</i>			
Flour	10	218	—
Sugar	10	255	—
Tissue paper	10	95	—
Newspaper	10	108	—
Wood (red oak)	10	134	—
Wood (Douglas fir)	10	138	—
Corrugated paper (light)	10	152	—
Corrugated paper (heavy)			
No coating	10	189	—
Coating (10% by weight)	15	435	—
Coating (15% by weight)	15	526	—
Coating (20% by weight)	15	714	—
Wood (hemlock)	—	—	175
Wool 100%	—	—	252
Wood (Douglas fir/fire retardant, FR)	10	251	—
<i>Synthetic Materials</i>			
Epoxy resin	—	—	457
Polystyrene (PS)	13	162	—
Acrylic fiber 100%	—	—	180
Polypropylene (PP)	15	193	291
PP/FR panel	15	315	—
Styrene-butadiene (SB)	10	198	—
Crosslinked polyethylenes (XLPE)	15	224-301	—
Polyvinyl ester	—	—	263
Polyoxymethylene	13	269	—
Nylon	15	270	—
Polyamide-6	—	—	379
Polymethylmethacrylate (PMMA)	11	274	—
Isophthalic polyester	—	—	296
Acrylonitrile-butadiene-styrene (ABS)	—	—	317
Polyethylene (high density) (PE)	15	321	364
PE/nonhalogenated fire retardants	15	652-705	—
Polyvinyl ester panels	13-15	440-700	—
Modified acrylic (FR)	—	—	526
Polycarbonate	15	331	—
Polycarbonate panel	16	420	—
<i>Halogenated Materials</i>			
Isoprene	10	174	—
Polyvinylchloride (PVC)	10	194	—
Plasticized PVC, LOI = 0.20	—	—	285
Plasticized PVC, LOI = 0.25	—	—	401
Plasticized PVC, LOI = 0.30	—	—	397
Plasticized PVC, LOI = 0.35	—	—	345
Rigid PVC, LOI = 0.50	—	—	388
Rigid PVC1	15	406	—
Rigid PVC2	15	418	—
PVC panel	17	321	—
PVC fabric	26	217	—
PVC sheets	15	446-590	—
Ethylene tetrafluoroethylene (ETFE), Tefzel™	27	356	—
Fluorinated ethylene-propylene (FEP), Teflon™	38	682	—
Teflon fabric	50	299	—
Teflon coated on metal	20	488	—
<i>Composite and Fiberglass-Reinforced Materials</i>			
Polyether ether ketone—30% fiberglass	—	—	301
Isophthalic polyester—77% fiberglass	—	—	426
Polyethersulfone—30% fiberglass	—	—	256
Polyester 1—fiberglass	—	—	430
Polyester 2—fiberglass	10	275	—
Polyester 3—fiberglass	10	382	—
Polyester 4—fiberglass	15	406	—
Polyester 5—fiberglass	10	338	—
Epoxy Kevlar™ (thin sheet)	—	—	120
Epoxy fiberglass (thin sheet)	10	156	198
Epoxy graphite	15	395	—
Epoxy 1—fiberglass	10	420	—
Epoxy 2—fiberglass	15	540	—
Epoxy 3—fiberglass	15	500	—

*Calculated from the ignition data reported in reference 20.

TABLE 3-4.2 Critical Heat Flux and Thermal Response Parameter of Materials (Continued)

Materials	CHF (kW/m ²) Flammability Apparatus	TRP (kW-s ^{1/2} /m ²)	
		Flammability Apparatus	Cone Calorimeter*
<i>Composite and Fiberglass-Reinforced Materials (Continued)</i>			
Epoxy 4—fiberglass	10	388	—
Epoxy resin—69% fiberglass	—	—	688
Epoxy-graphite 1	—	481	—
Epoxy-graphite 1/ceramic coating (CC)	—	2273	—
Epoxy-graphite 1/intumescent coating (IC)	—	962	—
Epoxy-graphite 1/IC-CC	—	1786	—
Polyvinyl ester 1—69% fiberglass	—	—	444
Polyvinyl ester 2—fiberglass	—	281	—
Polyvinyl ester 2—fiberglass/CC	—	676	—
Polyvinyl ester 2—fiberglass/IC	—	1471	—
Polyvinyl ester 2—fiberglass/IC-CC	—	1923	—
Graphite composite	40	400	—
Phenolic fiberglass (thin sheet)	33	105	172
Phenolic fiberglass (thick sheet)	20	610	—
Phenolic-graphite 1	20	333	—
Phenolic-graphite 2	—	—	400
Phenolic kevlar (thin sheet)	20	185	258
Phenolic kevlar (thick sheet)	15	403	—
Phenolic-graphite 1/CC	—	807	—
Phenolic-graphite 1/IC	—	1563	—
<i>Foams (Wall-Ceiling Insulation Materials, etc)</i>			
Polyurethane foams	13-40	55-221	—
Polystyrene foams	10-15	111-317	—
Phenolic	20	610	—
Phenolic laminate—45% glass	—	—	683
Latex foams	16	113-172	—
<i>Materials with Fiberweb, Net-Like and Multiplex Structures</i>			
Polypropylenes	8-15	108-417	—
Polyester-polypropylene	10	139	—
Wood pulp-polypropylene	8	90	—
Polyester	8-18	94-383	—
Rayon	14-17	161-227	—
Polyester-rayon	13-17	119-286	—
Wool-nylon	15	293	—
Nylon	15	264	—
Cellulose	13	159	—
Cellulose-polyester	13-16	149-217	—
<i>Electrical Cables—Power</i>			
PVC/PVC	13-25	156-341	—
PE/PVC	15	221-244	—
PVC/PE	15	263	—
Silicone/PVC	19	212	—
Silicone/cross linked polyolefin (XLPO)	25-30	435-457	—
EPR (ethylene-propylene rubber/EPR)	20-23	467-567	—
XLPE/XLPE	20-25	273-386	—
XLPE/EVA (ethyl-vinyl acetate)	12-22	442-503	—
XLPE/Neoprene	15	291	—
XLPO/XLPO	16-25	461-535	—
XLPO, PVF (polyvinylidene fluoride)/XLPO	14-17	413-639	—
EPR/Chlorosulfonated PE	14-19	283-416	—
EPR, FR	14-28	289-448	—
<i>Electrical Cables—Communications</i>			
PVC/PVC	15	131	—
PE/PVC	20	183	—
XLPE/XLPO	20	461-535	—
Si/XLPO	20	457	—
EPR-FR	19	295	—
Chlorinated PE	12	217	—
ETFE/EVA	22	454	—
PVC/PVF	30	264	—
FEP/FEP	36	638-652	—
<i>Conveyor Belts</i>			
Styrene-butadiene rubber (SBR)	10-15	336-429	—
Chloroprene rubber (CR)	20	760	—
CR/SBR	15	400	—
PVC	15-20	343-640	—

*Calculated from the ignition data reported in reference 20.

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height, chemical heat release rate, and heat flux transferred ahead of the pyrolysis front all increase. The pyrolysis and flame fronts move again, and the process keeps repeating itself and burning area keeps increasing. Fire propagation on the surface continues as long as the heat flux transferred ahead of the pyrolysis front (from the flame or external heat sources) satisfies the Critical Heat Flux, Thermal Response Parameter, and gasification requirements of the material.

The rate of movement of the pyrolysis front is generally used to define the fire propagation rate

$$u = \frac{dX_p}{dt} \quad (3)$$

where u is the fire propagation rate (mm or/s), and X_p is the pyrolysis front (mm or m).

The fire propagation rate can be determined in one of the several apparatuses: (1) the LIFT described by Quintiere in Section 2, Chapter 14; (2) the Flammability Apparatus (50- and 500-kW scale); the 50-kW scale apparatus is shown in Figure 3-4.2(b); and (3) the Fire Products Collector (10,000-kW scale Flammability Apparatus) shown in Figure 3-4.8. Examples of the type of data obtained from the Flammability Apparatus are shown in Figures 3-4.9 through 3-4.12. In Figure 3-4.12, heat release rates increase linearly with time during downward fire propagation, very similar to

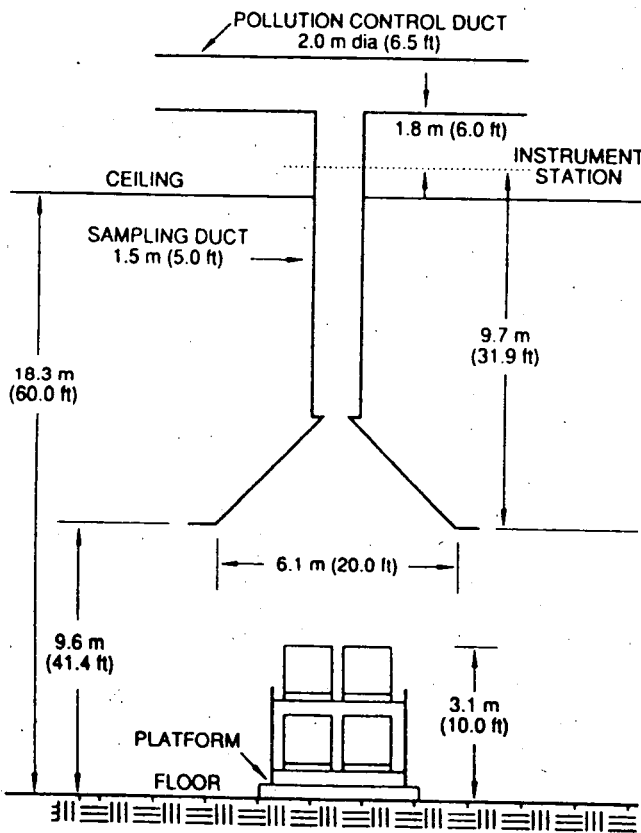


Fig. 3-4.8. The Fire Products Collector (10,000-kW-scale Flammability Apparatus) for large-scale combustion and fire propagation tests. Corrugated boxes with various products, arranged in two-pallet loads \times two-pallet loads \times two-pallet loads high are shown. The Fire Products Collector is designed by the Factory Mutual Research Corporation.

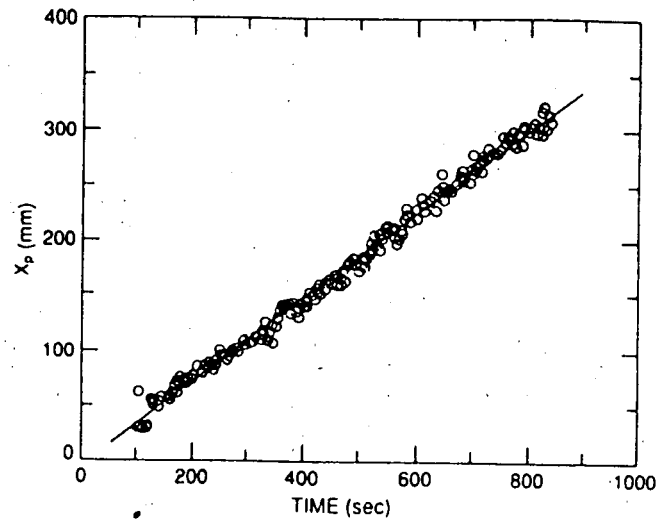


Fig. 3-4.9. Pyrolysis front versus time for the downward fire propagation for 300-mm long, 100-mm wide, and 25-mm thick PMMA vertical slab under opposed airflow condition in the Flammability Apparatus. Airflow velocity = 0.09 m/s. Oxygen mass fraction = 0.334. (Figure is taken from reference 2.)

the pyrolysis front values for the downward fire propagation in Figure 3-4.9.

The slopes of the lines in Figures 3-4.9 through 3-4.12 represent fire propagation rates. The upward fire propagation rate is much faster than the downward fire propagation rate. For downward fire propagation, linear increases in the pyrolysis front and heat release rates indicate decelerating fire propagation behavior. For upward fire propagation, non-linear increases in the pyrolysis front indicate accelerating fire propagation behavior.

Relationship between fire propagation rate, flame height, pyrolysis front, and heat release rate: Numerous researchers have found the following relationship between the

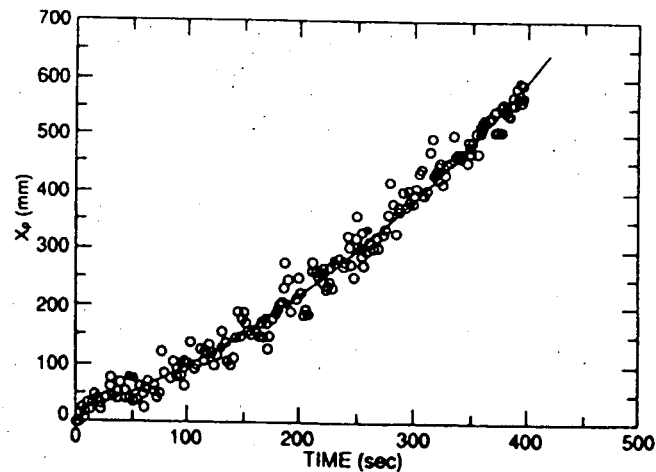


Fig. 3-4.10. Pyrolysis front versus time for the upward fire propagation for 600-mm long, 100-mm wide, and 25-mm thick PMMA vertical slab under co-airflow condition in the Flammability Apparatus. Airflow velocity = 0.09 m/s. Oxygen mass fraction = 0.233. (Figure is taken from reference 2.)

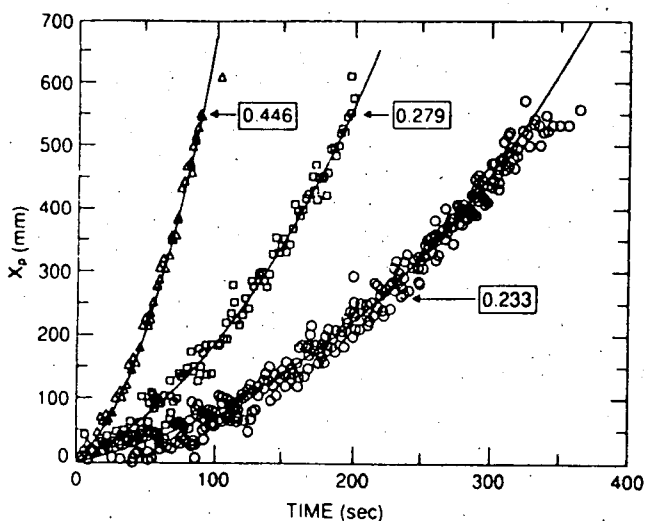


Fig. 3-4.11. Pyrolysis front versus time for the upward fire propagation for 600-mm long and 25-mm thick diameter PMMA cylinder under co-airflow condition in the Flammability Apparatus. Airflow velocity = 0.09 m/s. Numbers inside the frames are the mass fractions of oxygen in air. (Figure is taken from reference 2.)

flame height and pyrolysis front (as discussed by Quintiere in Section 2, Chapter 14 and reviewed in references 2 and 21)

$$X_f = aX_p^n \quad (4)$$

where X_f is the flame height (m), X_p is in m, $a = 5.35$, and $n = 0.67$ to 0.80 for steady wall fires.²

Fire propagation data for PMMA from the Flammability Apparatus² and for electrical cables from several standard tests for cables (ICEA, CSA FT-4, and UL-1581)⁹ satisfy Equation 4, as shown in Figure 3-4.13, with $a = 5.32$ and $n = 0.78$. The visual measurement of the pyrolysis front as damage length is used for the acceptance criterion in many of the standard tests for electrical cables. For example, for upward fire propagation in the CSA FT-4, damage length less than 60 percent of the total length of the cable tray for 20-min exposure time is used as the acceptance criterion.⁹ For horizontal fire propagation in the UL-1581 test, flame length of less than 40 percent of the total length of the cable tray is used as the acceptance criterion.⁹

The relationship between the flame height and the chemical heat release rate, expressed as the normalized chemical heat release rate (NCHRR), has been enumerated by McCaffrey in Section 2, Chapter 1. NCHRR is defined as (see Section 2, Chapter 1)

$$\text{NCHRR} = \frac{\dot{Q}_{ch}}{\rho c_p T_a g^{1/2} X_p^{3/2}} \quad (5)$$

where \dot{Q}_{ch} is the chemical heat release rate per unit width (kW/m), ρ is the density of air (g/m^3), c_p is the specific heat of air (kJ/g-K), T_a is the ambient temperature (K), g is acceleration due to gravity (m^2/s), and X_p is in m.

Many researchers have shown that the ratio of the flame height to pyrolysis front is a function of the heat release rate, such as the following relationship (as discussed by Quintiere in Section 2, Chapter 14 and reviewed in references 2 and 21)

$$\frac{X_f}{X_p} = a(\text{NCHRR})^n \quad (6)$$

where a and n are constants. This relationship reported in the literature (as reviewed in reference 2) for methane, ethane, and propylene is shown in Figure 3-4.14. The data for the upward fire propagation for PMMA from the Flammability Apparatus² and for the electrical cables from the several standard tests for cables (UL-1581, ICEA, and CSA FT-4) also satisfy this relationship as indicated in Figure 3-4.14.⁹

In Figure 3-4.14, data in the lower left-hand corner are for the low-intensity polyvinylchloride (PVC) electrical cable fire propagation in the standard tests for cables. These data show that for $\text{NCHRR} < 0.2$, $X_f/X_p < 1.5$, and $n = 1.0$. This is a characteristic property of materials for which there is either no fire propagation or a limited fire propagation beyond the ignition zone. These materials are defined as

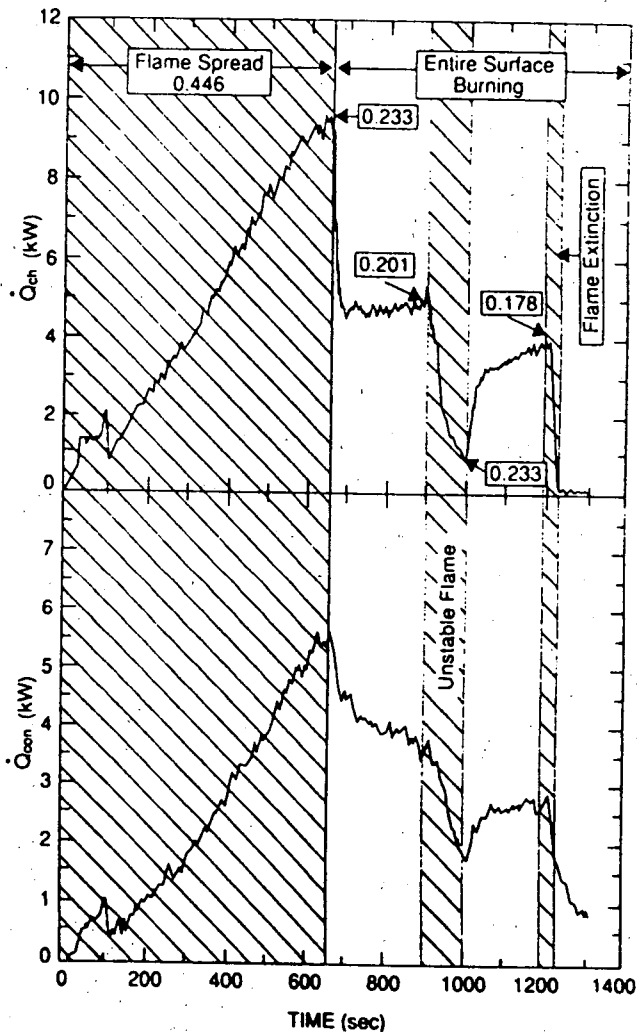


Fig. 3-4.12. Chemical and convective heat release rate versus time for the downward fire propagation, combustion, and flame extinction for 300-mm long, 100-mm wide, and 25-mm thick PMMA vertical slab under opposed airflow condition in the Flammability Apparatus. Airflow velocity = 0.09 m/s. Numbers inside the frames are the mass fractions of oxygen in air. (Figure is taken from reference 2.)

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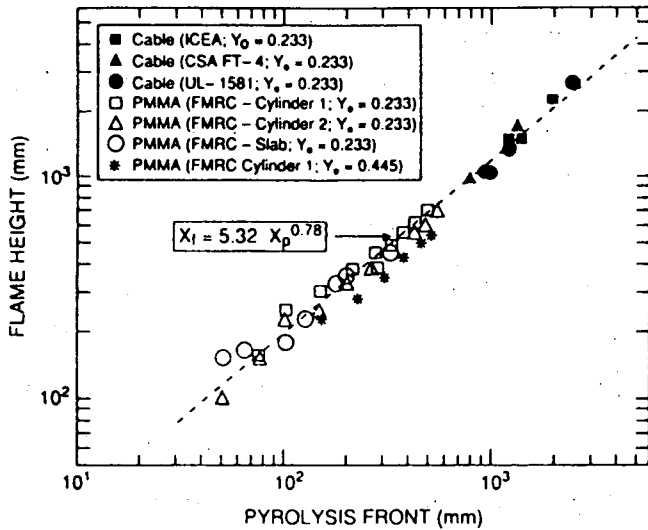


Fig. 3-4.13. Flame height versus pyrolysis front for the upward fire propagation in normal air. Data are for the vertical fire propagation for electrical cables contained in 2.44-m long, 310-mm wide, and 76-mm deep trays in standard tests for electrical cables (ICEA, CSA FT-4, and UL-1581) and for 600-mm long PMMA slabs (100-mm wide and 25-mm thick) and cylinder (25-mm diameter) in the Flammability Apparatus. Data for fire propagation in an oxygen mass fraction of 0.445 are also included. (Figure is taken from references 2 and 9.)

Group 1 materials.^{4,9-15} Cables with Group 1 material characteristics pass the standard tests for cables (UL-910, CSA FT-4, UL-1581, and ICEA). The data for higher intensity fire propagation in Figure 3-4.14 show that: (1) for $0.2 > \text{NCHRR} < 5$, $n = 3/4$, and $1.5 > X_f/X_p < 20$ (PMMA fire propagation and methane combustion); and (2) for $\text{NCHRR} > 5$, $n = 1/2$, and $X_f/X_p > 20$ (ethane and propylene combustion). Thus, the ratio of the flame height to pyrolysis front is a good indicator of the fire propagation characteristics of the materials. Materials for which flame height is close to the pyrolysis front during fire propagation can be useful indicators of decelerating fire propagation behavior.

Researchers have also developed many correlations between the flame heat flux transferred ahead of the pyrolysis front and heat release rate for downward, upward, and horizontal fire propagation (as discussed by Quintiere in Section 2, Chapter 14 and reviewed in references 2 and 21). For example, small- and large-scale fire propagation test data from the Flammability Apparatus [Figure 3-4.2(b)] and Fire Products Collector (Figure 3-4.8) suggest that, for thermally thick materials with highly radiating flames, the following semi-empirical relationship is satisfied³

$$\dot{q}_f^2 \propto \left[\frac{X_{rad}}{X_{ch}} \dot{Q}'_{ch} \right]^{1/3} \quad (7)$$

where \dot{q}_f is the flame heat flux transferred ahead of the pyrolysis front (kW/m^2) and X_{rad} is the radiative fraction of the combustion efficiency, X_{ch} . The fire propagation rate is expressed as³

$$\sqrt{u} \propto \left[\frac{X_{rad}}{X_{ch}} \dot{Q}'_{ch} \right]^{1/3} / \text{TRP} \quad (8)$$

The right-hand side of Equation 8, multiplied by 1000 with $X_{rad}/X_{ch} = 0.42$ is defined as the Fire Propagation Index (FPI)^{4,9-15}

$$\text{FPI} = 1000 \frac{(0.42 \dot{Q}'_{ch})^{1/3}}{\text{TRP}} \quad (9)$$

FPI describes the fire propagation behavior of materials under highly flame-radiating conditions prevalent in large-scale fires. The small- and large-scale fire propagation test data and understanding of the fire propagation suggest that the FPI values can be used to classify the materials into four groups:^{2-4,9-15}

1. $\text{FPI} < 7$ (Non-Propagating) Group N-1 Materials—Materials for which there is no fire propagation beyond the ignition zone. Flame is at critical extinction condition.
2. $7 < \text{FPI} < 10$ (Decelerating Propagation): Group D-1 Materials—Materials for which fire propagates beyond the ignition zone although in a decelerating fashion. Fire propagation beyond the ignition zone is limited.
3. $10 < \text{FPI} < 20$ (Non-Accelerating Propagation): Group 2 Materials—Materials for which fire propagates slowly beyond the ignition zone.
4. $\text{FPI} > 20$ (Accelerating Propagation): Group 3 Materials—Materials for which fire propagates rapidly beyond the ignition zone.

The FPI values for the upward fire propagation, under highly flame-radiating conditions, have been determined for numerous materials in the Flammability Apparatus. The highly radiating conditions are created by using a value of 0.40 for the mass fraction of oxygen. Two sets of tests are performed:

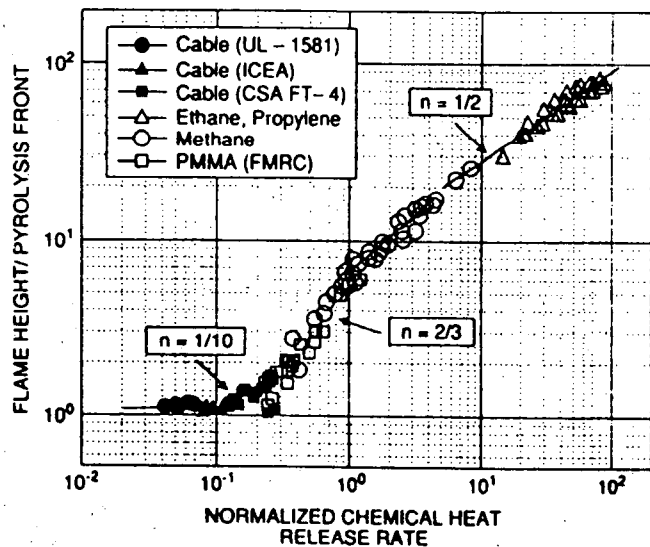


Fig. 3-4.14. Ratio of flame height to pyrolysis front versus the normalized chemical heat release rate for the upward fire propagation in normal air. Data for the diffusion flames of methane, ethane, and propylene are from the literature. Data for the cables are from the standard tests for electrical cables (ICEA, CSA FT-4, and UL-1581).⁹ Data for PMMA are from the Flammability Apparatus for 600-mm-long vertical PMMA slabs (100-mm wide, 25-mm thick) and cylinders (25-mm diameter).² (Figure is taken from reference 9.)

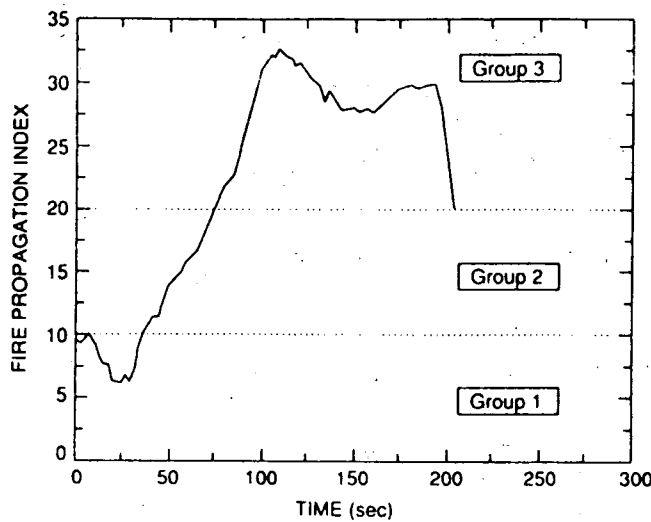


Fig. 3-4.15. Fire Propagation Index versus time for a polyethylene (PE)/polyvinylchloride (PVC) Group 3 cable determined in the Flammability Apparatus. This cable does not pass any standard tests for electrical cables.

1. Thermal Response Parameter Test: Ignition tests are performed in the Flammability Apparatus [Figure 3-4.2(a)], and the Thermal Response Parameter value is determined from the time to ignition versus external heat flux as described in the subsection on fire initiation (ignition).
2. Upward Fire Propagation Test: Fire propagation tests for vertical slabs, sheets, or cables are performed in the Flammability Apparatus [50- and 500-kW scale, Figure 3-4.2(b)]. About 300- to 600-mm-long, up to about 100-mm-wide, and up to about 100-mm-thick samples are used. The bottom 120 to 200 mm of the sample is in the ignition zone, where it is exposed to 50 kW/m² of external heat flux in the presence of a pilot flame. Beyond the ignition zone, fire propagates by itself, under co-airflow condition with an oxygen mass fraction of 0.40. During upward fire propagation, measurement is made for the chemical heat release rate as a function of time in each test.

The Thermal Response Parameter value and the chemical heat release rate are used in Equation 9 to calculate the Fire Propagation Index as a function of time. The Fire Propagation Index profile is used to classify materials into Group 1, 2, or 3.

Application of the Fire Propagation Index (FPI) to classify materials

Electrical Cables: The FMRC standard for cable fire propagation Class No. 3972¹⁴ is used to classify electrical cables, based on their upward fire propagation behavior, under highly flame-radiating conditions (oxygen mass fraction = 0.40), for protection needs in noncombustible occupancies. A noncombustible occupancy is defined as an occupancy where only specific types of combustibles are present, ignition sources are relatively small, and their contributions toward thermal and non-thermal hazards are negligible compared to the contributions of the combustibles. The Thermal Response Parameter and upward fire propagation tests are performed, and Equation 9 is used to calculate the Fire Propagation Index (FPI), as described above. Figure 3-4.15

shows an example of a typical profile for the Fire Propagation Index versus time for a polyethylene (PE)/polyvinylchloride (PVC) cable. This cable does not pass any of the standard electrical cable tray fire tests, and the FPI profile in Figure 3-4.15 shows that it is a Group 3 cable.

The following fire protection guidelines are recommended by FMRC for grouped cables:^{11,13,14}

1. Group 1 cables do not need additional fire protection in noncombustible occupancies with noncombustible construction.
2. Group 2 cables can be used without additional fire protection in noncombustible occupancies with noncombustible construction under certain conditions, and
3. Group 3 cables need fire protection.

Table 3-4.3 lists Fire Propagation Index values for selected electrical cables, composites, and conveyor belts.

EXAMPLE 3:

What type of fire behavior is represented by a 300-mm-wide, 8-m-high, and 25-mm-thick vertical sheet of a material with a Thermal Response Parameter value of 95 kW-s^{1/2}/m² if the peak chemical heat release during the upward fire propagation is 50 kW?

SOLUTION:

Fire propagation behavior is assessed by the FPI value. For the material, the chemical heat release rate per unit width, $Q'_{ch} = 50/0.3 = 167$ kW/m. Substituting this value in Equation 9, with TRP = 95 kW-s^{1/2}/m², FPI = 43. The TRP value is greater than 20, and thus the material is a Group 3 material and represents an accelerating fire propagation behavior.

EXAMPLE 4:

A noncombustible cable spreading room has an old and a new area with a 3-hr-rated solid fire wall between the two. The old area is filled with several trays of polyethylene (PE)/polyvinylchloride (PVC) communications cables, and the new area is filled with several trays of crosslinked polyolefin (XLPO/XLPO) communications cables. In order to determine the fixed fire protection needs for these two areas, cable samples were submitted to a testing laboratory. The laboratory reported the following test data:

1. Ignition Data:

Heat Flux (kW/m ²)	30	40	50	60	100
Time to Ignition (s)					
PE/PVC	76	27	14	8	2
XLPO/XLPO	—	716	318	179	45
2. Peak Chemical Heat Release Rate: During vertical fire propagation for 0.60-m-long cable sample in a highly radiating environment (oxygen mass fraction = 0.40), the following data were measured:

Cable	Peak Chemical Heat Release Rate Per Unit Cable Circumference (kW/m ²)
PE/PVC	100
XLPO/XLPO	20

The data were used to calculate the FPI values, which suggested that the area with PE/PVC cable trays needed fixed fire protection, whereas the area with XLPO/XLPO cable trays did not need fixed fire protection. Do you agree?

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SOLUTION:

The TRP values from the linear regression analysis of the ignition data are: 131 and 535 kW-s^{1/2}/m² for the PE/PVC and the XLPO/XLPO cable samples, respectively. The data for Q'_{ch} are given. Thus, from Equation 9, the FPI values for the PE/PVC and the XLPO/XLPO cable samples are 29 and 4, respectively. The FPI values suggest that the PE/PVC cable is a Group 3 cable and is expected to have an accelerating fire propagation behavior, and the XLPO/XLPO is a Group 1 cable and fire propagation is expected to be either limited to the ignition zone or decelerating. These calculations support that the cable spreading room area filled with the PE/PVC cable trays would need fixed fire protection, whereas it would not be needed for the area filled with the XLPO/XLPO cable trays.

Conveyor Belts: A conveyor belt standard is being developed at FMRC following the FMRC standard for cable fire propagation Class No. 3972.¹⁴ The Thermal Response Parameter and upward fire propagation tests are performed, and Equation 9 is used to calculate the Fire Propagation Index (FPI) as described above.

Conveyor belts are classified as propagating or non-propagating. For an approximately 600-mm-long and 100-mm-wide vertical conveyor belt, the data measured in the Flammability Apparatus under highly flame-radiating conditions show that the non-propagating fire condition is satisfied for $FPI \leq 7.0$ for the belts that show limited fire propagation in the large-scale fire propagation test gallery of the U.S. Bureau of Mines.^{12,22}

Table 3-4.3 lists Fire Propagation Index values for selected conveyor belts taken from references 12 and 22.

EXAMPLE 5:

Conveyor belts are made of solid woven or piles of elastomers, such as styrene-butadiene rubber (SBR), polychloroprene rubber (CR), polyvinylchloride (PVC), reinforced with fibers made of polymers, such as nylon. In large-scale fire propagation tests in a tunnel, fire on the surface of a CR-based conveyor belt was found to be non-propagating, whereas for a CR/SBR-based conveyor belt fire was found to be propagating. Small-scale tests showed that the CR- and CR/SBR-based conveyor belts had the following fire properties, respectively: (1) CHF = 20 and 15 kW/m²; (2) TRP = 760 and 400 kW-s^{1/2}/m²; and (3) peak Q'_{ch} = 114 and 73 kW/m under highly flame-radiating conditions (oxygen mass fraction = 0.40). Show that small-scale test results are consistent with the large-scale fire propagation behaviors of the two conveyor belts, using the criterion that, for non-propagating fire behavior, the Fire Propagation Index is equal to or less than 7.

SOLUTION:

Substituting the TRP and Q'_{ch} values in Equation 9, the FPI values for the CR- and CR/SBR-based conveyor belts are 5 and 8, respectively. Thus, the CR-based conveyor belt is expected to have a non-propagating fire behavior, whereas the CR/SBR-based conveyor belt is expected to have a propagating fire behavior. The small-scale test results, therefore, are consistent with the large-scale fire propagation behaviors of the two conveyor belts.

Composites and Fiberglass-Reinforced Materials: The use of composites and fiberglass-reinforced materials is increas-

TABLE 3-4.3 Fire Propagation Index for Cables, Composites, and Conveyor Belts, Determined in the Flammability Apparatus

	Diameter/ Thickness (mm)	FPI	Group	Fire Propagation*
Cables				
Polymethyl-methacrylate	25	30	3	P
Power Cables				
PVC/PVC	4-13	11-28	2-3	P
PE/PVC	11	16-23	3	P
PVC/PE	34	13	2	P
Silicone/PVC	16	17	2	P
Silicone/XLPO	55	6-8	1	N-D
EP/EP	10-25	6-8	1	N-D
XLPE/XLPE	10-12	9-17	1-2	D-P
XLPE/EVA	12-22	8-9	1	D
XLPE/Neoprene	15	9	1	D
XLPO/XLPO	16-25	8-9	1	D
XLPO, PVF/XLPO	14-17	6-8	1	N-D
EP/CLP	4-19	8-13	1-2	D-P
EP, FR/None	4-28	9	1	D
Communications Cables				
PVC/PVC	4	36	3	P
PE/PVC	4	28	3	P
PXLPE/XLPO	22-23	6-9	1	N-D
Si/XLPO	28	8	1	D
EP-FR/none	28	12	2	P
PECl/none	15	18	2	P
ETFE/EVA	10	8	1	D
PVC/PVF	5	7	1	N
FEP/FEP	8	4	1	N
FEP/FEP	10	5	1	N
Composites				
Polyester-1/glass (30/70)	4.8	13	2	P
Polyester-3/glass (30/70)	4.8	10	2	P
	19	8	1	D
	45	7	1	N
Phenolic-PVB/Kevlar™ (16/84)	4.8	8	1	D
Phenolic/Glass (20/80)	3.2	3	1	N
Epoxy-1/Glass (35/65)	4.4	9	1	D
Epoxy-2/Glass (35/65)	4.8	11	2	P
Epoxy-3/Glass (35/65)	4.4	10	2	P
Conveyor Belts†				
Styrene-butadiene rubber (SBR)		8-11	1-2	D-P
Chloroprene rubber (CR)		5	1	P
CR/SBR		8	1	D
PVC		4-10	1-2	N-P

*P: propagation; D: decelerating propagation; N: no propagation.
 †3 to 25 mm thick.

ing very rapidly because of low weight and high strength in applications such as aircraft, submarines, naval ships, military tanks, public transportation vehicles including automobiles, space vehicles, tote boxes, pallets, chutes, etc. Fire propagation, however, is one of the major concerns for the

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composites and fiberglass-reinforced materials; the Fire Propagation Index concept thus is used.^{4,10} For the determination of the Fire Propagation Index for the composites and fiberglass-reinforced materials, the Thermal Response Parameter and upward fire propagation tests are performed and Equation 9 is used, as discussed previously for electrical cables and conveyor belts.

The Fire Propagation Index concept used for the composites and fiberglass-reinforced materials is based on the knowledge gained during the development of the FMRC standard for cable fire propagation Class No. 3972¹⁴ and FMRC studies on conveyor belts.^{12,22} The non-propagating fire condition is satisfied in the Flammability Apparatus for $FPI \leq 7.0$, for about 600-mm-long and 100-mm-wide vertical composites and fiberglass-reinforced materials, under highly flame-radiating conditions (oxygen mass fraction = 0.40), very similar to the conveyor belts.

Table 3-4.3 lists Fire Propagation Index values for selected composites taken from references 4 and 10.

Interior Finish Wall/Ceiling Materials: Since 1971, Factory Mutual Research Corporation has used the 25-ft corner test as a standard test. The 25-ft corner test is performed in a 7.6-m (25-ft)-high, 15.2-m (50-ft)-long and 11.6-m (38-ft)-wide building corner configuration to evaluate the burning characteristics of interior finish wall and ceiling materials.²³⁻²⁶ The materials tested are typically panels with a metal skin over an insulation core material. The materials installed in the corner configuration are subjected to a growing exposure fire (peak heat release rate of about 3 MW) comprised of about 340 kg (750 lb) of 1.2-m (4-ft) x 1.2-m (4-ft) wood (oak) pallets stacked 1.5 m (5 ft) high at the base of the corner. The material is considered to have failed the test if within 15 min either: (1) fire propagation on the wall or ceiling extends to the limits of the structure, or (2) flame extends outside the limits of the structure through the ceiling smoke layer.

The fire environment within the 25-ft corner test structure has been characterized through heat flux and temperature measurements.^{23,25} It has been shown that the fire propagation boundary (pyrolysis front) measured by visual damage is very close to the Critical Heat Flux (CHF) boundary for the material, as shown in Figure 3-4.16, taken from reference 24. This is in agreement with the general understanding of the fire propagation process. Through small- and large-scale fire propagation tests for low-density, highly char-forming wall and ceiling insulation materials, using the Flammability Apparatus [Figure 3-4.2(a)], Fire Products Collector (Figure 3-4.8), and 25-ft corner test (Figure 3-4.16), a semi-empirical relationship has been developed for fire propagation rate for a 15-min test in the 25-ft corner test²³⁻²⁵

$$\frac{X_p}{X_t} = \frac{Q_{con}^*}{TRP} \quad (10)$$

where X_p is the average fire propagation length along the eaves (Figure 3-4.16) of the 25-ft corner test (pyrolysis front) measured visually (m), X_t is the total available length [11.6-m (38 ft)] in the 25-ft corner test, and Q_{con}^* is the convective heat release rate (kW/m^2).

The right-hand side of Equation 10 with the convective heat release rate measured at 50 kW/m^2 of external heat flux is defined as the convective flame spread parameter (FSP_c).^{24,25} Figure 3-4.17 shows a correlation between the convective flame spread parameter obtained from the Flammability Apparatus and the normalized fire propagation

length in the FMRC 25-ft corner test. Pass/fail regions, as determined from the 25-ft corner test, are indicated in the figure. Materials for which $FSP_c \leq 0.39$ pass the 25-ft corner test, and materials for which $FSP_c \geq 0.47$ are judged to be unacceptable (i.e., fail).²⁴⁻²⁶ The region where the FSP_c values are greater than 0.39 but less than 0.47 is uncertain.²⁴⁻²⁶

The correlation and pass/fail criterion shown in Figure 3-4.17 have been adopted in the FMRC Class No. 4880 for insulated wall or wall and ceiling panels.²⁶ In this standard, the 25-ft corner test has been replaced by the Flammability Apparatus [Figure 3-4.2(a)] tests. Two sets of tests are performed in the apparatus²⁴⁻²⁶

1. **Thermal Response Parameter Test:** Ignition tests are performed using approximately 100-mm x 100-mm and up to 100-mm-thick samples. Times to ignition at various external heat flux values are measured to determine the Thermal Response Parameter as described earlier.
2. **Convective Heat Release Rate Test:** Combustion tests are performed using about 100-mm x 100-mm and up to 100-mm-thick samples. Samples are burned in normal air under an external heat flux exposure of 50 kW/m^2 . During the test, measurement is made for the convective heat release as a function of time.

The data for the Thermal Response Parameter and convective heat release rate at 50 kW/m^2 of external heat flux are used to calculate the flame spread parameter (FSP_c) that accepts or rejects the sample.

Flaming and Nonflaming Fires

During fire propagation, the surface of the material regresses in a transient fashion with a rate slower than the fire propagation rate.² The surface regression becomes steady after fire propagates throughout the available surfaces. The surface regression continues until all the combustible components of the material are exhausted. During fire propagation and surface regression, the material generates vapors at a transient or steady rate. The generation rate of the material vapors is measured by the mass loss rate. In the presence of a flame and/or external heat flux, the mass loss rate, under steady state, is expressed as^{2,4,16}

$$\dot{m}^* = \frac{(\dot{q}_c^* + \dot{q}_{fr}^* + \dot{q}_{fc}^* - \dot{q}_{rr}^*)}{\Delta H_g} \quad (11)$$

where \dot{m}^* is the mass loss rate ($\text{g/m}^2\text{-s}$), \dot{q}_{fr}^* is the flame radiative heat flux transferred to the surface (kW/m^2), \dot{q}_{fc}^* is the flame convective heat flux transferred to the surface (kW/m^2), \dot{q}_{rr}^* is the surface re-radiation loss (kW/m^2), ΔH_g is the heat of gasification (kJ/g), and the total flame heat flux to the surface $\dot{q}_f^* = \dot{q}_{fr}^* + \dot{q}_{fc}^*$.

According to Equation 11, the generation rate of material vapors is governed by the external and flame heat flux, surface re-radiation loss, and the heat of gasification.

Heat of gasification: The heat of gasification for a melting material is expressed as²⁷

$$\Delta H_g = \int_{T_s}^{T_m} c_{p,s} dT + \Delta H_m + \int_{T_m}^{T_l} c_{p,l} dT + \Delta H_v \quad (12)$$

where ΔH_g is the heat of gasification (kJ/g); $c_{p,s}$ and $c_{p,l}$ are the specific heats of the solid and molten solid in kJ/g-K , respectively; ΔH_m and ΔH_v are the heats of melting and

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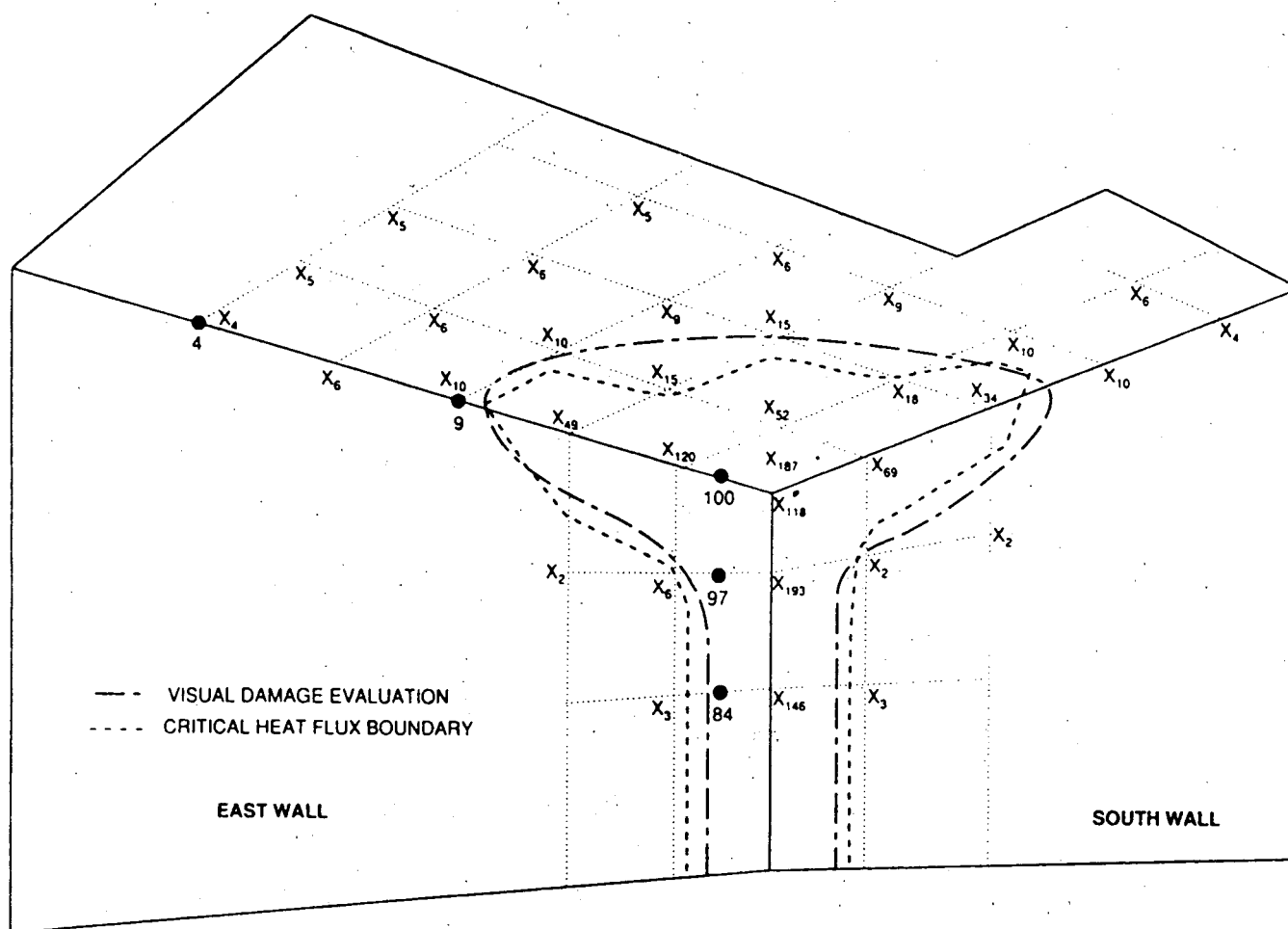


Fig. 3-4.16. Critical Heat Flux boundary and visual observations for the extent of fire propagation in the FMRC 25-ft corner test for a product that passes the tests.²⁴

vaporization at the respective melting and vaporization temperatures in kJ/g; and T_a , T_m , and T_v are the ambient temperature, melting temperature, and vaporization temperature in K, respectively. For materials that do not melt, but sublime, decompose, or char, Equation 12 is modified accordingly. The heat of gasification can be determined from: (1) the parameters on the right-hand side of Equation 12, which can be quantified by the thermal analysis techniques or calculated from the properties listed in the literature; and (2) nonflaming tests using apparatuses, such as the OSU, the Flammability Apparatus, or the Cone Calorimeter. The following are some examples of the techniques:

1. **Heats of Gasification of Polymers from the Differential Scanning Calorimetry:** The $c_{p,s}$, $c_{p,l}$, ΔH_m , and ΔH_v values for polymers have been quantified in the FMRC laboratory.²⁷ The techniques involve measurement of the specific heat as a function of temperature, such as shown in Figure 3-4.18 for polymethylmethacrylate, measured in our Flammability Laboratory. The specific heat increases with temperature; a value close to the vaporization temperature of PMMA is used in Equation 12. Further measurements are made of the heats of melting and

vaporization. Some examples of the data measured in our laboratory are listed in Table 3-4.4.

2. **Heat of Gasification from the Literature Data for the Heats of Gasification for Various Molecular Weight Hydrocarbons (Alkanes):** The *CRC Handbook of Chemistry and Physics*²⁸ listing for the heats of gasification for liquid and solid hydrocarbons (alkanes) satisfies the following relationship in the molecular weight range of 30 to 250 g/mole

$$\Delta H_g = -3.72 \times 10^{-6} M^2 + 0.0042 M + 0.164 \quad (13)$$

where M is the molecular weight of the hydrocarbon (g/mole).

The heats of gasification calculated from Equation 13 for various alkanes are listed in Table 3-4.4.

3. **Heat of Gasification from the Literature Data for the Specific Heats and Heats of Vaporization:** Water will be used as an example. The specific heat of liquid water, $c_{p,l} = 0.0042$ kJ/g-K,²⁹ and the heat of vaporization of water at 373 K is 2.26 kJ/g.²⁹ Assuming the ambient temperature to be 298 K and the vaporization temperature to be

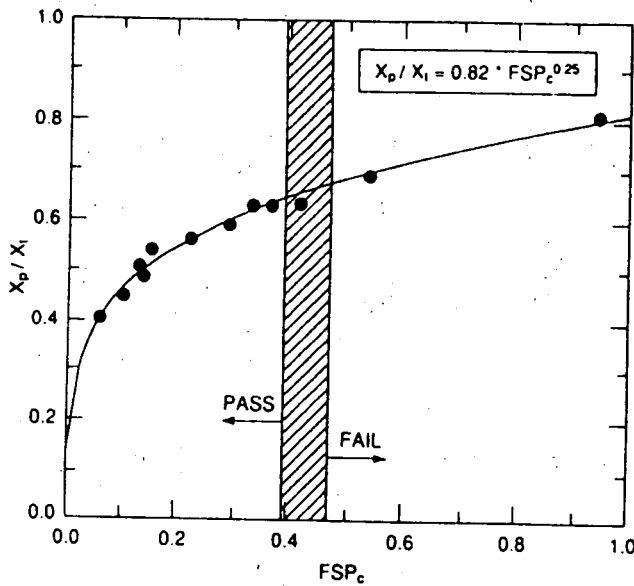


Fig. 3-4.17. Normalized fire propagation length measured in the 25-ft corner test versus the convective flame spread parameter obtained from the Flammability Apparatus. (Figure is taken from references 24 and 25.)

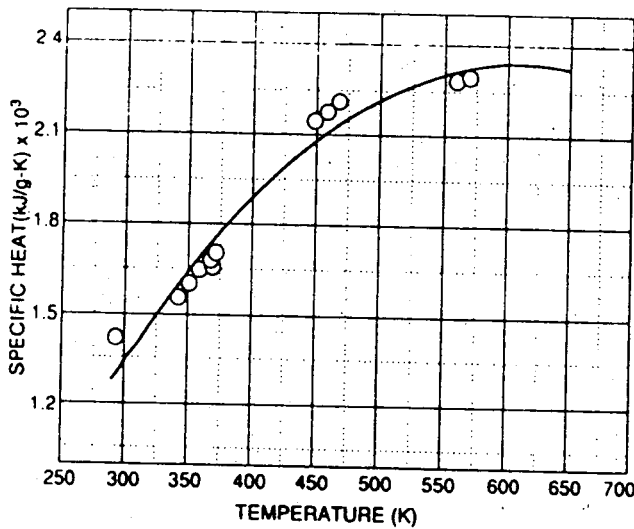


Fig. 3-4.18. Specific heat of polymethylmethacrylate versus temperature measured by a differential scanning calorimeter at the flammability laboratory of the Factory Mutual Research Corporation.

373 K, the heat of gasification of water from Equation 12 is calculated as follows

$$\int_{298}^{373} c_{p,i} dT = 0.0042(373 - 298) = 0.32 \text{ kJ/g};$$

$$\Delta H_{v,373} = 2.26 \text{ kJ/g};$$

$$\Delta H_g = 0.32 + 2.26 = 2.58 \text{ kJ/g}.$$

From the differential scanning calorimetry, the heat of gasification of water determined in the FMRC Flammability Laboratory is 2.59 kJ/g, which is in excellent agree-

ment with the calculated value. These two values for the heat of gasification of water are listed in Table 3-4.4.

4. Heat of Gasification from the Nonflaming Tests Using The Flammability Apparatus: The measurement for the heat of gasification from the nonflaming fire tests in the Flammability Apparatus was introduced in 1976.²⁷ In nonflaming fires, $\dot{q}_f = 0$, and Equation 11 becomes

$$\dot{m}'' = \frac{\dot{q}_c'' - \dot{q}_{rr}''}{\Delta H_g} \quad (14)$$

where mass loss rate is a linear function of the external heat flux, and the heat of gasification is the inverse of the slope of the straight line. This provides a convenient method to determine the heat of gasification in the nonflaming tests, where mass loss rate of the sample is measured at various external heat flux values. The heat of gasification is determined from the linear regression analysis of the average steady-state mass loss rate as a function of the external heat flux. In the Flammability Apparatus tests, approximately 100- × 100-mm square and up to 100-mm-thick samples are used with co-flowing nitrogen or air with an oxygen mass fraction of about 0.10.

Figure 3-4.19 shows a plot of the vaporization rate of water in a 0.0072 m² Pyrex™ glass dish against time at 50 kW/m² of external heat flux, measured in the Flammability Apparatus. The figure also includes the predicted mass loss rate using Equation 14, where

$$\dot{q}_{rr}'' = \epsilon \sigma (T_v^4 - T_a^4) \quad (15)$$

where ϵ is the emissivity of water (0.95 to 0.963 in the temperature range 298 to 373 K),³⁰ and σ is the Stefan-Boltzmann constant ($56.7 \times 10^{-12} \text{ kW/m}^2 \cdot \text{deg}^4$). For water, $T_v = 373 \text{ K}$ and $T_a = 298 \text{ K}$, and thus $\dot{q}_{rr}'' = 1 \text{ kW/m}^2$. From Equation 14, using $\dot{q}_c'' = 50 \text{ kW/m}^2$, $\dot{q}_{rr}'' = 1 \text{ kW/m}^2$, and $\Delta H_g = 2.57 \text{ kJ/g}$, $\dot{m}'' = 19.0 \text{ g/m}^2 \cdot \text{s}$. There is excellent agreement between the measured and predicted values at the steady state in Figure 3-4.19. Water vaporization tests

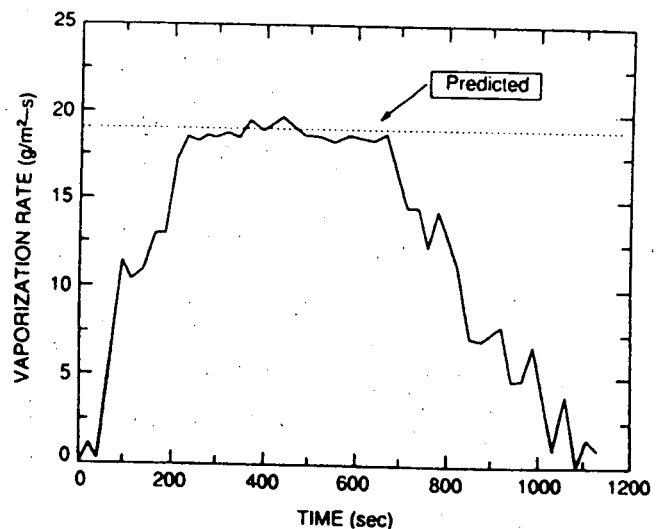


Fig. 3-4.19. Vaporization rate of water versus time measured in the Flammability Apparatus using 99.69 g of water in a Pyrex™ dish with an area of 0.0072 m². Water was exposed to an external heat flux of 50 kW/m².

TABLE 3-4.4 Surface Re-radiation and Heats of Gasification of Various Materials

Materials	Surface Re-radiation (kW/m ²)	Heat of Gasification (kJ/g)			
		Flam. App.*	Cone [†]	DSC [‡]	Cal [§]
Distilled water	0.63	2.58	—	2.59	2.58
<i>Hydrocarbons (Alkanes)</i>					
Hexane	0.50	—	—	—	0.50
Heptane	0.63	—	—	—	0.55
Octane	0.98	—	—	—	0.60
Nonane	1.4	—	—	—	0.64
Decane	1.8	—	—	—	0.69
Undecane	2.3	—	—	—	0.73
Dodecane	2.8	—	—	—	0.77
Tridecane	3.0	—	—	—	0.81
Tetradecane	3.0	—	—	—	0.85
Hexadecane	3.0	—	—	—	0.92
<i>Natural Materials</i>					
Filter paper	10	3.6	—	—	—
Corrugated paper	10	2.2	—	—	—
Wood (Douglas fir)	10	1.8	—	—	—
Plywood/FR	10	1.0	—	—	—
Particleboard	—	—	3.9	—	—
<i>Synthetic Materials</i>					
Epoxy resin	—	—	2.4	—	—
Polypropylene	15	2.0	1.4	2.0	—
Polyethylene (PE) (low density)	15	1.8	—	1.9	—
PE (high density)	15	2.3	1.9	2.2	—
PE foams	12	1.4-1.7	—	—	—
PE/25% chlorine (Cl)	12	2.1	—	—	—
PE/36% Cl	12	3.0	—	—	—
PE/48% Cl	10	3.1	—	—	—
Rigid polyvinylchloride (PVC)	15	2.5	2.3	—	—
PVC/plasticizer	10	1.7	—	—	—
Plasticized PVC, LOI = 0.20	10	2.5	2.4	—	—
Plasticized PVC, LOI = 0.25	—	—	—	—	—
Plasticized PVC, LOI = 0.30	—	—	2.1	—	—
Plasticized PVC, LOI = 0.35	—	—	2.4	—	—
Rigid PVC, LOI = 0.50	—	—	2.3	—	—
Polyisoprene	10	2.0	—	—	—
PVC panel	17	3.1	—	—	—
Nylon 6/6	15	2.4	—	—	—
Polyoxymethylene (Delrin™)	13	2.4	—	2.4	—
Polymethylmethacrylate (Plexiglas™)	11	1.6	1.4	1.6	—
Polycarbonate	11	2.1	—	—	—
Polycarbonate panel	16	2.3	—	—	—
Isophthalic polyester	—	—	3.4	—	—
Polyvinyl ester	—	—	1.7	—	—
Acrylonitrile-butadiene-styrene (ABS)	10	3.2	2.6	—	—
Styrene-butadiene	10	2.7	—	—	—
Polystyrene (PS) foams	10-13	1.3-1.9	—	—	—
PS (granular)	13	1.7	2.2	1.8	—
<i>Polyurethane (PU) foams</i>					
Flexible polyurethane (PU) foams	16-19	1.2-2.7	2.4	1.4	—
Rigid polyurethane (PU) foams	14-22	1.2-5.3	5.6	—	—
Polyisocyanurate foams	14-37	1.2-6.4	—	—	—
Phenolic foam	20	1.6	—	—	—
Phenolic foam/FR	20	3.7	—	—	—
Ethylenetetrafluoroethylene (Tefzel™)	27	0.9	—	—	—
Fluorinated ethylene propylene, FEP (Teflon™)	38	2.4	—	—	—
Tetrafluoroethylene, TFE (Teflon™)	48	0.8-1.8	—	—	—
Perfluoroalkoxy, PFA (Teflon™)	37	1.0	—	—	—
<i>Composite and Fiberglass-Reinforced Materials</i>					
Polyether ether ketone—30% fiberglass	—	—	7.9	—	—
Polyethersulfone—30% fiberglass	—	1.8	—	—	—
Polyester 1—fiberglass	—	—	2.5	—	—
Polyester 2—fiberglass	—	—	—	—	—
Polyester 3—fiberglass	10	1.4	—	—	—
Polyester 4—fiberglass	10	6.4	—	—	—
Polyester 5—fiberglass	15	5.1	—	—	—
Phenolic fiberglass (thick sheet)	10	2.9	—	—	—
Phenolic Kevlar™ (thick sheet)	20	7.3	—	—	—
	15	7.8	—	—	—

*From the Flammability Apparatus under nonflaming fire conditions.

[†]Calculated from the Cone Calorimeter data reported in references 20 and 31 for the mass loss rate at various external heat flux values in flaming fires.

[‡]From the flammability laboratory using the differential scanning calorimetry.

[§]Calculated from the data reported in the *CRC Handbook*.²⁸

and calculations are routinely used for the calibration of the Flammability Apparatus.

Heats of gasification determined from the mass loss rate as a function of external heat flux in nonflaming fire conditions in the Flammability Apparatus are listed in Table 3-4.4 for selected materials. Excellent agreement can be noted between the heats of gasification determined from the Flammability Apparatus and those obtained from the differential scanning calorimetry.

Heat of gasification can also be determined from the flaming fires if high external heat flux values are used such that $\dot{q}_c \gg \dot{q}_{fr} + \dot{q}_{fc} - \dot{q}_{rr}$ in Equation 11. This method has been used to calculate the heat of gasification from the Cone Calorimeter data for the mass loss rate in flaming fires reported in the literature.^{20,31} The values calculated from the Cone Calorimeter data are also listed in Table 3-4.4 and show a general agreement with the values from the Flammability Apparatus.

EXAMPLE 6:

Estimate the ignition temperature of a material with a Critical Heat Flux of 11 kW/m². Assume its surface emissivity to be unity, ambient temperature to be 20°C, and vaporization temperature to be approximately equal to the ignition temperature.

SOLUTION:

From Equation 15,

$$11(\text{kW/m}^2) = 56.7 \times 10^{-12}(\text{kW/m}^2\text{-deg}^4)(T_v^4)(\text{deg}^4) - 56.7 \times 10^{-12}(\text{kW/m}^2\text{-deg}^4) \times (298)^4(\text{deg}^4)$$

$$T_v \cong \left[\frac{11 \times 10^{12}}{56.7} + (298)^4 \right]^{1/4}$$

$$\cong (1940 \times 10^8 + 78.9 \times 10^8)^{1/4} \cong 670 \text{ K}$$

By assumption, vaporization temperature is equal to the ignition temperature, which is 670 K (397°C).

EXAMPLE 7:

A material with a surface re-radiation loss of 10 kW/m² and heat of gasification of 1.8 kJ/g was found to be involved in a fire with an exposed area of 2 m². The combined flame and external heat flux exposure to the material was estimated to be 70 kW/m². Estimate the peak mass loss rate at which the material may have been burning in the fire in terms of g/m²-s and g/s.

SOLUTION:

From Equation 11,

$$\dot{m}^* = \frac{70 - 10}{1.8} = 33 \text{ g/m}^2\text{-s}$$

The estimated peak mass loss rate that the material may have been burning in the fire is 33 g/m²-s, or 33 × 2 = 67 g/s.

Flame heat flux: For flaming fires, in the absence of external heat flux, from Equation 11

$$\dot{m}^* = \frac{(\dot{q}_{fr} + \dot{q}_{fc} - \dot{q}_{rr})}{\Delta H_g} \quad (16)$$

The results from numerous small- and large-scale fire tests show that, as the surface area of the material increases, the

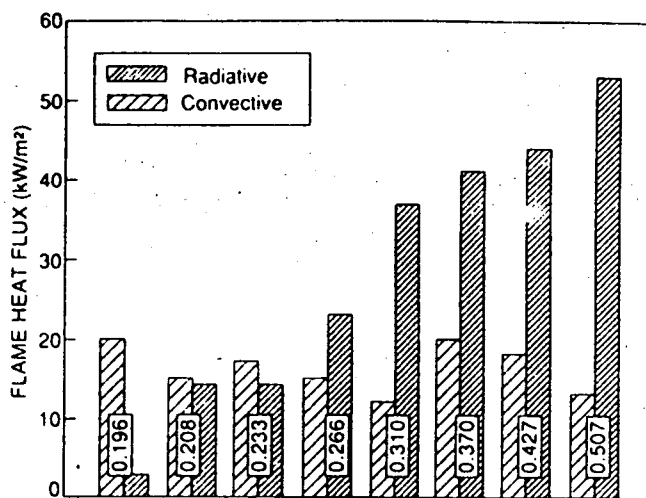


Fig. 3-4.20. Flame radiative and convective heat fluxes at various oxygen mass fractions for the steady-state combustion of 100- × 100-mm square × 25-mm-thick slabs of polypropylene in the Flammability Apparatus under co-airflow velocity of 0.09 m/s. Data taken from reference 33. Mass fractions of oxygen are indicated by the numbers inside the frames.

flame radiative heat flux increases and reaches an asymptotic limit, whereas the flame convective heat flux decreases and becomes much smaller than the flame radiative heat flux at the asymptotic limit in large-scale fires.³² It is also known that, in small-scale fires of fixed size, with buoyant turbulent diffusion flames, as the oxygen mass fraction is increased, the flame radiative heat flux increases and reaches an asymptotic limit, comparable to the asymptotic limit in large-scale fires, whereas the flame convective heat flux decreases and becomes much smaller than the flame radiative heat flux.³³

The effect of the mass fraction of oxygen on the flame radiative and convective heat fluxes in small-scale fires is shown in Figure 3-4.20 for 100- × 100-mm square × 25-mm-thick slabs of polypropylene. The data were measured in the Flammability Apparatus.³³ The increase in the flame radiative heat flux with increase in the mass fraction of oxygen is due to the increase in the flame temperature and soot formation and decrease in the residence time in the flame.³³ The oxygen mass fraction variation technique to simulate large-scale flame-radiative heat flux conditions in small-scale fires is defined as the *Flame Radiation Scaling Technique*.⁴

In the flame radiation scaling technique, the flame radiative and convective heat fluxes are determined from:³³ (1) the measurements for the mass loss rate at various oxygen mass fractions in the range of 0.12 (close to flame extinction) to about 0.60, under co-airflow conditions; (2) the convective heat transfer coefficient for the Flammability Apparatus, derived from the combustion of methanol; (3) the mass transfer number; and (4) Equation 16. In the Flammability Apparatus, the asymptotic limit is reached for the oxygen mass fraction ≥ 0.30. At the asymptotic limit, Equation 16 can be expressed as

$$\dot{m}_{asy}^* = \frac{\dot{q}_{f,asy} - \dot{q}_{rr}^*}{\Delta H_g} \quad (17)$$

where subscript *asy* represents the asymptotic limit. The asymptotic values for the mass loss rate and flame heat flux determined from the Flame Radiation Scaling Technique in

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TABLE 3-4.5 Asymptotic Values of Mass Loss Rate and Flame Heat Flux*

Material	\dot{m}'' (g/m ² -s)		\dot{q}''_f (kW/m ²)	
	S*	L†	S*	L†
Aliphatic Carbon-Hydrogen Atoms‡				
Polyethylene	26	—	61	—
Polypropylene	24	—	67	—
Heavy fuel oil (2.6-23 m)	—	36	—	29
Kerosene (30-80 m)	—	65	—	29
Crude oil (6.5-31 m)	—	56	—	44
n-Dodecane (0.94 m)	—	36	—	30
Gasoline (1.5-223 m)	—	62	—	30
JP-4 (1.0-5.3 m)	—	67	—	40
JP-5 (0.60-17 m)	—	55	—	39
n-Heptane (1.2-10 m)	66	75	32	37
n-Hexane (0.75-10 m)	—	77	—	37
Transformer fluids (2.37 m)	27-30	25-29	23-25	22-25
Aromatic Carbon-Hydrogen Atoms‡				
Polystyrene (0.93 m)	36	34	75	71
Xylene (1.22 m)	—	67	—	37
Benzene (0.75-6.0 m)	—	81	—	44
Aliphatic Carbon-Hydrogen-Oxygen Atoms‡				
Polyoxymethylene	16	—	50	—
Polymethylmethacrylate (2.37 m)	28	30	57	60
Methanol (1.2-2.4 m)	20	25	22	27
Acetone (1.52 m)	—	38	—	24
Aliphatic Carbon-Hydrogen-Oxygen-Nitrogen Atoms				
Flexible polyurethane foams	21-27	—	64-76	—
Rigid polyurethane foams	22-25	—	49-53	—
Aliphatic Carbon-Hydrogen-Halogen Atoms				
Polyvinylchloride	16	—	50	—
Tefzel™ (ETFE)	14	—	50	—
Teflon™ (FEP)	7	—	52	—

*S = Small-scale fires, pool diameter fixed at 0.10 m, flame radiation scaling technique was used in the Flammability Apparatus, $Y_0 \geq 0.30$.

†L = Large-scale fires in normal air.

‡ Numbers in m in parentheses are the pool diameters used in large-scale fires.

Note: Mass loss rates are from the data reported in the literature.

the Flammability Apparatus are listed in Table 3-4.5. The measured asymptotic values of the mass loss rate reported in the literature and flame heat flux in large-scale fires are also listed in Table 3-4.5. Flame heat flux values for the large-scale fires are derived from the asymptotic values of the mass loss rate and known values of surface re-radiation losses and heats of gasification.

The data in Table 3-4.5 show that the asymptotic flame heat flux values, determined in the Flammability Apparatus, using the Flame Radiation Scaling Technique, are in good agreement with the values measured in the large-scale fires. The asymptotic flame heat flux values vary from 22 to 77 kW/m², dependent primarily on the mode of decomposition and gasification rather than on the chemical structures of the materials. For example, for the liquids, which vaporize primarily as monomers or as very low molecular weight oligomer, the asymptotic flame heat flux values are in the range of 22 to 44 kW/m², irrespective of their chemical structures. For polymers, which vaporize as high molecular weight oligomer, the asymptotic flame heat flux values increase substantially to the range of 49 to 71 kW/m², irrespective of their chemical structures. The independence of the

asymptotic flame heat values from the chemical structures of materials is consistent with the dependence of flame radiation on optical thickness, soot concentration, and flame temperature in large-scale fires.

EXAMPLE 8:

Calculate the peak mass loss rate for polypropylene in large-scale fires, burning in the open, with no external heat sources in the surroundings.

SOLUTION:

In the calculation Equation 16 will be used. From Table 3-4.4, $\dot{q}''_{rr} = 15$ kW/m² and $\Delta H_g = 2.0$ kJ/g and from Table 3-4.5, $\dot{q}''_{f,asy} = 67$ kW/m². Using these values in Equation 16

$$\dot{m}'' = \frac{67 - 15}{2.0} = 26.0 \text{ g/m}^2\text{-s}$$

EXAMPLE 9:

Calculate the peak mass loss rate for polypropylene in large-scale fires, burning in the open, in the presence of a

burning object, which provides 20 kW/m² of heat flux to the polypropylene surface, in addition to its own flame heat flux of 67 kW/m².

SOLUTION:

In the calculation Equation 11 will be used with $q_c^* = 20 \text{ kW/m}^2$. From Table 3-4.4, $q_{rr}^* = 15 \text{ kW/m}^2$ and $\Delta H_g = 2.0 \text{ kJ/g}$ and from Table 3-4.5, $q_{f,ox}^* = 67 \text{ kW/m}^2$. Using these values in Equation 11

$$\dot{m}'' = \frac{67 + 20 - 15}{2.0} = 36.0 \text{ g/m}^2\text{-s}$$

Heat Release Rate

The determination of heat release rate in fires has been influenced by the principles and techniques used for the controlled combustion in the heating and power industries. Heat in the flowing combustion products (convective heat) and thermal radiation are used to generate steam, heat a furnace or space, produce mechanical power in internal combustion engines or gas turbines, etc. Heat is generated by injecting fuel (gas, liquid, or solid) into a hot environment, where it undergoes evaporation, gasification, and thermal decomposition or pyrolysis. Fuel vapors react chemically with oxygen and produce heat and products, such as carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbons, water (H₂O), and soot. Theoretical air requirement for complete combustion is estimated from an empirical guide, which suggests that, for every 10.6 kJ of heat in the fuel burned, 3.4 g of air are required for complete combustion.³⁴ Equivalently, the heat of combustion per unit mass of oxygen consumed (ΔH_O^*) is 13.4 kJ/g. Using $\Delta H_O^* \approx 13.4 \text{ kJ/g}$ to determine the heat release rate in fires from the mass consumption rate of oxygen is discussed in references 16 and 35. This technique is defined as the *Oxygen Consumption (OC) Calorimetry*.

A combustion process is characterized by its *combustion efficiency*, defined as the fraction of heat of complete combustion released in the chemical reactions, which is the ratio of the chemical heat release rate to the heat release rate for complete combustion or the ratio of the chemical heat of combustion to net heat of complete combustion. The calorific energy generated in chemical reactions leading to complete combustion per unit mass of fuel, water produced being in the vapor state, is defined as the *net heat of complete combustion*. The calorific energy generated in chemical reactions leading to varying degrees of incomplete combustion per unit mass of the fuel consumed is defined as the *chemical heat of combustion*. In the heating and power industries, combustion efficiency is determined routinely from the waste products (flue gas) analysis, especially for CO, CO₂, and O₂, and from the measurements of temperature in the combustion products-air mixture and thermal radiation. For

higher combustion efficiency, *mass fuel-to-air ratio* relative to the *stoichiometric mass fuel-to-air ratio* or the *equivalence ratio* is controlled by maintaining desired primary and secondary airflow.

The net heat of complete combustion is measured in the oxygen bomb calorimeter and is calculated from the standard heats of formation of the material, CO₂ and H₂O, the standard heat of formation of O₂ in its standard state being zero. For example, for polymethylmethacrylate (PMMA) and polystyrene (PS), the net heats of complete combustion measured in the oxygen bomb calorimeter by the FMRC Flammability Laboratory are 25.3 and 39.2 kJ/g, respectively; and from the standard heats of formation, they are 24.9 and 39.8 kJ/g, respectively. For soot generated from the combustion of PMMA and PS, the net heats of complete combustion measured in the oxygen bomb calorimeter by the FMRC Flammability Laboratory are 33.9 and 32.1 kJ/g, respectively, and 32.8 kJ/g from the standard heats of formation of graphite and CO₂.

In fires, complete combustion is rarely achieved and products of incomplete combustion, such as CO and smoke, are quite common. An example of incomplete combustion is given in Table 3-4.6, where chemical heat of combustion and combustion efficiency decrease as CO, carbon, and ethylene are formed at the expense of CO₂ and H₂O with reduced O₂ consumption, a typical condition found in the ventilation-controlled fires.³⁶ The chemical heat of combustion is the ratio of the chemical heat release rate to the mass loss rate. The upper limit of the combustion efficiency is 1.00, corresponding to complete combustion, and the lower limit is 0.46, corresponding to unstable combustion leading to flame extinction for combustion efficiency ≤ 0.40 .^{36,37}

Chemical heat release rate: The chemical heat release rate is determined from the *Carbon Dioxide Generation (CDG)* and *Oxygen Consumption (OC) Calorimetry*.

The CDG Calorimetry:^{2-4,16,33,36} The chemical heat release rate is determined from the following relationships

$$Q_{ch}^* = \Delta H_{CO_2}^* \dot{G}_{CO_2} + \Delta H_{CO}^* \dot{G}_{CO} \quad (18)$$

$$\Delta H_{CO_2}^* = \frac{\Delta H_T}{\Psi_{CO_2}} \quad (19)$$

$$\Delta H_{CO}^* = \frac{\Delta H_T - \Delta H_{CO} \Psi_{CO}}{\Psi_{CO}} \quad (20)$$

where Q_{ch}^* is the chemical heat release rate (kW/m²), $\Delta H_{CO_2}^*$ is the net heat of complete combustion per unit mass of CO₂ generated (kJ/g), ΔH_{CO}^* is the net heat of complete combustion per unit mass of CO generated (kJ/g), ΔH_T is the net heat of complete combustion per unit mass of fuel consumed (kJ/g), Ψ_{CO_2} is the stoichiometric yield for the maximum conversion of fuel to CO₂(g/g), Ψ_{CO} is the stoichiometric yield for the maximum conversion of fuel to CO (g/g), \dot{G}_{CO_2} ,

TABLE 3-4.6 Chemical Heat of Combustion and Combustion Efficiency of Polymethylmethacrylate

Reaction Stoichiometry	ΔH_{ch} (kJ/g)*	x_{ch}
C ₅ H ₈ O ₂ (g) + 6.0 O ₂ (g) = 5CO ₂ (g) + 4H ₂ O (g)	24.9	1.00
C ₅ H ₈ O ₂ (g) + 5.5 O ₂ (g) = 4CO ₂ (g) + 4H ₂ O (g) + CO (g)	22.1	0.89
C ₅ H ₈ O ₂ (g) + 4.5 O ₂ (g) = 3CO ₂ (g) + 4H ₂ O (g) + CO (g) + C (s)	18.2	0.73
C ₅ H ₈ O ₂ (g) + 3.0 O ₂ (g) = 2CO ₂ (g) + 3H ₂ O (g) + CO (g) + C (s) + 0.50 C ₂ H ₄ (g)	11.5	0.46

*Standard heat of formation in kJ/mole: PMMA (C₅H₈O₂) (g) = -442.7; O₂ (g) = 0; CO₂ (g) = -393.5; H₂O (g) = -241.8; CO (g) = -110.5; C (s) = 0; and C₂H₄ (g) = +26.2, where g is the gas and s is the solid.

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TABLE 3-4.7 Net Heats of Complete Combustion per Unit Mass of Fuel and Oxygen Consumed and Carbon Dioxide and Carbon Monoxide Generated for Carbon- and Hydrogen-Containing Fuels*

Fuel	Formula	ΔH_T (kJ/g)	ΔH_O^* (kJ/g)	$\Delta H_{CO_2}^*$ (kJ/g)	ΔH_{CO}^* (kJ/g)	Fuel	Formula	ΔH_T (kJ/g)	ΔH_O^* (kJ/g)	$\Delta H_{CO_2}^*$ (kJ/g)	ΔH_{CO}^* (kJ/g)
Normal Alkanes						Normal Alkenes (Continued)					
Methane	CH ₄	50.1	12.5	(18.2)	(18.6)	Heptene	C ₇ H ₁₄	44.6	12.9	14.1	12.2
Ethane	C ₂ H ₆	47.1	12.7	16.2	15.4	Octene	C ₈ H ₁₆	44.5	12.9	14.1	12.1
Propane	C ₃ H ₈	46.0	12.9	15.3	14.0	Nonene	C ₉ H ₁₈	44.3	12.9	14.1	12.1
Butane	C ₄ H ₁₀	45.4	12.7	15.1	13.7	Decene	C ₁₀ H ₂₀	44.2	12.9	14.1	12.2
Pentane	C ₅ H ₁₂	45.0	12.6	14.7	13.2	Dodecene	C ₁₂ H ₂₄	44.1	12.9	14.1	12.2
Hexane	C ₆ H ₁₄	44.8	12.7	14.6	12.9	Tridecene	C ₁₃ H ₂₆	44.0	12.9	14.1	12.2
Heptane	C ₇ H ₁₆	44.6	12.7	14.5	12.8	Tetradecene	C ₁₄ H ₂₈	44.0	12.9	14.1	12.2
Octane	C ₈ H ₁₈	44.5	12.6	14.4	12.7	Hexadecene	C ₁₆ H ₃₂	43.9	12.9	14.1	12.1
Nonane	C ₉ H ₂₀	44.3	12.7	14.3	12.5	Octadecene	C ₁₈ H ₃₆	43.8	12.9	14.1	12.1
Decane	C ₁₀ H ₂₂	44.4	12.7	14.3	12.4	Average		13.2	14.2	12.4	
Undecane	C ₁₁ H ₂₄	44.3	12.7	14.3	12.4	Cyclic Alkenes					
Dodecane	C ₁₂ H ₂₆	44.2	12.7	14.2	12.3	Cyclohexene	C ₆ H ₁₀	43.0	13.0	13.4	11.0
Tridecane	C ₁₃ H ₂₈	44.2	12.7	14.2	12.3	Methylcyclohexene	C ₇ H ₁₂	43.1	12.9	13.4	11.1
Kerosene	C ₁₄ H ₃₀	44.1	12.7	14.1	12.2	Average		13.0	13.4	11.1	
Hexadecane	C ₁₆ H ₃₄	44.1	12.7	14.2	12.3	Dienes					
Average						12.7	14.6	12.9			
Substituted Alkanes						Normal Alkynes					
Methylbutane	C ₅ H ₁₂	45.0	12.6	14.7	13.1	1-3 Butadiene	C ₄ H ₆	44.6	13.7	13.7	11.5
Dimethylbutane	C ₆ H ₁₄	44.8	12.7	14.6	13.0	Cyclooctadiene	C ₈ H ₁₂	43.2	13.3	13.3	10.9
Methylpentane	C ₆ H ₁₄	44.8	12.7	14.6	12.9	Average		13.5	13.5	11.2	
Dimethylpentane	C ₇ H ₁₆	44.6	12.7	14.5	12.9	Normal Alkynes					
Methylhexane	C ₇ H ₁₆	44.6	12.6	14.4	12.7	Acetylene	C ₂ H ₂	47.8	(15.6)	14.3	12.4
Isooctane	C ₈ H ₁₈	44.5	12.6	14.4	12.7	Heptyne	C ₇ H ₁₂	44.8	13.4	13.9	11.8
Methylethylpentane	C ₈ H ₁₈	44.5	12.6	14.4	12.7	Octyne	C ₈ H ₁₄	44.7	13.3	14.0	11.9
Ethylhexane	C ₈ H ₁₈	44.5	12.6	14.4	12.7	Decyne	C ₁₀ H ₁₈	44.5	13.2	13.9	11.9
Dimethylhexane	C ₈ H ₁₈	44.5	12.7	14.5	12.8	Dodecyne	C ₁₂ H ₂₂	44.3	13.2	14.0	12.0
Methylheptane	C ₈ H ₁₈	44.5	12.6	14.4	12.7	Average		13.3	14.0	12.0	
Average						12.6	14.6	12.8			
Cyclic Alkanes						Arenes					
Cyclopentane	C ₅ H ₁₀	44.3	12.8	13.9	11.9	Benzene	C ₆ H ₆	40.1	13.0	11.9	8.7
Methylcyclopentane	C ₆ H ₁₂	43.8	12.7	13.9	11.9	Toluene	C ₇ H ₈	39.7	12.9	12.1	9.0
Cyclohexane	C ₆ H ₁₂	43.8	12.7	13.8	11.7	Styrene	C ₈ H ₈	39.4	13.1	12.0	8.8
Methylcyclohexane	C ₇ H ₁₄	43.4	12.7	13.8	11.7	Ethylbenzene	C ₈ H ₁₀	39.4	12.9	12.3	9.4
Ethylcyclohexane	C ₈ H ₁₆	43.2	12.7	13.8	11.7	Xylene	C ₈ H ₁₀	39.4	13.0	12.4	9.5
Dimethylcyclohexane	C ₈ H ₁₆	43.2	12.7	13.8	11.7	Propylbenzene	C ₉ H ₁₂	39.4	12.9	12.5	9.6
Cyclooctane	C ₈ H ₁₆	43.2	12.7	13.9	11.9	Trimethylbenzene	C ₉ H ₁₂	39.2	12.9	12.5	9.7
Decalin	C ₁₀ H ₁₈	42.8	12.7	13.4	11.0	Cumene	C ₉ H ₁₂	39.2	12.9	12.9	9.6
Bicyclohexyl	C ₁₂ H ₂₂	42.6	12.6	13.3	11.0	Naphthalene	C ₁₀ H ₈	39.0	12.9	11.3	7.7
Average						12.7	13.8	11.6			
Normal Alkenes						Arenes					
Ethylene	C ₂ H ₄	48.0	13.8	15.0	13.6	Tetralin	C ₁₀ H ₁₂	39.0	12.9	12.2	9.2
Propylene	C ₃ H ₆	46.4	13.4	14.6	12.9	Butylbenzene	C ₁₀ H ₁₄	39.0	12.9	12.7	9.9
Butylene	C ₄ H ₈	45.6	14.3	14.3	12.5	Diethylbenzene	C ₁₀ H ₁₄	39.0	13.7	13.5	11.1
Pentene	C ₅ H ₁₀	45.2	14.3	14.3	12.5	p-Cymene	C ₁₀ H ₁₄	39.0	13.0	12.5	9.6
Hexene	C ₆ H ₁₂	44.9	12.9	14.1	12.2	Methylnaphthalene	C ₁₁ H ₁₀	38.9	12.9	11.5	8.1
Average						13.0	12.4	9.4			
Average						13.0	12.4	9.4			

*Data from references 38 and 39. Numbers in parentheses not used for averaging.

is the generation rate of CO₂ (g/m²-s), and \dot{G}_{CO}^* is the generation rate of CO (g/m²-s).

The values for the net heats of complete combustion per unit mass of fuel consumed and CO₂ and CO generated are listed in Tables 3-4.7 through 3-4.10. The values depend on the chemical structures of the materials. With some exceptions, the values remain approximately constant within each generic group of fuels. The average values are also

listed in the tables. From the average values, $\Delta H_{CO_2}^* = 13.3 \text{ kJ/g} \pm 11 \text{ percent}$, and $\Delta H_{CO}^* = 11.1 \text{ kJ/g} \pm 18 \text{ percent}$. In the CDG calorimetry, the CO correction for well-ventilated fires is very small, because of the small amounts of CO generated. The variations of 11 and 18 percent in the $\Delta H_{CO_2}^*$ and ΔH_{CO}^* values, respectively, would reduce significantly if values for low molecular weight hydrocarbons with small amounts of O, N, and halogen were used in averaging.

GENERATION OF HEAT AND CHEMICAL COMPOUNDS IN FIRES 3-73

TABLE 3-4.8 Net Heats of Complete Combustion per Unit Mass of Fuel and Oxygen Consumed and Carbon Dioxide and Carbon Monoxide Generated for Carbon-, Hydrogen-, and Oxygen-Containing Fuels*

Fuel	Formula	ΔH_T (kJ/g)	ΔH_O^* (kJ/g)	$\Delta H_{CO_2}^*$ (kJ/g)	ΔH_{CO}^* (kJ/g)	Fuel	Formula	ΔH_T (kJ/g)	ΔH_O^* (kJ/g)	$\Delta H_{CO_2}^*$ (kJ/g)	ΔH_{CO}^* (kJ/g)
Alcohols						Acids					
Methyl alcohol	CH ₄ O	20.0	13.4	14.5	12.9	Formic acid	CH ₂ O ₂	5.7	16.4	5.96	0
Ethyl alcohol	C ₂ H ₆ O	27.7	13.2	14.5	12.7	Acetic acid	C ₂ H ₄ O ₂	14.6	13.7	9.95	5.65
n-Propyl alcohol	C ₃ H ₈ O	31.8	13.3	14.5	12.7	Benzoic acid	C ₇ H ₆ O ₂	24.4	12.4	9.66	5.18
Isopropyl alcohol	C ₃ H ₈ O	31.8	13.3	14.5	12.7	Cresylic acid	C ₈ H ₈ O ₂	34.0	(16.0)	13.1	10.6
Allyl alcohol	C ₃ H ₆ O	31.4	14.2	13.8	11.7	Esters					
n-Butyl alcohol	C ₄ H ₁₀ O	34.4	13.3	14.5	12.8	Ethyl formate	C ₃ H ₆ O ₂	20.2	13.3	11.3	7.8
Isobutyl alcohol	C ₄ H ₁₀ O	34.4	13.3	14.5	12.8	n-Propyl formate	C ₄ H ₈ O ₂	23.9	13.2	12.0	8.8
Sec-butyl alcohol	C ₄ H ₁₀ O	34.4	13.3	14.5	12.8	n-Butyl formate	C ₅ H ₁₀ O ₂	26.6	13.0	12.3	9.4
Ter-butyl alcohol	C ₄ H ₁₀ O	34.4	13.3	14.5	12.8	Methyl acetate	C ₃ H ₆ O ₂	20.2	13.3	11.3	7.8
n-Amyl alcohol	C ₅ H ₁₂ O	36.2	13.3	14.5	12.8	Ethyl acetate	C ₄ H ₈ O ₂	23.9	13.2	12.0	8.8
Isobutyl carbinol	C ₅ H ₁₂ O	36.2	13.3	14.5	12.8	n-Propyl acetate	C ₅ H ₁₀ O ₂	26.6	13.0	12.3	9.4
Sec-butyl carbinol	C ₅ H ₁₂ O	36.2	13.3	14.5	12.8	n-Butyl acetate	C ₆ H ₁₂ O ₂	28.7	13.0	12.6	9.8
Methylpropylcarbinol	C ₅ H ₁₂ O	36.2	13.3	14.5	12.8	Isobutyl acetate	C ₆ H ₁₂ O ₂	28.7	13.0	12.6	9.8
Dimethylethylcarbinol	C ₅ H ₁₂ O	36.2	13.3	14.5	12.8	Amyl acetate	C ₇ H ₁₄ O ₂	30.3	13.0	12.8	10.1
n-Hexyl Alcohol	C ₆ H ₁₄ O	37.4	13.3	14.5	12.7	Cyclohexyl acetate	C ₈ H ₁₄ O ₂	31.5	13.3	12.7	10.0
Dimethylbutylalcohol	C ₆ H ₁₄ O	37.4	13.3	14.5	12.7	Octyl acetate	C ₁₀ H ₂₀ O ₂	33.6	12.9	13.1	10.6
Ethylbutyl alcohol	C ₆ H ₁₄ O	37.4	13.3	14.5	12.7	Ethylacetoacetate	C ₆ H ₁₀ O ₃	30.3	(17.6)	(14.9)	(13.5)
Cyclohexanol	C ₆ H ₁₂ O	37.3	13.7	14.1	12.2	Methyl propionate	C ₄ H ₈ O ₂	23.9	13.2	12.0	7.4
Benzyl alcohol	C ₇ H ₈ O	32.4	13.0	11.4	8.0	Ethyl propionate	C ₅ H ₁₀ O ₂	26.6	13.0	12.2	9.4
n-Heptyl alcohol	C ₇ H ₁₆ O	39.8	13.7	15.0	13.6	n-Butyl propionate	C ₇ H ₁₄ O ₂	30.3	13.0	12.8	10.1
n-Octyl alcohol	C ₈ H ₁₈ O	40.6	13.7	15.0	13.6	Isobutyl propionate	C ₇ H ₁₄ O ₂	30.3	13.0	12.8	10.1
n-Nonyl alcohol	C ₉ H ₂₀ O	40.3	13.4	14.7	13.0	Amyl propionate	C ₈ H ₁₈ O ₂	31.6	12.9	12.9	10.3
Average			13.3	14.5	12.8	Methyl butyrate	C ₅ H ₁₀ O ₂	26.6	13.0	12.3	9.4
Aldehydes						Ethyl butyrate	C ₆ H ₁₂ O ₂	28.7	13.0	12.6	9.8
Formaldehyde	CH ₂ O	18.7	(17.5)	12.7	10.1	Propyl butyrate	C ₇ H ₁₄ O ₂	30.3	13.0	12.8	10.1
Acetaldehyde	C ₂ H ₄ O	25.1	13.8	12.6	9.7	n-Butyl butyrate	C ₈ H ₁₆ O ₂	31.6	12.9	12.9	10.3
Butyraldehyde	C ₄ H ₈ O	33.8	13.9	13.9	11.7	Isobutyl butyrate	C ₈ H ₁₆ O ₂	31.6	12.9	12.9	10.3
Crotonaldehyde	C ₄ H ₆ O	34.8	15.2	13.8	11.8	Ethyl laurate	C ₁₄ H ₂₈ O ₂	37.2	13.3	13.8	11.6
Benzaldehyde	C ₇ H ₆ O	32.4	13.4	11.2	7.5	Ethyl lactate	C ₅ H ₁₀ O ₃	30.8	(18.9)	(16.5)	(16.0)
Ethyl hexaldehyde	C ₈ H ₁₆ O	39.4	13.7	12.7	9.9	Butyl lactate	C ₇ H ₁₄ O ₃	33.3	(16.8)	(15.8)	(14.8)
Average			14.2	13.3	10.6	Amyl lactate	C ₈ H ₁₆ O ₃	34.3	(16.4)	(15.6)	(14.5)
Ketones						Ethyl benzoate	C ₉ H ₁₀ O ₂	34.5	(15.4)	13.1	10.5
Acetone	C ₃ H ₆ O	29.7	13.4	13.1	10.5	Ethyl carbonate	C ₅ H ₁₀ O ₃	30.8	(18.9)	(16.5)	(16.0)
Methylethyl ketone	C ₄ H ₈ O	32.7	13.4	13.4	11.0	Ethyl oxalate	C ₄ H ₆ O ₄	28.7	(20.2)	(16.6)	(20.2)
Diethyl ketone	C ₅ H ₁₀ O	33.7	12.9	13.2	10.7	Ethyl malonate	C ₅ H ₈ O ₄	32.2	(17.9)	(19.3)	(20.4)
Cyclohexanone	C ₆ H ₁₀ O	35.9	13.8	13.3	11.0	Average					
Methyl butyl ketone	C ₆ H ₁₂ O	35.2	12.9	13.3	11.0	13.0	12.5	9.7			
Di-acetone alcohol	C ₆ H ₁₂ O ₂	37.3	(16.9)	(16.4)	(15.7)	Others					
Dipropyl ketone	C ₇ H ₁₄ O	38.6	13.8	14.3	12.5	Camphor	C ₁₀ H ₁₆ O	38.8	13.7	13.4	11.1
Phenylbutyl ketone	C ₁₁ H ₁₄ O	34.8	12.6	11.6	(8.4)	Cresol	C ₇ H ₈ O	34.6	13.7	12.1	9.1
Average			13.2	13.2	11.1	Resorcinol	C ₆ H ₆ O ₂	26.0	13.7	10.8	5.9
						Acrolein	C ₃ H ₄ O	29.1	14.6	12.3	9.4

*Data from references 38 and 39. Numbers in parentheses not used for averaging.

For the determination of the chemical heat release rate, generation rates of CO₂ and CO are measured and either the actual values or the average values of the net heat of complete combustion per unit mass of CO₂ and CO generated are used. The measurements for the generation rates of CO₂ and CO are described in the subsection entitled "Generation Rates of Chemical Compounds and Fire Ventilation."

The OC Calorimetry:^{2-4,17-19,33,35,36} The chemical heat release rate is determined from the following relationship

$$\dot{Q}_{ch} = \Delta H_O^* \dot{C}_O \quad (21)$$

$$\Delta H_O^* = \frac{\Delta H_T}{\Psi_O} \quad (22)$$

where ΔH_O^* is the net heat of complete combustion per unit mass of oxygen consumed (kJ/g), \dot{C}_O is the mass consumption rate of oxygen (g/m²-s), and Ψ_O is the stoichiometric mass-oxygen-to-fuel ratio (g/g).

The values for the net heats of complete combustion per unit mass of oxygen consumed are listed in Tables 3-4.7 through 3-4.10 along with the values for the net heats of complete combustion per unit mass of fuel consumed and CO₂ and CO generated. The average values of the net heat of

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TABLE 3-4.9 Net Heats of Complete Combustion per Unit Mass of Fuel and Oxygen Consumed and Carbon Dioxide and Carbon Monoxide Generated for Carbon-, Hydrogen-, Nitrogen-, and Sulfur-Containing Fuels*

Fuel	Formula	ΔH_T (kJ/g)	ΔH_O^* (kJ/g)	$\Delta H_{CO_2}^*$ (kJ/g)	ΔH_{CO}^* (kJ/g)
C-H-N Fuels					
Acrylonitrile	C ₃ H _{3.5} N	24.5	8.5	9.8	5.4
Diethylamine	C ₄ H ₁₁ N	38.0	11.2	15.8	14.8
n-Butylamine	C ₄ H ₁₁ N	38.0	11.2	15.8	14.8
sec-Butylamine	C ₄ H ₁₁ N	38.0	11.2	15.8	14.8
Pyridine	C ₅ H ₅ N	32.2	11.0	11.6	8.2
Aniline	C ₆ H ₇ N	33.8	11.2	11.9	8.7
Picoline	C ₆ H ₇ N	33.8	11.2	11.9	8.7
Triethylamine	C ₆ H ₁₅ N	39.6	11.6	15.2	13.8
Toluidine	C ₇ H ₉ N	34.9	11.3	12.1	9.1
Dimethylaniline	C ₈ H ₁₁ N	35.7	11.5	12.3	9.3
Di-n-butylamine	C ₈ H ₁₉ N	40.6	11.9	14.9	13.4
Quinoline	C ₉ H ₇ N	36.1	12.4	11.8	8.5
Quinaldine	C ₁₀ H ₉ N	36.7	12.4	11.9	8.7
Butylaniline	C ₁₀ H ₁₅ N	37.0	11.7	12.5	9.7
Tri-n-butylamine	C ₁₂ H ₂₇ N	41.6	12.1	14.6	12.9
	Average		11.5	15.4	14.1
C-H-S Fuels					
Carbon disulfide	CS ₂	13.6	10.8	(23.5)	(27.0)
Thiophene	C ₄ H ₄ S	31.9	14.0	15.2	14.0
Methylthiophene	C ₅ H ₆ S	33.2	13.6	14.8	13.2
Thiophenol	C ₆ H ₆ S	34.1	13.8	14.2	12.3
Hexyl mercaptan	C ₆ H ₁₄ S	33.0	11.6	14.8	13.2
Thiocresol	C ₇ H ₈ S	34.9	13.5	14.1	12.1
Heptyl mercaptan	C ₇ H ₁₆ S	33.7	11.6	14.4	12.7
Cresolmethylsulfide	C ₈ H ₁₁ S	36.2	13.4	15.9	15.0
Decylmercaptan	C ₁₀ H ₂₂ S	34.9	11.5	13.8	11.7
Dodecyl mercaptan	C ₁₂ H ₂₆ S	35.5	11.5	13.6	11.4
Hexyl sulfide	C ₁₂ H ₂₆ S	35.5	11.5	13.6	11.4
Heptyl sulfide	C ₁₄ H ₃₀ S	35.9	11.5	13.4	11.1
Octyl sulfide	C ₁₆ H ₃₄ S	36.3	11.5	13.3	10.9
Decyl sulfide	C ₂₀ H ₄₂ S	36.8	11.4	13.1	10.7
	Average		11.3	13.1	11.5

*Data from references 38 and 39. Numbers in parentheses not used for averaging.

complete combustion per unit mass of oxygen consumed are also listed in the tables. The values depend on the chemical structures of the materials. With some exceptions, the values remain approximately constant within each generic group of fuels. From the average values, $\Delta H_O^* = 12.8 \text{ kJ/g} \pm 7 \text{ percent}$. The ΔH_O^* value of 12.8 kJ/g is close to 13.4 kJ/g used in the heating and power industries³⁴ and 13.1 kJ/g $\pm 5 \text{ percent}$ reported in reference 35. The variation of 7 percent would reduce significantly if values for low molecular weight hydrocarbons with small amounts of O, N, and halogen were used in averaging.

For the determination of the chemical heat release rate, mass consumption rate of oxygen is measured, and either the actual values or the average values of the net heats of complete combustion per unit mass of oxygen consumed are used. The measurement for the consumption rate of oxygen is described in the subsection entitled "Generation Rates of Chemical Compounds and Fire Ventilation."

Convective heat release rate: The convective heat release rate is determined from the *Gas Temperature Rise (GTR) Calorimetry*, where the following relationship is used^{2-7,16,33,36}

$$\dot{Q}_{con}^* = \frac{\dot{m} c_p (T_g - T_a)}{A} \quad (23)$$

where \dot{Q}_{con}^* is the convective heat release rate (kW/m²), c_p is the specific heat of the combustion product-air mixture at the gas temperature (kJ/g-K), T_g is the gas temperature (K), T_a is ambient temperature (K), \dot{m} is the total mass flow rate of the fire product-air mixture (g/s), and A is the total exposed surface area of the material (m²).

Radiative heat release rate: Chemical heat release rate consists of a convective and a radiative component. Some fraction of the chemical heat release rate may be lost as conductive heat. In systems where heat losses are negligibly small, the radiative heat release rate can be obtained from the difference between the chemical and convective heat release rates^{2-4,16,33,36}

$$\dot{Q}_{rad}^* = \dot{Q}_{ch}^* - \dot{Q}_{con}^* \quad (24)$$

where \dot{Q}_{rad}^* is the radiative heat release rate (kW/m²).

Use of GTR, CDG, and OC calorimetries: In 1972 the GTR calorimetry was used for the first time by the Ohio State University (OSU) to determine the heat release rate.^{5,6} The apparatus used is now known as the OSU Heat Release Rate Apparatus; it is shown in Figure 3-4.1. The OSU Apparatus is an ASTM⁷ and an FAA standard test apparatus.⁸ In the GTR calorimetry, it is assumed that almost all the thermal radiation from the flame is transferred to the flowing fire products-air mixture, as the flames are inside an enclosed space and heat loss by conductive heat transfer is negligibly small. The OC calorimetry has now been adapted to the OSU apparatus.⁴¹

The CDG, OC, and GTR Calorimetries were used for the first time during the mid-1970s by the Factory Mutual Research Corporation (FMRC) to determine the chemical, convective, and radiative heat release rates.^{27,42-44} The apparatus used is now known as the Flammability Apparatus (50-kW scale); it is shown in Figure 3-4.2(a). Heat release rate from the CDG and OC calorimetries in the Flammability Apparatus was defined as the actual heat release rate until 1986,^{16,33,38,42-45} but after 1986 it was changed to the chemical heat release rate to account for the effects of: (1) the chemical structures of the materials and additives; (2) fire ventilation; (3) the two dominant modes of heat release, i.e., convective and radiative; and (4) the effects of the flame extinguishing and suppressing agents.

The Flammability Apparatus is a standard test apparatus for electrical cables;¹⁴ for wall and ceiling insulation materials, replacing the 25-ft corner test;²⁶ and is expected to be adopted as a standard test apparatus for conveyor belts, composites, sample storage commodities, and other applications related to the commercial and industrial fire protection needs in the future.

In 1982 the National Institute of Standards and Technology (NIST) used the OC calorimetry,^{17,18} following the methodology described in reference 35. The apparatus developed to use this methodology, known as the Cone Calorimeter, is shown in Figure 3-4.3. The Cone Calorimeter became an ASTM standard test apparatus in 1990.¹⁹

Sampling ducts have been designed for the Flammability Apparatus and the Cone Calorimeter to measure the mass generation rates of CO₂ and CO and mass consumption rate

GENERATION OF HEAT AND CHEMICAL COMPOUNDS IN FIRES 3-75

TABLE 3-4.10 Net Heats of Complete Combustion per Unit Mass of Fuel and Oxygen Consumed and Carbon Dioxide and Carbon Monoxide Generated for Polymeric Materials*

Fuel	Formula [†]	ΔH_T^* (kJ/g)	ΔH_O^* (kJ/g)	$\Delta H_{CO_2}^*$ (kJ/g)	ΔH_{CO}^* (kJ/g)	Fuel	Formula [†]	ΔH_T^* (kJ/g)	ΔH_O^* (kJ/g)	$\Delta H_{CO_2}^*$ (kJ/g)	ΔH_{CO}^* (kJ/g)
Carbon-Hydrogen Atoms in the Structure						Carbon-Hydrogen-Oxygen-Nitrogen Atoms in the Structure (Continued)					
Polyethylene	CH ₂	43.6	12.8	13.9	11.8	<i>Rigid polyurethane foams</i>					
Polypropylene	CH	43.4	12.7	13.8	11.7	GM29	CH _{1.0} O _{0.23} N _{0.10}	26.0	12.6	10.7	6.8
Polyisobutylene	CH ₂	43.7	12.7	13.9	11.9	GM31	CH _{1.2} O _{0.22} N _{0.10}	25.0	11.9	10.2	6.1
Polybutadiene	CH _{1.5}	42.8	13.1	13.1	10.7	GM37	CH _{1.2} O _{0.20} N _{0.08}	28.0	12.7	11.2	7.5
Polystyrene	CH	39.2	12.7	12.2	9.2	<i>Rigid polyisocyanurate foams</i>					
<i>Expanded polystyrene</i>						GM41	CH _{1.0} O _{0.19} N _{0.11}	26.2	12.5	10.4	6.4
GM47	CH _{1.1}	38.1	12.4	11.3	7.7	GM43	CH _{0.93} O _{0.20} N _{0.11}	22.2	10.8	8.9	(4.0)
GM49	CH _{1.1}	38.1	12.4	11.3	7.7	Average 12.5 10.9 7.2					
GM51	CH	35.6	11.6	10.8	7.0	Carbon-Hydrogen-Chlorine Atoms in the Structure					
GM53	CH _{1.1}	37.6	12.4	11.3	7.7	<i>Polyethylene with</i>					
Average 12.5 12.4 9.5						25% chlorine CH _{1.9} Cl _{0.13} 31.6 12.7 13.4 10.8					
Carbon-Hydrogen-Oxygen-Nitrogen Atoms in the Structure						36% chlorine CH _{1.8} Cl _{0.22} 26.3 12.8 12.9 10.2					
Polyoxymethylene	CH ₂ O	15.4	14.4	10.5	6.6	48% chlorine CH _{1.7} Cl _{0.36} 20.6 12.8 12.3 9.4					
Polymethylmethacrylate	CH _{1.6} O _{0.4}	25.2	13.1	11.5	8.0	Polychloroprene CH _{1.3} Cl _{0.30} 25.3 13.3 12.7 9.5					
Polyester	CH _{1.4} O _{0.22}	32.5	13.9	12.5	9.6	Polyvinylchloride CH _{1.5} Cl _{0.50} 16.4 11.7 11.7 8.2					
Epoxy	CH _{1.3} O _{0.20}	28.8	12.1	10.8	6.9	Polyvinylidenechloride CHCl 9.0 13.5 9.8 (5.5)					
Polycarbonate	CH _{0.88} O _{0.19}	29.7	13.1	10.7	6.9	Average 12.8 12.1 9.6					
Cellulose triacetate	CH _{1.3} O _{0.67}	17.6	13.3	9.6	5.1	Carbon-Hydrogen-Fluorine Atoms in the Structure[‡]					
Polyethylene-terephthalate	CH _{0.80} O _{0.40}	22.0	13.2	9.6	5.1	Teflon TFE	CF ₂	6.2	9.7	(7.1)	(1.1)
Rigid phenolic foam	CH _{1.1} O _{0.24}	36.4	(16.8)	(14.0)	(12.0)	Teflon FEP	CF _{1.8}	4.8	(6.9)	(5.0)	(0)
Polyacrylonitrile (PAN)	CHN _{0.33}	30.8	10.7	12.3	9.4	Tefzel ETFE	CHF	12.6	12.6	9.2	(4.4)
Red oak	CH _{1.7} O _{0.72} N _{0.001}	17.1	13.2	10.2	6.0	Teflon PFA	CF _{1.7} O _{0.01}	5.0	(8.0)	(5.3)	(0)
Douglas fir	CH _{1.7} O _{0.74} N _{0.002}	16.4	12.4	9.5	5.0	Kel-F (CTFE)	CF _{1.5} Cl _{0.50}	6.5	11.8	8.6	(3.5)
Nylon	CH _{1.8} O _{0.17} N _{0.17}	30.8	11.9	13.3	10.8	Halar (E-CTFE)	CHF _{0.75} Cl _{0.25}	12.0	9.8	9.8	(5.4)
<i>Flexible polyurethane foams</i>						Kynar (PVF ₂)	CHF	13.3	12.4	9.1	(4.2)
GM21	CH _{1.8} O _{0.30} N _{0.05}	26.2	12.1	11.5	8.0	Tedlar (PVF)	CH _{1.5} F _{0.50}	13.5	(6.5)	(7.1)	(1.1)
GM23	CH _{1.8} O _{0.35} N _{0.06}	27.2	13.7	12.5	9.7	Carbon-Hydrogen-Oxygen-Silicone Atoms in the Structure					
GM25	CH _{1.7} O _{0.32} N _{0.07}	24.6	12.0	11.1	7.5	Silicone-1	CH _{1.3} O _{0.25} Si _{0.18}	21.7	12.6	11.0	7.4
GM27	CH _{1.7} O _{0.30} N _{0.08}	23.2	11.2	10.4	6.2	Silicone-2	CH _{1.5} O _{0.30} Si _{0.26}	21.3	13.9	12.4	9.4
						Silicone-3	CH ₃ O _{0.50} Si _{0.50}	25.1	14.5	21.0	23.0

*From the data measured in our Flammability Laboratory.

†From the data for the elemental composition of the polymeric materials measured in the FMRC Flammability Laboratory.

‡From the data measured by our Flammability Laboratory in the oxygen bomb calorimeter and corrected for water as a gas and for the residue.

§Trade names from reference 40.

of oxygen for use in the CDG and OC calorimetries. (See Equations 18 and 21.) The CDG and OC calorimetries are used in the Flammability Apparatus (50-, 500-, and 10,000-kW scale). In the OSU Apparatus and the Cone Calorimeter, only the OC calorimetry is used.

The CDG and OC calorimetries are also used in numerous large-scale fire tests, such as the CDG calorimetry in the wind-aided turbulent horizontal flame spread in large-scale fire test galleries at the Londonderry Occupational Safety Centre in Australia and Pittsburgh Research Center, U.S. Bureau of Mines.^{46,47}

In the GTR calorimetry, a thermopile located in the flue gas chimney is used in the OSU Apparatus, and a thermocouple located in the sampling duct is used in the Flammability Apparatus, where heat losses by conduction are negligibly small. The Cone Calorimeter has not been designed for the GTR calorimetry.

The radiative heat release rate is determined from the difference between the chemical and convective heat release rates only in the Flammability Apparatus.

Figure 3-4.21 shows a typical example of the heat release rate profile. The profile is for the chemical heat release rate of polypropylene, determined from the CDG and OC calorimetries in the Flammability Apparatus (500-kW scale). The polypropylene sample was 100 mm in diameter and 25 mm in thickness. It was exposed to an external heat flux of 50 kW/m² under co-flowing normal air. In the figure, solid, molten, and boiling-liquid zones are indicated.

In the solid zone in Figure 3-4.21, combustion is at the steady state between about 400 and 900 sec. During the steady-state combustion, a very thin liquid film is present at the surface. In the molten zone, the thickness of the liquid film and chemical heat release rate increase rapidly during combustion. At the end of the zone, the entire sample is

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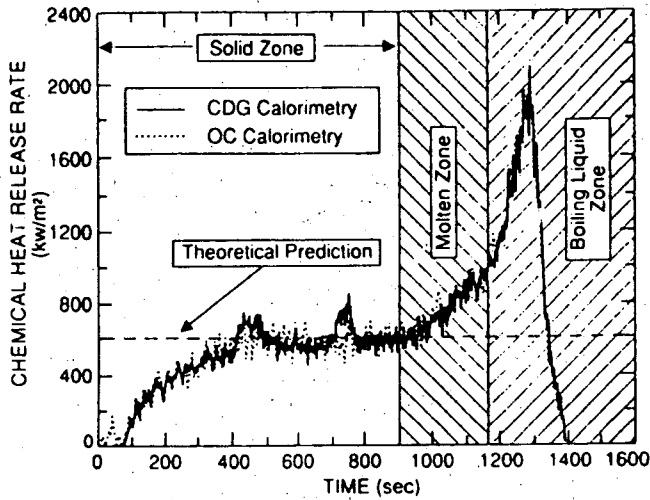


Fig. 3-4.21. Chemical heat release rate for 100-mm diameter and 25-mm-thick slab of polypropylene exposed to an external heat flux of 50 kW/m² and 0.09 m/s co-flowing normal air in the Flammability Apparatus. The theoretical prediction is based on the Heat Release Parameter for polypropylene listed in Table 3-4.12.

present as a liquid. In the boiling-liquid zone, the liquid boils vigorously, chemical heat release rate increases exponentially until the sample is consumed, the base diameter of the flame is considerably larger than the diameter of the sample dish (100 mm), and the flames are as high as 1.5 m (5 ft). This zone is the most dangerous zone.

The chemical heat release rate profiles from the CDG and OC calorimetries are very similar, as expected.

Energy released in a fire: The total amount of heat generated as a result of chemical reactions in the combustion of a material is defined as the chemical energy. The chemical energy has a convective and a radiative component

$$E_{ch} = E_{con} + E_{rad} \quad (25)$$

where E_{ch} is the chemical energy (kJ), E_{con} is the convective energy (kJ), and E_{rad} is the radiative energy (kJ). The chemical energy and its convective and radiative components are calculated by the summation of the respective heat release rates

$$E_i = A \sum_{n=t_{ig}}^{n=t_{cx}} Q_i^*(t_n) \Delta t_n \quad (26)$$

where E_i is the chemical, convective, or radiative energy (kJ), A is the total surface area of the material burning (m²), t_{ig} is the ignition time (s), and t_{cx} is the flame extinction time (s). The total mass of the material lost during combustion is measured directly from the initial and final mass and is calculated by the summation of the mass loss rate

$$W_f = A \sum_{n=t_{ig}}^{n=t_{cx}} \dot{m}^*(t_n) \Delta t_n \quad (27)$$

where W_f is the total mass of the material lost in the combustion (g).

Heat release rate can also be expressed as the product of the mass loss rate and the heat of combustion

$$Q_i^* = \Delta H_i \dot{m}^* \quad (28)$$

where ΔH_i is the chemical, convective, or radiative heat of combustion (kJ/g). The average chemical, convective, or radiative heats of combustion are calculated from the relationship based on Equations 26 and 27

$$\Delta \bar{H}_i = \frac{E_i}{W_f} \quad (29)$$

where $\Delta \bar{H}_i$ is the average chemical, convective, or radiative heat of combustion (kJ/g). The average chemical heat of combustion determined in the Cone Calorimeter is defined as the effective heat of combustion.¹⁷⁻¹⁹

Heat release parameter (HRP): Heat release parameter (HRP) is defined as the amount of energy generated per unit amount of energy absorbed. From Equations 11 and 28

$$Q_i^* = \left(\frac{\Delta H_i}{\Delta H_g} \right) (\dot{q}_c^* + \dot{q}_f^* - \dot{q}_{rr}^*) \quad (30)$$

where $\Delta H_i/\Delta H_g$ is defined as the chemical, convective, or radiative Heat Release Parameter, (HRP)_{ch}, (HRP)_{con}, or (HRP)_{rad}, respectively.⁴ The HRP values are characteristic fire properties of materials, but depend on fire ventilation. The chemical Heat Release Parameter is independent of fire size.

In Figure 3-4.21, the theoretical prediction is from Equation 30, with chemical Heat Release Parameter = .19, external heat flux = 50 kW/m², and surface re-radiation = 18 kW/m² with negligibly small flame heat flux. The theoretical prediction is very close to the measured value in the solid zone.

Experimental data support Equation 30, as shown in Figures 3-4.22 through 3-4.24, where the average peak or steady-state chemical heat release rates are plotted against the net heat flux. Linear relationship between the chemical heat release rate and net heat flux is satisfied. For the condition $\dot{q}_c^* \gg \dot{q}_f^* - \dot{q}_{rr}^*$, the average value of the Heat Release Parameter is calculated from the summation of the heat release rate and the external heat flux

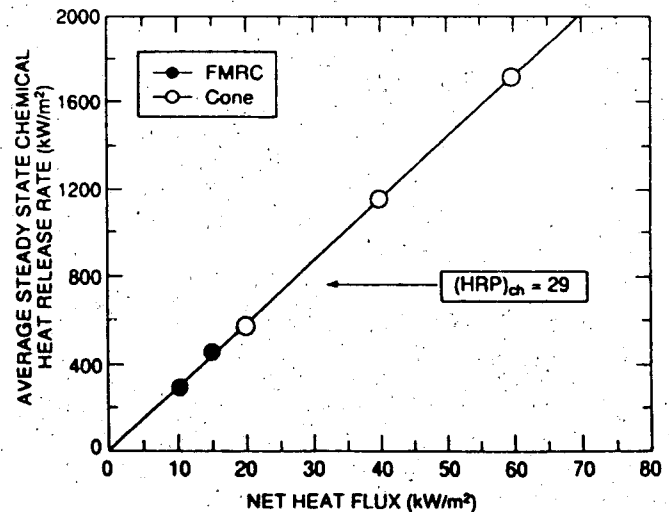


Fig. 3-4.22. Average steady-state chemical heat release rate versus net heat flux for polystyrene slab. Net heat flux is the sum of the external and flame heat flux minus the surface re-radiation.

$$\overline{(HRP)}_i = \frac{E_i}{A \sum_{n=1}^n \dot{q}_c^n \Delta t_n} \quad (31)$$

Complete and incomplete combustion: In fires, combustion is never complete. Thus, the chemical heat release rate or the chemical heat of combustion is less than the heat release rate for complete combustion or the net heat of complete combustion. The ratio of the chemical heat release rate to the heat release rate for complete combustion or the ratio of the chemical heat of combustion to net heat of complete combustion is defined as combustion efficiency^{2-4,16,33,36}

$$\chi_{ch} = \frac{\dot{Q}_{ch}^*}{\dot{Q}_T^*} = \frac{\dot{m}^* \Delta H_{ch}}{\dot{m}^* \Delta H_T} = \frac{\Delta H_{ch}}{\Delta H_T} \quad (32)$$

where χ_{ch} is the combustion efficiency, and \dot{Q}_T^* is the heat release rate for complete combustion (kW/m^2). The convective and radiative components of the combustion efficiency are defined in a similar fashion^{2-4,16,33,36}

$$\chi_{con} = \frac{\dot{Q}_{con}^*}{\dot{Q}_T^*} = \frac{\dot{m}^* \Delta H_{con}}{\dot{m}^* \Delta H_T} = \frac{\Delta H_{con}}{\Delta H_T} \quad (33)$$

$$\chi_{rad} = \frac{\dot{Q}_{rad}^*}{\dot{Q}_T^*} = \frac{\dot{m}^* \Delta H_{rad}}{\dot{m}^* \Delta H_T} = \frac{\Delta H_{rad}}{\Delta H_T} \quad (34)$$

where χ_{con} is the convective component of the combustion efficiency, and χ_{rad} is the radiative component of the combustion efficiency. From the definitions

$$\Delta H_{ch} = \Delta H_{con} + \Delta H_{rad} \quad (35)$$

$$\chi_{ch} = \chi_{con} + \chi_{rad} \quad (36)$$

The chemical, convective, and radiative heat release rates, heats of combustion or combustion efficiencies depend on the chemical structures of the materials and fire ventilation. The distribution of the chemical heat into convective and radiative components changes with fire size.

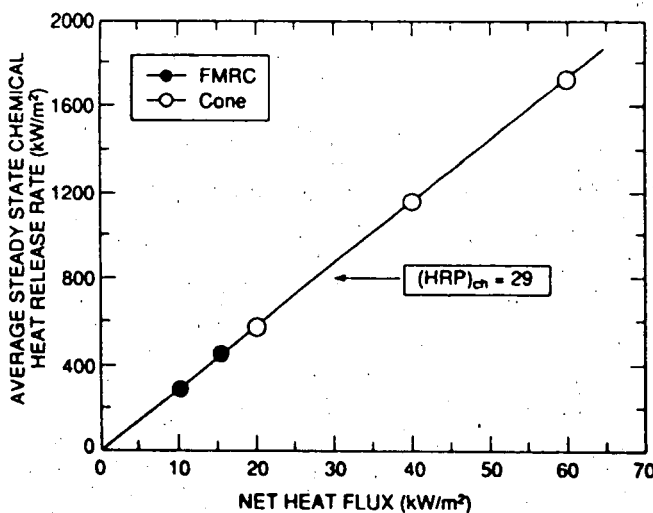


Fig. 3-4.23. Average steady-state chemical heat release rate versus the net heat flux for high molecular weight hydrocarbon liquid burning in a 100-mm-diameter dish. The Cone Calorimeter data were measured at the research laboratory of the Dow-Corning Corporation, Midland, MI. Net heat flux is the sum of the external and flame heat flux minus the surface re-radiation.

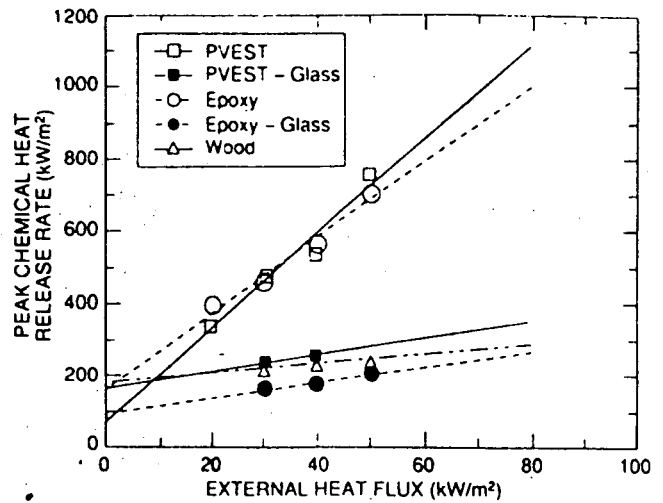


Fig. 3-4.24. Peak chemical heat release rate versus the external heat flux for 100- × 100-mm × 3- to 11-mm-thick slab of polyvinyl ester (PVEST), PVEST/fiberglass, epoxy, epoxy/fiberglass, and wood (hemlock). Data measured in the Cone Calorimeter as reported in reference 20 are shown.

The larger the fire size, the larger the fraction of the chemical heat distributed into the radiative component.

The chemical, convective, and radiative heats of combustion and the Heat Release Parameter values for the well-ventilated fires are listed in Tables 3-4.11 and 3-4.12, respectively. Comparisons between the limited data from the OSU Apparatus and the Flammability Apparatus and the Cone Calorimeter are satisfactory.

EXAMPLE 10:

Heptane was burned in a 2-m-diameter pan, and measurements were made for the mass loss rate, mass generation rates of CO and CO_2 , and mass consumption rate of O_2 . The average values in $\text{g/m}^2\text{-s}$ for the mass loss rate, mass generation rates of CO and CO_2 , and mass consumption rate of O_2 were 66, 9, 181, and 216, respectively. For large-scale fires of heptane, the literature values are: $\chi_{ch} = 0.93$, $\chi_{con} = 0.59$, and $\chi_{rad} = 0.34$. The net heat of complete combustion for heptane reported in the literature is 44.6 kJ/g. Calculate the chemical heat release rate and show that it is consistent with the rate based on the literature value of the combustion efficiency. Also calculate the convective and radiative heat release rates.

SOLUTION:

From Table 3-4.7, the net heat of complete combustion per unit mass of oxygen consumed is 12.7 kJ/g; the net heat of complete combustion per unit mass of CO_2 generated is 14.5 kJ/g; and the net heat of complete combustion per unit mass of CO generated is 12.8 kJ/g. From the CDG Calorimetry (Equation 18)

$$\begin{aligned} \dot{Q}_{ch}^* &= 14.5 \times 181 + 12.8 \times 9 \\ &= 2625 + 115 = 2740 \text{ kW/m}^2 \end{aligned}$$

(Text continued on page 3-84)

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TABLE 3-4.11 *Yields of Fire Products and Chemical, Convective, and Radiative Heats of Combustion for Well-Ventilated Fires**

Material	ΔH_T (kJ/g)	Y_{CO_2}	Y_{CO}	Y_{ch}	Y_s	ΔH_{ch}	ΔH_{con}	ΔH_{rad}
<i>Common Gases</i>								
Methane	50.1	2.72	—	—	—	49.6	42.6	7.0
Ethane	47.1	2.85	0.001	0.001	0.013	45.7	34.1	11.6
Propane	46.0	2.85	0.005	0.001	0.024	43.7	31.2	12.5
Butane	45.4	2.85	0.007	0.003	0.029	42.6	29.6	13.0
Ethylene	48.0	2.72	0.013	0.005	0.043	41.5	27.3	14.2
Propylene	46.4	2.74	0.017	0.006	0.095	40.5	25.6	14.9
1,3-Butadiene	44.6	2.46	0.048	0.014	0.125	33.6	15.4	18.2
Acetylene	47.8	2.60	0.042	0.013	0.096	36.7	18.7	18.0
<i>Common Liquids</i>								
Methyl alcohol	20.0	1.31	0.001	—	—	19.1	16.1	3.0
Ethyl alcohol	27.7	1.77	0.001	0.001	0.008	25.6	19.0	6.5
Isopropyl alcohol	31.8	2.01	0.003	0.001	0.015	29.0	20.6	8.5
Acetone	29.7	2.14	0.003	0.001	0.014	27.9	20.3	7.6
Methylethyl ketone	32.7	2.29	0.004	0.001	0.018	30.6	22.1	8.6
Heptane	44.6	2.85	0.010	0.004	0.037	41.2	27.6	13.6
Octane	44.5	2.84	0.011	0.004	0.038	41.0	27.3	13.7
Kerosene	44.1	2.83	0.012	0.004	0.042	40.3	26.2	14.1
Benzene	40.1	2.33	0.067	0.018	0.181	27.6	11.0	16.5
Toluene	39.7	2.34	0.066	0.018	0.178	27.7	11.2	16.5
Styrene	39.4	2.35	0.065	0.019	0.177	27.8	11.2	16.6
Hydrocarbon	43.9	2.64	0.019	0.007	0.059	36.9	24.5	12.4
Mineral oil	41.5	2.37	0.041	0.012	0.097	31.7	—	—
Polydimethyl siloxane	25.1	0.93	0.004	0.032	0.232	19.6	—	—
Silicone	25.1	0.72	0.006	0.008	—	15.2	12.7	2.5
<i>Natural Materials</i>								
Tissue paper	—	—	—	—	—	11.4	6.7	4.7
Newspaper	—	—	—	—	—	14.4	—	—
Wood (red oak)	17.1	1.27	0.004	0.001	0.015	12.4	7.8	4.6
Wood (Douglas fir)	16.4	1.31	0.004	0.001	—	13.0	8.1	4.9
Wood (pine)	17.9	1.33	0.005	0.001	—	12.4	8.7	3.7
Corrugated paper	—	—	—	—	—	13.2	—	—
Wood (hemlock) [†]	—	—	—	—	0.015	13.3	—	—
Wool 100% [†]	—	—	—	—	0.008	19.5	—	—
<i>Synthetic Materials—Solids (abbreviations/names in the nomenclature)</i>								
ABS [†]	—	—	—	—	0.105	30.0	—	—
POM	15.4	1.40	0.001	0.001	—	14.4	11.2	3.2
PMMA	25.2	2.12	0.010	0.001	0.022	24.2	16.6	7.6
PE	43.6	2.76	0.024	0.007	0.060	38.4	21.8	16.6
PP	43.4	2.79	0.024	0.006	0.059	38.6	22.6	16.0
PS	39.2	2.33	0.060	0.014	0.164	27.0	11.0	16.0
Silicone	21.7	0.96	0.021	0.006	0.065	10.6	7.3	3.3
Polyester-1	32.5	1.65	0.070	0.020	0.091	20.6	10.8	9.8
Polyester-2	32.5	1.56	0.080	0.029	0.089	19.5	—	—
Epoxy-1	28.8	1.59	0.080	0.030	—	17.1	8.5	8.6
Epoxy-2	28.8	1.16	0.086	0.026	0.098	12.3	—	—
Nylon	30.8	2.06	0.038	0.016	0.075	27.1	16.3	10.8
Polyamide-6 [†]	—	—	—	—	0.011	28.8	—	—
IPST [†]	—	—	—	—	0.080	23.3	—	—
PVEST [†]	—	—	—	—	0.076	22.0	—	—
Silicone rubber	21.7	0.96	0.021	0.005	0.078	10.9	—	—
<i>Polyurethane (Flexible) Foams</i>								
GM21	26.2	1.55	0.010	0.002	0.131	17.8	8.6	9.2
GM23	27.2	1.51	0.031	0.005	0.227	19.0	10.3	8.7
GM25	24.6	1.50	0.028	0.005	0.194	17.0	7.2	9.8
GM27	23.2	1.57	0.042	0.004	0.198	16.4	7.6	8.8

GENERATION OF HEAT AND CHEMICAL COMPOUNDS IN FIRES 3-79

TABLE 3-4.11 Yields of Fire Products and Chemical, Convective, and Radiative Heats of Combustion for Well-Ventilated Fires* (Continued)

Material	ΔH_f (kJ/g)	Y_{CO_2}	Y_{CO}	Y_{ch}	Y_s	ΔH_{ch}	ΔH_{con}	ΔH_{rad}
		(g/g)				(kJ/g)		
<i>Polyurethane (Rigid) Foams</i>								
GM29	26.0	1.52	0.031	0.003	0.130	16.4	6.8	9.6
GM31	25.0	1.53	0.038	0.002	0.125	15.8	7.1	8.8
GM35	28.0	1.58	0.025	0.001	0.104	17.6	7.8	9.8
GM37	28.0	1.63	0.024	0.001	0.113	17.9	8.7	9.2
GM41	26.2	1.18	0.046	0.004	—	15.7	5.7	10.0
GM43	22.2	1.11	0.051	0.004	—	14.8	6.4	8.4
<i>Polystyrene Foams</i>								
GM47	38.1	2.30	0.060	0.014	0.180	25.9	11.4	14.5
GM49	38.2	2.30	0.065	0.016	0.210	25.6	9.9	15.7
GM51	35.6	2.34	0.058	0.013	0.185	24.6	10.4	14.2
GM53	37.6	2.34	0.060	0.015	0.200	25.9	11.2	14.7
<i>Polyethylene Foams</i>								
1	41.2	2.62	0.020	0.004	0.056	34.4	20.2	14.2
2	40.8	2.78	0.026	0.008	0.102	36.1	20.6	15.5
3	40.8	2.60	0.020	0.004	0.076	33.8	18.2	15.6
4	40.8	2.51	0.015	0.005	0.071	32.6	19.1	13.5
<i>Phenolic Foams</i>								
1†	—	—	—	—	0.002	10.0	—	—
2†	—	—	—	—	—	10.0	—	—
<i>Halogenated Materials (abbreviations/names in the nomenclature)</i>								
<i>Polyethylene with</i>								
25% chlorine	31.6	1.71	0.042	0.016	0.115	22.6	10.0	12.6
36% chlorine	26.3	0.83	0.051	0.017	0.139	10.6	6.4	4.2
48% chlorine	20.6	0.59	0.049	0.015	0.134	7.2	3.9	3.3
PVC	16.4	0.46	0.063	0.023	0.172	5.7	3.1	2.6
PVC-1† (LOI = 0.50)	—	—	—	—	0.098	7.7	—	—
PVC-2† (LOI = 0.50)	—	—	—	—	0.076	8.3	—	—
PVC† (LOI = 0.20)	—	—	—	—	0.099	11.3	—	—
PVC† (LOI = 0.25)	—	—	—	—	0.078	9.8	—	—
PVC† (LOI = 0.30)	—	—	—	—	0.098	10.3	—	—
PVC† (LOI = 0.35)	—	—	—	—	0.088	10.8	—	—
PVC panel	—	—	—	—	—	7.3	—	—
ETFE (Tefzel™)	12.6	0.54	0.060	0.020	0.042	5.4	—	—
PFA (Teflon™)	5.0	0.37	0.097	—	0.002	4.7	—	—
FEP (Teflon™)	4.8	0.25	0.116	—	0.003	4.1	—	—
TFE (Teflon™)	6.2	0.38	0.092	—	0.003	4.2	—	—
<i>Building Products†</i>								
Particleboard (PB)	—	1.2	0.004	—	—	14.0	—	—
Fiberboard (FB)	—	1.4	0.015	—	—	14.0	—	—
Medium-density FB	—	1.2	0.002	—	—	14.0	—	—
Wood panel	—	1.2	0.002	—	—	15.0	—	—
Melamine-faced PB	—	0.8	0.025	—	—	10.7	—	—
Gypsumboard (GB)	—	0.3	0.027	—	—	4.3	—	—
Paper on GB	—	0.4	0.028	—	—	5.6	—	—
Plastic on GB	—	0.4	0.028	—	—	14.3	—	—
Textile on GB	—	0.4	0.025	—	—	13.0	—	—
Textile on rock wool	—	1.8	0.091	—	—	25.0	—	—
Paper on PB	—	1.2	0.003	—	—	12.5	—	—
Rigid PU	—	1.1	0.200	—	—	13.0	—	—
EPS	—	1.9	0.054	—	—	28.0	—	—

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TABLE 3-4.11 Yields of Fire Products and Chemical, Convective, and Radiative Heats of Combustion for Well-Ventilated Fires* (Continued)

Material	ΔH_T (kJ/g)	Y_{CO_2}	Y_{CO}	Y_{ch}	Y_s	ΔH_{ch}	ΔH_{con}	ΔH_{rad}
<i>Composite and Fiberglass-Reinforced Materials (FGR) (abbreviations/names in the nomenclature)</i>								
PEEK/FGR [†]	—	—	—	—	0.042	20.5	—	—
IPST/FGR [†]	—	—	—	—	0.032	27.0	—	—
PES/FGR [†]	—	—	—	—	0.049	27.5	—	—
PEST1/FGR [†]	—	—	—	—	—	16.0	—	—
PEST2/FGR [†]	—	—	—	—	—	12.9	—	—
PEST1/FGR	—	—	—	—	—	19.0	—	—
PEST2/FGR	—	—	—	—	—	13.9	—	—
PEST3/FGR	—	1.47	0.055	0.007	0.070	17.9	10.7	7.2
PEST4/FGR	—	1.24	0.039	0.004	0.054	16.0	9.9	6.1
PEST5/FGR	—	0.71	0.102	0.019	0.068	9.3	6.5	2.8
Epoxy/FG [†]	—	—	—	—	0.056	27.5	—	—
PVEST/FGR	—	—	—	—	0.079	26.0	—	—
Kevlar [™] /Phenolic	—	1.27	0.025	0.002	0.041	14.8	11.1	3.7
Phenolic-1/FGR	—	0.98	0.066	0.003	0.023	11.9	8.9	3.0
Phenolic-2/FGR [†]	—	—	—	—	0.016	22.0	—	—
<i>Aircraft Panel Materials</i>								
Epoxy/FGR/paint	—	0.828	0.114	0.016	0.166	11.3	6.2	5.1
Epoxy/Kevlar [™] /paint	—	0.873	0.091	0.016	0.126	11.4	6.3	5.1
Phenolic/FGR/paint	—	1.49	0.027	0.002	0.059	22.9	11.5	11.4
Phenolic/Kevlar [™] /paint	—	1.23	0.088	0.011	0.094	18.6	8.9	9.7
Phenolic/graphite/paint	—	1.67	0.026	0.003	0.062	24.6	14.0	10.6
Polycarbonate	—	—	—	—	—	20.5	—	—
<i>Electrical Cables (abbreviations/names in the nomenclature)</i>								
<i>Polyethylene/Polyvinylchloride</i>								
1	—	2.08	0.100	0.021	0.076	31.3	11.6	19.7
2	—	1.75	0.050	0.013	0.115	25.1	11.1	14.0
3	—	1.67	0.048	0.012	—	24.0	13.0	11.0
4	—	1.39	0.166	0.038	—	22.0	14.0	8.1
5	—	1.29	0.147	0.042	0.136	20.9	10.7	10.2
<i>EPR/Hypalon</i>								
1	—	1.95	0.072	0.014	—	29.6	15.8	13.9
2	—	1.74	0.076	0.022	—	26.8	17.0	9.8
3	—	1.21	0.072	0.014	—	19.0	12.3	6.7
4	—	0.99	0.090	0.085	0.082	17.4	6.6	10.8
5	—	0.95	0.122	0.024	—	17.3	7.5	9.8
6	—	0.89	0.121	0.022	0.164	13.9	9.2	4.7
<i>Silicone</i>								
1	—	1.65	0.011	0.001	—	25.0	17.5	7.3
2	—	1.47	0.029	0.001	—	24.0	20.0	4.0
<i>XLPE/XLPE</i>								
1	—	1.78	0.114	0.029	0.120	28.3	12.3	16.0
2	—	0.83	0.110	0.024	0.120	12.5	7.5	5.0
<i>XLPE/Neoprene</i>								
1	—	0.68	0.122	0.031	—	12.6	5.9	6.7
2	—	0.63	0.082	0.014	0.175	10.3	4.9	5.5
<i>Silicone/PVC</i>								
1	16.4	0.76	0.110	0.015	0.111	10.0	—	—
2	16.4	1.19	0.065	0.005	0.119	15.6	—	—
<i>PVC/Nylon/PVC-Nylon</i>								
1	—	0.63	0.084	0.024	—	10.2	5.0	5.2
2	—	0.49	0.082	0.032	0.115	9.2	4.8	4.4

TABLE 3-4.11 Yields of Fire Products and Chemical, Convective, and Radiative Heats of Combustion for Well-Ventilated Fires* (Continued)

Material	ΔH_f (kJ/g)	Y_{CO_2}	Y_{CO}	Y_{CH}	Y_s	ΔH_{ch}	ΔH_{con}	ΔH_{rad}
		(g/g)				(kJ/g)		
PTFE								
1	—	0.180	0.091	0.012	0.011	3.2	2.7	0.4
2	6.2	0.389	0.103	—	0.005	5.7	—	—
<i>Materials with Fiberwab, Nafike, and Multiplex Structure (abbreviations/names in the nomenclature)</i>								
Dlefin	—	1.49	0.006	—	—	16.5	13.3	3.2
PP-1	—	1.25	0.0025	—	—	14.0	10.8	3.2
PP-2	—	1.56	0.0048	—	—	17.2	10.5	6.7
Polyester-1	—	2.21	0.015	—	—	24.8	8.9	15.7
Polyester-2	—	1.51	0.0079	—	—	16.8	9.1	7.7
Polyester-3	—	2.55	0.020	—	—	28.5	22.6	5.9
Polyester-4	—	1.92	0.014	—	—	21.4	12.4	9.0
Rayon-1	—	1.80	0.043	—	—	20.3	14.1	6.2
Rayon-2	—	1.91	0.043	0.002	—	21.5	13.3	8.2
Rayon-3	—	1.16	0.047	—	—	13.5	8.3	5.2
Polyester-Rayon	—	1.52	0.005	—	—	16.8	9.1	7.7
Polyester-polyamide	—	1.82	0.008	—	—	20.2	10.4	9.8
Rayon-PE	—	1.50	0.027	—	—	16.9	8.72	8.2
<i>Two to Eight 100- × 100- × 100-mm Corrugated Paper Boxes with and without the Polymers with Three-Dimensional Arrangement (abbreviations/names in the nomenclature)^g</i>								
Empty	—	1.53	0.023	0.001	—	14.2	10.7	3.5
With PVC (62%-thick)	—	1.01	0.073	0.007	0.119	10.7	9.5	1.2
With PC (59%-thick)	—	1.73	0.047	0.002	0.061	18.4	13.5	4.9
With PS (58%-thick)	—	1.40	0.138	0.026	0.285	16.2	12.5	3.7
With PS (60%-thin)	—	1.88	0.068	0.020	0.140	19.4	10.1	9.3
With PS (40%-thin)	—	1.74	0.042	0.005	0.167	18.0	11.7	6.7
With ABS (59%-thick)	—	1.53	0.089	0.008	0.143	16.1	12.7	3.4
With PET (41%-thin)	—	1.87	0.050	0.006	0.053	19.9	11.8	8.1
With PU (40%-foam)	—	1.56	0.024	—	—	14.4	8.6	5.8
<i>High-Pressure Liquid Spray Combustion^h</i>								
<i>Hydraulic Fluids</i>								
<i>Organic polyol esters</i>								
1	36.6	—	—	—	—	35.5	—	—
2	35.7	—	—	—	—	35.1	—	—
3	40.3	—	—	—	—	37.2	—	—
4	37.0	—	—	—	—	35.7	—	—
<i>Phosphate esters</i>								
1	31.8	—	—	—	—	29.3	—	—
2	32.0	—	—	—	—	29.6	—	—
<i>Water-in-Oil Emulsions</i>								
1	27.6	—	—	—	—	2.5	—	—
<i>Polyglycol-in-Water</i>								
1	11.0	—	—	—	—	10.4	—	—
2	11.9	—	—	—	—	11.1	—	—
3	14.7	—	—	—	—	12.2	—	—
4	12.1	—	—	—	—	10.6	—	—
<i>Liquid Fuels</i>								
Mineral oil	46.0	—	—	—	—	44.3	—	—
Methanol	20.0	—	—	—	—	19.8	—	—
Ethanol	27.7	—	—	—	—	26.2	—	—
Heptane	44.4	—	—	—	—	40.3	—	—

*Data measured in the Flammability Apparatus. Data measured in the Cone Calorimeter are identified by superscripts [†] and [‡]. Some of the data are corrected to reflect well-ventilated fire conditions. All the data are reported for turbulent fires, i.e., materials exposed to higher external heat flux values.

Dashes: either not measured or are less than 0.001.

[†] Calculated from the data measured in the Cone Calorimeter as reported in references 20 and 31.

[‡] Calculated from the data measured in the Cone Calorimeter as reported in reference 48.

^g 100- × 100- × 100-mm corrugated paper boxes with and without the 99- × 99- × 99-mm polymer boxes or pieces on corrugated paper compartments. The boxes are arranged in one and two layers, about 12 mm apart, with one to four boxes in each layer, separated by about 12 mm. All the boxes are placed on a very light metal frame made of rods with screen base. Measurements made in the Flammability Apparatus; numbers in parenthesis are the weight percents.

^h Data from reference 49 measured in high-pressure liquid spray combustion in the Fire Products Collector (10,000-kW scale apparatus in Figure 3-4.8).

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TABLE 3-4.12 Chemical and Convective Heat Release Parameters

Materials	(HRP) _{ch}			(HRP) _{con}		
	Flammability Apparatus	Cone*	Cal [†]	Flammability Apparatus	OSU [†]	Cal [†]
<i>Liquids and Gases (Hydrocarbons, Alkanes)</i>						
Hexane	—	—	83	—	—	56
Heptane	—	—	75	—	—	50
Octane	—	—	68	—	—	46
Nonane	—	—	64	—	—	42
Decane	—	—	59	—	—	39
Undecane	—	—	55	—	—	36
Dodecane	—	—	52	—	—	34
Tridecane	—	—	50	—	—	32
Kerosene	—	—	47	—	—	17
Hexadecane	—	—	44	—	—	28
<i>Solids (abbreviations/names in the nomenclature)</i>						
ABS	—	14	—	—	—	—
Acrylic sheet	—	6	—	—	—	—
Epoxy	—	11	—	—	—	—
IPST	—	6	—	—	—	—
Polyamide	21	—	—	—	—	—
Polypropylene	19	—	—	11	—	—
Polyethylene	17	21	—	12	—	—
Polystyrene	16	19	—	6	—	—
Polymethylmethacrylate	15	14	—	10	—	—
Nylon	12	—	—	7	—	—
Polyamide-6	—	21	—	—	—	—
Filled phenolic foam—50% inert	—	1	—	—	—	—
Polycarbonate	9	—	—	—	—	—
Polyoxymethylene	6	—	—	5	—	—
Polyethylene/25% CI	11	—	—	5	—	—
Plasticized-PVC-3, LOI 0.25	—	5	—	—	—	—
Plasticized-PVC-4, LOI 0.30	—	5	—	—	—	—
Plasticized-PVC-5, LOI 0.35	—	5	—	—	—	—
Polyethylene/36% CI	4	—	—	2	—	—
Rigid PVC-1, LOI 0.50	—	3	—	—	—	—
Rigid PVC-2	2	3	—	1	—	—
PVC panel	2	—	—	—	—	—
Polyethylene/48% CI	2	—	—	—	—	—
PVEST	—	13	—	—	—	—
ETFE (Tefzel™)	6	—	—	—	—	—
PFA (Teflon™)	5	—	—	—	—	—
FEP (Teflon™)	2	—	—	—	—	—
TFE (Teflon™)	2	—	—	—	—	—
Wood (hemlock)	—	1	—	—	—	—
Wood (Douglas fir)	7	—	—	5	—	—
Wool	—	5	—	—	—	—
<i>Composites and Fiberglass-Reinforced Materials (FGR) (abbreviations/names in the nomenclature)</i>						
Bismaleimide/graphite/ceramic (CC)	—	1	—	—	—	—
Epoxy/FGR	—	2	—	—	—	—
Epoxy/graphite	2	—	—	—	—	—
Epoxy/graphite/CC	2	—	—	—	—	—
Epoxy/graphite/intumescent (IC)	2	—	—	—	—	—
IPST/FGR	—	1	—	—	—	—
PEEK/FGR	—	3	—	—	—	—
PES/FGR	—	1	—	—	—	—
PEST-1/FGR	3	—	—	—	—	—

GENERATION OF HEAT AND CHEMICAL COMPOUNDS IN FIRES 3-83

TABLE 3-4.12 Chemical and Convective Heat Release Parameters (Continued)

Materials	(HRP) _{ch}			(HRP) _{con}		
	Flammability Apparatus	Cone*	Cal [†]	Flammability Apparatus	OSU [‡]	Cal [†]
<i>Composites and Fiberglass-Reinforced Materials (FGR) (Continued)</i>						
PEST-6/FGR	3	—	—	—	—	—
Pheno/FGR	—	1	—	—	—	—
Phenolic/Kevlar™	2	—	—	—	—	—
Phenolic/graphite	1	—	—	—	—	—
PVEST-1/FGR	3	—	—	—	—	—
PVEST-1/FGR/CC	3	—	—	—	—	—
PVEST-1/FGR/IC	1	—	—	—	—	—
PVEST-2/FGR	7	—	—	—	—	—
PVEST-3/FGR	2	—	—	—	—	—
<i>Aircraft Panel Materials</i>						
Epoxy fiberglass	4	5	—	2	1	—
Epoxy Kevlar™	4	4	—	2	2	—
Phenolic Kevlar™	5	4	—	2	—	—
Phenolic graphite	4	3	—	1	—	—
Phenolic fiberglass	4	3	—	2	1	—
Polycarbonate panel	9	—	—	—	—	—
<i>Foams</i>						
<i>Polystyrene</i>						
GM53	20	—	—	6	—	—
GM49	19	—	—	8	—	—
GM51	18	—	—	9	—	—
<i>Flexible Polyurethane</i>						
GM 21	7	—	—	3	3	—
GM 23	9	—	—	5	6	—
GM 25	14	—	—	6	4	—
GM 27	9	—	—	4	2	—
Phenolic	—	1	—	—	—	—
<i>Electrical Cables (abbreviations/names in the nomenclature)</i>						
PVC/PVC-1 (Group 3)	15	—	—	—	—	—
PE/PVC (Group 3)	19	—	—	—	—	—
PP,PEST/PVC (Group 3)	11	—	—	—	—	—
PVC/PVC-2 (Group 3)	14	—	—	—	—	—
Chlorinated PE (Group 2)	5	—	—	—	—	—
PVC/PVC-3 (Group 2)	4	—	—	—	—	—
EPR/PVC (Group 2)	6	—	—	—	—	—
PVC/EPR (Group 2)	4	—	—	—	—	—
XLPE/XLPE (Group 2)	6	—	—	—	—	—
EPR/hypalon-1 (Group 2)	6	—	—	—	—	—
EPR/hypalon-2 (Group 2)	4	—	—	—	—	—
EPR/hypalon-3 (Group 1)	3	—	—	—	—	—
EPR/hypalon-4 (Group 1)	3	—	—	—	—	—
EPR/EPR-1 (Group 1)	3	—	—	—	—	—
EPR/EPR-2 (Group 1)	3	—	—	—	—	—
EPR/EPR-3 (Group 1)	2	—	—	—	—	—
XLPE-EVA-1 (Group 1)	3	—	—	—	—	—
XLPE-EVA-2 (Group 1)	3	—	—	—	—	—
ETFA (Group 1)	3	—	—	—	—	—
PVC/PVF ₂ (Group 1)	1	—	—	—	—	—
FEP/FEP-1 (Group 1)	2	—	—	—	—	—
FEP/FEP-2 (Group 2)	2	—	—	—	—	—

*Calculated from the data reported in references 20 and 31.

†Calculated from the data in references 38 and 39.

‡From reference 50.

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From OC Calorimetry (Equation 21)

$$\dot{Q}_{ch}^* = 12.7 \times 216 = 2743 \text{ kW/m}^2$$

The chemical heat release rate from the CDG and OC calorimetries are in excellent agreement, the average being 2742 kW/m².

The chemical heat of combustion is the products of net heat of complete combustion (44.6 kJ/g) and the combustion efficiency (0.93), which is 41.5 kJ/g.

The chemical heat release is the product of the mass loss rate (66 g/m²-s) and chemical heat of combustion (41.5 kJ/g), which is 2739 kW/m², compared to the averaged value 2742 kW/m² from the CDG and OC calorimetries. Thus, the chemical heat release determined from the measurements is consistent with the rate from the literature value of the combustion efficiency.

The convective heat release rate is equal to the convective heat of combustion and the mass loss rate. The convective heat of combustion is equal to the convective component of the combustion efficiency ($X_{com} = 0.59$) times the net of complete combustion (44.6 kJ/g). Thus, the convective heat release rate for heptane = $66 \times 0.59 \times 44.6 = 1737 \text{ kW/m}^2$. In a similar fashion, the radiative heat release rate = $66 \times 0.34 \times 44.6 = 1001 \text{ kW/m}^2$.

EXAMPLE 11:

From Radiation Scaling Technique, the asymptotic mass loss rate values in g/m²-s, expected in large-scale fires, as listed in Table 3-4.5, for polyethylene, polystyrene, polyvinylchloride, and Teflon™ are 26, 36, 16, and 7, respectively. The chemical heats of combustion in kJ/g listed in Table 3-4.11 for these materials are 38.4, 27.0, 5.7, and 4.1, respectively. Estimate the chemical heat release rates expected in large-scale fires of polyethylene, polystyrene, polyvinylchloride, and Teflon™. (Teflon™ in this chapter refers mainly to FEP, except in cases where it is identified otherwise.)

SOLUTION:

The chemical heat release rate is calculated from Equation 28. The chemical heat release rates estimated in the large-scale fires are: (1) polyethylene: $26 \times 38.4 = 998 \text{ kW/m}^2$; (2) polystyrene: $36 \times 27.0 = 972 \text{ kW/m}^2$; (3) polyvinylchloride: $16 \times 5.7 = 91 \text{ kW/m}^2$; and (4) Teflon™: $7 \times 4.1 = 28 \text{ kW/m}^2$.

EXAMPLE 12:

Heat release rate is the product of the Heat Release Parameter and the net heat flux absorbed by the material, as indicated in Equation 30. This concept is used in various models to predict fire propagation and heat release rates, whereas values for the Heat Release Parameter are taken from a handbook, such as this handbook, and net heat flux is estimated through correlations. The lower the value of the Heat Release Parameter for a fixed value of the net heat flux, the lower the heat release rate.

The values for the surface re-radiation, flame heat flux for large-scale fires, and chemical Heat Release Parameter are listed in Tables 3-4.4, 3-4.5, and 3-4.12, respectively. Calculate the chemical heat release rates expected in large-scale fires of heptane, kerosene, polyethylene, polypropylene, polystyrene, polymethylmethacrylate, polyvinylchloride, and Teflon™.

SOLUTION:

The chemical heat release rates are calculated from the relationship $[(HRP)_{ch} \times (\dot{q}_f^* - \dot{q}_r^*)]$, which is Equation 30: (1) heptane: $(75)(37 - 1) = 2700 \text{ kW/m}^2$; (2) kerosene: $(47)(29 - 1) = 1316 \text{ kW/m}^2$; (3) polyethylene: $(17)(61 - 15) = 782 \text{ kW/m}^2$; (4) polypropylene: $(19)(67 - 15) = 988 \text{ kW/m}^2$; (5) polystyrene: $(16)(75 - 13) = 992 \text{ kW/m}^2$; (6) polymethylmethacrylate: $(15)(57 - 11) = 690 \text{ kW/m}^2$; (7) polyvinylchloride: $(2)(50 - 15) = 70 \text{ kW/m}^2$; and (8) Teflon™: $(2)(52 - 38) = 28 \text{ kW/m}^2$.

The example shows the importance of the Chemical Heat Release Parameter, flame heat flux, and surface re-radiation.

Heat release rate and fire ventilation: In the majority of fires, hazards are due to fires occurring in enclosed spaces. In early stages, a building fire is well-ventilated, and is easy to control and extinguish. However, if the fire is allowed to grow, especially with limited enclosure ventilation and large material surface area, it becomes a ventilation-controlled fire and can lead to flashover, a very dangerous condition. In ventilation-controlled fires, the chemical reactions between oxygen from air and products of incomplete combustion from the decomposed and gasified material (e.g., smoke, CO, hydrocarbons, and other intermediate products) remain incomplete and heat release rate decreases.³⁶

In ventilation-controlled fires, heat release rate depends on the air supply rate and the mass loss rate, in addition to other factors. For ventilation-controlled fires, the effects of the mass flow rate of air and fuel mass loss rate are characterized, most commonly, by the local equivalence ratio

$$\phi = \frac{S m^* A}{\dot{m}_{air}} \quad (37)$$

where ϕ is the equivalence ratio, S is the stoichiometric mass air-to-fuel ratio (g/g), m^* is the mass loss rate (g/m²-s), A is the exposed area of the material burning (m²), and \dot{m}_{air} is the mass flow rate of air (g/s).

Generalized state-relationships between mass fractions of major species (O₂, fuel, CO₂, H₂O, CO, and H₂) and temperature as functions of local equivalence ratios for hydrocarbon-air diffusion flames are available.⁵¹ The relationships suggest that the generation efficiencies of CO, fuel vapors, water, CO₂, and hydrogen and consumption efficiency of O₂ are in approximate thermodynamic equilibrium for well-ventilated combustion, but deviate from equilibrium for ventilation-controlled combustion. This concept has been used for fires of polymeric materials.³⁶ In the tests, chemical and convective heat release rates, mass loss rate, and generation rates of fire products have been measured for various equivalence ratios in the Flammability Apparatus [Figure 3-4.2(a)] and in the Fire Research Institute's (FRI) 0.022-m³ enclosure in Tokyo, Japan, described in reference 36. The combustion efficiency and its convective component are found to decrease as fires become fuel rich, due to increase in the equivalence ratio. The ratio of the combustion efficiency and its convective component or chemical and convective heats of combustion for ventilation-controlled to well-ventilated combustion is expressed as³⁶

$$\zeta_{ch} = \frac{(X_{ch})_{vc}}{(X_{ch})_{wv}} = \frac{(\Delta H_{ch}/\Delta H_T)_{vc}}{(\Delta H_{ch}/\Delta H_T)_{wv}} = \frac{(\Delta H_{ch})_{vc}}{(\Delta H_{ch})_{wv}} \quad (38)$$

$$\zeta_{con} = \frac{(X_{con})_{vc}}{(X_{con})_{wv}} = \frac{(\Delta H_{con}/\Delta H_T)_{vc}}{(\Delta H_{con}/\Delta H_T)_{wv}} = \frac{(\Delta H_{con})_{vc}}{(\Delta H_{con})_{wv}} \quad (39)$$

where ζ_{ch} and ζ_{con} are the ratio of the combustion efficiency

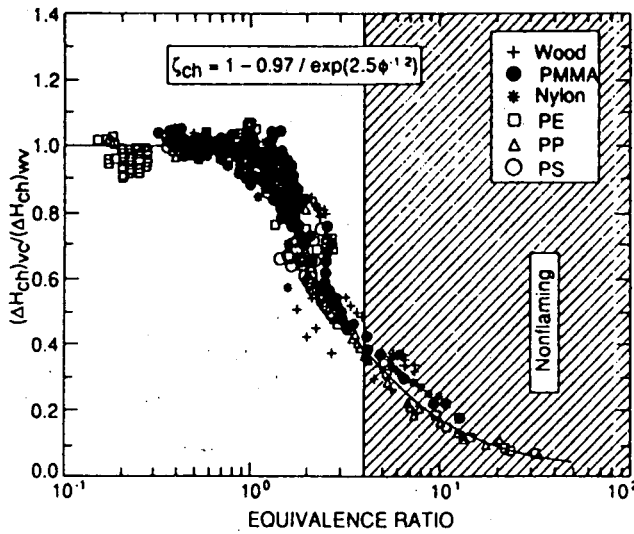


Fig. 3-4.25. Ratio of the ventilation-controlled to well-ventilated chemical heat of combustion versus the equivalence ratio. Data are measured in the Flammability Apparatus and in the Fire Research Institute's enclosure.³⁶ Subscript vc represents ventilation-controlled fires, and subscript wv represents well-ventilated fires.

and its convective component or chemical and convective heats of combustion for ventilation-controlled to well-ventilated combustion, subscript vc represents ventilation-controlled fire, and wv represents well-ventilated fire.

The experimental data for the ratios of the chemical and convective heats of combustion for ventilation-controlled to well-ventilated fires at various equivalence ratios are shown in Figures 3-4.25 and 3-4.26. The data are measured in the Flammability Apparatus and the FRI 0.022-m³ enclosure, details of which are described in reference 36. The data for the polymers indicated in the figures satisfy the following general correlations, irrespective of their chemical structures³⁶

$$\frac{(\Delta H_{ch})_{vc}}{(\Delta H_{ch})_{wv}} = 1 - \frac{0.97}{\exp(\Phi/2.15)^{-1.2}} \quad (40)$$

$$\frac{(\Delta H_{con})_{vc}}{(\Delta H_{con})_{wv}} = 1 - \frac{1.0}{\exp(\Phi/1.38)^{-2.8}} \quad (41)$$

The effects of ventilation on the chemical and convective heats of combustion are reflected by the magnitudes of the expressions within the parentheses on the right-hand sides of Equations 40 and 41. For a well-ventilated fire, $\Phi \ll 1.0$ and $(\Delta H_{ch})_{vc} = (\Delta H_{ch})_{wv}$ and $(\Delta H_{con})_{vc} = (\Delta H_{con})_{wv}$.

As a fire changes from well-ventilated to ventilation-controlled, equivalence ratio increases and the magnitudes of the expressions within the parentheses on the right-hand sides of Equations 40 and 41 increase. Thus with increase in the equivalence ratio, the chemical and convective heats of combustion decrease. The decrease in the convective heat of combustion is higher than it is for the chemical heat of combustion, because the coefficients for the equivalence ratios are different. The correlation thus suggests that higher fraction of the chemical heat of combustion is expected to be converted to the radiative heat of combustion as fires change from well-ventilated to ventilation-controlled. This is in general agreement with the observations for the ventilation-controlled fires in buildings.

Equations 40 and 41 can be used in models for the assessment of the ventilation-controlled fire behavior of materials, using chemical and convective heats of combustion for well-ventilated fires such as from Table 3-4.11.

EXAMPLE 13:

Calculate the chemical heats of combustion at equivalence ratios of 1, 2, and 3 for red oak, polyethylene, polystyrene, and nylon using Equation 40 and data from Table 3-4.11 for well-ventilated fires.

SOLUTION:

Material	Chemical Heats of Combustion (kJ/g)			
	$\Phi \ll 1.0$	$\Phi = 1.0$	$\Phi = 2.0$	$\Phi = 3.0$
Red oak	12.4	11.4	8.3	6.2
Polyethylene	38.4	35.3	25.9	19.3
Polystyrene	27.0	24.9	18.2	13.6
Nylon	27.1	24.9	18.2	13.6

Generation of Chemical Compounds and Consumption of Oxygen

Chemical compounds (smoke, toxic, corrosive, and odorous compounds) are the main contributors to nonthermal hazard and thus the assessments of their chemical natures and generation rates, relative to the airflow rate, are of critical importance for the protection of life and property.¹

In fires, compounds are generated as a result of gasification and decomposition of the material and burning of the species in the gas phase with air in the form of a diffusion flame. In general, generation of the fire products and consumption of oxygen in diffusion flames occur in two zones.³⁶

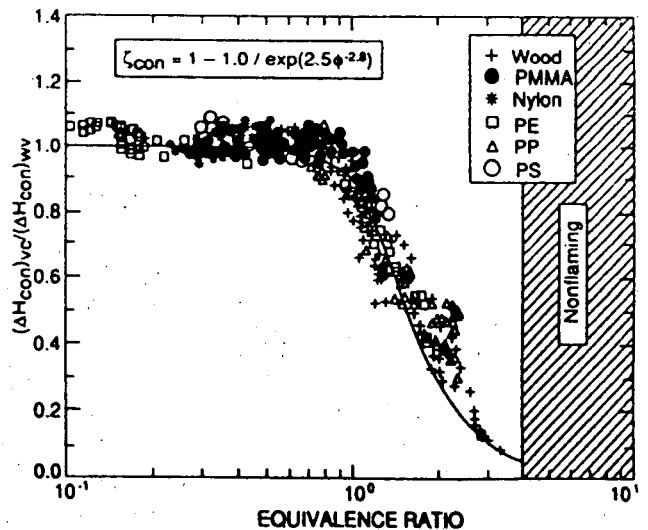


Fig. 3-4.26. Ratio of the ventilation-controlled to well-ventilated convective heat of combustion versus the equivalence ratio. Data are measured in the Flammability Apparatus and in the Fire Research Institute's enclosure.³⁶ Subscript vc represents ventilation-controlled fires, and subscript wv represents well-ventilated fires.

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- Reduction Zone:** In this zone, the material melts, decomposes, gasifies, and/or generates species that react to form smoke, CO, hydrocarbons, and other intermediate products. Very little oxygen is consumed in this region. The extent of conversion of the material to smoke, CO, hydrocarbons, and other products depends on the chemical nature of the material.
- Oxidation Zone:** In this zone, the reduction zone products (smoke, CO, hydrocarbons, and other intermediates) react with varying degrees of efficiency with the oxygen from air and generate chemical heat and varying amounts of products of complete combustion, such as CO₂ and H₂O. The lower the reaction efficiency, the higher the amounts of reduction zone products emitted from a fire. The reaction efficiency of the reduction zone products with oxygen depends on the concentrations of the products relative to the oxygen concentration, temperature, and mixing of the products and air. For example, in laminar diffusion flames, smoke is emitted when the temperature of the oxidation zone falls below about 1300 K.

The hot ceiling layer in a building fire may be considered in terms of oxidation and reduction zone products. In building fires with plenty of ventilation, the concentrations of the reduction zone products are higher in the central region of the ceiling layer, whereas the concentrations of the oxidation zone products are higher closer to the room opening. As the air supply rate or oxygen concentration, available to the fire, decreases due to restrictions in the ventilation, the ceiling layer expands and starts occupying greater room volume with increase in the concentrations of the reduction zone products. Under these conditions, large amounts of the reduction zone products are released within the building increasing the nonthermal hazard.

The generation rate of a fire product is directly proportional to the mass loss rate, the proportionality constant being defined as the yield of the product^{1-4,9-16,33,36-39,42-45}

$$\dot{G}_j^* = y_j \dot{m}^* \quad (42)$$

where \dot{G}_j^* is the mass generation rate of product j (g/m²-s), and y_j is the yield of product j (g/g). The total mass of the product generated is obtained by the summation of the generation rate

$$W_j = A \sum_{n=t_0}^{n=t_f} \dot{G}_j^*(t_n) \Delta t_n \quad (43)$$

where W_j is the total mass of product j generated from the flaming and/or nonflaming fire of the material (g), t_0 is the time when the sample is exposed to heat (s), and t_f is the time when there is no more vapor formation (s). From Equations 27, 42, and 43, the average value of the yield of product j is

$$\bar{y}_j = \frac{W_j}{W_f} \quad (44)$$

The mass consumption rate of oxygen is also directly proportional to the mass loss rate^{1-4,9-16,33,36-39,42-45}

$$\dot{C}_O^* = c_O \dot{m}^* \quad (45)$$

where \dot{C}_O^* is the mass consumption rate of oxygen (g/m²-s), and c_O is the mass of oxygen consumed per unit mass of fuel (g/g).

The mass generation rates of fire products and mass consumption rate of oxygen are determined by measuring

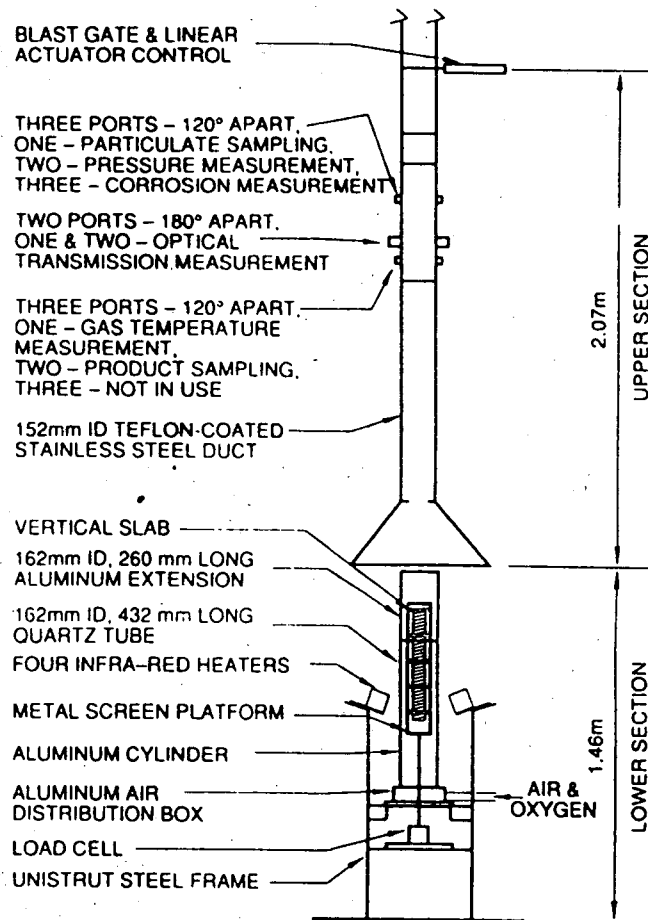


Fig. 3-4.27. Sketch of the Flammability Apparatus showing locations where measurements are made for the product concentration, optical transmission, particulate concentration, and corrosion.

the volume fractions of the products and oxygen and the total volumetric or mass flow rate of the fire products-air mixture^{2,3,36}

$$\dot{G}_j^* = \frac{f_j \dot{V} \rho_j}{A} = f_j \dot{W} \left(\frac{\rho_j}{\rho_g A} \right) \quad (46)$$

$$\dot{C}_O^* = \frac{f_O \dot{V} \rho_O}{A} = f_O \dot{W} \left(\frac{\rho_O}{\rho_g A} \right) \quad (47)$$

where f_j is the volume fraction of product j , f_O is the volume fraction of oxygen, \dot{V} is the total volumetric flow rate of the fire product-air mixture (m³/s), \dot{W} is the total mass flow rate of the fire product-air mixture (g/s), ρ_j is the density of product j at the temperature of the fire product-air mixture (g/m³), ρ_g is the density of the hot fire product-air mixture (g/m³), ρ_O is the density of oxygen at the temperature of the fire product-air mixture (g/m³), and A is the total area of the material burning (m²).

For volume fraction measurements, sampling ducts are used where fire products and air are well mixed, such as in the Flammability Apparatus (Figure 3-4.2, parts (a) and (b) and 3-4.8) and in the Cone Calorimeter (Figure 3-4.3). Figure 3-4.27 shows the measurement locations in the sampling duct of the Flammability Apparatus. The volume fractions are

measured by various types of instruments; e.g., in the Flammability Apparatuses, they are measured continuously: (1) by commercial infrared analyzers for CO and CO₂; (2) by a high-sensitivity commercial paramagnetic analyzer for oxygen; (3) by a commercial flame ionization analyzer for the mixture of low molecular weight gaseous hydrocarbons; and (4) by a turbidimeter, designed by the Flammability Laboratory,⁵² for smoke. The turbidimeter measures the optical density defined as

$$D = \frac{\ln\left(\frac{I_0}{I}\right)}{\ell} \quad (48)$$

where D is the optical density (1/m), I/I_0 is the fraction of light transmitted through smoke, and ℓ is the optical path length (m). The volume fraction of smoke is obtained from the following relationship⁵²

$$f_s = \frac{D\lambda \times 10^{-6}}{\Omega} \quad (49)$$

where f_s is the volume fraction of smoke, λ is the wavelength of the light source (μm), and Ω is the coefficient of particulate extinction taken as 7.0.⁵² In the Flammability Apparatuses, optical density is measured at wavelengths of 0.4579 μm (blue), 0.6328 μm (red), and 1.06 μm (IR). In the Cone Calorimeter, optical density is measured by using a helium-neon laser with a wavelength of 0.6328 μm (red).

From Equations 46 and 49

$$\begin{aligned} \dot{G}_s^* &= \frac{f_s \dot{V} \rho_s \times 10^{-6}}{A} = \left(\frac{D\lambda}{7}\right) \left(\frac{\rho_s \dot{V} \times 10^{-6}}{A}\right) \\ &= \left(\frac{D\lambda}{7}\right) \left(\frac{\rho_s}{\rho_a}\right) \left(\frac{\dot{W} \times 10^{-6}}{A}\right) \end{aligned} \quad (50)$$

In the Flammability Apparatuses and the Cone Calorimeter, the fire products in the sampling duct are diluted about 20 times and thus the density of air, $\rho_a = 1.2 \times 10^3 \text{ g/m}^3$, and the density of smoke, $\rho_s = 1.1 \times 10^6 \text{ g/m}^3$, as suggested in reference 52, are used.

$$\begin{aligned} \dot{G}_s^* &= \left(\frac{1.1 \times 10^6 \times 10^{-6}}{7}\right) \left(\frac{\dot{V}}{A}\right) D\lambda \\ &= \left(\frac{1.1 \times 10^6 \times 10^{-6}}{7 \times 1.2 \times 10^3}\right) \left(\frac{\dot{W}}{A}\right) D\lambda \end{aligned} \quad (51)$$

For blue wavelength of light ($\lambda = 0.4579 \mu\text{m}$)

$$\dot{G}_s^* = 0.0720 \left(\frac{D_{blue} \dot{V}}{A}\right) = 0.0600 \times 10^{-3} \left(\frac{D_{blue} \dot{W}}{A}\right) \quad (52)$$

For red wavelength of light ($\lambda = 0.6328 \mu\text{m}$)

$$\dot{G}_s^* = 0.0994 \left(\frac{D_{red} \dot{V}}{A}\right) = 0.0829 \times 10^{-3} \left(\frac{D_{red} \dot{W}}{A}\right) \quad (53)$$

For infrared wavelength of light ($\lambda = 1.06 \mu\text{m}$)

$$\dot{G}_s^* = 0.1666 \left(\frac{D_{IR} \dot{V}}{A}\right) = 0.1388 \times 10^{-3} \left(\frac{D_{IR} \dot{W}}{A}\right) \quad (54)$$

where D_{blue} , D_{red} , and D_{IR} are the optical densities measured at wavelengths of 0.4579, 0.6328, and 1.06 μm , respectively. These optical densities and total mass flow rate of the fire products-air mixture, \dot{W} , are measured continuously in the Flammability Apparatuses and the Cone Calorimeter, and A is known. The generation rates of smoke obtained from the optical densities at three wavelengths in

the Flammability Apparatus are averaged. The smoke mass generated in the test is also measured continuously in the Flammability Apparatus by a commercial smoke mass monitoring instrument. The data are used to calculate the mass generation rate of smoke. The smoke generation rates obtained from the optical density and smoke mass monitor show very good agreement.

In the Cone Calorimeter, the smoke data are reported in terms of the average specific extinction area (m^2/kg)¹⁹

$$\bar{\tau} = \frac{\sum_i \dot{V}_i D_i \Delta t_i}{W_f} \quad (55)$$

where $\bar{\tau}$ is the average specific extinction area determined in the Cone Calorimeter (m^2/g). Multiplying both sides of Equation 55 by $\rho_s \lambda \times 10^{-6}/7$ and rearranging

$$\begin{aligned} \bar{\tau}(\rho_s \lambda / 7) \times 10^{-6} &= \frac{\sum_i [(D_i \lambda \times 10^{-6} / 7) \rho_s \dot{V}_i \Delta t_i]}{W_f} \\ &= \frac{W_s}{W_f} = \bar{y}_s \end{aligned} \quad (56)$$

In the Cone Calorimeter, $\lambda = 0.6328 \mu\text{m}$ for red wavelength and using $\rho_s = 1.1 \times 10^6 \text{ g/m}^3$, as suggested in reference 52, the average yield of smoke from the average specific extinction area determined in the Cone Calorimeter can be calculated from the following expression

$$\bar{y}_s = 0.0994 \times 10^{-3} \bar{\tau} \quad (57)$$

where \bar{y}_s is the average yield of smoke (g/g).

The smoking characteristics of a material are also reported in terms of mass optical density (MOD)^{1,4,16,50}

$$\text{MOD} = \left[\frac{\log_{10}\left(\frac{I_0}{I}\right)}{\ell} \right] \left[\frac{\dot{V}}{A \dot{m}^*} \right] = \left[\frac{D}{2.303} \right] \left[\frac{\dot{V}}{A \dot{m}^*} \right] \quad (58)$$

From Equations 42 and 50, with $\rho_s = 1.1 \times 10^6 \text{ g/m}^3$ and $\lambda = 0.6328 \mu\text{m}$

$$y_s = \left(\frac{\lambda \rho_s}{7.0}\right) \left(\frac{D \dot{V} \times 10^{-6}}{A \dot{m}^*}\right) = 0.0994 (\text{MOD}/2.303) \quad (59)$$

MOD is generally reported with \log_{10} , however if it is changed to \log_e and m^2/kg by multiplying it by 2.303 and dividing it by 1000, it becomes the specific extinction area, a terminology used in reporting the cone calorimeter data.

The average data for the yields of CO, CO₂, mixture of gaseous hydrocarbons, and smoke for well-ventilated fires are listed in Table 3-4.11.

EXAMPLE 14:

For a fiberglass-reinforced material, the following data were measured for combustion in normal air at an external heat flux value of 50 kW/m^2 :

Total mass of the sample lost (g)	229
Total mass generated (g)	
CO	0.478
CO ₂	290
Hydrocarbons	0.378
Smoke	6.31
Total energy generated (kJ)	3221

3-88 DESIGN CALCULATIONS

Calculate the average yields of CO, CO₂, hydrocarbons, and smoke and the average chemical heat of combustion.

SOLUTION:

The average yields are calculated from Equation 44, and the average chemical heats of combustion are calculated from Equation 29.

Average yields (g/g)	
CO	0.0021
CO ₂	1.27
Hydrocarbons	0.002
Smoke	0.028
Average chemical heats of combustion (kJ/g)	14.1

EXAMPLE 15:

A circular sample of polystyrene, about 0.007 m² in area and 25 mm in thickness, was burned in normal air in the presence of external heat flux. In the test, measurements were made for the mass loss rate and light obscuration by smoke in the sampling duct with an optical path length of 0.149 m. The total volumetric flow rate of the mixture of fire products and air through the sampling duct was 0.311 m³/s, and the wavelength of light source used was 0.6328 μm. At the steady-state combustion of polystyrene, the measured mass loss rate was 33 g/m²-s with smoke obscuring 83.5 percent of the light. Calculate the yield of smoke from the data using a value of 1.1 × 10⁶ g/m³ for the density of smoke.

SOLUTION:

Optical density from Equation 48:

$$D = \frac{\ln(I_0/I)}{l} = \frac{\ln(100/83.5)}{0.149} = 121 \text{ (1/m)}$$

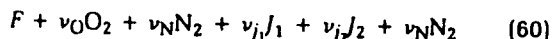
Smoke generation rate from Equation 51

$$\dot{G}_s = \frac{1.1 \dot{V} D \lambda}{7 \times A} = \frac{1.1 \times 0.311 \times 1.21 \times 0.6328}{7 \times 0.007} = 5.35 \text{ g/m}^2\text{-s}$$

Smoke yield from Equation 42

$$y_s = \frac{5.35 \text{ g/m}^2\text{-s}}{33 \text{ g/m}^2\text{-s}} = 0.162 \text{ g/g}$$

Efficiencies of oxygen mass consumption and mass generation of products: A chemical reaction between oxygen and a fuel monomer of a material can be expressed as



where F is the fuel monomer of a material; ν_O and ν_N are the stoichiometric coefficients for oxygen and nitrogen, respectively; and ν_{j_1} and ν_{j_2} are the stoichiometric coefficients for the maximum possible conversion of the fuel monomer to products J_1 and J_2 , respectively.

The stoichiometric mass oxygen-to-fuel ratio for the maximum possible conversion of the fuel monomer is expressed as

$$\Psi_O = \frac{\nu_O M_O}{M_f} \quad (61)$$

where Ψ_O is the stoichiometric mass oxygen-to-fuel ratio for the maximum possible conversion of the fuel monomer to products; M_O is the molecular weight of oxygen (32 g/mole); and M_f is the molecular weight of the fuel monomer of the

material (g/mole), which is calculated from its elemental composition. For the elemental composition measurements, microanalytical techniques are used.

The stoichiometric yield for the maximum possible conversion of the fuel monomer of the material to a product is expressed as

$$\Psi_j = \frac{\nu_j M_j}{M_f} \quad (62)$$

where Ψ_j is the stoichiometric yield for the maximum possible conversion of the fuel monomer of the material to product j , and M_j is the molecular weight of product (g/mole).

The stoichiometric yields for some selected materials, calculated from the elemental composition data from the flammability laboratory, are listed in Table 3-4.13 for fuel monomer conversion to CO, CO₂, hydrocarbons, smoke, HCl, and HF. The stoichiometric yields depend on the number of atoms relative to the carbon atom. The yields provide an insight into the nature of products and their amounts expected to be generated in flaming and nonflaming fires, when expressed as the stoichiometric oxygen mass consumption rate and stoichiometric mass generation rates of products

$$\dot{C}_{\text{stoich},O} = \Psi_O \dot{m}'' \quad (63)$$

$$\dot{G}_{\text{stoich},j} = \Psi_j \dot{m}'' \quad (64)$$

where $\dot{C}_{\text{stoich},O}$ and $\dot{G}_{\text{stoich},j}$ are the stoichiometric oxygen mass consumption rate and stoichiometric mass generation rate of product j for the maximum possible conversion of the fuel monomer to the product, respectively (g/m²-s).

In fires, the actual oxygen mass consumption rate and the mass generation rates of products are significantly less than the stoichiometric rates. The ratio of the actual oxygen mass consumption rate to stoichiometric rates is thus defined as the *efficiency of oxygen mass consumption or product mass generation*^{2-4,16,36}

$$\eta_O = \frac{\dot{C}_{\text{actual},O}}{\dot{C}_{\text{stoich},O}} = \frac{c_O \dot{m}''}{\Psi_O \dot{m}''} = \frac{c_O}{\Psi_O} \quad (65)$$

$$\eta_j = \frac{\dot{G}_{\text{actual},j}}{\dot{G}_{\text{stoich},j}} = \frac{y_j \dot{m}''}{\Psi_j \dot{m}''} = \frac{y_j}{\Psi_j} \quad (66)$$

where η_O is efficiency of oxygen mass consumption, and η_j is the generation efficiency of product j ; subscript represents the actual oxygen mass consumption rate or the actual mass generation rate of a product.

EXAMPLE 16:

A material is made up of carbon, hydrogen, and oxygen. The weight of the material is distributed as follows: 54 percent as carbon, 6 percent as hydrogen, and 40 percent as oxygen. Calculate the chemical formula of the fuel monomer of the material.

SOLUTION:

From the atomic weights and the weight percent of the atoms, the number of atoms are: carbon (C): 54/12 = 4.5; hydrogen (H): 6/1 = 6.0; and oxygen (O): 40/16 = 2.5. Thus the chemical formula of the fuel monomer of the material is C_{4.5}H_{6.0}O_{2.5} or dividing by 4.5, CH_{1.33}O_{0.56}.

TABLE 3-4.13 Stoichiometric Yields of Major Products*

Material	Formula	Carbon-Hydrogen Atoms in the Structure						
		Ψ_{O}	Ψ_{CO_2}	Ψ_{CO}	Ψ_{s}	Ψ_{HC}	Ψ_{HCl}	Ψ_{HF}
PE	CH ₂	3.43	3.14	2.00	0.857	1.00	0	0
PP	CH ₂	3.43	3.14	2.00	0.857	1.00	0	0
PS	CH	3.08	3.38	2.15	0.923	1.00	0	0
<i>Expanded Polystyrene</i>								
GM47	CH _{1.1}	3.10	3.36	2.14	0.916	1.00	0	0
GM49	CH _{1.1}	3.10	3.36	2.14	0.916	1.00	0	0
GM51	CH	3.08	3.38	2.15	0.923	1.00	0	0
GM53	CH _{1.1}	3.10	3.36	2.14	0.916	1.00	0	0
Carbon-Hydrogen-Oxygen-Nitrogen Atoms in the Structure								
POM	CH ₂ O	1.07	1.47	0.933	0.400	0.467	0	0
PMMA	CH _{1.6} O _{0.40}	1.92	2.20	1.40	0.600	0.680	0	0
Nylon	CH _{1.8} O _{0.17} N _{0.17}	2.61	2.32	1.48	0.634	0.731	0	0
Wood (pine)	CH _{1.7} O _{0.83}	1.21	1.67	1.06	0.444	0.506	0	0
Wood (oak)	CH _{1.7} O _{0.72} N _{0.001}	1.35	1.74	1.11	0.476	0.543	0	0
Wood (Douglas fir)	CH _{1.7} O _{0.74} N _{0.002}	1.32	1.72	1.10	0.469	0.536	0	0
Polyester	CH _{1.4} O _{0.22}	2.35	2.60	1.65	0.709	0.792	0	0
Epoxy	CH _{1.3} O _{0.20}	2.38	2.67	1.70	0.727	0.806	0	0
Polycarbonate	CH _{0.88} O _{0.19}	2.26	2.76	1.76	0.754	0.872	0	0
PET	CH _{0.80} O _{0.40}	1.67	2.29	1.46	0.625	0.667	0	0
Phenolic foam	CH _{1.1} O _{0.24}	2.18	2.60	1.65	0.708	0.773	0	0
PAN	CHN _{0.33}	2.87	2.50	1.59	0.681	0.681	0	0
<i>Flexible Polyurethane Foams</i>								
GM21	CH _{1.8} O _{0.30} N _{0.05}	2.24	2.28	1.45	0.622	0.715	0	0
GM23	CH _{1.8} O _{0.35} N _{0.06}	2.11	2.17	1.38	0.593	0.682	0	0
GM25	CH _{1.7} O _{0.32} N _{0.07}	2.16	2.22	1.41	0.606	0.692	0	0
GM27	CH _{1.7} O _{0.30} N _{0.08}	2.21	2.24	1.43	0.612	0.698	0	0
<i>Rigid Polyurethane Foams</i>								
GM29	CH _{1.1} O _{0.23} N _{0.10}	2.22	2.42	1.54	0.660	0.721	0	0
GM31	CH _{1.2} O _{0.22} N _{0.10}	2.28	2.43	1.55	0.662	0.729	0	0
GM37	CH _{1.2} O _{0.20} N _{0.08}	2.34	2.51	1.60	0.685	0.753	0	0
<i>Rigid Polyisocyanurate Foams</i>								
GM41	CH _{1.0} O _{0.19} N _{0.11}	2.30	2.50	1.59	0.683	0.740	0	0
GM43	CH _{0.93} O _{0.20} N _{0.11}	2.25	2.49	1.58	0.679	0.732	0	0
Carbon-Hydrogen-Oxygen-Silicone Atoms in the Structure								
Silicone-1 ¹	CH _{1.3} O _{0.25} Si _{0.18}	1.98	1.97	1.25	0.537	0.595	0	0
Silicone-2 ²	CH _{1.5} O _{0.30} Si _{0.26}	1.86	1.72	1.09	0.469	0.528	0	0
Silicone-3 ³	CH ₃ O _{0.50} Si _{0.50}	1.73	1.19	0.757	0.324	0.405	0	0
Carbon-Hydrogen-Oxygen-Chlorine-Fluorine Atoms in the Structure								
<i>Fluoropolymers</i>								
PVF (Tedlar™)	CH _{1.5} F _{0.50}	1.74	1.91	1.22	0.522	0.587	0	0.435
PVF ₂ (Kynar™)	CHF	1.00	1.38	0.875	0.375	0.406	0	0.594
ETFE (Tefzel™)	CH _{1.0} F _{0.99}	1.01	1.38	0.880	0.377	0.409	0	0.622
E-CTFE (Halar™)	CHF _{0.75} Cl _{0.25}	0.889	1.22	0.778	0.333	0.361	0.257	0.417
PFA (Teflon™)	CF _{1.7} O _{0.01}	0.716	1.00	0.630	0.270	0	0	0.765
FEP (Teflon™)	CF _{1.8}	0.693	0.952	0.606	0.260	0	0	0.779
TFE (Teflon™)	CF ₂	0.640	0.880	0.560	0.240	0	0	0.800
CTFE (Kel-F™)	CF _{1.5} Cl _{0.50}	0.552	0.759	0.483	0.207	0	0.310	0.517
<i>Chloropolymers</i>								
PE-25% Cl	CH _{1.9} Cl _{0.13}	2.56	2.38	1.52	0.650	0.753	0.254	0
PE-36% Cl	CH _{1.8} Cl _{0.22}	2.16	2.05	1.30	0.558	0.642	0.368	0
Neoprene	CH _{1.25} Cl _{0.25}	1.91	2.00	1.27	0.546	0.602	0.409	0
PE-42% Cl	CH _{1.8} Cl _{0.29}	1.94	1.84	1.17	0.501	0.576	0.424	0
PE-48% Cl	CH _{1.7} Cl _{0.36}	1.73	1.67	1.06	0.456	0.521	0.493	0
PVC	CH _{1.5} Cl _{0.50}	1.42	1.42	0.903	0.387	0.436	0.581	0
PVCl ₂	CHCl	0.833	0.917	0.583	0.250	0.271	0.750	0

*Calculated from the data for the elemental compositions of the materials in the FMRC flammability laboratory; subscript hc is total gaseous hydrocarbons; s is soot.
¹ η_{SO_2} = 0.483.
² η_{SO_2} = 0.610.
³ η_{SO_2} = 0.811.

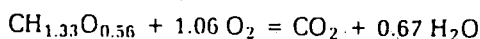
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EXAMPLE 17:

For the material in example 16, calculate the stoichiometric mass oxygen-to-fuel ratio, stoichiometric mass air-to-fuel ratio, and stoichiometric yields for maximum possible conversion of the fuel monomer of the material to CO, CO₂, hydrocarbons, water, and smoke. Assume smoke to be pure carbon, and hydrocarbons as having the same carbon atom to hydrogen atom ratio as the original fuel monomer.

SOLUTION:

1. For stoichiometric yields of CO₂ and water and the stoichiometric mass oxygen and air-to-fuel ratio for the maximum possible conversion of the fuel monomer of the material to CO₂ and H₂O, the following expression represents the maximum possible conversion of the fuel monomer of the material to CO₂ and H₂O



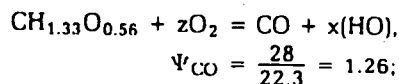
The molecular weight of the fuel monomer of the material is $1 \times 12 + 1.33 \times 1 + 0.56 \times 16 = 22.3$, the molecular weight of oxygen is 32, the molecular weight of CO₂ is 44, and the molecular weight of H₂O is 18. Thus,

$$\begin{aligned} \Psi_{\text{CO}_2} &= \frac{44}{22.3} = 1.97, \\ \Psi_{\text{H}_2\text{O}} &= \frac{0.67 \times 18}{22.3} = 0.54, \text{ and} \\ \Psi_{\text{O}} &= \frac{1.06 \times 32}{22.3} = 1.52; \end{aligned}$$

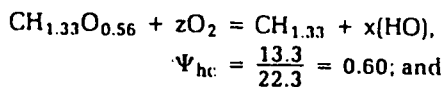
The stoichiometric mass air-to-fuel ratio can be obtained by dividing Ψ_{O} by 0.233; i.e., $1.52/0.233 = 6.52$.

2. For stoichiometric yields of CO, hydrocarbons, and smoke for the maximum possible conversion of the fuel monomer of the material to these products, the following expressions represent the maximum possible conversion of the fuel monomer of the material to these products

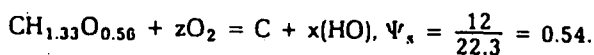
For CO



For hydrocarbons



For smoke



EXAMPLE 18:

For the material in examples 16 and 17, the generation efficiencies of CO₂, CO, hydrocarbons, and smoke are 0.90, 0.004, 0.002, and 0.036, respectively; the heat of gasification is 1.63 kJ/g; the surface re-radiation loss is 11 kW/m²; and the predicted asymptotic flame heat flux value for large-scale fires is 60 kW/m². Calculate the yields and asymptotic values for the generation rates of CO₂, CO, hydrocarbons, and smoke expected in large-scale fires.

SOLUTION:

1. Yields from Equation 66 and data from example 17

$$\begin{aligned} Y_{\text{CO}_2} &= 0.90 \times 1.97 = 1.77 \text{ g/g;} \\ Y_{\text{CO}} &= 0.004 \times 1.26 = 0.005 \text{ g/g;} \\ Y_{\text{hc}} &= 0.002 \times 0.60 = 0.001 \text{ g/g;} \text{ and} \\ Y_s &= 0.036 \times 0.54 = 0.019 \text{ g/g.} \end{aligned}$$

2. Asymptotic values for the mass loss rate from Equation 11

$$\dot{m}'' = \frac{60 - 11}{1.63} = 30 \text{ g/m}^2\text{-s}$$

3. Asymptotic values for the mass generation rates of products from Equation 42 and the above data

$$\begin{aligned} \dot{G}_{\text{CO}_2} &= 1.77 \times 30 = 53 \text{ g/m}^2\text{-s;} \\ \dot{G}_{\text{CO}} &= 0.005 \times 30 = 0.159 \text{ g/m}^2\text{-s;} \\ \dot{G}_{\text{hc}} &= 0.001 \times 30 = 0.036 \text{ g/m}^2\text{-s;} \text{ and} \\ \dot{G}_s &= 0.019 \times 30 = 0.584 \text{ g/m}^2\text{-s.} \end{aligned}$$

Generation rates of fire products and fire ventilation: As discussed previously, the effects of decrease in fire ventilation, as characterized by the increase in the local equivalence ratio, are reflected in the increase in the generation rates of the reduction zone products (smoke, CO, hydrocarbons, and others). For example, for flaming wood crib enclosure fires, as the equivalence ratio increases, the combustion efficiency decreases, flame becomes unstable, and the generation efficiency of CO reaches its peak for the equivalence ratio between about 2.5 and 4.0.³⁶

The ventilation-controlled building fires are generally characterized by two layers: (1) a ceiling vitiated layer, identified as "upper layer," and (2) an uncontaminated layer below, identified as "lower layer." Incorporation of these two layers is the classical two-zone modeling of fires in enclosed spaces. Under many conditions, the depth of the "upper layer" occupies a significant fraction of the volume of the enclosed space. Eventually, the interface between the "upper layer" and the "lower layer" positions itself so that it is very close to the floor, very little oxygen is available for combustion, and most of the fuel is converted to the reduction zone products, i.e., smoke, CO, hydrocarbons, and others.

The ventilation-controlled large- and small-enclosure and laboratory-scale fires and fires in the vitiated "upper layer" under the experimental hoods have been studied in detail, and are discussed or reviewed in references 36 and 53 through 56. The results from these types of fires are very similar. Detailed studies³⁶ performed for the generation rates of fire products for various fire ventilation conditions in the Flaminability Apparatus [Figure 3-4.2(a)], and in the Fire Research Institute's (FRI) enclosure, show that with increase in the equivalence ratio: (1) generation efficiencies of oxidation zone products, such as CO₂, and reactant consumption efficiency (i.e., oxygen) decrease, and (2) generation efficiencies of the reduction zone products, such as smoke, CO, and hydrocarbons increase.

Generalized correlations have been established between the generation efficiencies and the equivalence ratio for the oxidation and reduction zone products. The changes in the consumption or generation efficiencies of the products are expressed as ratios of the efficiencies for the ventilation-controlled (vc) to well-ventilated (wv) fires:

Reactants (Oxygen)

$$\zeta_{\text{O}} = \frac{(\eta_{\text{O}})_{\text{vc}}}{(\eta_{\text{O}})_{\text{wv}}} = \frac{(c_{\text{O}}/\Psi_{\text{O}})_{\text{vc}}}{(c_{\text{O}}/\Psi_{\text{O}})_{\text{wv}}} = \frac{(c_{\text{O}})_{\text{vc}}}{(c_{\text{O}})_{\text{wv}}} \quad (67)$$

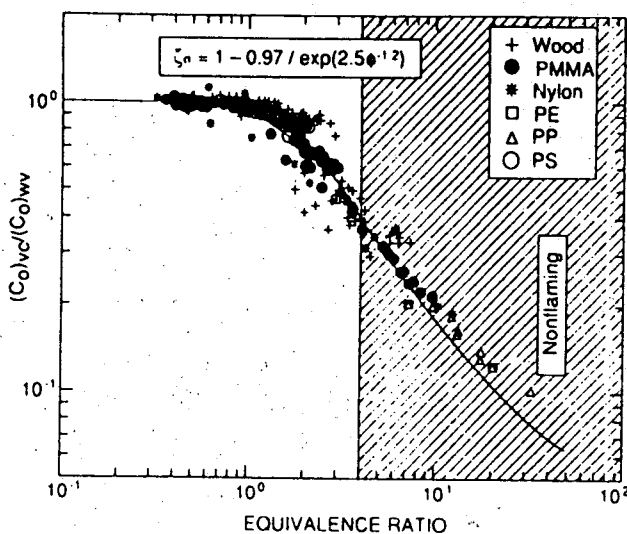


Fig. 3-4.28. Ratio of the mass of oxygen consumed per unit mass of the fuel for ventilation-controlled to well-ventilated fires. Data are measured in the Flammability Apparatus and in the Fire Research Institute's enclosure.³⁶ Subscript vc represents ventilation-controlled fires, and subscript wv represents well-ventilated fires.

Oxidation Zone Products (Carbon Dioxide, Water, etc.)

$$\zeta_{oxid} = \frac{(\eta_j)_{vc}}{(\eta_j)_{wv}} = \frac{(y_j/\Psi_j)_{vc}}{(y_j/\Psi_j)_{wv}} = \frac{(y_j)_{vc}}{(y_j)_{wv}} \quad (68)$$

where ζ_{oxid} is the oxidation zone product generation efficiency ratio.

Reduction Zone Products (Smoke, Carbon Monoxide, Hydrocarbons, etc.)

$$\zeta_{red} = \frac{(\eta_j)_{vc}}{(\eta_j)_{wv}} = \frac{(y_j/\Psi_j)_{vc}}{(y_j/\Psi_j)_{wv}} = \frac{(y_j)_{vc}}{(y_j)_{wv}} \quad (69)$$

where ζ_{red} is the reduction zone product generation efficiency ratio.

The relationships between the ratios of the mass of oxygen consumed per unit mass of fuel, the yields of the products for the ventilation-controlled to well-ventilated fires, and the equivalence ratio are shown in Figures 3-4.28 through 3-4.32. The ratios for oxygen and CO₂ (an oxidation zone product) do not depend on the chemical structures of the materials; whereas the ratios for the reduction zone products do depend on the chemical structures of the materials.

Oxygen and CO₂: The relationships for oxygen consumed and carbon dioxide generated are shown in Figures 3-4.28 and 3-4.29, respectively. The relationships are very similar to the relationships for the chemical and convective heats of combustion ratios (Equations 40 and 41), as expected

$$\frac{(CO)_{vc}}{(CO)_{wv}} = 1 - \frac{0.97}{\exp(\Phi/2.14)^{-1.2}} \quad (70)$$

$$\frac{(y_{CO_2})_{vc}}{(y_{CO_2})_{wv}} = 1 - \frac{1.00}{\exp(\Phi/2.15)^{-1.2}} \quad (71)$$

Carbon Monoxide: The relationship between the ratio of the CO yields for ventilation-controlled to well-ventilated

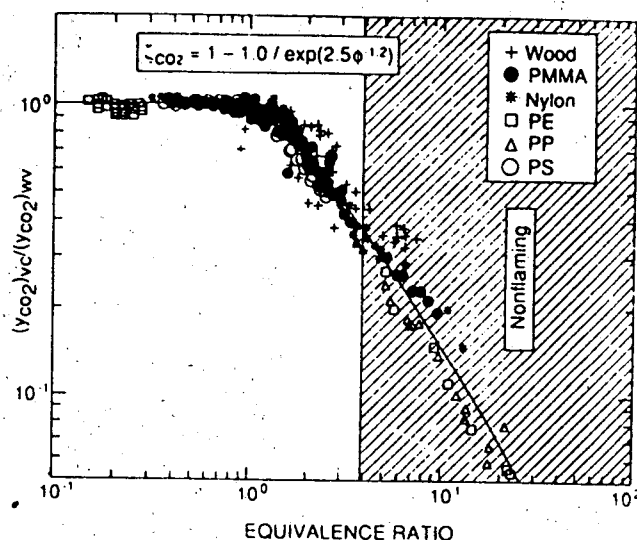


Fig. 3-4.29. Ratio of the mass of carbon dioxide generated per unit mass of the fuel for ventilation-controlled to well-ventilated fires. Data are measured in the Flammability Apparatus and in the Fire Research Institute's enclosure.³⁶ Subscript vc represents ventilation-controlled fires, and subscript wv represents well-ventilated fires.

fires and the equivalence ratio is shown in Figure 3-4.30. The data suggest the following relationship³⁶

$$\frac{(y_{CO})_{vc}}{(y_{CO})_{wv}} = 1 + \frac{\alpha}{\exp(2.5\Phi^{-\xi})} \quad (72)$$

where α and ξ are the correlation coefficients, which depend on the chemical structures of the materials. The values for the correlation coefficients for CO are listed in Table 3-4.14.

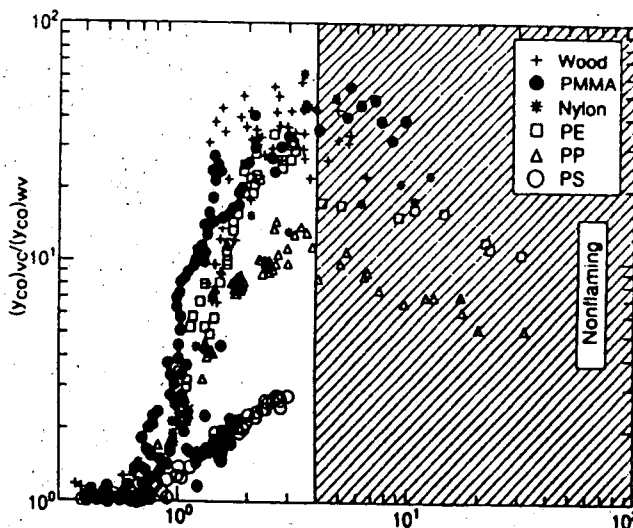


Fig. 3-4.30. Ratio of the mass of carbon monoxide generated per unit mass of the fuel for ventilation-controlled to well-ventilated fires. Data are measured in the Flammability Apparatus and in the Fire Research Institute's enclosure.³⁶ Subscript vc represents ventilation-controlled fires, and subscript wv represents well-ventilated fires.

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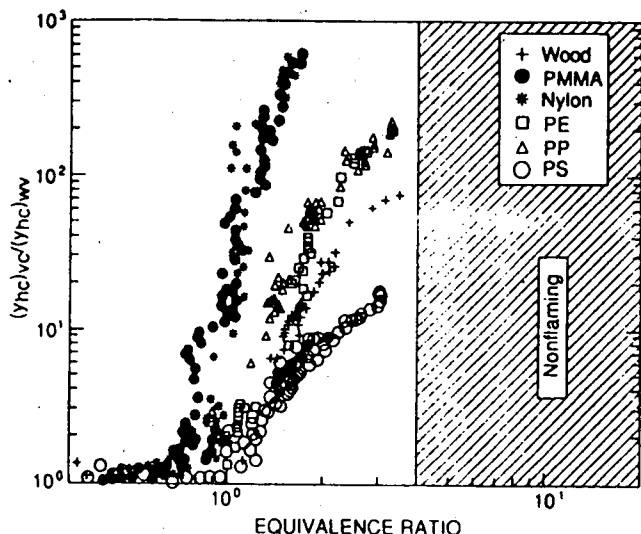


Fig. 3-4.31. Ratio of the mass of hydrocarbons generated per unit mass of the fuel for ventilation-controlled to well-ventilated fires. Data are measured in the Flammability Apparatus and in the Fire Research Institute's enclosure.³⁶ Subscript vc represents ventilation-controlled fires, and subscript wv represents well-ventilated fires.

The increase in the ratio of the carbon monoxide yields for the ventilation-controlled to well-ventilated fires with the equivalence ratio is due to the preferential conversion of the fuel carbon atoms to CO. The experimental data show the following order for the preferential conversion: wood (C-H-O aliphatic structure) > PMMA (C-H-O aliphatic structure) > nylon (C-H-O-N aliphatic structure) > PE (C-H aliphatic linear unsaturated structure) > PP (C-H aliphatic branched unsaturated structure) > PS (C-H aro-

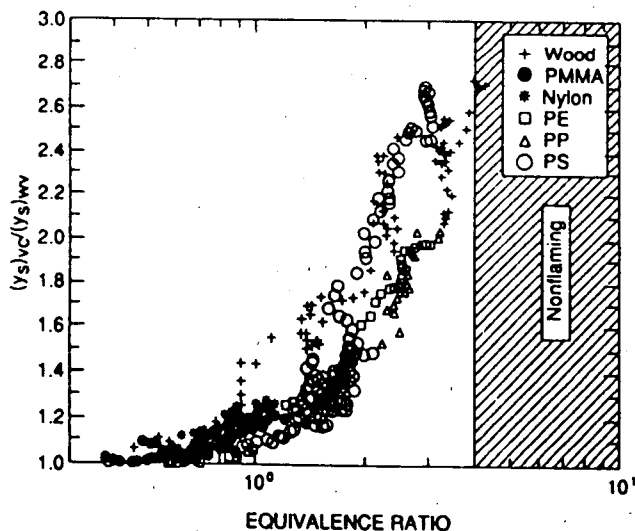


Fig. 3-4.32. Ratio of the mass of smoke generated per unit mass of the fuel for ventilation-controlled to well-ventilated fires. Data are measured in the Flammability Apparatus and in the Fire Research Institute's enclosure.³⁶ Subscript vc represents ventilation-controlled fires, and subscript wv represents well-ventilated fires.

TABLE 3-4.14 Correlation Coefficients to Account for the Effects of Ventilation on the Generation Rates of CO, Hydrocarbons, and Smoke

Material	CO		Hydrocarbons		Smoke	
	α	ξ	α	ξ	α	ξ
PS	2	2.5	25	1.8	2.8	1.3
PP	10	2.8	220	2.5	2.2	1.0
PE	26	2.8	220	2.5	2.2	1.0
Nylon	36	3.0	1200	3.2	1.7	0.8
PMMA	43	3.2	1800	3.5	1.6	0.6
Wood	44	3.5	200	1.9	2.5	1.2

matic structure). A similar trend is found for the liquid and gaseous fuels, such as shown in Table 3-4.15.³⁶ The presence of O and N atoms in the fuels with aliphatic C-H structure appears to enhance preferential fuel carbon atom conversion to CO.

Hydrocarbons: The relationship between the ratio of the hydrocarbon yields for ventilation-controlled to well-ventilated fires and the equivalence ratio is shown in Figure 3-4.31. The data suggest the following relationship³⁶

$$\frac{(y_{hc})_{vc}}{(y_{hc})_{wv}} = 1 + \frac{\alpha}{\exp(5.0\Phi - \xi)} \quad (73)$$

The correlation coefficient values for hydrocarbons are listed in Table 3-4.14. The numerator in the second term on the right-hand side of Equation 73 is 10 to 40 times that of CO, whereas the denominator is twice that for CO. This suggests that there is a significantly higher preferential fuel conversion to hydrocarbons than to CO, with increase in the equivalence ratio. The order for the preferential fuel conversion to hydrocarbons is very similar to CO, except for wood; i.e., PMMA > nylon > PE = PP > wood > PS. The exception for wood may be due to char-forming tendency of the fuel, which lowers the C to H ratio in the gas phase.

Smoke: The relationship between the ratio of the smoke yields for ventilation-controlled to well-ventilated fires and the equivalence ratio is shown in Figure 3-4.32. The data suggest the following relationship³⁶

TABLE 3-4.15 Carbon Monoxide Generation Efficiency for Ventilation-Controlled and Well-Ventilated Combustion*

Fuel	Well-Ventilated (wv) [†] $\Phi < 0.05$	Ventilation-Controlled (vc) $\Phi = 4.0$		$\frac{(y_{CO})_{vc}}{(y_{CO})_{wv}}$
		Ref. 54	Ref. 57	
Methane	0.001	0.10	—	100
Propane	0.001	—	0.12	120
Propylene	0.004	0.10	—	25
Hexane	0.002	0.10	0.52 [‡]	50 (260 [‡])
Methanol	0.001	0.27	1.00 [‡]	270 (1000 [‡])
Ethanol	0.001	0.18	0.66 [‡]	180 (660 [‡])
Isopropanol	0.002	0.21	—	105
Acetone	0.002	0.21	0.63 [‡]	105 (315 [‡])

*Table taken from reference 36.

[†]From Flammability Apparatus.

[‡]Nonflaming.

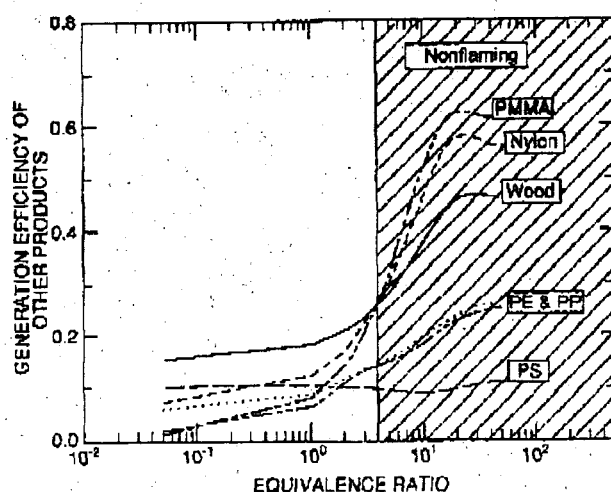


Fig. 3-4.33. Generation efficiency of products other than CO , CO_2 , hydrocarbons, and smoke versus the equivalence ratio.

$$\frac{(y_o)_{\text{w}}}{(y_s)_{\text{w}}} = 1 + \frac{\alpha}{\exp[2.5\Phi^{-1/2}]} \quad (74)$$

The correlation coefficient values for smoke are listed in Table 3-4.14. The values of the correlation coefficients in the second term on the right-hand side of Equation 74 suggest that, with the increase in the equivalence ratio, the preferential fuel conversion to smoke is lower than it is to hydrocarbons and CO . Also, the order for the preferential conversion of the fuel carbon atom to smoke is opposite to the order for the conversion to CO and hydrocarbons, except for wood. The order is: $\text{PS} > \text{wood} > \text{PE} = \text{PP} > \text{nylon} > \text{PMMA}$, suggesting that the order is probably due to decrease in the preference for the reactions between OH and CO compared to the reactions between OH and soot.

Other Reduction Zone Products: Since the sum of the generation efficiencies of all the products for a material cannot

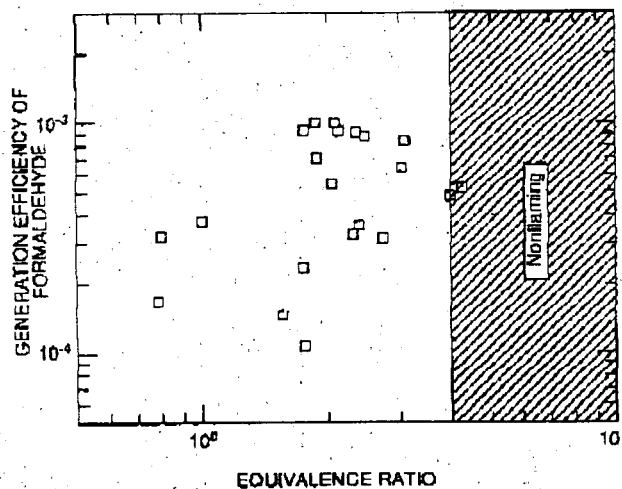


Fig. 3-4.34. Generation efficiency of formaldehyde generated from wood versus the equivalence ratio.

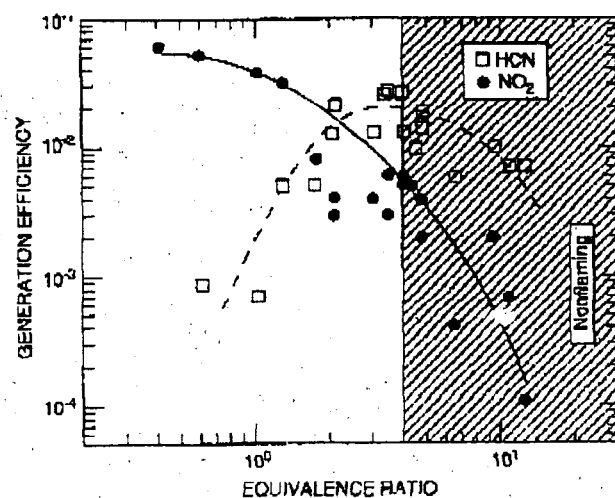


Fig. 3-4.35. Generation efficiencies of hydrogen cyanide and nitrogen dioxide generated from nylon versus the equivalence ratio.

exceed unity, the generation efficiency of products other than CO , CO_2 , hydrocarbons, and smoke is

$$\eta_{\text{other}} = 1 - (\eta_{\text{CO}} + \eta_{\text{CO}_2} + \eta_{\text{hc}} + \eta_s) \quad (75)$$

where η_{other} is the generation efficiency of products other than CO , CO_2 , hydrocarbons, and smoke. The generation efficiency of other products can be calculated from Equations 71 through 75 using correlation coefficients from Table 3-4.14. The generation efficiency values for other products calculated in this fashion for various equivalence ratios are shown in Figure 3-4.33. The figure shows that, for equivalence ratios greater than 4, where fires are nonflaming, about 10 to 60 percent of fuel carbon is converted to products other than CO , CO_2 , soot, and hydrocarbons.

The order for the preferential conversion of fuel carbon to other products in the nonflaming zone is: PS (C-H aromatic structure) < $\text{PE} \text{ \& \ PP}$ (C-H aliphatic structure) < wood (C-H-O aliphatic structure) < nylon (C-H-O-N aliphatic structure) < PMMA (C-H-O aliphatic structure). It thus appears that, in nonflaming fire, fuels with C-H structures are converted mainly to CO , smoke, and hydrocarbons, rather than to other products, whereas fuels with C-H-O and C-H-O-N structures are converted mainly to products other than CO , CO_2 , smoke, and hydrocarbons. Some of the products include formaldehyde (HCHO) and hydrogen cyanide (HCN).³⁶

Generation Efficiencies of Formaldehyde, Hydrogen Cyanide, and Nitrogen Dioxide: The experimental data for the generation efficiencies of formaldehyde, hydrogen cyanide, and nitrogen dioxide versus the equivalence ratio are shown in Figures 3-4.34 and 3-4.35.

Formaldehyde is generated in the pyrolysis of wood (C-H-O structure). It is attacked rapidly by oxygen (O) and hydroxyl (OH) radicals in the flame, if unlimited supply of oxygen is available. Thus, only traces of formaldehyde are found in well-ventilated fires. The generation efficiency of formaldehyde, however, increases with the equivalence ratio, indicating reduced concentrations of O and OH radicals

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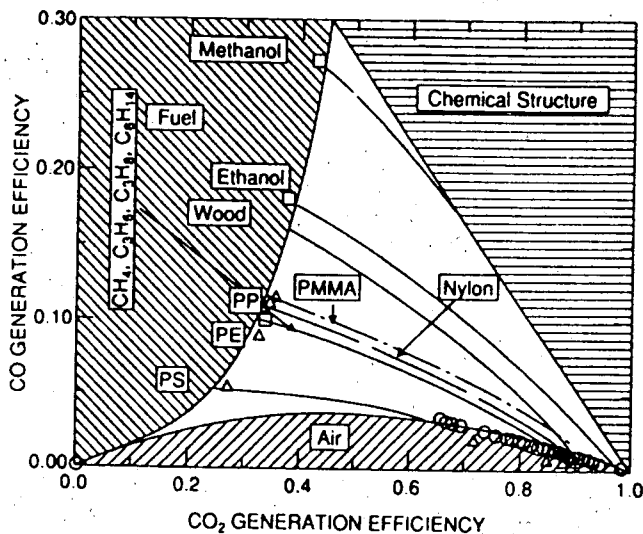


Fig. 3-4.36. Relationship between the generation efficiencies of CO₂ and CO. Data taken from reference 36.

and gas temperature due to lack of oxygen available for combustion.

In fires, hydrogen cyanide is formed in the reduction zone from materials with hydrogen and nitrogen atoms in the structure, such as nylon (C-H-O-N structure). Nitrogen dioxide (NO₂), on the other hand, is formed in the oxidation zone, as a result of the oxidation of hydrogen cyanide. The data in Figure 3-4:35 show that the generation efficiency of hydrogen cyanide increases and the generation efficiency of NO₂ decreases with the equivalence ratio. This observation supports that O and OH radical concentrations decrease with increase in the equivalence ratio. The decrease in the generation efficiency of hydrogen cyanide in the nonflaming fire suggests decrease in the fuel mass transfer rate.

Relationship Between the Generation Efficiencies of CO₂ and CO: The relationship between the generation efficiencies of CO₂ and CO is shown in Figure 3-4.36, where the data are taken from reference 36. CO is generated in the reduction zone of the flame as a result of the oxidative pyrolysis of the fuel, and is oxidized to CO₂ in the oxidation zone of the flame. The generation efficiency of CO₂ is independent of the chemical structure of the fuel (Figure 3-4.29), whereas the generation efficiency of CO depends on the chemical structure of the fuel (Figure 3-4.30). In Figure 3-4.36, the curves represent approximate predictions based on the correlation coefficients from Table 3-4.14 and Equations 71 and 72.

The relationship between the generation efficiencies of CO₂ and CO is quite complex. The boundary of the shaded region marked "air" in Figure 3-4.36 is drawn using the data for the well-ventilated combustion for equivalence ratios less than 0.05. The boundary of the "air" region may be considered as equivalent to the lower flammability limit. No flaming combustion is expected to occur in this region, as the fuel-air mixture is below the lower flammability limit; however, nonflaming combustion, generally identified as moldering, may continue. The boundary of the shaded region marked "fuel" is drawn using the data for the ventilation-controlled combustion for equivalence ratio of 4.0, and may be considered as equivalent to the upper flammability limit. In the "fuel" region, no flaming combustion is expected to occur, as the fuel-air mixture is above the upper

flammability limit; however, nonflaming processes may continue. The shaded region marked "chemical structure," and drawn to the right of the methanol curve, is an imaginary region as it is not expected to exist, because there are no stable carbon-containing fuel structures below the formaldehyde with a structure of HCHO. For the stable fuels with C-H-O structures, formaldehyde (HCHO) and methanol (CH₃OH) have the lowest molecular weights (30 and 32, respectively); thus, data for HCHO and CH₃OH probably would be comparable.

The curves in Figure 3-4.36 show that, in flaming combustion, with increase in the equivalence ratio, the preference for fuel carbon atom conversion to CO, relative to the conversion to CO₂, follows the order: methanol (C-H-O structure) > ethanol (C-H-O structure) > wood (C-H-O structure) > PMMA (C-H-O structure) > nylon (C-H-O-N structure) > PP (C-H aliphatic unsaturated branched structure) ≥ (CH₄, C₃H₆, C₃H₈, C₆H₁₄) ≥ PE (C-H aliphatic unsaturated linear structure) > PS (C-H aromatic unsaturated structure). Thus for fires in enclosed spaces, generation of higher amounts of CO relative to CO₂ at high local equivalence ratios is expected for fuels with C-H-O structures compared to the fuels with C-H structures. The reason for higher amounts of CO relative to CO₂ for fuels with C-H-O structures is that CO is easily generated in fuel pyrolysis, but is oxidized only partially to CO₂ due to limited amounts of oxidant available.

Relationship Between the Generation Efficiencies of CO and Smoke: The relationship between the generation efficiencies of CO and smoke is shown in Figure 3-4.37, where data are taken from reference 36. CO and smoke are both generated in the reduction zone of the flame as a result of the oxidative pyrolysis of the fuel, and their generation efficiencies depend on the chemical structure of the fuel (Figures 3-4.30 and 3-4.32). In Figure 3-4.37, the curves represent approximate predictions based on the correlation coefficients from Table 3-4.14 and Equations 72 and 74.

The relationship in Figure 3-4.37 is quite complicated. The boundary of the shaded region marked "air" is drawn using the data for the well-ventilated combustion for equivalence ratios less than 0.05. The boundary of the shaded

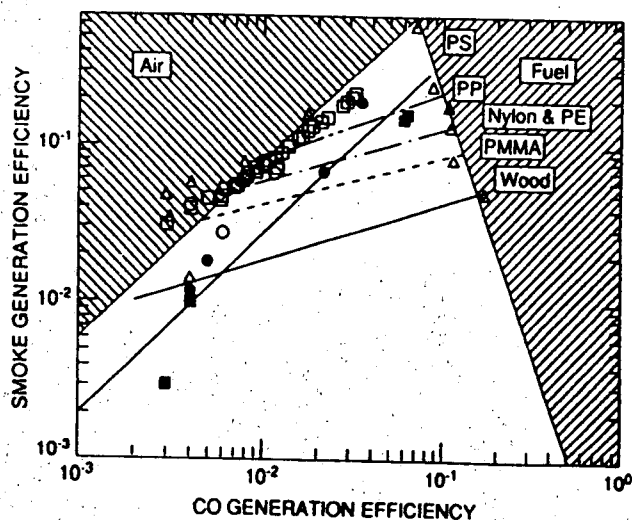


Fig. 3-4.37. Relationship between the generation efficiencies of CO and smoke. Data taken from reference 36.

region marked "fuel" is drawn using the data for the ventilation-controlled combustion for equivalence ratio of 4.0. The boundary for the region marked "air" may be considered as equivalent to the lower flammability limit, and the boundary for the region marked "fuel" may be considered as equivalent to the upper flammability limit.

In Figure 3-4.37, the order for the preference for fuel carbon atom conversion to smoke relative to conversion to CO is: wood (C-H-O structure) < PMMA (C-H-O structure) < nylon (C-H-O-N structure) < FP (C-H aliphatic unsaturated branched structure) = PE (C-H aliphatic unsaturated linear structure) < PS (C-H aromatic structure). The generation efficiency of smoke for "S", which is a polymer with aromatic C-H structure, is the highest; and the generation efficiency of smoke for wood, which is a polymer with aliphatic C-H-O structure, is the lowest.

Generalized Relationships to Calculate Chemical, Convective, and Radiative Heats of Combustion and Yields of Products at Various Equivalence Ratios

The following relationship is the generalized form of Equations 40, 41, and 70 through 74

$$fp = fp_{\infty} \left[1 + \frac{\alpha}{\exp(\Phi/\beta) - \xi} \right] \quad (76)$$

where fp is the fire property; α , β , and ξ are the correlation coefficients characteristic of the chemical structures of the polymers, and subscript ∞ represents infinite amount of air; fp determined under turbulent flame conditions is a constant for each polymer. The fire properties are heat of combustion (or combustion efficiency) and yields (or generation efficiencies) of products. Three conditions can be identified: (1) for $\Phi \gg \beta$, $fp = fp_{\infty}(1 + \alpha)$; (2) for $\Phi \ll \beta$, $fp = fp_{\infty}$; and (3) $\Phi = \beta$, $fp = fp_{\infty}(1 + \alpha/2.7)$. Thus, the parameter α is associated primarily with the magnitude of the fire properties in nonflaming fires (high Φ values). The parameter β is associated with the fire properties in the transition region between the fires with an infinite amount of air and the fires with a very restricted amount of air. The parameter ξ is associated with the range of Φ values for the transition region. A high value of α is indicative of a strong effect of ventilation on the fire and its properties and *vice versa*. High values of β and ξ are indicative of rapid change of fire from flaming to nonflaming by a small change in the equivalence ratio, such as for the highly fire-retarded or halogenated materials for which flaming combustion in normal air itself is unstable.

Chemical heat of combustion versus equivalence ratio for the nonhalogenated polymers: From Equation 76

$$\Delta H_{ch} = \Delta H_{ch,\infty} \left[1 - \frac{0.97}{\exp(\Phi/2.15) - 1.2} \right] \quad (77)$$

The values of $\Delta H_{ch,\infty}$ for several polymers are listed in Table 3-4.11.

Chemical heat of combustion versus equivalence ratio for the halogenated polymers (polyvinylchloride):

$$\Delta H_{ch} = \Delta H_{ch,\infty} \left[1 - \frac{0.30}{\exp(\Phi/0.53) - 11} \right] \quad (78)$$

As can be noted from the terms inside the brackets in Equations 77 and 78, the effect of ventilation on the chemical heat of combustion is much stronger for PVC than it is for the nonhalogenated polymers. The effect for PVC occurs at $\Phi \geq 0.4$, which is significantly lower than $\Phi \geq 2.0$ found for the nonhalogenated polymers.^{36,58} For PVC homopolymer, the flaming combustion changes to nonflaming combustion for $\Phi \geq 0.70$, which is also significantly lower than $\Phi \geq 4.0$ found for the nonhalogenated polymers. This is consistent with the highly halogenated nature of PVC and its mode of decomposition. The decomposition of PVC is characterized by the release of HCl, which is initiated at temperatures as low as about 100°C. At temperatures of up to about 200 to 220°C, HCl is the major effluent. Presence of oxygen in the air enhances HCl release. The generation of HCl from PVC leads to the formation of double bonds and release of various aromatic/unsaturated hydrocarbons (benzene, ethylene, propylene, butylene, etc.).

Convective heats of combustion versus equivalence ratio for the nonhalogenated polymers: From Equation 76

$$\Delta H_{con} = \Delta H_{con,\infty} \left[1 - \frac{1.0}{\exp(\Phi/1.38) - 2.5} \right] \quad (79)$$

The values of $\Delta H_{con,\infty}$ for several polymers are listed in Table 3-4.11.

Radiative heats of combustion versus equivalence ratio for the nonhalogenated polymers: Radiative heats of combustion are obtained from the difference between the chemical and the convective heats of combustion

$$\Delta H_{rad} = \Delta H_{ch} - \Delta H_{con} \quad (80)$$

Consumption of oxygen for the nonhalogenated polymers: From Equation 76

$$CO = CO_{\infty} \left[1 - \frac{0.97}{\exp(\Phi/2.14) - 1.2} \right] \quad (81)$$

Yield of carbon dioxide for the nonhalogenated polymers: From Equation 76

$$Y_{CO_2} = Y_{CO_2,\infty} \left[1 - \frac{1.0}{\exp(\Phi/2.15) - 1.2} \right] \quad (82)$$

$Y_{CO_2,\infty}$ values are listed in Table 3-4.11.

Yield of carbon dioxide for the halogenated polymers (PVC): From Equation 76

$$Y_{CO_2} = Y_{CO_2,\infty} \left[1 - \frac{0.30}{\exp(\Phi/0.53) - 11} \right] \quad (83)$$

From the terms inside the brackets in Equations 82 and 83, a stronger effect of ventilation on the yield of CO_2 for PVC than for the nonhalogenated polymers can be noted. $Y_{CO_2,\infty}$ values are listed in Table 3-4.11.

Yields of carbon monoxide, hydrocarbons, and smoke for the nonhalogenated polymers: From Equation 76

Polystyrene

$$Y_{CO} = Y_{CO,\infty} \left[1 + \frac{2.0}{\exp(\Phi/1.44) - 2.5} \right] \quad (84)$$

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$$y_{hc} = y_{hc,\infty} \left[1 + \frac{25}{\exp(\Phi/2.45) - 1.8} \right] \quad (85)$$

$$y_s = y_{s,\infty} \left[1 + \frac{2.8}{\exp(\Phi/2.02) - 1.3} \right] \quad (86)$$

The $y_{CO,\infty}$, $y_{hc,\infty}$, and $y_{s,\infty}$ values are listed in Table 3-4.11.

Polyethylene and Polypropylene

$$y_{CO} = y_{CO,\infty} \left[1 + \frac{10}{\exp(\Phi/1.39) - 2.8} \right] \quad (87)$$

$$\left[y_{hc} = y_{hc,\infty} \left[1 + \frac{220}{\exp(\Phi/1.90) - 2.5} \right] \right] \quad (88)$$

$$y_s = y_{s,\infty} \left[1 + \frac{2.2}{\exp(\Phi/2.50) - 1.0} \right] \quad (89)$$

The $y_{CO,\infty}$, $y_{hc,\infty}$, and $y_{s,\infty}$ values are listed in Table 3-4.11.

Polymethylmethacrylate

$$y_{CO} = y_{CO,\infty} \left[1 + \frac{43}{\exp(\Phi/1.33) - 3.2} \right] \quad (90)$$

$$y_{hc} = y_{hc,\infty} \left[1 + \frac{1800}{\exp(\Phi/1.58) - 3.5} \right] \quad (91)$$

$$y_s = y_{s,\infty} \left[1 + \frac{1.6}{\exp(\Phi/4.61) - 0.60} \right] \quad (92)$$

The $y_{CO,\infty}$, $y_{hc,\infty}$, and $y_{s,\infty}$ values are listed in Table 3-4.11.

Wood

$$y_{CO} = y_{CO,\infty} \left[1 + \frac{44}{\exp(\Phi/1.30) - 3.5} \right] \quad (93)$$

$$y_{hc} = y_{hc,\infty} \left[1 + \frac{200}{\exp(\Phi/2.33) - 1.9} \right] \quad (94)$$

$$y_s = y_{s,\infty} \left[1 + \frac{2.5}{\exp(\Phi/2.15) - 1.2} \right] \quad (95)$$

The $y_{CO,\infty}$, $y_{hc,\infty}$, and $y_{s,\infty}$ values are listed in Table 3-4.11.

Nylon

$$y_{CO} = y_{CO,\infty} \left[1 + \frac{36}{\exp(\Phi/1.36) - 3.0} \right] \quad (96)$$

$$y_{hc} = y_{hc,\infty} \left[1 + \frac{1200}{\exp(\Phi/1.65) - 3.2} \right] \quad (97)$$

$$y_s = y_{s,\infty} \left[1 + \frac{1.7}{\exp(\Phi/3.14) - 0.8} \right] \quad (98)$$

The $y_{CO,\infty}$, $y_{hc,\infty}$, and $y_{s,\infty}$ values are listed in Table 3-4.11.

Yields of Carbon Monoxide, Hydrocarbons, and Smoke for the Halogenated Polymers (Polyvinylchloride)

From Equation 76

$$y_{CO} = y_{CO,\infty} \left[1 + \frac{6.5}{\exp(\Phi/0.42) - 8.0} \right] \quad (99)$$

$$y_s = y_{s,\infty} \left[1 + \frac{0.38}{\exp(\Phi/0.42) - 8.0} \right] \quad (100)$$

$$y_s = y_{s,\infty} \left[1 + \frac{2.8}{\exp(\Phi/2.02) - 1.3} \right] \quad (101)$$

From the above relationships for PVC, for $0.40 \geq \Phi \geq 1.0$, the maximum CO and smoke yields reach about 60 percent of the stoichiometric yields, listed in Table 3-4.13. For nonhalogenated polymers, the maximum CO and smoke yields reach ≤ 30 percent of the stoichiometric yields for $\Phi \geq 2.0$. Polystyrene is the only polymer, within the above group of polymers, for which the smoke yield exceeds that of PVC. These trends suggest that CO and smoke are generated much easier from PVC than from the nonhalogenated polymers, possibly due to the formation of double bonds, as HCl is eliminated at temperatures as low as 100°C from the PVC structure, and formation of various compounds occurs with aromatic/unsaturated bonds.

For the non-halogenated polymers considered with $\Phi \geq 4.0$, the CO yield is lowest and the smoke yield is highest for polystyrene, an aromatic ring-containing polymer; whereas, for polymethylmethacrylate, an aliphatic carbon-hydrogen-oxygen-atom-containing polymer, the CO yield is highest and smoke yield is lowest. This suggests that aromatic ring structure promotes smoke formation, whereas the strong C-O bond in the structure remains intact as ventilation is reduced.

EXAMPLE 19:

Following example 13, calculate the yields of CO and smoke at equivalence ratios of 1, 2, and 3 for polystyrene, polyethylene, wood, and nylon using Equations 84 and 86, 87 and 89, 93 and 95, and 96 and 98, respectively.

SOLUTION:

Material	Yield (g/g)							
	$\Phi < 1.0$		$\Phi = 1.0$		$\Phi = 2.0$		$\Phi = 3.0$	
	CO	Smoke	CO	Smoke	CO	Smoke	CO	Smoke
Polystyrene	0.060	0.164	0.070	0.202	0.137	0.331	0.162	0.417
Polyethylene	0.024	0.060	0.043	0.071	0.191	0.098	0.238	0.117
Wood	0.004	0.015	0.018	0.018	0.145	0.028	0.171	0.034
Nylon	0.038	0.075	0.149	0.086	1.04	0.105	1.28	0.120

PREDICTION OF FIRE PROPERTIES USING SMOKE POINT

Smoke emission characteristics of fuels have been expressed for decades by smoke point, defined as a minimum laminar axisymmetric diffusion flame height (or fuel volumetric or mass flow rate) at which smoke just escapes from the flame tip.^{38,39,59-74} Smoke point values have been measured for numerous gases, liquids, and solids.^{38,39,59-64}

Almost all the knowledge on smoke formation, oxidation, and emission from diffusion flames is based on the combustion of fuels containing carbon and hydrogen atoms (hydrocarbons).^{61,66-69} On the basis of the chemical structure, hydrocarbons are divided into two main classes: (1) aliphatic and (2) aromatic; fuels containing both aliphatic and aromatic units are known as arenes. Aliphatic fuels have open-chain structure, and aromatic fuel structures consist of

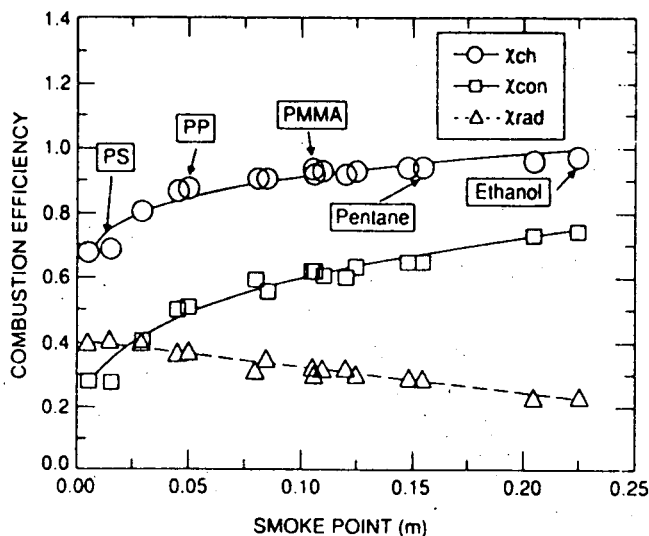


Fig. 3-4.38. Relationships between the combustion efficiency and its convective and radiative components, and the smoke point. Data were measured in the Flammability Apparatus, and reported in references 38 and 39.

benzene rings. Aliphatic hydrocarbons are divided into three families: (1) alkanes (C_nH_{2n+2}), where n is an integer; the suffix "ane" indicates a single bond; (2) alkenes (C_nH_{2n}); the suffix "ene" indicates a double bond, and "diene" two double bonds between carbon-carbon atoms; and (3) alkynes ($C_{2n}H_{2n-2}$); the suffix "yne" indicates a triple bond. The integer n can vary from one in a gas, such as methane, to several thousands in solid polymers, such as polyethylene. In cyclic aliphatic fuels, carbon atoms are also arranged as rings. Dienes are classified as: (1) conjugated—double bonds alternate with single bonds, (2) isolated—double bonds separated by more than one single bond, and (3) allens—double bonds with no separation. Conjugated dienes are more stable than other dienes.

Solid carbon particles present in smoke are defined as soot.^{61,66} Soot is generally formed in the fuel-rich regions of the flame and grows in size through gas-solid reactions, followed by oxidation (burnout) to produce gaseous products, such as CO and CO₂. Time that is available for soot formation in the flame is a few milliseconds. Soot particle inception occurs from the fuel molecule via oxidation and/or pyrolysis products, which typically includes unsaturated hydrocarbons, especially acetylene, polyacetylenes, and polyaromatic hydrocarbons (PAH). Acetylene, polyacetylenes, and PAH are relatively stable with respect to decomposition. Acetylene and PAH are often considered the most likely precursors for soot formation in flames. PAH have the same role in diffusion flames for both aliphatic and aromatic fuels. In all flames, irrespective of the fuel, initial detection of soot particles takes place on the centerline when a temperature of 1350 K is encountered. Thus, even though the extent of conversion of a fuel into soot may significantly change from fuel to fuel, a common mechanism of soot formation is suggested.

Soot production in the flame depends on the chemical structure, concentration, and temperature of the fuel, flame temperature, pressure, and oxygen concentration.^{61,66-69} The diffusion-controlled flame ends when fuel and oxidant are in stoichiometric ratio on the flame axis. The flame is followed by a soot after-burning zone, which is partially chemically controlled. The soot oxidation zone increases from about 10

to 50 percent of the visible flame length as the soot concentration increases. Flame luminosity and smoke emission in the plume depend on overall soot production and oxidation. Flames emit soot when soot temperature in the oxidation zone falls below 1300 K. The soot temperature decreases downstream because of radiation losses and diffusion of fresh cold air, both of which quench soot oxidation. At high soot concentrations, flame emissivity approaches unity, and flame luminosity becomes independent of the amount of soot.

Smoke point, carbon-to-hydrogen ratio, aromaticity, and flame temperature have been suggested as useful parameters to assess relative smoke emission characteristics of fuels in laminar diffusion flames.^{38,39,59-64} The soot-forming tendency of fuels is inversely proportional to smoke point. General trends observed for smoke points for hydrocarbon fuels in laminar diffusion flames are: aromatics < alkynes < alkenes < alkanes. Smoke point values have been correlated with flame radiation, combustion efficiency and its convective and radiative components, and generation efficiencies of products.^{38,39,59-64} Figures 3-4.38 through 3-4.40 show the relationships between the smoke point and the combustion efficiency and its convective and radiative components, and generation efficiencies of CO and smoke. The data were measured in the Flammability Apparatus [Figure 3-4.2(a)], and reported in references 38 and 39. The following relationships have been found from the data^{38,39}

$$X_{ch} = 1.15L_{sp}^{0.10} \quad (102)$$

where X_{ch} is the combustion efficiency (-), and L_{sp} is the smoke point (m) as measured in the Flammability Apparatus.

$$X_{rad} = 0.41 - 0.85L_{sp} \quad (103)$$

where X_{rad} is the radiative component of the combustion efficiency (-). This correlation is very similar to the one reported in the literature.⁶²

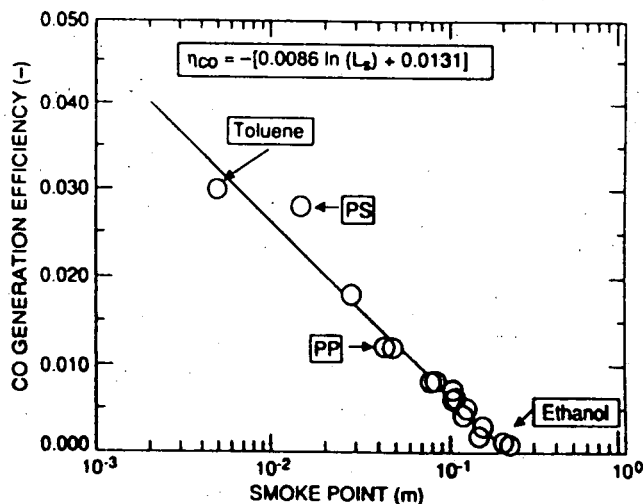


Fig. 3-4.39. Relationships between the CO generation efficiency and the smoke point. Data were measured in the Flammability Apparatus, and reported in references 38 and 39.

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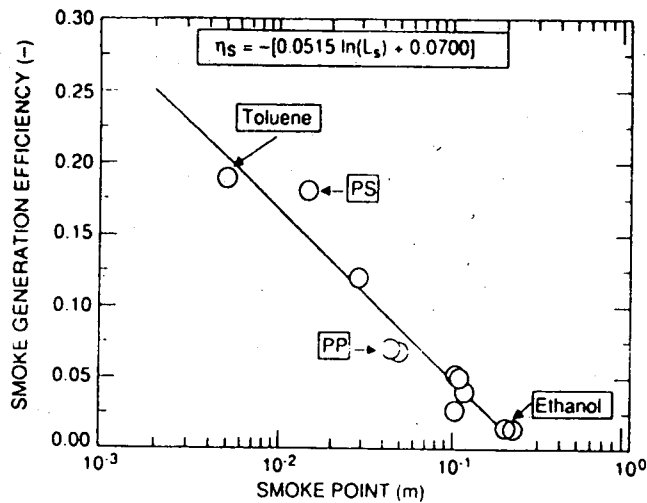


Fig. 3-4.40. Relationships between the smoke generation efficiency and the smoke point. Data were measured in the Flammability Apparatus, and reported in references 38 and 39.

$$\chi_{con} = \chi_{ch} - \chi_{rad} \quad (104)$$

where χ_{con} is the convective component of the combustion efficiency (-).

$$\eta_{CO} = -[0.0086 \ln(L_{sp}) + 0.0131] \quad (105)$$

where η_{CO} is the generation efficiency of CO (-).

$$\eta_s = -[0.0515 \ln(L_{sp}) + 0.0700] \quad (106)$$

where η_s is the generation efficiency of smoke (-).

The highest value of L_{sp} that has been measured is 0.240 m for ethane. Although methane and methanol would be expected to have smoke points higher than 0.240 m, they have not been measured experimentally. Since the combustion efficiency cannot exceed unity, and the generation efficiencies of CO and smoke cannot be negative, the relationships in Equations 102 through 106 are valid for $0 > L_{sp} \leq 0.240$ m.

Smoke point decreases with increase in the molecular weight. The smoke point values for monomers and polymers, however, show different types of dependencies: (1) the smoke point values for ethylene and polyethylene are 0.097 and 0.045 m, respectively; (2) the smoke point values for propylene and polypropylene are 0.030 and 0.050 m, respectively; and (3) the smoke point values for styrene and polystyrene are 0.006 and 0.015 m, respectively. The smoke point data for polymers support the accepted vaporization mechanisms of polymers;⁷⁵ i.e., polyethylene, polypropylene, and polystyrene vaporize as higher molecular weight oligomers rather than as monomers, and thus their smoke point values are different than the values for the monomers. The smoke point values suggest that polyethylene is expected to have higher smoke emission than ethylene, whereas polypropylene and polystyrene are expected to have lower smoke emissions than propylene and styrene.

The correlations show that emissions of CO and smoke are very sensitive to changes in the smoke point values compared to combustion efficiency and its convective and radiative components. This is expected from the understanding of the relationship between the smoke point and

chemical structures of fuels. For example, a decrease of 33 percent in the smoke point value of 0.15 m to 0.10 m produces a decrease of 4 and 12 percent in the combustion efficiency and its convective component, respectively, and an increase of 14 percent in the radiative component of the combustion efficiency; however, the generation efficiencies of CO and smoke increase by 89 and 67 percent, respectively.

Equations 102 through 106 can be used to estimate the fire properties of gases, liquids, and solids from their smoke point values. The smoke point values, however, depend strongly on the apparatus and cannot be used as reported. One of the approaches is to establish correlations between the smoke point values measured in different apparatuses and a single apparatus for which relationships such as given in Equations 102 through 106 are available. This type of approach has been described in references 38 and 39 for the Flammability Apparatus, where smoke point values for 165 fuels, reported in the literature, were translated to the values for the Flammability Apparatus. The fire properties (chemical, convective, and radiative heats of combustion and yields of CO and smoke) estimated in this fashion, from Equations 102 through 106, are listed in Tables 3-4.16 through 3-4.18. In the tables, molecular formula and weight, stoichiometric mass air-to-fuel ratio, and net heat of complete combustion have also been tabulated. The estimated data in the tables have been validated by direct measurements in the small- and large-scale fires using several fuels.^{38,39}

The data in Tables 3-4.16 through 3-4.18 show linear dependencies on the molecular weight of the fuel monomer within each group.^{38,39}

$$\Delta H_i = h_i \pm \frac{m_i}{M} \quad (107)$$

$$y_j = a_j \pm \frac{b_j}{M} \quad (108)$$

where ΔH_i is the net heat of complete combustion or chemical, convective, or radiative heat of combustion (kJ/g); y_j is the yield of product j (g/g); M is the molecular weight of fuel monomer (g/mole); h_i is the mass coefficient for the heat of combustion (kJ/g); m_i is the mass coefficient for the heat of combustion (kJ/mole); a_j is the mass coefficient for the product yield (g/g); and b_j is the molar coefficient for the product yield (g/mole). The coefficients depend on the chemical structures of the fuel; m_i and b_j become negative with the introduction of oxygen, nitrogen, and sulfur atoms into the chemical structure. Relationships in Equations 107 and 108 support the suggestion⁶⁹ that generally smaller molecules offer greater resistance to smoke formation and emission. The relationships suggest that for gases, liquids, and solids gasifying as high molecular weight fuels, $\Delta H_i \approx h_i$ and $y_j \approx a_j$.

The variations of chemical, convective, and radiative heats of combustion and yields of CO and smoke with the chemical structures of the fuels are similar to the smoke point variations.

EXAMPLE 20:

The following smoke point values have been reported in the literature:

Polymer	PE	PP	PMMA	PS
Smoke point (m)	0.045	0.050	0.105	0.015

For well-ventilated conditions, estimate: (1) the chemical, convective, and radiative heats of combustion using Equations

GENERATION OF HEAT AND CHEMICAL COMPOUNDS IN FIRES 3-99

TABLE 3-4.16 Combustion Properties of Fuels with Carbon and Hydrogen Atoms in the Chemical Structure

Hydrocarbon	Formula	M (g/mole)	S	Heat of Combustion (kJ/g)				Yield (g/g)	
				ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	CO	Smoke
<i>Normal Alkanes</i>									
Ethane	C ₂ H ₆	30	16.0	47.1	45.7	34.1	11.6	0.001	0.013
n-Propane	C ₃ H ₈	44	15.6	46.0	43.7	31.2	12.5	0.005	0.024
n-Butane	C ₄ H ₁₀	58	15.4	45.4	42.6	29.6	13.0	0.007	0.029
n-Pentane	C ₅ H ₁₂	72	15.3	45.0	42.0	28.7	13.3	0.008	0.033
n-Hexane	C ₆ H ₁₄	86	15.2	44.8	41.5	28.1	13.5	0.009	0.035
n-Heptane	C ₇ H ₁₆	100	15.1	44.6	41.2	27.6	13.6	0.010	0.037
n-Octane	C ₈ H ₁₈	114	15.1	44.5	41.0	27.3	13.7	0.010	0.038
n-Nonane	C ₉ H ₂₀	128	15.0	44.4	40.8	27.0	13.8	0.011	0.039
n-Decane	C ₁₀ H ₂₂	142	15.0	44.3	40.7	26.8	13.9	0.011	0.040
n-Undecane	C ₁₁ H ₂₄	156	15.0	44.3	40.5	26.6	13.9	0.011	0.040
n-Dodecane	C ₁₂ H ₂₆	170	14.9	44.2	40.4	26.4	14.0	0.011	0.041
n-Tridecane	C ₁₃ H ₂₈	184	14.9	44.2	40.3	26.3	14.0	0.012	0.041
n-Tetradecane	C ₁₄ H ₃₀	198	14.9	44.1*	40.3	26.2	14.1	0.012	0.042
Hexadecane	C ₁₆ H ₃₄	226	14.9	44.1	40.1	26.0	14.1	0.012	0.042
<i>Branched Alkanes</i>									
Methylbutane	C ₅ H ₁₂	72	15.3	45.0	40.9	27.2	13.8	0.012	0.042
Dimethylbutane	C ₆ H ₁₄	86	15.2	44.8	40.3	26.3	14.0	0.014	0.046
Methylpentane	C ₆ H ₁₄	86	15.2	44.8	40.3	26.3	14.0	0.014	0.046
Dimethylpentane	C ₇ H ₁₆	100	15.1	44.6	39.9	25.7	14.1	0.015	0.049
Methylhexane	C ₇ H ₁₆	100	15.1	44.6	39.9	25.7	14.1	0.015	0.049
Trimethylpentane	C ₈ H ₁₈	114	15.1	44.5	39.6	25.3	14.3	0.016	0.052
Methylethylpentane	C ₈ H ₁₈	114	15.1	44.5	39.6	25.3	14.3	0.016	0.052
Ethylhexane	C ₈ H ₁₈	114	15.1	44.5	39.6	25.3	14.3	0.016	0.052
Dimethylhexane	C ₈ H ₁₈	114	15.1	44.5	39.6	25.3	14.3	0.016	0.052
Methylheptane	C ₈ H ₁₈	114	15.1	44.5	39.6	25.3	14.3	0.016	0.052
<i>Cyclic Alkanes</i>									
cyclo-Pentane	C ₅ H ₁₀	70	14.7	44.3	39.2	24.1	15.1	0.018	0.055
Methylcyclopentane	C ₆ H ₁₂	84	14.7	43.8	38.2	23.0	15.2	0.019	0.061
Cyclohexane	C ₆ H ₁₂	84	14.7	43.8	38.2	23.0	15.2	0.019	0.061
Methylcyclohexane	C ₇ H ₁₄	98	14.7	43.4	37.5	22.3	15.2	0.021	0.066
Ethylcyclohexane	C ₈ H ₁₆	112	14.7	43.2	36.9	21.7	15.3	0.021	0.069
Dimethylcyclohexane	C ₈ H ₁₆	112	14.7	43.2	36.9	21.7	15.3	0.021	0.069
Cyclooctane	C ₈ H ₁₆	112	14.7	43.2	36.9	21.7	15.3	0.021	0.069
Decalin	C ₁₀ H ₁₈	138	14.4	42.8	36.2	20.9	15.3	0.023	0.073
Bicyclohexyl	C ₁₂ H ₂₂	166	14.5	42.6	35.7	20.4	15.3	0.023	0.076
<i>Alkenes</i>									
Ethylene	C ₂ H ₄	28	14.7	48.0	41.5	27.3	14.2	0.013	0.043
Propylene	C ₃ H ₆	42	14.7	46.4	40.5	25.6	14.9	0.017	0.095
Butylene	C ₄ H ₈	56	14.7	45.6	40.0	24.8	15.2	0.019	0.067
Pentene	C ₅ H ₁₀	70	14.7	45.2	39.7	24.2	15.4	0.020	0.065
Hexene	C ₆ H ₁₂	84	14.7	44.9	39.4	23.9	15.5	0.021	0.064
Heptene	C ₇ H ₁₄	98	14.7	44.6	39.3	23.7	15.6	0.021	0.063
Octene	C ₈ H ₁₆	112	14.7	44.5	39.2	23.5	15.7	0.022	0.062
Nonene	C ₉ H ₁₈	126	14.7	44.3	39.1	23.3	15.8	0.022	0.062
Decene	C ₁₀ H ₂₀	140	14.7	44.2	39.0	23.2	15.8	0.022	0.061
Dodecene	C ₁₂ H ₂₄	168	14.7	44.1	38.9	23.1	15.9	0.023	0.061
Tridecene	C ₁₃ H ₂₆	182	14.7	44.0	38.9	23.0	15.9	0.023	0.061
Tetradecene	C ₁₄ H ₂₈	196	14.7	44.0	38.8	22.9	15.9	0.023	0.060
Hexadecene	C ₁₆ H ₃₂	224	14.7	43.9	38.8	22.8	16.0	0.023	0.060
Octadecene	C ₁₈ H ₃₆	252	14.7	43.8	38.7	22.8	16.0	0.023	0.060
Polyethylene	(C ₂ H ₄) _n	601	14.7	43.6	36.8	20.6	16.2	0.027	0.077
Polypropylene	(C ₃ H ₆) _n	720	14.7	43.4	37.0	21.1	15.9	0.025	0.072
<i>Cyclic Alkenes</i>									
Cyclohexene	C ₆ H ₁₀	82	14.2	43.0	35.7	20.2	15.5	0.029	0.085
Methylcyclohexene	C ₇ H ₁₂	96	14.3	43.1	35.8	19.8	16.0	0.029	0.085
Pinene	C ₁₀ H ₁₆	136	14.1	36.0	33.5	18.9	14.6	0.039	0.114

3-100 DESIGN CALCULATIONS

TABLE 3-4.16 Combustion Properties of Fuels with Carbon and Hydrogen Atoms in the Chemical Structure (Continued)

Hydrocarbon	Formula	M (g/mole)	S	Heat of Combustion (kJ/g)				Yield (g/g)	
				ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	CO	Smoke
<i>Alkynes and Butadiene</i>									
Acetylene	C ₂ H ₂	26	13.2	47.8	36.7	18.7	18.0	0.042	0.096
Heptyne	C ₇ H ₁₂	96	14.3	44.8	36.0	18.8	17.1	0.036	0.094
Octyne	C ₈ H ₁₄	110	14.4	44.7	35.9	18.9	17.1	0.036	0.094
Decyne	C ₁₀ H ₁₈	138	14.4	44.5	35.9	18.9	17.0	0.035	0.094
Dodecyne	C ₁₂ H ₂₂	166	14.5	44.3	35.9	18.9	17.0	0.035	0.094
1, 3-Butadiene	C ₄ H ₆	54	14.0	44.6	33.6	15.4	18.2	0.048	0.125
<i>Arenes</i>									
Benzene	C ₆ H ₆	78	13.2	40.1	27.6	11.0	16.5	0.067	0.181
Toluene	C ₇ H ₈	92	13.4	39.7	27.7	11.2	16.5	0.066	0.178
Styrene	C ₈ H ₈	104	13.2	39.4	27.8	11.2	16.6	0.065	0.177
Ethylbenzene	C ₈ H ₁₀	106	13.6	39.4	27.8	11.2	16.6	0.065	0.177
Xylene	C ₈ H ₁₀	106	13.6	39.4	27.8	11.2	16.6	0.065	0.177
Indene	C ₉ H ₈	116	13.0	39.2	27.9	11.3	16.6	0.065	0.176
Propylbenzene	C ₉ H ₁₂	120	13.7	39.2	27.9	11.3	16.6	0.065	0.175
Trimethylbenzene	C ₉ H ₁₂	120	13.7	39.2	27.9	11.3	16.6	0.065	0.175
Cumene	C ₉ H ₁₂	120	13.7	39.2	27.9	11.3	16.6	0.065	0.175
Naphthalene	C ₁₀ H ₈	128	12.9	39.0	27.9	11.3	16.6	0.065	0.175
Tetralin	C ₁₀ H ₁₂	132	13.5	39.0	27.9	11.4	16.6	0.064	0.174
Butylbenzene	C ₁₀ H ₁₄	134	13.8	39.0	27.9	11.4	16.6	0.064	0.174
Diethylbenzene	C ₁₀ H ₁₄	134	13.8	39.0	27.9	11.4	16.6	0.064	0.174
p-Cymene	C ₁₀ H ₁₄	134	13.8	39.0	27.9	11.4	16.6	0.064	0.174
Methylnaphthalene	C ₁₁ H ₁₀	142	13.0	38.9	28.0	11.4	16.6	0.064	0.174
Pentylbenzene	C ₁₁ H ₁₆	148	13.9	38.8	28.0	11.4	16.6	0.064	0.173
Dimethylnaphthalene	C ₁₂ H ₁₂	156	13.2	38.8	28.0	11.4	16.6	0.064	0.173
Cyclohexylbenzene	C ₁₂ H ₁₈	160	13.7	38.7	28.0	11.4	16.6	0.064	0.173
Diisopropylbenzene	C ₁₂ H ₁₈	162	14.0	38.7	28.0	11.4	16.6	0.064	0.173
Triethylbenzene	C ₁₂ H ₁₈	162	14.0	38.7	28.0	11.4	16.6	0.064	0.173
Triamylbenzene	C ₂₁ H ₃₆	288	14.3	38.1	28.2	11.6	16.6	0.063	0.169
Polystyrene	(C ₈ H ₈) _n	200	13.2	39.2	29.6	14.0	15.6	0.050	0.135

102 through 104 and data for the net heat of complete combustion from Table 3-4.11; and (2) yields of CO and smoke using Equations 105 and 106 and stoichiometric yields from Table 3-4.13.

SOLUTION:

(1) From Equations 102 through 104 and Table 3-4.11

Polymer	PE	PP	PMMA	PS
ΔH_T (kJ/g)	43.6	43.4	25.2	39.2
ΔH_{ch} (kJ/g)	36.8	37.0	23.1	29.6
ΔH_{con} (kJ/g)	20.6	21.1	15.0	14.0
ΔH_{rad} (kJ/g)	16.2	15.9	8.1	15.6

(2) From Equations 105 and 107 and Table 3-4.13

Polymer	PE	PP	PMMA	PS
Ψ_{CO}	2.00	2.00	1.40	2.15
Ψ_s	0.857	0.857	0.600	0.923
ν_{CO} (g/g)	0.027	0.025	0.009	0.050
ν_s (g/g)	0.077	0.072	0.028	0.135

**NONTHERMAL DAMAGE
DUE TO FIRE PRODUCTS**

Damage due to heat is defined as thermal damage, and damage due to smoke, toxic, and corrosive products is defined

as nonthermal damage.¹ Nonthermal damage depends on the chemical nature and deposition of products on the walls, ceilings, building furnishings, equipment, components, etc., and the environmental conditions. The severity of the nonthermal damage increases with time. Examples of nonthermal damage to property are: corrosion, electrical malfunctions, discoloration, odors, etc.

Most commercial and industrial occupancies are susceptible to nonthermal fire damage. Examples of typical commercial and industrial occupancies are telephone central offices, computer rooms, power plant control rooms, space satellites in operation, under construction or in storage, department and grocery stores, hotels, restaurants, various manufacturing facilities, and transportation vehicles such as aircraft, ships, trains, and buses.

For this chapter, the subject of corrosion for commercial and industrial occupancies has been reviewed based on the knowledge derived from the telephone central office (TCO) experience for the deposition of atmospheric pollutants and fire products on equipment, severity of corrosion damage, and ease of cleaning the equipment.⁷⁶⁻⁷⁹ Galvanized zinc or zinc-chromated finishes represent a major portion of the structural components of the TCO equipment as well as the HVAC ductwork.⁷⁷⁻⁷⁹ Unfortunately all zinc surfaces are sensitive to corrosion attack by corrosive products. For example, on exposure to HCl gas, zinc forms zinc chloride, which is very hygroscopic and picks up moisture from air with relative humidity as low as 10 percent to form electrically conductive

TABLE 3-4.17 Combustion Properties of Fuels with Carbon, Hydrogen, and Oxygen Atoms in the Chemical Structure

Hydrocarbon	Formula	M (g/mole)	S	Heat of Combustion (kJ/g)				Yield (g/g)	
				ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	CO	Smoke
<i>Aliphatic Esters</i>									
Ethyl formate	$C_3H_6O_2$	74	6.5	20.2	19.9	13.5	6.3	0.003	0.011
n-Propyl formate	$C_4H_8O_2$	88	7.8	23.9	23.4	15.4	8.0	0.005	0.019
n-Butyl formate	$C_5H_{10}O_2$	102	8.8	26.6	26.0	16.7	9.3	0.007	0.025
Methyl acetate	$C_3H_6O_2$	74	6.5	20.2	19.9	13.5	6.3	0.003	0.011
Ethyl acetate	$C_4H_8O_2$	88	7.8	23.9	23.4	15.4	8.0	0.005	0.019
n-Propyl acetate	$C_5H_{10}O_2$	102	8.8	26.6	26.0	16.7	9.3	0.007	0.025
n-Butyl acetate	$C_6H_{12}O_2$	116	9.5	28.7	28.0	17.8	10.2	0.008	0.029
Isobutyl acetate	$C_6H_{12}O_2$	116	9.5	28.7	28.0	17.8	10.2	0.008	0.029
Amyl acetate	$C_7H_{14}O_2$	130	10.0	30.3	29.5	18.6	11.0	0.009	0.033
Cyclohexyl acetate	$C_8H_{14}O_2$	142	10.2	31.5	30.6	19.1	11.5	0.010	0.035
Octyl acetate	$C_{10}H_{20}O_2$	172	11.2	33.6	32.6	20.2	12.5	0.012	0.039
Ethyl acetoacetate	$C_6H_{10}O_3$	130	7.4	30.3	29.5	18.6	11.0	0.009	0.033
Methyl propionate	$C_4H_8O_2$	88	7.8	23.9	23.4	15.4	8.0	0.005	0.019
Ethyl propionate	$C_5H_{10}O_2$	102	8.8	26.6	26.0	16.7	9.3	0.007	0.025
n-Butyl propionate	$C_7H_{14}O_2$	130	10.0	30.3	29.5	18.6	11.0	0.009	0.033
Isobutyl propionate	$C_7H_{14}O_2$	130	10.0	30.3	29.5	18.6	11.0	0.009	0.033
Amyl propionate	$C_8H_{16}O_2$	144	10.5	31.6	30.8	19.2	11.6	0.010	0.035
Methyl butyrate	$C_5H_{10}O_2$	102	8.8	26.6	26.0	16.7	9.3	0.007	0.025
Ethyl butyrate	$C_6H_{12}O_2$	116	9.5	28.7	28.0	17.8	10.2	0.008	0.029
Propyl butyrate	$C_7H_{14}O_2$	130	10.0	30.3	29.5	18.6	11.0	0.009	0.033
n-Butyl butyrate	$C_8H_{16}O_2$	144	10.5	31.6	30.8	19.2	11.6	0.010	0.035
Isobutyl butyrate	$C_8H_{16}O_2$	144	10.5	31.6	30.8	19.2	11.6	0.010	0.035
Ethyl laurate	$C_{14}H_{28}O_2$	228	12.0	37.2	35.6	26.5	9.1	0.008	0.031
Ethyl oxalate	$C_4H_6O_4$	102	6.1	28.7	27.7	21.3	6.4	0.001	0.003
Ethyl malonate	$C_5H_8O_4$	132	7.7	32.2	31.0	23.4	7.5	0.003	0.015
Ethyl lactate	$C_5H_{10}O_3$	118	7.0	30.8	29.6	22.5	7.1	0.001	0.010
Butyl lactate	$C_7H_{14}O_3$	146	8.5	33.3	32.0	24.1	7.9	0.004	0.018
Amyl lactate	$C_8H_{16}O_3$	160	9.0	34.3	32.9	24.7	8.2	0.005	0.021
Ethyl carbonate	$C_5H_{10}O_3$	118	7.0	30.8	29.6	22.5	7.1	0.001	0.010
<i>Aliphatic Alcohols</i>									
Methyl alcohol	CH_4O	32	6.4	20.0	19.1	16.1	3.0	0.001	0.001
Ethyl alcohol	C_2H_6O	46	9.0	27.7	25.6	19.0	6.5	0.001	0.008
n-Propyl alcohol	C_3H_8O	60	10.3	31.8	29.0	20.6	8.5	0.003	0.015
Isopropyl alcohol	C_3H_8O	60	10.3	31.8	29.0	20.6	8.5	0.003	0.015
n-Butyl alcohol	$C_4H_{10}O$	74	11.1	34.4	31.2	21.6	9.6	0.004	0.019
Isobutyl alcohol	$C_4H_{10}O$	74	11.1	34.4	31.2	21.6	9.6	0.004	0.019
Sec butyl alcohol	$C_4H_{10}O$	74	11.1	34.4	31.2	21.6	9.6	0.004	0.019
Ter butyl alcohol	$C_4H_{10}O$	74	11.1	34.4	31.2	21.6	9.6	0.004	0.019
n-Amyl alcohol	$C_5H_{12}O$	88	11.7	36.2	32.7	22.2	10.4	0.005	0.022
Isobutyl carbinol	$C_5H_{12}O$	88	11.7	36.2	32.7	22.2	10.4	0.005	0.022
Sec butyl carbinol	$C_5H_{12}O$	88	11.7	36.2	32.7	22.2	10.4	0.005	0.022
Methylpropyl carbinol	$C_5H_{12}O$	88	11.7	36.2	32.7	22.2	10.4	0.005	0.022
Dimethylethyl carbinol	$C_5H_{12}O$	88	11.7	36.2	32.7	22.2	10.4	0.005	0.022
n-Hexyl alcohol	$C_6H_{14}O$	102	12.1	37.4	33.7	22.7	11.0	0.006	0.024
Dimethylbutyl alcohol	$C_6H_{14}O$	102	12.1	37.4	33.7	22.7	11.0	0.006	0.024
Ethylbutyl alcohol	$C_6H_{14}O$	102	12.1	37.4	33.7	22.7	11.0	0.006	0.024
Allyl alcohol	C_3H_6O	58	9.5	31.4	28.6	20.4	8.2	0.003	0.014
Cyclohexanol	$C_6H_{12}O$	100	11.7	37.3	33.6	22.6	11.0	0.005	0.024
<i>Aliphatic Ketones</i>									
Acetone	C_3H_6O	58	9.5	29.7	27.9	20.3	7.6	0.003	0.014
Methyl ethyl ketone	C_4H_8O	72	10.5	32.7	30.6	22.1	8.6	0.004	0.018
Cyclohexanone	$C_6H_{10}O$	98	11.2	35.9	33.7	24.1	9.6	0.005	0.023
Di-acetone alcohol	$C_8H_{12}O_2$	116	9.5	37.3	35.0	24.9	10.1	0.006	0.026
<i>Other Aliphatic Fuels</i>									
Monoethyl ether	$C_4H_{10}O_2$	90	8.4	26.7	25.8	20.0	5.8	0.001	0.007
Monoethylether acetate	$C_6H_{12}O_3$	132	7.8	32.2	31.0	23.2	7.7	0.001	0.011
Monoethylether diacetate	$C_8H_{10}O_4$	146	6.1	33.3	32.0	24.2	7.9	0.001	0.009
Glycerol triacetate	$C_9H_{14}O_6$	218	6.0	36.9	35.4	26.3	9.1	0.002	0.011
<i>Other Aromatic Fuels</i>									
Benzaldehyde	C_7H_6O	106	10.4	32.4	21.2	8.1	13.2	0.062	0.166
Benzyl alcohol	C_7H_8O	108	10.8	32.6	22.9	9.8	13.1	0.050	0.137
Cresylic acid	C_8H_8O	136	9.1	34.0	25.1	11.6	13.5	0.039	0.107
Ethyl benzoate	$C_9H_{10}O_2$	150	9.6	34.5	27.4	14.1	13.3	0.030	0.084
Phenylbutyl ketone	$C_{11}H_{14}O$	162	11.9	34.8	26.3	12.6	13.7	0.041	0.115

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TABLE 3-4.18 Combustion Properties of Fuels with Carbon, Hydrogen, Nitrogen, and Sulfur Atoms in the Chemical Structure

Hydrocarbon	Formula	M (g/mole)	S	Heat of Combustion (kJ/g)				Yield (g/g)	
				ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	CO	Smoke
<i>Aliphatic Fuels with Carbon, Hydrogen, and Nitrogen</i>									
Diethylamine	C ₄ H ₁₁ N	73	14.6	38.0	34.0	21.3	12.6	0.012	0.039
n-Butylamine	C ₄ H ₁₁ N	73	14.6	38.0	34.0	21.3	12.6	0.012	0.039
sec-Butylamine	C ₄ H ₁₁ N	73	14.6	38.0	34.0	21.3	12.6	0.012	0.039
Triethylamine	C ₆ H ₁₅ N	101	14.6	39.6	35.3	22.0	13.3	0.014	0.044
Di-n-butylamine	C ₈ H ₁₉ N	129	14.6	40.6	36.1	22.4	13.7	0.014	0.047
Tri-n-butylamine	C ₁₂ H ₂₇ N	185	14.7	41.6	37.0	22.9	14.1	0.015	0.049
<i>Aromatic Fuels with Carbon, Hydrogen, and Nitrogen</i>									
Pyridine	C ₅ H ₅ N	79	12.6	32.2	24.0	11.5	12.5	0.037	0.104
Aniline	C ₆ H ₇ N	93	12.9	33.8	25.0	11.7	13.3	0.043	0.119
Picoline	C ₆ H ₇ N	93	12.9	33.8	25.0	11.7	13.3	0.043	0.119
Toluidine	C ₇ H ₉ N	107	13.2	34.9	25.8	11.9	13.9	0.048	0.130
Dimethylaniline	C ₈ H ₁₁ N	121	13.3	35.7	26.4	12.1	14.3	0.051	0.139
Quinoline	C ₉ H ₇ N	129	12.5	36.1	26.7	12.1	14.5	0.052	0.143
Quinaldine	C ₁₀ H ₉ N	143	12.7	36.7	27.1	12.2	14.8	0.055	0.149
Butylaniline	C ₁₀ H ₁₅ N	149	13.6	37.0	27.2	12.2	15.0	0.056	0.151
<i>Aliphatic Fuels with Carbon, Hydrogen, and Sulfur</i>									
Hexyl mercaptan	C ₆ H ₁₄ S	118	12.2	33.0	30.1	17.9	12.2	0.012	0.040
Heptyl mercaptan	C ₇ H ₁₆ S	132	12.5	33.7	30.4	18.1	12.3	0.013	0.044
Decyl mercaptan	C ₁₀ H ₂₂ S	174	13.0	34.9	31.1	18.4	12.7	0.016	0.051
Dodecyl mercaptan	C ₁₂ H ₂₆ S	202	13.3	35.5	31.4	18.6	12.8	0.017	0.054
Hexyl sulfide	C ₁₂ H ₂₆ S	202	13.3	35.5	31.4	18.6	12.8	0.017	0.054
Heptyl sulfide	C ₁₄ H ₃₀ S	230	13.4	35.9	31.6	18.7	13.0	0.018	0.057
Octyl sulfide	C ₁₆ H ₃₄ S	258	13.6	36.3	31.8	18.8	13.1	0.019	0.059
Decyl sulfide	C ₂₀ H ₄₂ S	314	13.8	36.8	32.1	18.9	13.2	0.020	0.061
<i>Aromatic Fuels with Carbon, Hydrogen, and Sulfur</i>									
Thiophene	C ₄ H ₄ S	84	9.8	31.9	23.4	10.8	12.6	0.031	0.086
Methylthiophene	C ₅ H ₆ S	98	10.5	33.2	24.1	10.9	13.2	0.039	0.107
Thiophenol	C ₆ H ₆ S	110	10.6	34.1	24.6	11.0	13.6	0.045	0.122
Thiocresol	C ₇ H ₈ S	124	11.1	34.9	25.0	11.0	14.0	0.050	0.135
Cresolmethyl sulfide	C ₈ H ₁₁ S	155	11.6	36.2	25.7	11.1	14.5	0.058	0.155

liquid zinc chloride solution. The solution flows on the surfaces, drips down or runs onto equipment, resulting in very serious electrical shorting problems. In two major TCO losses, zinc chloride played a key role in both the rate of restoration as well as the ability to salvage equipment.

In TCO fires involving PVC-based cables, contamination levels in the range of about 5 to 900 microgram/cm² have been observed.⁷⁷⁻⁷⁹ In general, an electronic switch would be expected to accumulate zinc chloride levels in the range of about 5 to 9 microgram/cm² from the interaction with the environment over its expected lifetime of 20+

years. Clean equipment is expected to have less than about 2 microgram/cm² of chloride contamination, whereas contaminated equipment can have as high as 900 microgram/cm². Thus, equipment contamination levels and ease of restoration have been classified into four levels,⁷⁷⁻⁷⁹ as listed in Table 3-4.19.

Corrosion

Corrosion is defined as an unwanted chemical reaction and/or destruction or deterioration of a material because of

TABLE 3-4.19 Contamination Levels for the Surface Deposition of Chloride Ions for Electronic Equipment*

Chloride Ion (microgram/cm ²)	Level	Damage/Cleaning/Restoration
2	One	No damage expected. No cleaning and restoration required.
< 30	Two	Equipment can be easily restored to service by cleaning, with little impact on long-term reliability.
30 to 90	Three	Equipment can also be restored to service by cleaning, as long as no unusual corrosion problems arise, and the environment is strictly controlled soon after the fire.
> 90	Four	The effectiveness of cleaning the equipment dwindles, and the cost of cleaning quickly approaches the replacement cost. Equipment contaminated with high chloride levels may require severe environmental controls even after cleaning, in order to provide potentially long-term reliable operation.

*Data taken from reference 77.

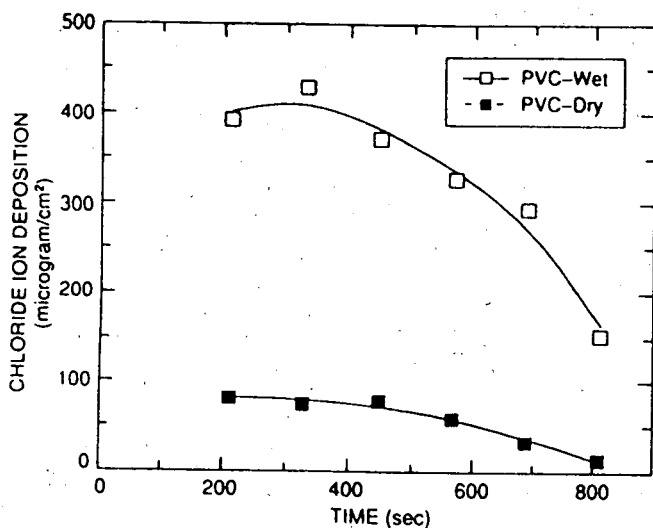


Fig. 3-4.41. Deposition of HCl on wet and dry cellulosic filter paper during the pyrolysis of PVC at an external heat flux of 20 kW/m² under co-airflow with 10 percent of oxygen concentration in the Flammability Apparatus. Flow velocity 0.09 m/s with filter paper at right angle to the flow. Data used in figure are taken from reference 81.

reaction with its environment. Factors that are considered to be important for the extent of corrosion damage are: (1) oxygen, (2) nature and concentrations of the fire products, (3) relative humidity, (4) temperature, (5) nature of the target and its orientation relative to the flow of the fire products-air mixture, (6) flow velocity of the fire products-air mixture, (7) presence of extinguishing agents, (8) techniques used for cleaning the exposed surface and their implementation time after the fire, and others.

Most of the knowledge on corrosion damage has been based on air pollution, e.g., due to acid rain. Acid deposition is generally described as "acid rain."⁸⁰ Rain usually includes all forms of precipitation (rain, snow, sleet, hail, etc.). Acid deposition is a broader term and includes the uptake of gases by surfaces, impact of fog, and settling of dust and small particles.⁸⁰ Precipitation is one of the principal removal mechanisms by which the atmosphere cleanses itself. Acids in rain precipitation result mainly from sulfuric, nitric, and hydrochloric acids, either absorbed directly into precipitation or formed in the aqueous phase from precursor compounds.

In general, all forms of pollution deposition not involving precipitation are referred to as dry, including dew and fog processes.⁸⁰ With the exception of nitric acid vapors, most gases do not readily deposit on dry, inert surfaces. However, if the gas is soluble in water, the presence of a liquid film (resulting from condensation, for example) will generally accelerate dry deposition. In these cases, the amount deposited on the surfaces will depend not only on the concentration of the pollutant, but also on the relative frequency of encountering a wet surface.

Data in Figure 3-4.41, taken from reference 81, show that the deposition of HCl on wet filter paper is almost four times as high as the deposition on dry paper, in agreement with reference 80. HCl was generated by exposing PVC to an external heat flux of 20 kW/m² in an inert environment in the Flammability Apparatus. The chloride ion deposition is

high in the initial stages and decreases with time, which is consistent with the decomposition mechanism of PVC. The decomposition of PVC is characterized by the release of HCl, which is initiated at a temperature as low as about 100°C. At a temperature of up to about 200 to 220°C, HCl is the major effluent. Presence of oxygen in the air enhances HCl release. The generation of HCl from PVC leads to the formation of double bonds and release of CO and various aromatic/unsaturated hydrocarbons (benzene, toluene, ethylene, propylene, butylene, etc). The yields of some of these products from the combustion and pyrolysis of PVC are listed in Table 3-4.20, taken from reference 82.

Deposition of HCl on walls of enclosures has also been quantified in larger-scale fire tests. For example, in the fire tests with PVC floor covering performed in a 2.8- x 2.8- x 2.4-m-high unventilated room, about 50 percent of the original chloride ions in PVC were deposited on the walls.⁸³ With the exception of vinyl film (wallpaper) and super-gloss enamel paint on polyethylene, the chloride ion deposition on all other surfaces was in the range of 30 to 90 microgram/cm². The differences in the chloride ion deposition on various materials on the wall appear to be related to hydrophilic (water attracting) and hydrophobic (water repelling) nature of the surfaces, i.e., filter paper is hydrophilic and vinyl film is hydrophobic, in agreement with reference 80. This deposition corresponds to the third level of contamination for TCOs. (See Table 3-4.19.)

The corrosion damage in fires follows the basic corrosion relationship

$$D_{corr} = \mu c^m t^n \quad (109)$$

where D_{corr} is metal corrosion (penetration depth or metal loss in microns, angstroms, mils); t is the exposure time (minutes, days); c is the concentration of the corrosive product (g/m³); and μ , m , and n are empirical constants. The constant μ may be defined as a corrosion parameter characteristic of the corrosive nature of the product. The constant n is a function of the corrosion resistance characteristics of the film at the surface. When the film on the surface protects the surface and inhibits further corrosion by diffusion, $n = 1/2$.⁸⁰ When the film is permeable to corrosive gases and offers no protection, $n = 1$.⁸⁰

For short-term exposure of metal surfaces to aqueous solutions of corrosive fire products, $n = 1$, and from Equation 109

$$R_{corr} = \mu c^m \quad (110)$$

where R_{corr} is corrosion rate ($\text{\AA}/\text{min}$).

For long-term exposure of metal surfaces to aqueous solutions of corrosive fire products, as a protective layer of corrosion byproducts is formed at the surface, $n = 1/2$, and from Equation 109

$$R_{corr} = \frac{\mu c^m}{t^{1/2}} \quad (111)$$

showing that corrosion rate decreases with time.

Figure 3-4.42 shows a plot of the corrosion rate of a mild steel probe exposed to aqueous solutions of hydrochloric and nitric acid of varying concentrations for 24 hrs. The data used in the figure are taken from reference 81. No protective layer is formed for 24 hrs, and thus Equation 110 is followed. From linear regression analysis, $\mu = 2.08 (\text{\AA}/\text{min})(\text{g}/\text{m}^3)^{-1/2}$ and $m = 1/2$. This relationship suggests that the corrosion

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TABLE 3-4.20 Yield of CO, HCl, Benzene, and Toluene from the Combustion/Pyrolysis of Polyvinylchloride*

Combustible [†]	Air/Inert	Yield (g/g)			
		CO	HCl	Benzene	Toluene
PVC Homopolymer					
Rigid PVC sheet (49.3% Cl)	inert	—	0.480	0.022	0.002
	air	—	0.479	0.022	0.001
Rigid PVC-1	inert	—	0.555	0.058	0.008
	air	—	0.472	0.044	0.004
Rigid PVC-2	air	0.356	0.513	—	—
PVC resin	air	—	0.486	0.048	0.001
PVC homopolymer-1	air	0.422	0.583	0.031	0.001
PVC homopolymer-2	air	0.413	0.584	0.036	0.001
PVC homopolymer-3	air	0.299	0.500	0.029	0.001
PVC homopolymer-4	air	0.429	0.580	0.043	0.004
PVC + Plasticizer					
PVC (33% Cl) + dioctylphthalate (67%)	air	0.275	0.269	—	—
PVC (31% Cl) + tricresylphosphate	air	0.248	0.269	—	—
PVC + Plasticizer + Acid Neutralizer					
PVC (%) + dioctylphthalate (%) + K ₂ CO ₃ (%)					
42.4 + 42.4 + 15.2	N ₂	—	0.171	—	—
38.2 + 38.2 + 23.6	N ₂	—	0.111	—	—
32.5 + 32.5 + 35.0	N ₂	—	0.029	—	—
PVC (%) + dioctylphthalate (%) + CaCO ₃ (%)					
45.5 + 45.5 + 9.0	N ₂	—	0.221	—	—
41.7 + 41.7 + 16.0	N ₂	—	0.171	—	—
35.7 + 35.7 + 28.6	N ₂	—	0.117	—	—
Electrical Cables					
PVC jacket	air	—	0.277-0.408	—	—
FR PVC insulation	air	—	0.204-0.285	—	—
Insulation (51% PVC + 49% Plasticizer + additives)	air	0.067	0.273	0.010	0.001
Insulation (57% PVC + 43% Plasticizer + additives)	air	0.090	0.333	0.011	0.001
PVC cable	air	—	0.263	0.033	0.001
General Products					
Floor tile (33% PVC + 70% CaCO ₃ + inert)	air	0.031	0.073	0.001	—
PVC-nylon brattice cloth	air	—	0.174	0.048	0.001
PVC-nylon fabric	air	—	0.254	0.051	0.001
FR PVC-nylon product	air	—	0.206	0.025	0.001
FR PVC	air	—	0.300	0.020	0.001

*From reference 82.

[†]FR—fire retarded, K₂CO₃—potassium carbonate; CaCO₃—calcium carbonate.

rate does not increase rapidly with the concentration of the corrosive products. For example, if the concentration of the corrosive product is increased ten times, the corrosion rate would increase only by a factor of three.

For corrosion in the gas phase, the presence of water is essential or the volume fraction of water ≠ 0. The experimental data for corrosion in the gas phase suggest that $m = 1$ in Equation 110, which can be expressed in the following modified form

$$R_{corr} = \frac{\mu y_{corr} \dot{m}^* A}{f_{water} \dot{V}} \quad (112)$$

where y_{corr} is the yield of the corrosive product (g/g), \dot{m}^* is the mass loss rate of the material (g/m²-s), A is the total exposed surface area of the material (m²), f_{water} is the volume fraction of water generated in the combustion of the material and present in the humid air, and \dot{V} is the total volumetric flow rate of fire product-air mixture (m³/s). All

the terms in Equation 112 can be measured, and thus the corrosion parameter, μ , can be calculated for the generalized application of the corrosion data.

Corrosion measurements: For corrosion measurements, fire products are generated in small-scale tests and the corrosion is measured by exposing metal probes to the products in the gas phase at various relative humidities or in the aqueous solutions of the products. The common tests methods are:

1. The Flammability Apparatus test method (Figures 3-4.2(a), 3-4.2(b), and 3-4.27);^{1,58,81,84-86}
2. The Cone Calorimeter test method (Figure 3-4.3);^{87,88}
3. The Radiant Combustion/Exposure test method;^{87,89}
4. The CNET (Centre National d'Etudes des Telecommunications) corrosion test method;^{87,90,91}
5. The DIN 57472 test method;^{87,92} and
6. The DIN 53436 with metal sheets and CNET corrosion probe test method.⁹³

Corrosion Measurements in the Gas Phase: The measurements are made in the Flammability Apparatus, the Cone Calorimeter, the CNET, and the Radiant Combustion/Exposure test methods. For the measurements, either high-sensitivity Rohrback Cosasco (RC) atmospheric metal corrosion probes or CNET metal corrosion probes are used.

The RC corrosion probes are manufactured by a vacuum deposition technique to obtain an open matrix with little resistance to in-depth diffusion of products, resulting in rapid corrosion. It is designed to monitor short-term corrosion (16 to 24 hrs) for environments with small concentrations of corrosive products. The RC probe consists of two metal strips (5,000 to 90,000 Å), embedded in an epoxy-fiberglass plate. One metal strip is coated and acts as a reference, and the other noncoated metal strip acts as a sensor. As the sensor strip corrodes and loses its thickness, its resistance changes. The change in resistance, which represents the extent of corrosion of the metal, is measured as a function of time, by the difference in the resistance between the two strips. The probe readings remain reliable up to about half the thickness of the metal strip (probes are identified as 2500 to 45,000 Å probes).

The CNET probe consists of an epoxy-fiberglass plate embedded with about 170,000 Å thick copper conductors. The change in the resistance of the probe is recorded at the beginning and at the end of the test to determine the extent of corrosion.

The corrosion in the gas phase is measured during the tests every minute and every hour after the test for 16 to 24 hrs. The corrosion rate is calculated as a function of time, using the following type of relationship

$$\dot{R}_c = \frac{D_{c_1} - D_{c_2}}{t_2 - t_1} \quad (113)$$

where \dot{R}_c is the corrosion rate in Å/min, D_{c_1} is the metal thickness in angstroms at time t_1 (s), and D_{c_2} is the metal thickness in angstroms at time t_2 (s).

Data have been reported in the literature for the gas-phase corrosion, mass loss rate, and total volumetric rate of

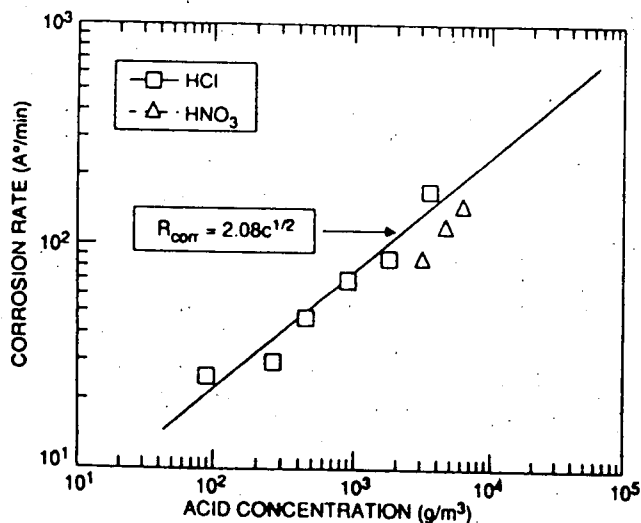


Fig. 3-4.42. Corrosion rate of a mild steel probe versus hydrochloric and nitric acid concentrations. Data used in figure are taken from reference 81.

TABLE 3-4.21 Corrosion Rate per Unit Fuel Vapor Concentration in the Gas Phase for Flaming and Nonflaming Fires with Variable Oxygen Concentration in the Flammability Apparatus and the Radiant Combustion/Exposure Chamber

Polymer*	O ₂ (%)	F/NF ¹	Water Present ²	Corrosion Rate ³	
				FLAM ⁴	RC/E ⁵
EVA	21	F	no	nd	0.001
EVA-FR1	21	F	no	nd	0.021
PE	21	F	no	nd	0.002
PE-FR1	21	F	no	nd	0.024
PE-FR1	21	F	yes	nd	0.036
PE-FR2	21	F	no	nd	0.022
PE-FR2	21	F	yes	nd	0.024
PE-FR2	21	F	no	nd	0.014
PE-FR2	21	F	yes	nd	0.016
PE/25% Cl	10	N	yes	0.14	nd
PE/36% Cl	10	NF	yes	0.15	nd
PE/48% Cl	10	NF	yes	0.19	nd
PVC	10	NF	yes	0.15	nd
	21	NF	no	nd	0.027
	21	NF	yes	0.12	0.087
	21	F	yes	1.0	nd
TFE	0	NF	yes	0.0036	nd
	10	NF	yes	0.011	nd
	40	NF	yes	0.035	nd
	21	F	yes	0.42	nd

*See nomenclature.

¹F: flaming, NF: nonflaming.

²Increased humidity in the gas phase with water.

³Per unit fuel vapor concentration (Å/min)/(g/m³).

⁴The Flammability Apparatus test method.^{1,58,81,84-87}

⁵The Radiant Combustion/Exposure test method.^{88,90} 1500-min average.

Note: FR-1: red phosphorus fire retardant, FR-2: bromine fire retardant, EVA: ethylene-vinyl acetate copolymer, PE: polyethylene, Cl: chlorine, TFE: tetrafluoroethylene (Teflon™), and nd: not determined.

fire products-air mixture with relative humidity maintained approximately constant. From Equation 112

$$\frac{\dot{R}_{corr}}{(\dot{m}^2 A/V)} = \frac{\mu V_{corr}}{f_{water}} \quad (114)$$

where f_{water} is approximately constant, and thus the values of $\dot{R}_{corr}/(\dot{m}^2 A/V)$ can be used to assess the relative corrosion nature of the fire products generated from various materials. Tables 3-4.21 and 3-4.22 list the values of the corrosion rate per unit fuel vapor concentration, $\dot{R}_{corr}/(\dot{m}^2 A/V)$. The data show that:

1. For significant gas-phase corrosion, it is necessary to have hydrogen atoms in the structure of the halogenated materials as suggested by the stoichiometric yields listed in Table 3-4.13. For example, the corrosion rates per unit fuel vapor concentration for PVC (hydrogen atoms in the structure) and Teflon™ (no hydrogen atoms in the structure) differ by a factor of seven. The difference is probably due to: (a) the inefficiency of the hydrolysis process during the conversion of fluorocarbon products generated from Teflon™ to HF, and (b) the high water solubility of HCl generated from PVC.
2. The corrosion rates per unit fuel vapor concentration for halogenated materials with hydrogen atoms in the structure are high [greater than 0.14 (Å/min)/(g/m³)], whereas,

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TABLE 3-4.22 Corrosion Rate per Unit Fuel Vapor Concentration in the Gas Phase for Flaming Fires in Air in the Radiant Combustion/Exposure Chamber*

Sample Description	Corrosion Rate†
Crosslinked polyolefin (XLPO) + metal hydrate	0.007
HD polyethylene (PE) + chlorinated PE blend	>0.098
Chlorinated PE + fillers	>0.098
Ethylvinylacetate (EVA) PO + ATH filler	0.012
Polyphenylene oxide/polystyrene (PS) blend	0.005
Polyetherimide	0.002
Polyetherimide/siloxane copolymer	0.005
Intumescent polypropylene (PP)	0.025
Polyolefin copolymer + mineral filler	0.046
XLPO + mineral filler	0.011
XLPO + ATH	0.003
XLPO + ATH	0.007
EVA-PO + mineral filler	0.013
PO + mineral filler	0.016
CLPE + chlorinated additive	>0.098
Polyvinylidene fluoride	>0.098
Polytetrafluoroethylene	>0.098
Polyvinylchloride (PVC)	>0.098
PVC wire	>0.098
PE homopolymer	0.006
Douglas fir	0.006
EVA-PO copolymer	0.003
Nylon 6,6	0.008
XLPE copolymer + brominated additives	0.091

*From reference 87.

†Per unit fuel vapor concentration (\dot{A}/min)/(g/m³); average gas-phase concentration = 17.0 g/m³.

they are negligibly small for fires of nonhalogenated materials [less than 0.007 (\dot{A}/min)/(g/m³)], as expected.

- Fire retardation of nonhalogenated materials by halogenated materials increases the corrosion rate per unit fuel vapor concentration for the nonhalogenated materials from less than 0.007 to 0.011 to 0.046 (\dot{A}/min)/(g/m³). These values, however, are still about 1/10 the values for the halogenated materials.
- Increase in the corrosion rate per unit fuel vapor concentration due to the presence of water is not significant for halogenated materials with hydrogen atoms in the structure, as expected, as water is generated in the combustion process.
- Increase in the oxygen concentration in the environment increases the corrosion rate per unit fuel vapor concentration.

Corrosion Measurements in the Aqueous Solution: The measurements are made in the Flammability Apparatus and the DIN 57472 test methods. For the measurements, Rohrback Cosasco (RC) loop-type metal corrosion probes are used. The probes are exposed to the aqueous solutions of the fire products. The probe consists of a metal loop attached to an epoxy-fiberglass rod, with a built-in reference. The metal loop acts as a sensor. As the sensor loop corrodes and loses its thickness, its resistance changes. The extent of corrosion is measured by the difference in the resistance between the loop and the reference. The corrosion rate is determined from Equation 113.

The fire products are either bubbled directly into known volumes of water or are collected in the gas phase on cellulose-based filter papers of known area. After the test, the color, odor, and mass of the products deposited on the filter papers are determined. The fire products are extracted with a known volume of deionized water.

The corrosion in the aqueous solution is measured every hour for 16 to 24 hrs. In some cases, concentrations of corrosive ions, such as chloride, bromide, and fluoride, are also determined using selective ion electrodes in the Flammability Apparatus test method. In the DIN 57472 test standard, pH and conductivity of the solution are measured.

The solution-phase corrosion parameters measured by the Flammability Apparatus test method show that they are comparable for all the halogenated materials and are significantly higher than the values for the gas phase.

Smoke Damage

Smoke is a mixture of black carbon and aerosol.^{94,95} Smoke is generated by many sources and is released to the environment, causing pollution, reduction in visibility, and nonthermal damage (discoloration, odor, electrical shorting and conduction, corrosion, etc.). The estimated influx of black carbon to the environment from burning is 0.5 to 2 × 10¹⁵ g/yr.⁹⁴ Black carbon is often called charcoal, soot, elemental carbon, etc.⁹⁴ The particulate organic matter (POM) in aerosols consists of:⁹⁴ (1) hydrocarbons—these are the alkanes, alkenes, and some aromatics, with aliphatics constituting the greatest fraction. They range from C₁₇ to C₃₇; (2) polycyclic aromatic hydrocarbons; (3) oxidized hydrocarbons—these classes include acids, aldehydes, ketones, quinones, phenols, and esters, as well as the less stable epoxides and peroxides. They may be produced directly in combustion processes or through oxidations in the atmosphere; (4) organo-nitrogen compounds—the aza-arenes are the only types of this class that have been so far analyzed, and they are one or two orders of magnitude less than the polycyclic aromatic hydrocarbons; and (5) organo-sulfur compounds—heterocyclic sulfur compounds, such as benzothiazole, have been reported in urban aerosols.

The environmental behavior of black carbon introduced by combustion processes depends on the characteristics of the source, aerosol properties, chemical composition of black carbon, and meteorology.⁹⁴ The yield of black carbon depends on the material and combustion conditions, as discussed in previous sections. Table 3-4.23 lists data, taken from reference 94, for the yield of black carbon from some industrial combustion processes.

TABLE 3-4.23 Yield of Black Carbon from Some Industrial Combustion Processes*

Fuel	Source	Yield (g/kg)
Natural gas	Steam generator	3 × 10 ⁻⁴
	Domestic water heater	0.1
	Heating boiler	0.01-0.07
Gasoline	Automobile engine	0.1
Diesel	Automobile engine	2-4
	Truck/bus engine	0.6-1
Jet A	Aircraft turbine	0.5-3
Fuel oil (#2)	Utility turbine	0.08

*Data taken from reference 94.

TABLE 3-4.24 Most Frequently Occurring Smoke Particle Radii in Fires of Some Materials*

Material	Smoke Particle Radius (microns)
Coal	0.078
Polystyrene	0.078
Kerosene	0.079
Polypropylene	0.079
Polyethylene	0.077
Propylene	0.076
Ethylene	0.072
Heptane	0.077
Propane	0.068
Nylon	0.075
PMMA	0.068
Douglas fir	0.062
Polyethylene with chlorine	0.090
Polychloroprene	0.090
PVC	0.083
Styrene-butadiene rubber with chlorine	0.073

*Data taken from reference 97.

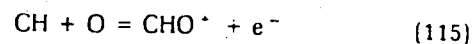
Multi-modal distributions of black carbon issuing from flames, diesel engines, and freeway traffic show that the "nuclei mode" has a geometric mean radius between 0.0025 and 0.020 microns and probably results from the condensation of gaseous carbon moieties.⁹⁴ The "accumulation mode" encompasses particles in the size range 0.075 to 0.25 microns and apparently results from the coagulation and condensation of the "nuclei mode" particles.⁹⁴ Finally in the case of vehicular emissions there is a "coarse mode" at several microns that is attributed to the precipitation of fine particles on the walls of exhaust systems and a subsequent entrainment in the issuing gases.⁹⁴ The coal-fired utility boilers produce soot with peaks at particle radius of about 0.05 microns.⁹⁴ Long-range transport of particles shows that about 60 percent of the soot is less than 0.05 microns radius size class.⁹⁴ The larger particles are probably removed preferentially from the air during its travel.

In fires, large variations in smoke particle size, due to coagulation and condensation, have been found. As the smoke moves away from the fire origin large particles settle down to the floor, leaving small particles in the gas phase,⁹⁶ similar to the long-range transport in the atmosphere discussed in reference 94. The data from various fires show that initially the smoke particles are in the "coarse mode." The particle size decreases slowly with time, suggesting that large particles settle down from the hot layer at the ceiling.

Relationships between transport of heat and smoke generated in large enclosure fires and for smoke characterization have been developed and data have been reported for the most frequently occurring smoke particle radius.⁹⁷ These data are listed in Table 3-4.24, which shows that radii of the smoke particles vary between 0.062 to 0.09 microns, belonging to the lower end of the "accumulation mode."

It thus appears that, in fires, smoke damage in the room of fire origin is expected to be due to particles of several microns in radius in the "coarse mode," whereas smoke damage downstream of the fire is expected to be due to particles with radius less than 0.1 micron in the lower end of the "accumulation mode."

Although concentration, size, physical, and optical properties, and chemical composition of smoke particles have been studied in detail, very little is known about the charges on the particles.⁹⁸ It has been suggested that soot nucleation and growth occur near the highly ionized regions of the flames in combustion processes, possibly suggesting that some of the charges are transferred to smoke particles. In hydrocarbon-oxygen flames, the following reaction is considered to be the dominant reaction for the charge separation⁹⁸



Charges on smoke particles generated in flaming and nonflaming fires of wood, cotton wick, polyurethane, heptane with 3 percent toluene, and an alcohol have been examined.⁹⁸ The results show that, in nonflaming fires, initially a very small fraction of particles is charged. During aging, the charge increases slowly. For flaming polyurethane fires, where large amounts of black carbon are generated, smoke carries a high initial charge: 70 percent of the particles in the size interval from 0.018 to 0.032 microns are charged. Similar results are found for heptane. Flaming wood fires, however, show particle charges between that of nonflaming fires of wood and cotton wick and that of flaming fires of polyurethane. In the flaming fire of alcohol, there is no smoke.

Char and black carbon are efficient absorbers of HCl. In the combustion of plasticized PVC wire, about 25 percent of the original chloride ions are retained in the char, and the ions are predominantly inorganic in nature.⁹⁹ In the combustion of PE-PVC cables in rooms, smoke particles that settle down in the room contain about 33 percent by weight of inorganic chloride ions, and less than 2 percent of the theoretically expected mass of the chloride ions leaves the enclosure.⁹⁶ In the combustion of 79.5 percent PVC-20.5 percent PE, 19 mg of HCl/g of smoke is loosely bound and 27 mg of HCl/g of smoke is tightly bound to carbon.¹⁰⁰

It thus appears that, for nonthermal fire damage, the important factors are: (1) concentrations of fire products and their deposition on surfaces, (2) chemical and physical nature of the products, (3) nature of the surfaces, (4) presence of moisture, and other factors. These factors depend on: (1) fire initiation and spread, (2) generation rates of fire products and their chemical and physical natures, (3) relative humidity and temperature, (4) in-flow rate of air and its mixing with the products and the flow velocity of the mixture, (5) nature and orientation of the target relative to the flow of the products, (6) exposure duration, (7) presence or absence of fire extinguishing agents, etc.

FIRE CONTROL/SUPPRESSION/EXTINGUISHMENT

For the prevention of loss of life and property in fires, both active and passive fire protection techniques are used.¹⁰¹ Passive fire protection is provided by: (1) modifying the chemical structures of the materials for high resistance to ignition and fire propagation, (2) incorporating fire retardants within the materials, (3) coating and wrapping the surfaces, (4) separating materials by inert fire barriers, (5) modifying configuration and arrangement of materials, etc. Active fire protection is provided by the application of agents to control, suppress, and/or extinguish fires. The

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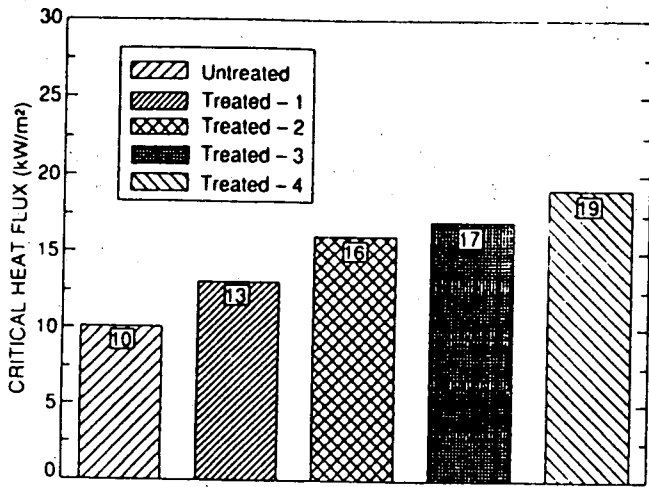


Fig. 3-4.43. Critical Heat Flux for untreated and treated tri-wall corrugated paper sheet. The amount of passive fire protection agent is increasing from Treated 1 to 4. Data obtained from the ignition experiments in the Flammability Apparatus. Numbers indicated on top of each bar are the Critical Heat Flux values.

most commonly used liquid and gaseous agents at the present time are: water, CO₂, N₂, and halons* 1211 (CBrClF₂), 1301 (CBrF₃), and 2402 (CBrF₂CBrF₂). Because of the contribution of halons to depletion of the stratospheric ozone layer, they will not be used in the future. There is thus an intense effort underway to develop alternative fire suppressants to replace ozone-layer-depleting halons.

The mechanisms of passive and active fire protection are generally known.^{37,101-108} Flame extinction by liquid and gaseous agents is mainly due to physical processes (such as removal of heat from the flame and burning surface and creation of nonflammable mixtures) and/or chemical processes (such as termination of chemical reactions). The effectiveness of water is mainly due to removal of heat from the burning surface as a result of vaporization. The effectiveness of halons is mainly due to termination of chemical reactions. N₂ and CO₂ are effective mainly due to creation of nonflammable mixtures by reducing mass fraction of oxygen.

Passive Fire Protection

Passive fire protection is provided by various chemical and physical means, as follows.

Increasing the resistance to ignition and fire propagation by increasing the Critical Heat Flux (CHF) and Thermal Response Parameter (TRP) values: The Critical Heat Flux is expressed as

$$CHF = \sigma(T_{ig}^4 - T_a^4) \quad (116)$$

where σ is the Stefan-Boltzmann constant (56.7×10^{-12} kW/m²·K⁴), T_{ig} is the ignition temperature (K), and T_a is the ambient temperature (K). TRP is defined in Equations 1 and 2, and its relationship to fire propagation in Equations 8 and 9.

The relationships between time to ignition, fire propagation rate, Fire Propagation Index, and TRP (Equations 2, 8,

and 9) show that the time to ignition is directly proportional to the TRP value to the power two; and the fire propagation rate and the Fire Propagation Index are inversely proportional to the TRP value to the power two and one, respectively. Thus the higher the TRP value, the longer the time to ignition, the slower the fire propagation rate, and the lower the FPI value. For high TRP values with FPI < 7, there is no fire propagation beyond the ignition zone, defined as the nonfire-propagating behavior. Also, for materials with high CHF values, higher heat flux exposure is required to initiate a fire.

The CHF and TRP values can be increased by modifying the pertinent parameters, such as increase in the chemical bond dissociation energy and decrease in thermal diffusion (combination of the density, specific heat, and thermal conductivity). Figures 3-4.43 and 3-4.44 show the CHF and TRP values for a tri-wall corrugated paper sheet containing various amounts of a passive fire protection agent (identified as agent A here); the data were obtained from the ignition experiments in the Flammability Apparatus. Figure 3-4.45 shows the TRP value for a single-wall corrugated paper sheet containing various amounts of the passive fire protection agent A; the data were obtained from the ignition experiments in the Flammability Apparatus. The CHF and TRP values increase with increase in the amount of agent; thus, the passive fire protection agent would complement the active fire protection agents. Corrugated paper boxes treated with higher amounts of the passive fire protection agent are expected to require reduced amounts of the active fire protection agents for fire control, suppression, or extinguishment compared to the amounts of the active fire protection agents required for the untreated boxes.

The passive fire protection requirements for various materials can be assessed from the data for CHF and TRP listed in Table 3-4.2.

Decreasing the values of the Heat Release Parameter (HRP) and the flame heat flux: Heat release rate is equal to the Heat Release Parameter (HRP) times the net heat flux (Equation 30). HRP is the ratio of the heat of combustion to heat of gasification, and thus the HRP value can be decreased

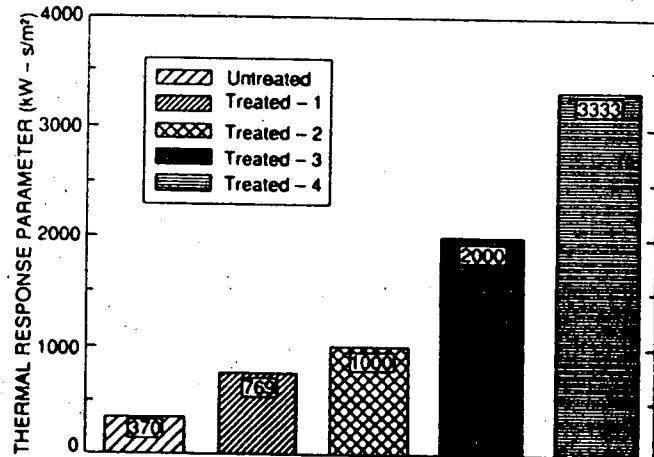


Fig. 3-4.44. Thermal Response Parameter for untreated and treated tri-wall corrugated paper sheet. The amount of passive fire protection agent is increasing from Treated 1 to 4. Data obtained from the ignition experiments in the Flammability Apparatus. Numbers indicated on top of each bar are the Thermal Response Parameter values.

*The numbers represent: First: number of carbon atoms; second: number of fluorine atoms; third: number of chlorine atoms; fourth: number of bromine atoms.

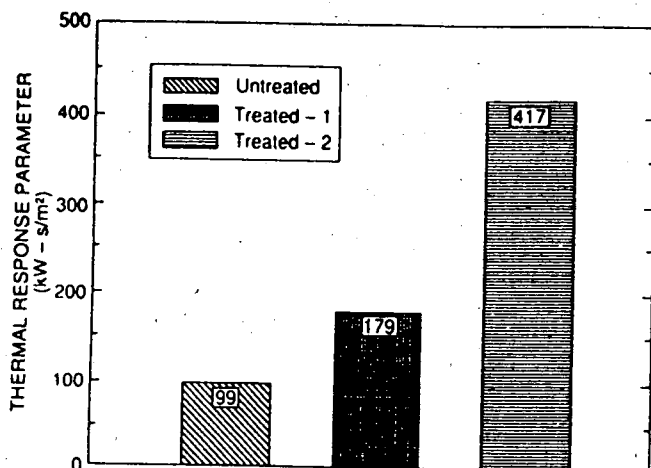


Fig. 3-4.45. Thermal Response Parameter for untreated and treated single-wall corrugated paper sheet. The amount of passive fire protection agent is increasing from Treated 1 to 2. Data obtained from the ignition experiments in the Flammability Apparatus. Numbers indicated on top of each bar are the Thermal Response Parameter values.

by decreasing the heat of combustion and/or increasing the heat of gasification by various chemical and physical means. An examination of data in Table 3-4.11 for heats of combustion shows that introduction of oxygen, nitrogen, sulfur, halogen, and other atoms into the chemical structures of the materials reduces the heat of combustion. For example, the heat of combustion decreases when the hydrogen atoms attached to carbon atoms in polyethylene are replaced by the halogen atoms, such as by fluorine in Teflon™. The chemical heat of combustion decreases from 38.4 kJ/g to 4.2 kJ/g (Table 3-4.11), and the chemical HRP value decreases from 17 to 2 (Table 3-4.12).

The HRP values can also be reduced by increasing the heat of gasification and decreasing the heat of combustion by retaining the major fraction of the carbon atoms in the solid phase, a process defined as charring. Several passive fire protection agents are available commercially to enhance the charring characteristics of materials.

Figure 3-4.46 shows the reduction in the chemical heat release rate as a result of increase in charring of a tri-wall corrugated paper sheet by the passive fire protection agent A; the data were obtained from the combustion experiments in the Flammability Apparatus. The amount of the agent A is increasing from Treated 1 to 3. There is a very significant decrease in the chemical heat release rate of the tri-wall corrugated paper sheet by the passive fire protection agent A, which will complement the active fire protection agents. Corrugated paper boxes treated with higher amounts of the passive fire protection agent are expected to require reduced amounts of the active fire protection agents for fire control, suppression, or extinguishment compared to the one required for the untreated boxes.

The effect on flame heat flux by passive fire protection is determined by using the radiation scaling technique, where combustion experiments are performed in oxygen concentration higher than the ambient values. Very little is known about this subject. Table 3-4.5 lists some of the flame heat flux values derived from the radiation scaling technique, but no systematic study has been performed for the effectiveness

of passive fire protection. For liquids that vaporize primarily as monomers or as very low molecular weight oligomers, the flame heat flux values are in the range of 22 to 44 kW/m², irrespective of their chemical structures. For solid materials, which vaporize as high molecular weight oligomers, the flame heat flux values increase substantially to the range of 49 to 71 kW/m², irrespective of their chemical structures. The independence of the asymptotic flame heat flux values from the chemical structures of materials is consistent with the dependence of flame radiation on optical thickness, soot concentration, and flame temperature in large-scale fires. Passive fire protection agents, which can reduce the molecular weight of the vaporized materials, would be effective in reducing the flame heat flux and complement the active fire protection agents.

Changing the molten behavior of materials: Figure 3-4.47 shows the chemical heat release rate versus time for the well-ventilated combustion of a 90-mm-diameter and 25-mm-thick slab of polypropylene exposed to an external heat flux of 50 kW/m². The data were measured in the Flammability Apparatus. For about 900 sec, the polypropylene slab burns as a solid with a thin liquid layer at the surface. The measured and calculated values of the heat release rate under this condition agree very well. The heat release rate was calculated from Equation 30 with $\dot{q}_c \gg \dot{q}_f - \dot{q}_{rr}$.

Between about 900 and 1150 sec, the polypropylene slab melts rapidly. At about 1150 sec, the entire sample changes to a liquid and burns as a boiling liquid pool fire. The chemical heat release rate triples at this stage. This is the most dangerous stage in a fire and presents a serious challenge to the active fire protection agents, such as water applied as a spray from sprinklers. Inert passive fire protection agents that eliminate the boiling liquid pool fire stage will be effective in complementing the active fire protection agents, such as water.

Changing the nature of the fire products: Nonhalogenated passive fire protection agents or agents that reduce or

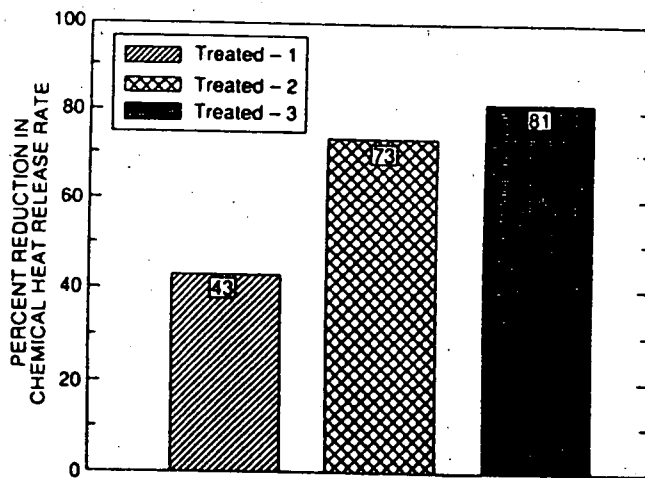


Fig. 3-4.46. Percent reduction in the chemical heat release rate of untreated tri-wall corrugated paper sheet by a passive fire protection agent. The amount of the passive fire protection agent is increasing from Treated 1 to 3. Data from the combustion experiments in the Flammability Apparatus. Numbers indicated on top of each bar are the percent reductions in the chemical heat release rate.

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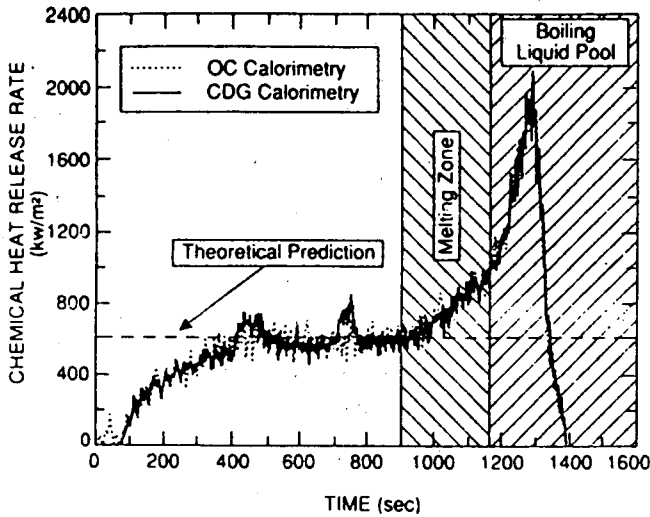


Fig. 3-4.47. Chemical heat release rate in the well-ventilated combustion in normal air of a 90-mm-diameter and 25-mm-thick slab of polypropylene exposed to 50 kW/m² of external heat flux in the Flammability Apparatus. (See Fig. 3-4.21.)

eliminate the release of halogenated and highly aromatic products and enhance release of aliphatic products; rich in hydrogen and oxygen atoms but poor in carbon atoms, are effective in reducing the nonthermal damage due to smoke and corrosion. Some of the passive fire protection agents, available commercially, interact with the materials in the solid as well as in the gas phase during pyrolysis and combustion.

The critical parameter that needs to be examined in the presence and absence of the passive fire protection agents is the ratio of the generation rate of products [such as for smoke, CO, corrosive products (HCl), and others] to heat release rate. The effectiveness of the passive fire protection agent is reflected in the small values of the ratios at fire control, suppression, and/or extinguishment stage.

Active Fire Protection

Active fire protection is provided by applying agents to the flame and/or to the surface of the burning material. The fire control, suppression, and extinguishment have been described by the fire point equation.^{104,106} According to the fire point theory, the convective heat flux from the flame to surface as flame extinction condition is reached is expressed as^{104,106}

$$\dot{q}_{fc} = \phi \Delta H_T \dot{m}_{cr}^* \quad (117)$$

where \dot{q}_{fc} is convective flame heat flux from the flame to the surface as the extinction condition is reached (kW/m²); ϕ is the maximum fraction of combustion energy that the flame reactions may lose to the sample surface by convection without flame extinction and is defined as the kinetic parameter for flame extinction; ΔH_T is the net heat of complete combustion (kJ/g); and \dot{m}_{cr}^* is the critical mass loss rate for flame extinction (g/m²-s). The kinetic parameter is defined as^{104,106}

$$\phi = \frac{\Delta H_{g,con}}{\Delta H_T} \quad (118)$$

where $\Delta H_{g,con}$ is the flame convective energy transfer to the fuel per unit mass of fuel gasified (kJ/g). The kinetic parameter is expected to be higher for fast-burning material vapors

and lower for slower burning material vapors, such as materials containing halogens, sulfur, nitrogen, etc. It is suggested that, at flame extinction, combustion is controlled primarily by the convective heat transfer, and thus the critical mass loss rate would follow Spalding's mass transfer number theory¹⁰³

$$\dot{m}_{cr}^* = \frac{h}{c_p} \ln(B_{cr} + 1) \quad (119)$$

where h is the convective heat transfer coefficient (kW/m²-K), c_p is the specific heat of air (kJ/g-K), and B_{cr} is the critical mass transfer number, defined as

$$B_{cr} = \frac{Y_O \Delta H_O^* - c_p(T_s - T_a)}{\Delta H_{g,con}} \quad (120)$$

where Y_O is the oxygen mass fraction (-); ΔH_O^* is the net heat of complete combustion per unit mass of oxygen consumed (kJ/g), which is approximately constant (Tables 3-4.7 through 3-4.10); T_s is the surface temperature (K); and T_a is the ambient temperature (K). For ambient conditions, $Y_O \Delta H_T \gg c_p(T_s - T_a)$. From equations 118 through 120

$$\phi = \frac{Y_O \Delta H_O^*}{\Delta H_T \exp(\dot{m}_{cr}^* c_p / h) - 1} \quad (121)$$

The fire point theory^{104,106} and experimental data show that the critical mass loss rate for flame extinction is similar to the critical mass loss rate for ignition,^{16,53,105,107,109} the critical mass loss rate for ignition, however, has to be measured at the time period where the sustained flame is just being established. The data for the critical mass loss rate for ignition and flame extinction and the kinetic parameter for flame extinction are listed in Table 3-4.25. The values for the critical mass loss rate for ignition from the Flammability Apparatus (reference 16) are measured at the time period where the sustained flame is just being established, and thus are higher than the values from the University of Edinburgh (reference 109). The University of Edinburgh data are probably measured just before the sustained flame is established. For polymethylmethacrylate, the critical mass loss rate for ignition from the Flammability Apparatus (reference 16) agrees with the critical mass loss rate for flame extinction from reference 107.

The data in Table 3-4.25 show that the values of the kinetic parameter are higher for the aliphatic materials than the values for the aromatic and chlorinated materials, which is opposite to the trend for the heat of combustion. The data suggest that the materials can be arranged in the following decreasing order of the kinetic parameter values (using FMRC values): polyoxymethylene ($\phi = 0.43$) > polymethylmethacrylate ($\phi = 0.28$) > polyethylene, polypropylene, and polyethylene foams ($\phi = 0.27$ to 0.25) > polystyrene ($\phi = 0.21$) > polyurethane, polystyrene, and polyisocyanurate foams and chlorinated polyethylenes ($\phi = 0.09$ to 0.19). As expected from the fire point theory,^{104,106} the reactivity of the vapors in the gas phase follows the kinetic parameter.

The combustion efficiency and product generation efficiencies follow the reactivity of the vapors in the gas phase, such as shown in Figure 3-4.48 for the combustion efficiency. The lower the value of the kinetic parameter (Equation 121), the lower the reactivity of the material vapors, which is reflected in the: (1) reduced values of the combustion efficiency (Equations 32 through 34), (2) reduced values of the generation efficiencies (Equation 66) of the oxidation zone products (such as CO₂), and (3) increased values of the

GENERATION OF HEAT AND CHEMICAL COMPOUNDS IN FIRES 3-111

TABLE 3-4.25 Critical Mass Loss Rate for Ignition and Kinetic Parameter for Flame Extinction

Material	Critical Mass Loss Rate (g/m ² -s)		Kinetic Parameter	
	Ref. 16*	Ref. 109 [†]	Ref. 16*	Ref. 109 [†]
Polyoxymethylene	4.5	1.7	0.43	1.05
Polymethylmethacrylate	3.2	1.9	0.28	0.53
Polyethylene	2.5	1.3	0.27	—
Polypropylene	2.7	1.1	0.24	0.50
Polyethylene foams				
1	2.6	—	0.24	—
2	2.6	—	0.25	—
3	2.5	—	0.25	—
4	2.6	—	0.25	—
Chlorinated polyethylenes				
25% chlorine	6.6	—	0.15	—
36% chlorine	7.5	—	0.09	—
48% chlorine	7.6	—	0.08	—
Polystyrene	4.0	0.80	0.21	0.78
Polystyrene foams				
GM47	6.3	—	0.11	—
GM49	4.9	—	0.14	—
GM51	6.3	—	0.10	—
GM53	5.7	—	0.11	—
Polyurethane foams (flexible)				
GM21	5.6	—	0.16	—
GM23	5.3	—	0.17	—
GM25	5.7	—	0.15	—
GM27	6.5	—	0.12	—
1/CaCO ₃	7.2	—	0.19	—
Polyurethane foams (rigid)				
GM29	7.9	—	0.10	—
GM31	8.4	—	0.09	—
GM35	6.9	—	0.11	—
Polyisocyanurate foams (rigid)				
GM41	6.8	—	0.12	—
GM43	5.5	—	0.15	—
Phenolic foam	5.5	—	0.17	—

*Ignition data measured in the Flammability Apparatus.
[†]Ignition data measured at the University of Edinburgh, U.K.

generation efficiencies of the reduction zone products (such as smoke, CO, and hydrocarbons).

The flame extinction can also be expressed in terms of the critical heat release rate

$$Q_{cr,i}^* = \Delta H_i \dot{m}_{cr}^* \quad (122)$$

where $Q_{cr,i}^*$ is the critical heat release rate (chemical, convective, or radiative in kW/m²), and ΔH_i is the heat of combustion (chemical, convective, and radiative in kJ/g). Table 3-4.26 lists the critical chemical, convective, and radiative heat release rates for flame extinction, where critical mass loss rate values are taken from Table 3-4.25 and heats of combustion from Table 3-4.11.

The data in Table 3-4.26 suggest that the critical heat release rate for flame extinction is weakly dependent on the chemical nature of the material, contrary to the critical mass loss rate. The critical heat release rates thus can be averaged, which are 100 ± 7 , 53 ± 9 , and 47 ± 10 kW/m² for the chemical, convective, and radiative heat release rates, respectively. For materials with highly reactive vapors, such as polyethylene, large amounts of extinguishing agent are needed to reduce the heat release rate to the critical value.

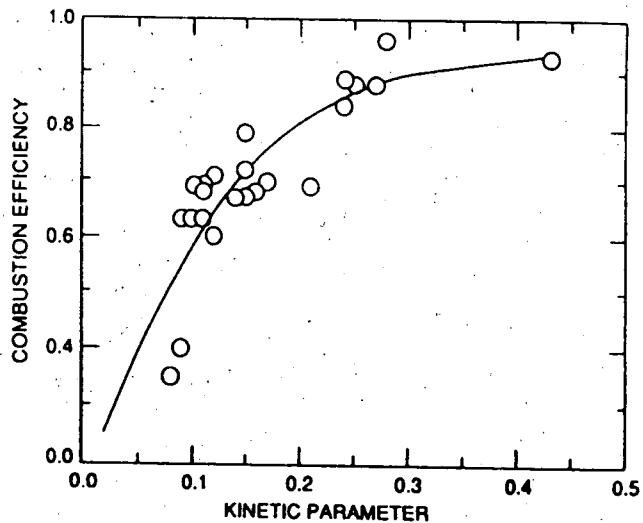


Fig. 3-4.48. Kinetic parameter for flame extinction versus the combustion efficiency and production generation efficiencies. Data are measured in the Flammability Apparatus.

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TABLE 3-4.26 Critical Chemical, Convective, and Radiative Heat Release Rates for Flame Extinction*

Material	Critical Heat Release Rate (kW/m ²)		
	Chemical	Convective	Radiative
Polyoxymethylene	(65)	50	(14)
Polymethylmethacrylate	77	53	24
Polyethylene	96	55	42
Polypropylene	104	61	43
Polyethylene foams	88	51	38
Chlorinated polyethylenes	95	48	47
Polystyrenes	108	44	64
Polyurethane foams (flexible)	101	48	53
Polyurethane foams (rigid)	102	44	58
Average	96 ± 10	51 ± 6	46 ± 12

*Critical mass loss rates from the Flammability Apparatus, and heats of combustion from Table 3-4.11.

For materials with highly non-reactive vapors, such as Teflon™, it is difficult to reach the critical heat release rate values unless high external heat flux is applied.

The energy balance at the surface as the flame extinction condition is reached is¹⁰³

$$\dot{m}'' = \frac{\phi \Delta H_T \dot{m}_{cr}'' + \dot{q}_c'' - \dot{q}_{rr}'' - \dot{q}_{agent}''}{\Delta H_g} \quad (123)$$

$$\dot{Q}_i = \frac{\Delta H_i}{\Delta H_g} (\phi \Delta H_T \dot{m}_{cr}'' + \dot{q}_c'' - \dot{q}_{rr}'' - \dot{q}_{agent}'') \quad (124)$$

where \dot{q}_c'' is the external heat flux (kW/m²); \dot{q}_{rr}'' is the surface re-radiation loss (kW/m²); \dot{q}_{agent}'' is the heat flux removed from the surface or from the flame by the agent as the flame extinction condition is reached (kW/m²); ΔH_i is the chemical, convective, or radiative heat of combustion (kJ/g); and ΔH_g is the heat of gasification (kJ/g). $\Delta H_i/\Delta H_g$ is defined as the Heat Release Parameter (HRP).

Flame suppression/extinguishment by water: The heat flux removed from the surface of a burning material by water, as a result of vaporization, is expressed as¹⁰³

$$\dot{q}_w'' = \epsilon_w \dot{m}_w'' \Delta H_{iv} \quad (125)$$

where ϵ_w is the water application efficiency, \dot{m}_w'' is the water application rate per unit surface area of the material (g/m²-s), and ΔH_{iv} is the heat of gasification of water (2.58 kJ/g). If only part of the water applied to a hot surface evaporates and the other part forms a puddle, such as on a horizontal surface, blockage of flame heat flux to the surface and escape of the fuel from the material surface are expected. Equation 125 thus is modified as

$$\dot{q}_w'' = \dot{m}_w'' (\epsilon_w \Delta H_{iv} + \delta_{iv}) \quad (126)$$

where δ_{iv} is the energy associated with the blockage of flame heat flux to the surface and escape of the fuel vapors per unit mass of the fuel gasified (kJ/g).

From Equations 123 and 126

$$\dot{m}_w'' = \frac{\dot{q}_c''}{\epsilon_w \Delta H_{iv} + \delta_{iv}} + \frac{\phi \Delta H_T \dot{m}_{cr}'' - \dot{q}_{rr}'' - \dot{m}'' \Delta H_g}{\epsilon_w \Delta H_{iv} + \delta_{iv}} \quad (127)$$

At flame extinction, $\dot{m}'' = \dot{m}_{cr}''$ and from Equation 127

$$\dot{m}_{w,ex}'' = \frac{\dot{q}_c''}{\epsilon_w \Delta H_{iv} + \delta_{iv}} + \frac{\dot{m}_{cr}'' (\phi \Delta H_T - \Delta H_g) - \dot{q}_{rr}''}{\epsilon_w \Delta H_{iv} + \delta_{iv}} \quad (128)$$

where $\dot{m}_{w,ex}''$ is the water application rate per unit surface area of the material for flame extinction (g/m²-s). As discussed in reference 103, in the absence of the external heat flux with no water puddle formation at the surface, the critical water application rate for flame extinction is

$$\dot{m}_{w,cr}'' = \frac{\dot{m}_{cr}'' (\phi \Delta H_T - \Delta H_g) - \dot{q}_{rr}''}{\epsilon_w \Delta H_{iv}} \quad (129)$$

where $\dot{m}_{w,cr}''$ is the critical water application rate (g/m²-s), which is related to the fundamental fire property of the material. The calculated values of the critical water application rate for materials are listed in Table 3-4.27, where efficiency of water application was taken as unity. The values were calculated from Equation 128, using data from Table 3-4.11 for the net heats of complete combustion, from Table 3-4.25 for the critical mass loss rate and the kinetic parameter, from Table 3-4.4 for the heats of gasification and surface

TABLE 3-4.27 Critical Water Application Rates for Flame Extinction

Material	\dot{q}_r'' (kW/m ²)	ΔH_T (kJ/g)	ΔH_g (kJ/g)	\dot{m}_{cr}'' (g/m ² -s)	ϕ (g/m ² -s)	Critical Water Appl. Rate (g/m ² -s)
Polyoxymethylene	13	15.4	2.4	4.5	0.43	2.3
Polymethylmethacrylate	11	25.2	1.6	3.2	0.28	2.5
Polyethylene	15	43.6	1.8	2.5	0.27	3.8
Polypropylene	15	43.4	2.0	2.7	0.24	3.0
Polyethylene foams						
1	12	41.2	1.7	2.6	0.24	3.6
2	13	40.8	1.4	2.6	0.25	3.8
3	12	40.8	1.8	2.5	0.25	3.5
4	12	40.8	1.5	2.6	0.25	4.1
Chlorinated polyethylenes						
25% chlorine	12	31.6	2.1	6.6	0.15	2.1
36% chlorine	12	26.3	3.0	7.5	0.12	0
48% chlorine	10	20.6	3.1	7.6	0.13	0
Polystyrene	13	39.2	1.7	4.0	0.21	5.1

re-radiation loss, and using a value of 2.59 kJ/g for the heat of gasification of water.

All the materials listed in Table 3-4.27 burn in normal air without the external heat flux, except polyethylene with 36 and 48 percent chlorine by weight. The critical water application rate for flame extinction for materials that do not burn in normal air without the external heat flux is zero. The materials in Table 3-4.27 that burn without the external heat flux can be arranged in the following order of increased water application rate required for flame extinction: polyoxymethylene, polymethylmethacrylate, and polyethylene with 25 percent chlorine (2.1 to 2.5 g/m²-s) < polyethylene and polypropylene (3.5 to 4.1 g/m²-s) < polystyrene (5.1 g/m²-s).

The data in Table 3-4.27 suggest that the critical water application rate required for flame extinction, with no water puddle at the surface, can be calculated to support the experimental data. The input data for the calculation can be obtained from the measurements for the fire properties in the small-scale apparatuses, such as the oxygen bomb calorimetry, the Flammability Apparatus, the OSU Apparatus, and the Cone Calorimeter. The properties and respective tests are: (1) surface re-radiation loss [from the Critical Heat Flux (CHF) and critical mass loss rate, using ignition tests], (2) heat of gasification using the nonflaming tests, (3) net heat of complete combustion from the oxygen bomb calorimeter, and (4) kinetic parameter (Equation 121) where the ratio of the convective heat transfer coefficient to specific heat is needed. The ratio can be obtained from the methanol combustion at variable oxygen mass fractions and external heat flux for known inlet airflow rates, a procedure that has been used in the Flammability Apparatus for such applications.³³

The first term on the right-hand side of Equation 128 can be considered as the term to account for the effects of fire size as well as the shapes and arrangements of the materials. As the fire intensity increases due to changes in the shape, size, and arrangements of the material, heat flux to the surface of the material increases, and water application rates above and beyond the critical water application rate for flame extinction thus would be required. For example, water application rate for extinguishment of fires burning at the asymptotic limits can be calculated from: (1) the values of the flame heat flux to the surface listed in Table 3-4.5, in place of the external heat flux in Equation 128; and (2) the data for the critical water application rate for flame extinction listed in Table 3-4.27. The calculated water application rates for extinguishment of fires burning at the asymptotic limits are listed in Table 3-4.28. The data show that the first term of Equation 128 becomes very dominant at the asymptotic limit compared to the second term, which is the critical water application rate. In Table 3-4.28, the water application rates at the asymptotic limits are thus calculated on the basis of flame heat flux alone.

Numerous small- and large-scale tests have been performed to assess the extinguishment of fires by water sprays.^{103-108,110-113} For example, small-scale fire suppression/extinguishment tests are performed in the Flammability Apparatus [Figures 3-4.2(a) and (b)], and large-scale fire suppression/extinguishment tests are performed in the Fire Products Collector (Figure 3-4.8) and at the Test Center, mostly at the 30-ft site (Figure 3-4.49).^{27,37,101,102,105,110-114}

Small-Scale Fire Suppression/Extinguishment Tests Using Water and Materials with Two- and Three-Dimensional Configurations Burning in Co- and Natural-Airflow Conditions:

TABLE 3-4.28 Water Application Rate for the Extinguishment of Fires at the Asymptotic Limits*

Material	$m_{w,cr}^*$ (g/m ² -s)	q_f^* (kW/m ²)	Water Appl. Rate (g/m ² -s)
<i>Aliphatic Carbon-Hydrogen Atoms</i>			
Polyethylene	3.8	61	27
Polypropylene	3.0	67	29
Heavy fuel oil (2.6-23 m)	?	29	11†
Kerosene (30-80 m)	?	29	11†
Crude oil (6.5-31 m)	?	44	17†
n-Dodecane (0.94 m)	?	30	12†
Gasoline (1.5-223 m)	?	30	12†
JP-4 (1.0-5.3 m)	?	40	16†
JP-5 (0.60-17 m)	?	39	15†
n-Heptane (1.2-10 m)	?	37	14†
n-Hexane (0.75-10 m)		37	14†
Transformer fluids (2.37 m)			
<i>Aromatic Carbon-Hydrogen Atoms</i>			
Polystyrene (0.93 m)	5.1	75	34
Xylene (1.22 m)	?	37	14†
Benzene (0.75-6.0 m)	?	44	17†
<i>Aliphatic Carbon-Hydrogen-Oxygen Atoms</i>			
Polyoxymethylene	2.3	50	22
Polymethylmethacrylate (2.37 m)	2.5	60	26
Methanol (1.2-2.4 m)	?	27	10†
Acetone (1.52 m)	?	24	9†
<i>Aliphatic Carbon-Hydrogen-Halogen Atoms</i>			
Polyvinylchloride	0	50	19
Tefzel™ (ETFE)	0	50	19
Teflon™ (FEP)	0	52	20

*For water application efficiency of unity with no water puddle at the surface.
 †Calculated from the flame heat flux alone. Because water does not stay at the surface, the flame extinction of liquid pool fires with water is not an efficient process. The efficiency of unity used in the calculations thus may not be correct and actual water application rates would probably be higher than calculated.

Several studies have been performed for these types of configurations and airflow conditions.¹⁰¹⁻¹⁰⁸ For example, small-scale fire suppression/extinguishment tests using water are performed in the Flammability Apparatus, under co- and natural airflow conditions. In the tests, measurements are made, in the presence and absence of water, for the Critical Heat Flux (CHF); Thermal Response Parameter (TRP); mass loss rate; chemical, convective, and radiative heat release rates; generation rates of CO and CO₂; hydrocarbons; smoke; optical transmission through smoke; corrosion in the gas phase; and other products (depending on the need).

The test samples used, with and without the external heat flux, consist of: (1) two-dimensional samples: 100 × 100 mm square and 100-mm-diameter circular samples up to 50 mm in thickness; and (2) three-dimensional samples identified as "sample commodities": (a) cross piles of sticks, defined as the "crib"; single crib is used in the test; and (b) 50-, 75-, and 100-mm cubic boxes; one to eight boxes are arranged in one to four layers with a separation of about 12 mm between the boxes and the layers. The designation used for the arrangement of the boxes is: number of boxes along the length × number of boxes along the width × number of layers, i.e.,

3-114 DESIGN CALCULATIONS

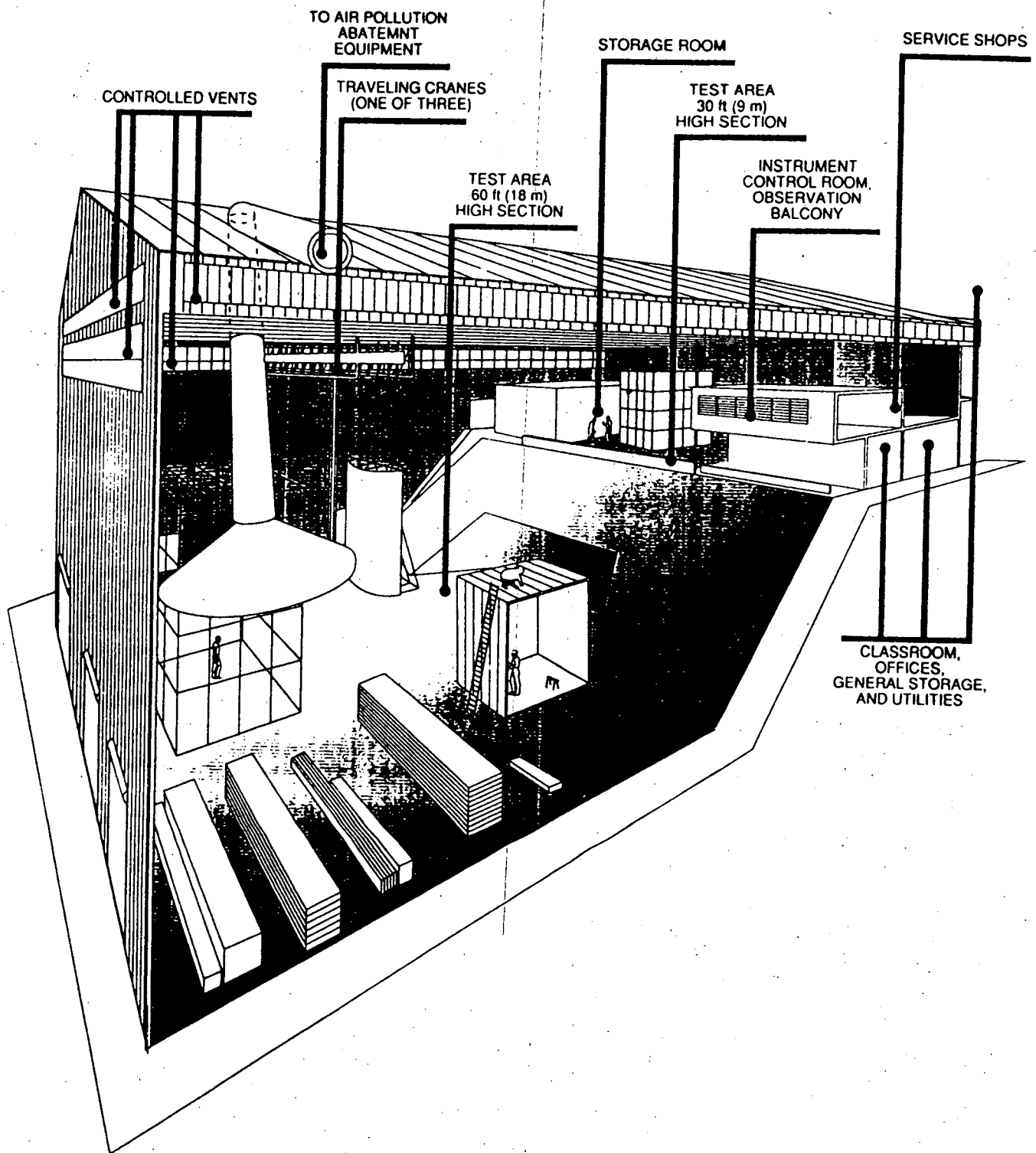


Fig. 3-4.49. The Factory Mutual Research Corporation's Test Center at West Gloucester, RI, where large-scale fire tests are performed.

1. One box with a single layer:
1 × 1 × 1 sample commodity,
2. Two boxes with a single layer:
2 × 1 × 1 sample commodity,
3. Two boxes with two layers:
1 × 1 × 2 sample commodity,
4. Three boxes with three layers:
1 × 1 × 3 sample commodity,

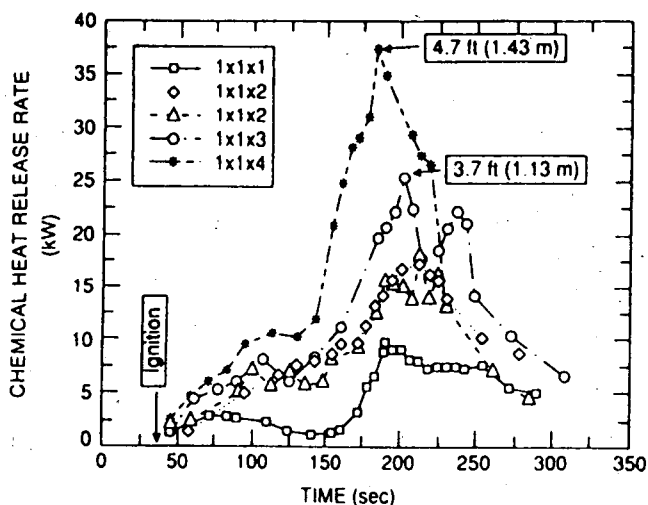


Fig. 3-4.50. Free-burning chemical heat release rate versus time for 100-mm cubic empty corrugated paper boxes arranged as one box per layer for a total of four layers. Each layer is about 12 mm apart. Visual flame heights are indicated for two arrangements. Data were measured in the Flammability Apparatus.

5. Four boxes with four layers:
1 × 1 × 4 sample commodity.
6. Four boxes with a single layer:
2 × 2 × 1 sample commodity.
7. Eight boxes with two layers:
2 × 2 × 2 sample commodity.

There are provisions to use more than eight boxes and four layers. The arrangements have strong effect on the fire intensity as shown in Figure 3-4.50, where chemical heat release rate is plotted against time for 100-mm cubic box with one box to a layer for a total of four layers. Visual flame heights from the bottom of the first box are indicated for two arrangements. The data were measured in the Flammability Apparatus. The data show that the increase in the chemical heat release rate is more than expected from the increase in the surface area. For example, the surface area increases by a factor of 4 from one to four boxes, whereas the peak chemical heat release rate increases by a factor of 5, even though all the surface areas are not burning. This is indicative of the enhancement of the flame heat flux in a three-dimensional arrangement.

In the three-dimensional arrangement of the sample commodities, the water application rate for fire suppression/extinguishment is expected to be governed by the first term rather than by the second term in Equation 128 (see Table 3-4.28), due to the enhancement of the flame heat flux. With water application efficiency of unity and no water puddle at the surface, the water application rate required for flame suppression/extinguishment for the three-dimensional arrangement of sample commodities, from Table 3-4.28 for solids, is expected to be in the range of 19 to 34 g/m²-s. These rates are about ten times the critical water application rates for flame extinction (Table 3-4.27).

Figures 3-4.51 through 3-4.53 show examples of the fire extinguishment test data from the Flammability Apparatus for 100-mm-diameter and 13-mm-thick circular Whatman No. 3 cellulosic filter paper slabs.¹¹⁴ Figure 3-4.51 is a plot of the average heat flux removed from the surface of wet filter paper by the gasification of water versus the average heat

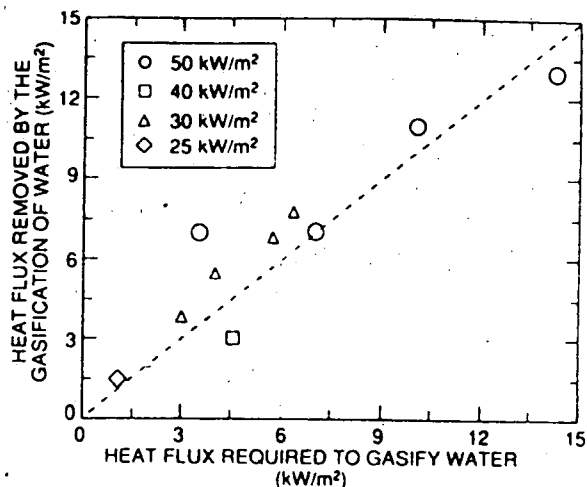


Fig. 3-4.51. Average heat flux removed from the surface by the gasification of water versus the average heat flux required for the gasification of water. The data are for 100-mm-diameter and 13-mm-thick horizontal wetted slabs of the Whatman No. 3 cellulosic filter paper. The slabs were exposed to external heat fluxes in the range of 25 to 50 kW/m² in the Flammability Apparatus under co-flow conditions in normal air. The slabs were wetted with different amounts of water until saturation. Data are taken from reference 114.

flux required to gasify the water. The average heat flux removed from the surface, during the test time period, is calculated from Equation 123 using the measured values of the mass loss rate with and without the water on the surface, and the values from Table 3-4.4 for the heats of gasification and surface re-radiation loss of filter paper. The average heat

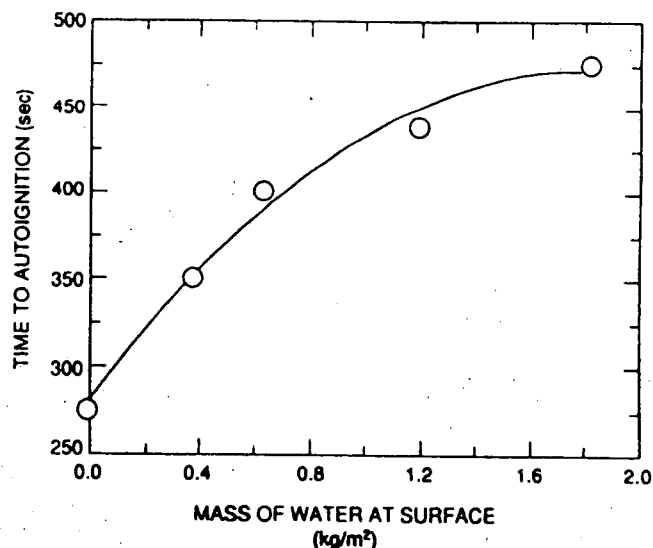


Fig. 3-4.52. Time to autoignition versus the total amount of water used to wet the 100-mm-diameter and 13-mm-thick horizontal wetted slabs of the Whatman No. 3 cellulosic filter paper. The slabs were exposed to external heat fluxes in the range of 25 to 50 kW/m² in the Flammability Apparatus under co-flow conditions in normal air. The slabs were wetted with different amounts of water until saturation. Data are taken from reference 114.

3-116 DESIGN CALCULATIONS

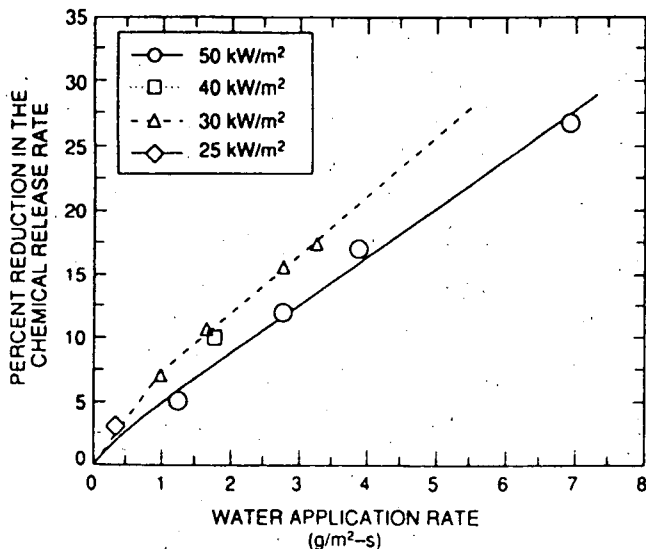


Fig. 3-4.53. Percent reduction in the chemical heat release rate versus the water application rate for the combustion of 100-mm-diameter and 13-mm-thick horizontal wetted slabs of the Whatman No. 3 cellulosic filter paper. The slabs were exposed to external heat fluxes in the range of 25 to 50 kW/m² in the Flammability Apparatus under co-flow conditions in normal air. Data are taken from reference 114.

flux required to gasify the water, during the test time period, is calculated from Equation 125 using the measured values of the mass of water applied to the surface, where efficiency of application is unity. As expected from the published literature on this subject,^{101-108,114} there is excellent agreement between the heat flux removed from the surface by water and heat flux required to gasify it.

The data in Figure 3-4.52 show that the time to sustained autoignition for the filter paper increases with increase in the amount of water at the surface, as expected due to removal of energy by: (1) the gasification of water and (2) blockage of flame heat flux to the surface and escape of the fuel vapors. It is well known that the wetting action of water delivered from sprinklers is effective in resisting the fire jump across the aisles of stored commodities in warehouses. The wetting action of water is considered to be one of the major advantages of the sprinkler fire protection.

Figure 3-4.53 shows the percent reduction in the chemical heat release rate versus the water application rate for the cellulosic filter paper sample exposed to various heat fluxes. From Equation 124, the reduction in the chemical heat release rate for a fixed external heat flux value can be expressed as follows

$$Q_{ch}^* - Q_{ch,w}^* = \frac{\Delta H_{ch}}{\Delta H_g} \dot{q}_w^* \quad (130)$$

where $Q_{ch,w}^*$ is the chemical heat release rate in the presence of water (kW/m²). $\Delta H_{ch}/\Delta H_g$ is the Heat Release Parameter (HRP). From Equations 126 and 130

$$Q_{ch}^* - Q_{ch,w}^* = \text{HRP}(\epsilon_w \Delta H_w + \delta_w) \dot{m}_w^* \quad (131)$$

In the tests, the water was applied directly to the surface and there was no puddle formation on the surface, thus $\epsilon_w = 1$

and $\delta_w = 0$. For cellulosic filter paper, HRP = 3.6 and the heat of gasification of water is 2.6 kJ/g. Using these values in Equation 131

$$\frac{Q_{ch}^* - Q_{ch,w}^*}{Q_{ch}^*} \times 100 = \left[\frac{100 \times 3.6 \times 2.6}{Q_{ch}^*} \right] \dot{m}_w^* \quad (132)$$

or, the percent reduction in the chemical heat release rate is

$$\frac{Q_{ch}^* - Q_{ch,w}^*}{Q_{ch}^*} \times 100 = \frac{936}{Q_{ch}^*} \dot{m}_w^* \quad (133)$$

Equation 133 suggests that a plot of the percentage reduction in the chemical heat release rate versus the water application rate should be a straight line with a slope of $936/Q_{ch}^*$. For the external heat flux values of 25, 30, 40, and 50 kW/m², the free-burning chemical heat release rates are 120, 190, 210, and 235 kW/m², respectively. Thus the slopes at these fluxes are 7.8, 4.9, 4.5, and 4.0 (g/m²-s)⁻¹, respectively. The slopes of the lines from the experimental data for 30 and 50 kW/m² in Figure 3-4.53 are 7 and 3.9 (g/m²-s)⁻¹, respectively, in excellent agreement with the expected slopes from Equation 133. Thus the experimental data support the heat balance mechanism for flame extinction by the gasification of water, as long as there is no water puddle at the surface.

Small-Scale Fire Suppression/Extinguishment Tests Using Water with Horizontal and Vertical Slabs Burning under Natural Airflow Condition: Several studies have been performed in this type of configuration.¹⁰³⁻¹⁰⁸ For example, fire extinguishment tests have been performed with water applied to the burning vertical and horizontal slabs of polymethylmethacrylate (PMMA), polyoxymethylene (POM), polyethylene (PE), and polystyrene (PS).¹⁰⁷ The horizontal slabs were 0.18-m squares and the vertical slabs were 0.18 m wide and 0.37 m high.¹⁰⁷ The slabs were exposed to external heat flux values in the range 0 to 17 kW/m² in normal air in the presence of water applied at a rate of 0 to 7.8 g/m²-s.¹⁰⁷ The water application efficiency was close to unity.

Figure 3-4.54 shows the time to flame extinction and mass loss rate for various external heat fluxes applied to the

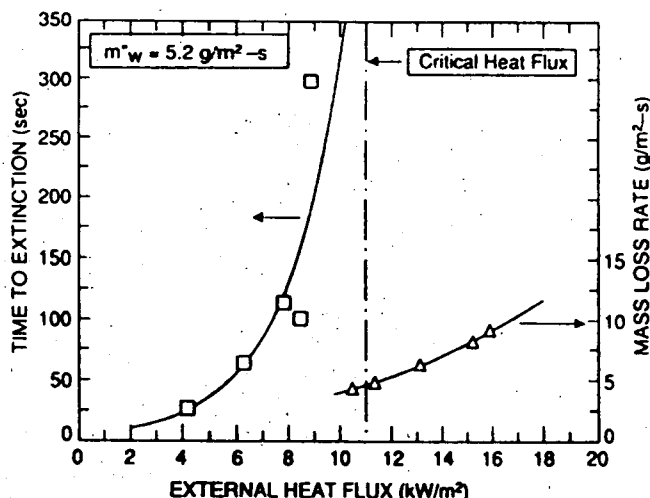


Fig. 3-4.54. Time to flame extinction and mass loss rate at various external heat fluxes for the combustion of a 0.18-m-wide, 0.37-m-high, and 50-mm-thick vertical slab of polymethylmethacrylate in the presence of water with an application rate of 5.2 g/m²-s. Data are taken from the study reported in reference 107.

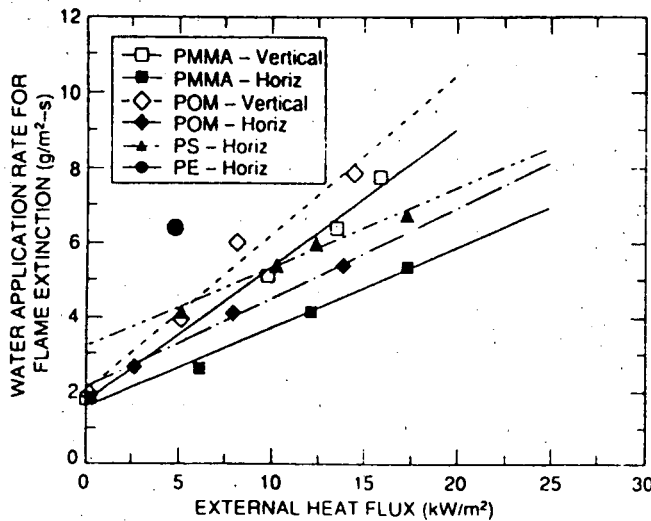


Fig. 3-4.55. Water application rate required for flame extinction of horizontal and vertical slabs of polymethylmethacrylate (PMMA), polyoxymethylene (POM), polystyrene (PS), and polyethylene (PE) burning in normal air at various external heat fluxes. Data are taken from the study reported in reference 107.

surface of the vertical PMMA slab burning in normal air with a water application rate of 5.2 g/m²-s; the data in the figure are taken from the study reported in reference 107. With increase in the external heat flux, the time to flame extinction increases until, close to the Critical Heat Flux (CHF) value of 11 kW/m² (Table 3-4.2), it goes to infinity (no flame extinction). The mass loss rate data in Figure 3-4.54 show that, close to the CHF value, the mass loss rate approaches the critical rate of 3.2 g/m²-s, determined from the ignition experiments (Table 3-4.26). These data support the fire point theory.^{104,106}

Figure 3-4.55 shows water application rates required for flame extinction for vertical slabs of polymethylmethacrylate (PMMA), polyoxymethylene (POM), polystyrene (PS), and polyethylene (PE) burning in normal air with various external heat flux exposure. The data satisfy Equation 127:

Polymethylmethacrylate
 Vertical

$$\dot{m}_w^* = 0.37\dot{q}_c^* + 1.67 \quad (R^2 = 0.99) \quad (134)$$

Horizontal

$$\dot{m}_w^* = 0.22\dot{q}_c^* + 1.56 \quad (R^2 = 0.99) \quad (135)$$

Polyoxymethylene
 Vertical

$$\dot{m}_w^* = 0.42\dot{q}_c^* + 1.97 \quad (R^2 = 0.98) \quad (136)$$

Horizontal

$$\dot{m}_w^* = 0.24\dot{q}_c^* + 2.08 \quad (R^2 = 0.99) \quad (137)$$

Polystyrene
 Horizontal

$$\dot{m}_w^* = 0.22\dot{q}_c^* + 3.1 \quad (R^2 = 0.98) \quad (138)$$

Equations 134 and 136 show that, for vertical slabs, the inverse of the slope is equal to 2.7 and 2.3 kJ/g for PMMA and POM, respectively, which are close to the heat of gasification of water (2.6 kJ/g). Thus, the effect of water puddle at the surface is negligible as expected for the vertical surfaces. Equations 135, 137, and 138 show that, for horizontal surfaces, the inverse of the slopes for PMMA, POM, and PS are 4.6, 4.1, and 4.6 kJ/g, respectively, which are almost twice the value for the heat of gasification of water. The data for the horizontal slabs thus suggest that the blockage of flame heat flux and escape of the fuel from the surface is as important as the gasification of water. The energy associated with the blockage is about the same magnitude as the energy associated with the gasification of water.

Large-Scale Fire Suppression/Extinguishment Tests Using Water: Numerous large-scale fire suppression/extinguishment tests have been performed.^{101-106,111-114} In almost all cases the materials are heterogeneous and the configurations are three dimensional, identified as "commodities." Tests are performed under natural airflow conditions with water applied from a series of sprinklers. The sprinklers are either at the ceiling or close to the top surface of the commodities. At FMRC, large-scale fire suppression/extinguishment tests are performed in the Fire Products Collector (Figure 3-4.8) and at the FMRC Test Center, mostly at the 30-ft site (Figure 3-4.49).^{27,37,101,102,105,110-114}

FMRC classifies a stored commodity by its potential fire protection challenge, which is essentially dependent on the commodity's ability to release heat in a fire in the presence of water.¹¹⁰ Most stored commodities are classified into one of the six classes, such as the following examples.¹¹⁰

Noncombustible: Do not burn and do not, by themselves, require sprinkler protection.

Combustibles: Class I: Example—noncombustible products on wood pallets or noncombustible products packaged in ordinary corrugated paper boxes or wrapped in ordinary paper on wood pallets. Class I commodity is simulated by glass jars in compartmented corrugated paper boxes.

Class II: Example—Class I products in more combustible packaging, such as wood crates or multiple-thickness corrugated boxes. Class II commodity is simulated by metal-lined double tri-wall corrugated paper boxes.

Class III: Example—packaged or unpackaged wood, paper, or natural-fiber cloth, or products made from them, on wood pallets. Class III commodity is simulated by using paper cups in compartmented corrugated paper boxes.

Class IV: Class I, II, and III commodities containing no more than 25 percent (by volume) or 15 percent by weight of high-heat-release-rate synthetic materials. Class IV commodity is simulated by polystyrene (15 percent by weight) and paper cups in compartmented corrugated paper boxes.

Group A Plastics: Simulated by polystyrene cups in compartmented corrugated paper boxes.

For the tests in the Fire Products Collector, the commodities are used in a 2 × 2 × 2 arrangement (two pallet loads along the length × two pallet loads along the width × two layers).^{101,102,110,113} Each pallet load consists of a wood pallet with eight 0.53-cubic corrugated paper boxes, containing products under test, in a 2 × 2 × 2 arrangement (two boxes along the length × two boxes along the width in two

3-118 DESIGN CALCULATIONS

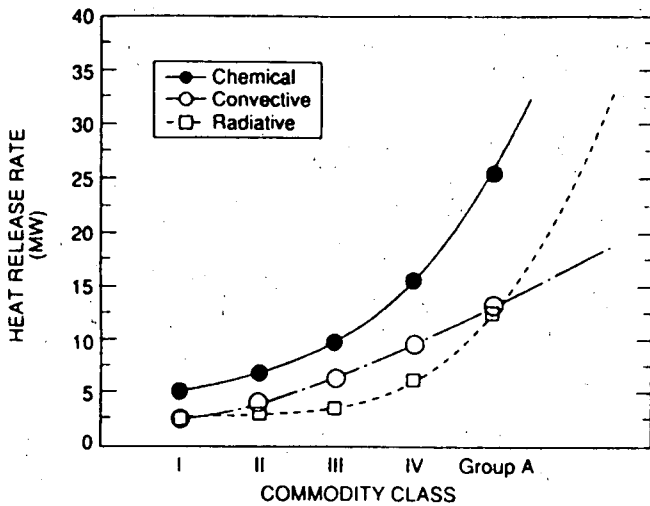


Fig. 3-4.56. Calculated average peak heat release rates for free-burning fires of simulated commodities from the data measured in the Fire Products Collector (10,000-kW-scale Flammability Apparatus). Data are taken from references 101, 102, 110, 113, and 114.

layers, with boxes touching each other). Each pallet load is a 1-m (42-in.) cube of product and separated by about 150 mm. This arrangement leads to the test commodity consisting of eight pallet loads with 64 corrugated paper boxes containing products with overall dimensions of 2.3 m (7.5 ft) x 2.3 m (7.5 ft) x 2.9 m (9.7 ft) high.

In the Fire Products Collector (10,000-kW-scale Flammability Apparatus) fire suppression/extinguishment tests, water is applied at the top of the commodity, in a uniform fashion, with application rates in the range of 0 to 407 g/m²-s (0 to 0.6 gpm per sq ft). The range of the water application rates is about ten times the predicted range for the three-dimensional arrangements (Table 3-4.28 with water application efficiency of unity and no water puddles at the surfaces). It thus appears that blockage of flame heat flux to the surface and escape of fuel vapors are as important as gasification of water for the fire suppression/extinguishment of the commodities, similar to the flame extinction for horizontal slabs (Equations 135, 137, and 138) in small-scale tests, discussed previously.

Figure 3-4.56 shows the calculated values of the free-burning average peak heat release rate for the simulated Class I through Group A plastic commodities. In the calculations data measured in the Fire Products Collector (10,000-kW-scale Flammability Apparatus) were used.¹¹⁴ The Class I through Class III commodities were made of cellulosic materials and had lower heat release rates. This behavior is expected on the basis of the values of: (1) surface re-radiation loss and heat of gasification (Table 3-4.4), (2) flame heat flux (close to polyoxymethylene, Table 3-4.5), (3) heat of combustion (Table 3-4.11), and (4) Heat Release Parameter (Table 3-4.12) for wood and paper. The heat release rates for Class I through Class III commodities increase gradually from Class I through Class III.

Introduction of polystyrene from about 15 percent (Class IV) to 100 percent (plastics Group A) inside the corrugated paper boxes results in an exponential increase in the chemical and radiative heat release rates as indi-

cated in Figure 3-4.56. This behavior is expected on the basis of the higher values of: (1) heat of gasification (Table 3-4.4), (2) flame heat flux (Table 3-4.5), (3) heat of combustion (Table 3-4.11), and (4) Heat Release Parameter (Table 3-4.12) for polystyrene compared to the values for the cellulosic materials in Class I through III commodities. The higher intensity fire due to the introduction of polystyrene is also indicated by the higher water application rates required for fire suppression/extinguishment in Figure 3-4.57. The higher water requirement for fire suppression/extinguishment for Class IV and plastics Group A commodities is expected from Equation 128, due to higher value of the flame heat flux which dominates the water application rate requirements.

Flame Extinction by the Processes in the Gas Phase

The process of flame extinction by gaseous, powdered, and foaming agents and by increase in the local equivalence ratio is predominantly a gas-phase process and thus is different from the process of flame extinction by water, which occurs predominantly in the solid phase at the surface of the material. The kinetic parameter for flame extinction defined in Equation 118, however, is still applicable¹⁰³

$$\phi = \frac{\phi_0 - \kappa Y_{j,ex} \left[\frac{1 + \Delta c_p (T_{ad} - T_a) + \Delta H_D}{\Delta H_D^0 Y_0} \right]}{1 - Y_{j,ex}} \quad (139)$$

where ϕ is the kinetic parameter in the presence of the extinguishing agent, ϕ_0 is the kinetic parameter in the absence of the extinguishing agent, κ is the ratio between the kinetic parameters at the flame temperature and at the adiabatic flame temperature, $Y_{j,ex}$ is the mass fraction of the

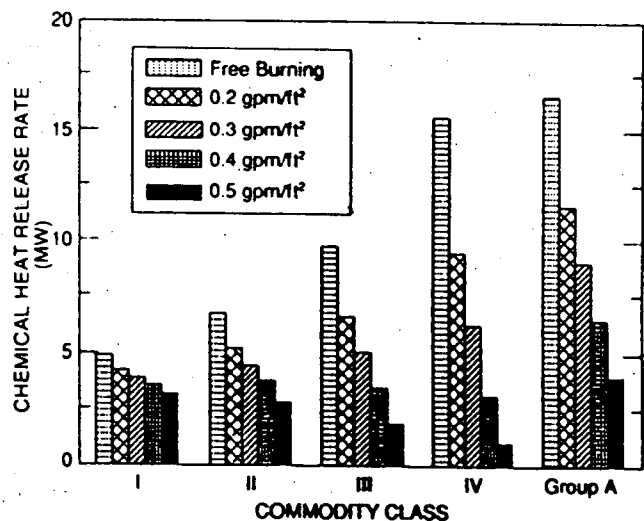


Fig. 3-4.57. Calculated average peak chemical heat release rates at various water application rates for fires of simulated commodities from the data measured in the Fire Products Collector (10,000-kW-scale Flammability Apparatus). Data are taken from references 101, 102, 110, 113, and 114. One gpm/ft² = 769 g/m²-s.

extinguishing agent, Δc_p is the difference between the heat capacities of the extinguishing agent and the fire products (kJ/g-K), T_{ad} is the adiabatic flame temperature at the stoichiometric limit (K), T_0 is the initial temperature of the reactants (K), and ΔH_D is the heat of dissociation (kJ/g).

Equation 139 shows that the addition of an extinguishing agent reduces the kinetic parameter from its normal value and includes the effects of four flame extinction mechanisms:¹⁰³ (1) dilution, effects are included in the $\kappa Y_{j,ex}$ term; (2) added thermal capacity, effects are included in Δc_p ; (3) chemical inhibition, effects are included through increases in T_{ad} value; for most fuels the adiabatic flame temperature at the stoichiometric limit is about 1700 K,¹⁰³ more reactive fuels, such as hydrogen, have lower adiabatic flame temperature at the stoichiometric limit, and less reactive or retarded materials have higher values of the adiabatic flame temperature at the stoichiometric limit; and (4) kinetic chain breaking and endothermic dissociation through Δc_p and ΔH_D terms.

From Equation 123 in the presence of an extinguishing agent that works in the gas phase

$$\dot{m}'' = \frac{\varphi \Delta H_T \dot{m}_{cr}'' + \dot{q}_c'' - \dot{q}_{rr}''}{\Delta H_g} \quad (140)$$

For a fixed value of the external heat flux, the addition of an extinguishing agent reduces the normal value of the kinetic parameter by one or more of the four mechanisms expressed by Equation 139; the mass loss rate decreases and approaches the critical value at which the flame is extinguished. Increase in the external heat flux would increase the mass loss rate, and further addition of the extinguishing agent would be needed to reduce the mass loss to its critical value and to reestablish the flame extinction condition. Continued increase in the extinguishing agent with external heat flux will result in the first term in the denominator on the right-hand side of Equation 140 to become zero, and the equation will represent a nonflaming fire.

For a fixed airflow rate, as is generally the case in enclosure fires where the extinguishing agent working in the gas phase is used, increase in the mass loss rate due to external heat flux results in an increase in the equivalence ratio, defined in Equation 36. As the equivalence ratio increases and approaches values of 4.0 and higher, the combustion efficiency approaches values less than or equal to 0.40, flames are extinguished, and nonflaming conditions become important.^{36,37} Thus the upper limit for the application of the extinguishing agent working in the gas phase is dictated by the equivalence ratio ≥ 4.0 and/or the combustion efficiency ≤ 0.40 . Under nonflaming conditions, increase in the external heat flux increases the generation rate of the fuel vapors and the reduction-zone products.

Flame Extinction by Reduced Mass Fraction of Oxygen

Flame extinction by reduced mass fraction of oxygen can be the result of: (1) dilution and heat capacity effects due to the addition of inert gases, such as N_2 , CO_2 , etc.; and (2) chemical effects due to the retardation of chemical reactions and reduction in the flame heat flux to the surface, especially the radiative component.

Theoretical and experimental analyses have been performed for flame extinction by reduced oxygen mass frac-

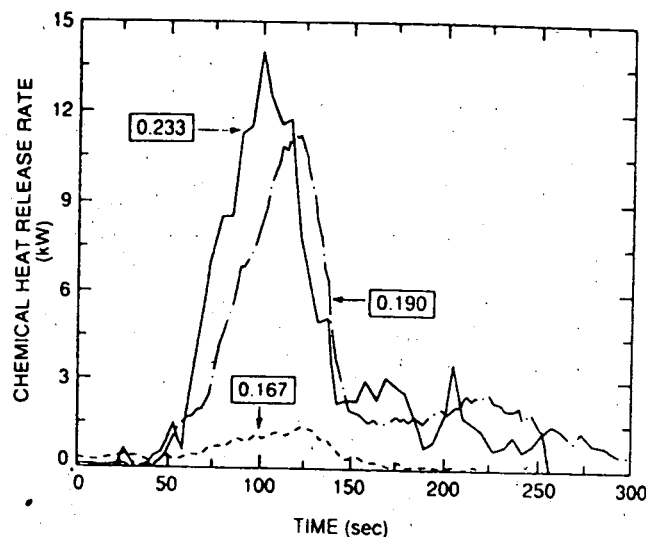


Fig. 3-4.58. Chemical heat release rate versus time for 50-mm empty corrugated paper boxes in a $2 \times 2 \times 2$ arrangement (two boxes along the length \times two boxes along the width \times two layers, for a total of eight boxes separated by about 12 mm). Measurements were made in the Flammability Apparatus with no external heat flux under the co-flow condition at various oxygen mass fractions, which are indicated in the figure.

tions. For example, for polymethylmethacrylate (PMMA), an oxygen mass fraction value of 0.180 is predicted for flame extinction¹¹⁵ compared to the experimental values of 0.181 for a 70-mm-wide, 190-mm-high, and 19-mm-thick vertical PMMA slab¹¹⁶ and 0.178 for a 100-mm-wide, 25-mm-thick, and 300- and 610-mm-high vertical slabs of PMMA, and 25-mm-diameter and 610-mm-high vertical cylinder of PMMA.² The critical values of the chemical, convective, and radiative heat release for PMMA are 106, 73, and 33 kW/m², respectively,² showing a trend similar to one reported in Table 3-4.26. At oxygen mass fractions equal to or less than 0.201, flames are unstable and faint blue in color.²

The effect of increased external heat flux on flame extinction due to reduced oxygen mass fraction has been examined for the buoyant turbulent diffusion flames. For example, for rectangular and circular horizontal PMMA slabs, 0.06 to 0.10 m² in area and 0.03 to 0.05 m in thickness, exposed to external heat flux values of 0, 40, 60, and 65 kW/m², flame extinction is found at oxygen mass fractions of 0.178, 0.145, 0.134, and 0.128, respectively.²⁷ The data support Equation 140 and show that, for buoyant turbulent diffusion flames, flaming can occur up to relatively low oxygen mass fraction values; the only condition is that, in the gas phase, the reactant-oxidizer mixture is within the flammability limit.

The effect of reduced oxygen mass fraction on flame extinction of materials in the three-dimensional arrangement, where flame heat flux is enhanced, has been examined. Figure 3-4.58 shows an example where chemical heat release rates at oxygen mass fractions of 0.233, 0.190, and 0.167 versus time are shown for the combustion of 50-mm cubes of empty corrugated paper boxes in a $2 \times 2 \times 2$ arrangement. The weight of each box is about 13 g (839 g/m²). The measurements are from the Flammability Apparatus.

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In Figure 3-4.58, at oxygen mass fraction of 0.167, the flame is close to the extinction condition, only 10.5 percent of the initial weight of the boxes is consumed, which is equivalent to consumption of a single box with a surface area of about 0.0155 m². The peak chemical heat release rate close to flame extinction, in Figure 3-4.58, is about 1.5 kW or 97 kW/m², using a surface area of 0.0155 m². This value is in excellent agreement with the average value in Table 3-4.26, derived from the critical mass loss rates for ignition. The data in Figure 3-4.58 for the three-dimensional arrangement of the corrugated boxes thus support the fire point theory,^{104,106} independence of the critical heat release rate for flame extinction from the geometrical arrangement and surface areas of the materials, and Equations 139 and 140 as originally formulated in reference 103.

NOMENCLATURE

<i>A</i>	total exposed surface area of the material (m ²)
<i>a_j</i>	mass coefficient for the product yield (g/g)
<i>b_j</i>	molar coefficient for the product yield (g/mole)
<i>B_{cr}</i>	critical mass transfer number ($\frac{Y_{O_2} \Delta H_{O_2}^*}{\Delta H_{g,con}}$)
CHF	Critical Heat Flux (kW/m ²)
\dot{C}_O	mass consumption rate of oxygen (g/m ² -s)
$\dot{C}_{stoch,O}$	stoichiometric mass consumption rate of oxygen (g/m ² -s)
<i>c_O</i>	mass of oxygen consumed per unit mass of fuel (g/g)
<i>c_p</i>	specific heat (kJ/g-K)
Δc_p	difference between the heat capacities of the extinguishing agent and the fire products (kJ/g-K)
CDG	Carbon Dioxide Generation calorimetry
<i>D</i>	optical density $\{[\ln(I_0/I)]/\ell\}$ (1/m)
<i>D_{corr}</i>	metal corrosion (penetration depth or metal loss in microns, angstroms, mils)
<i>E_j</i>	total amount of heat generated in the combustion of a material (kJ)
<i>f_j</i>	volume fraction of a product (-)
<i>f_p</i>	fire property
FPI	Fire Propagation Index 1000 (0.42 \dot{Q}_{ch}^*) ^{1/3} /TRP
\dot{G}_j^*	mass generation rate of product <i>j</i> (g/m ² -s)
$\dot{G}_{stoch,j}^*$	stoichiometric mass generation rate of product <i>j</i> (g/m ² -s)
GTR	Gas Temperature Rise calorimetry
ΔH_i	heat of combustion per unit mass of fuel vaporized (kJ/g)
ΔH_{CO}	heat of complete combustion of CO (10 kJ/g)
ΔH_D	heat of dissociation (kJ/g)
ΔH_g	heat of gasification at ambient temperature (kJ/g)
$\Delta H_{g,con}$	flame convective energy transfer to the fuel per unit mass of fuel gasified (kJ/g)
ΔH_m	heat of melting at the melting temperature (kJ/g)
ΔH_T	net heat of complete combustion per unit of fuel vaporized (kJ/g)
ΔH_v	heat of vaporization at the vaporization temperature (kJ/g)
ΔH_w	heat of gasification of water (2.58 kJ/g)
ΔH_{CO}^*	net heat of complete combustion per unit mass of CO generated (kJ/g)
$\Delta H_{CO_2}^*$	net heat of complete combustion per unit mass of CO ₂ generated (kJ/g)

$\Delta H_{O_2}^*$	net heat of complete combustion per unit mass of oxygen consumed (kJ/g)
HRP	Heat Release Parameter ($\Delta H_i/\Delta H_g$)
<i>h_j</i>	mass coefficient for the heat of combustion (kJ/g)
<i>l/l₀</i>	fraction of light transmitted through smoke (-)
<i>j</i>	fire product
<i>k</i>	thermal conductivity (kW/m-K)
<i>L_p</i>	smoke point (m)
ℓ	optical path length (m)
\dot{m}^*	mass loss rate (g/m ² -s)
\dot{m}_w^*	water application rate per unit surface area of the material (g/m ² -s)
<i>M</i>	molecular weight (g/mole)
<i>m_i</i>	molar coefficient for the heat of combustion (kJ/mole)
MOD	mass optical density (DV/Aim^*) (m ² /g)
<i>m_{air}</i>	mass flow rate of air (g/s)
OC	Oxygen Consumption calorimetry
\dot{q}_e^*	external heat flux (kW/m ²)
\dot{q}_i^*	flame heat flux (kW/m ²)
\dot{Q}_i^*	heat release rate per unit sample surface area ($\dot{m}^* \Delta H_{ch}$) (kW/m ²)
\dot{Q}_l^*	heat release rate per unit sample width (kW/m)
<i>R_{corr}</i>	corrosion rate (Å/min)
<i>S</i>	stoichiometric mass air-to-fuel ratio (g/g)
<i>t</i>	time (s)
<i>t_f</i>	time at which there is no more vapor formation (s)
<i>t₀</i>	time at which the sample is exposed to heat (s)
<i>T</i>	temperature (K)
ΔT_{ig}	ignition temperature above ambient (K)
TRP	Thermal Response Parameter [$\Delta T_{ig}(kpc_p)$] ^{1/2} (kW-s ^{1/2} /m ²)
<i>u</i>	fire propagation rate [dX_p/dt] (mm/s or m/s)
<i>v_g</i>	co-flow air velocity (m/s)
\dot{V}	total volumetric flow rate of fire product-air mixture (m ³ /s)
\dot{W}	total mass flow rate of the fire product-air mixture (g/s)
<i>W_f</i>	total mass of the material lost in the flaming and nonflaming fire (g)
<i>W_j</i>	total mass of product <i>j</i> generated in the flaming and nonflaming fire (g)
<i>X_f</i>	flame height (m or mm)
<i>X_p</i>	pyrolysis front (mm or m)
<i>X_i</i>	total length available for fire propagation (m or mm)
<i>y_j</i>	yield of product <i>j</i> (\dot{G}_j^*/\dot{m}^*)
<i>Y_{ext}</i>	mass fraction of the extinguishing agent (-)
<i>Y_O</i>	mass fraction of oxygen (-)

Greek

α	correlation coefficient (nonflaming fire) (-)
β	correlation coefficient (transition region) (-)
δ_{iv}	energy associated with the blockage of flame heat flux to the surface and escape of fuel vapors per unit mass of the fuel gasified (kJ/g)
ϵ_{iv}	water application efficiency
ϕ	kinetic parameter for flame extinction
ξ	correlation coefficient (transition region) (-)
Φ	equivalence ratio ($S\dot{m}^*/\dot{m}_{air}$)
χ_{ch}	combustion efficiency ($\dot{Q}_{ch}^*/\dot{m}^* \Delta H_T$) (-)

X_{con}	convective component of the combustion efficiency ($\dot{Q}_{con}/\dot{m}^* \Delta H_T$) (-)
X_{rad}	radiative component of the combustion efficiency ($\dot{Q}_{rad}/\dot{m}^* \Delta H_T$) (-)
η_j	generation efficiency ($G_j^*/\dot{m}^* \Psi_j$) (-)
κ	ratio between the kinetic parameters for the flame temperature and adiabatic flame temperature (-)
λ	wavelength of light (μm)
σ	Stefan-Boltzmann constant (56.7×10^{-12} kW/m ² -K ⁴)
τ	average specific extinction area (m ² /g)
μ	corrosion parameter (angstrom-minutes-ml units)
ρ	density (g/m ³)
ν_j	stoichiometric coefficient of product j (-)
ν_O	stoichiometric coefficient of oxygen (-)
Ψ_j	stoichiometric yield for the maximum conversion of fuel to product j (-)
Ψ_O	stoichiometric mass oxygen-to-fuel ratio (g/g)
ζ	ratio of fire properties for ventilation-controlled to well-ventilated combustion
ζ_{oxid}	oxidation zone product generation efficiency ratio (-)
ζ_{red}	reduction zone product generation efficiency ratio (-)

Subscripts

a	air or ambient
ad	adiabatic
asy	asymptotic
ch	chemical
con	convective
$corr$	corrosion
cr	critical
e	external
ex	extinguishment
f	flame or fuel
fc	flame convective
fr	flame radiative
g	gas
$g.con$	flame convective energy for fuel gasification
i	chemical, convective, radiative
ig	ignition
j	fire product
n	net
0	initial
$oxid$	oxidation zone of a flame
rad	radiation
red	reduction zone of a flame
$stoich$	stoichiometric for the maximum possible conversion of fuel monomer to a product
rr	surface re-radiation
s	surface
vc	ventilation-controlled fire
w	water
wv	well-ventilated fire
∞	infinite amount of air

Superscripts

\cdot	per unit time (s ⁻¹)
\cdot	per unit width (m ⁻¹)
\cdot	per unit area (m ⁻²)

Definitions

Chemical heat of combustion	calorific energy generated in chemical reactions leading to varying degrees of incomplete combustion per unit fuel mass consumed
Convective heat of combustion	calorific energy carried away from the flame by the fire products-air mixture per unit fuel mass consumed
Heat of gasification	energy absorbed to vaporize a unit mass of fuel originally at ambient temperature
Heat release parameter	calorific energy generated per unit amount of calorific energy by the fuel
Kinetic parameter for flame extinction	maximum fraction of combustion energy that the flame reactions may lose to the sample surface by convection without flame extinction
Net heat of complete combustion	calorific energy generated in chemical reactions leading to complete combustion, with water as a gas, per unit fuel mass consumed
Radiative heat of combustion	calorific energy emitted as thermal radiation from the flame per unit fuel mass consumed

Abbreviations

ABS	acrylonitrile-butadiene-styrene
CPVC	chlorinated polyvinylchloride
CR	neoprene or chloroprene rubber
CSP (or CSM)	chlorosulfonated polyethylene rubber (Hypalon™)
CTFE	chlorotrifluoroethylene (Kel-F™)
E-CTFE	ethylene-chlorotrifluoroethylene (Halar™)
EPR	ethylene propylene rubber
ETFE	ethylenetetrafluoroethylene (Tefzel™)
EVA	ethylvinyl acetate
FEP	fluorinated polyethylene-polypropylene (Teflon™)
IPST	isophthalic polyester
PAN	polyacrylonitrile
PC	polycarbonate
PE	polyethylene
PEEK	polyether ether ketone
PES	polyethersulphone
PEST	polyester
PET	polyethyleneterephthalate (Melinex™, Mylar™)
PFA	perfluoroalkoxy (Teflon™)
PMMA	polymethylmethacrylate
PO	polyolefin
POM	polyoxymethylene
PP	polypropylene
PS	polystyrene
PTFE	polytetrafluoroethylene (Teflon™)
PU	polyurethane
PVEST	polyvinylester
PVCl ₂	polyvinylidene chloride (Saran™)
PVF	polyvinyl fluoride (Tedlar™)
PVF ₂	polyvinylidene fluoride (Kynar™, Dyflor™)
PVC	polyvinylchloride
SBR	styrene-butadiene rubber
TFE	tetrafluoroethylene (Teflon™)
XLPE	crosslinked polyethylene

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ATTACHMENT 6.11

Symposium Series 599, Fire and Polymers II
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Fire and Polymers II

Materials and Tests for Hazard Prevention

Gordon L. Nelson, EDITOR
Florida Institute of Technology

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Fire and Polymers II: Materials and Tests for Hazard Prevention

Presents approaches to increasing the effectiveness of flame retardancy in polymers. Discusses non-halogen flame retardants, including phosphorus, metals, and metal compounds. Describes the use of char forming materials and the effects of surface changes on flammability. Provides a discussion on the state-of-the-art of smoke and toxicity issues. Reviews the latest tools and models for fire performance assessment. Examines regulation, corrosivity, recycling, environmental questions, and real scale performance assessment issues in the U.S. and Europe.

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FIRE PROPERTIES OF MATERIALS FOR MODEL BASED ASSESSMENTS FOR HAZARDS AND PROTECTION NEEDS

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Fire properties for model based assessments for hazards and protection needs are identified and test methods used for their measurements are discussed. Four types of test methods are used: 1) Ignition, 2) Combustion (non-flaming: pyrolysis/smoldering and flaming), 3) Fire Propagation, and 4) Flame Extinction. The test methods are used to quantify: 1) *Critical Heat Flux (CHF)*: it is used to estimate the strength of the ignition source to initiate a fire; 2) *Thermal Response Parameter (TRP)*: it is used to estimate the delay in the fire initiation and rate of fire propagation; 3) *surface re-radiation loss*: it is used to estimate the generation rate of the fuel vapors or the mass loss rate; 4) *heat of gasification*: it is used to estimate the generation rate of the fuel vapors or the mass loss rate; 5) *flame heat flux*: it is used to estimate the fire propagation rate and the generation rate of the fuel vapors or the mass loss rate; 6) *yield of a product*: it is used to estimate the generation rate of the product; 7) *heat of combustion*: it is used to estimate the heat release rate; 8) *Corrosion Index*: it is used to estimate the corrosion damage by the fire products; 9) *Flame Extinction Index*: it is used for the estimation of fire protection needs; 10) *Fire Propagation Index (FPI)*: it is used to classify the materials for their fire propagation behavior;

The incorporation of the four tests methods in the most widely used apparatuses are enumerated. The apparatuses are: 1) the Ohio State University (OSU) Heat Release Apparatus; 2) the Flammability Apparatus at the Factory Mutual Research Corporation (FMRC), and 3) the Cone Calorimeter. Examples of the fire property data are included in tables.

INTRODUCTION

For better protection to life and property from fires, various design changes and modifications are performed on the materials, buildings and their furnishings, fire detection and fixed and mobile fire protection systems. The design changes and modifications are made based on the past fire loss experiences, small-scale "standard" and full-scale fire test results and/or model based assessments. Small-scale "standard" test results are unreliable as they cannot account for the variations in the fire scenarios. Large-scale tests are expensive to perform and results cannot account for the variations in the fire scenarios either. Fire model based assessments for hazards and protection needs for the fire scenarios of concern are becoming more reliable and less expensive and thus their use is increasing rapidly.

As a result of the rapid increase in the use of the fire models, there is a great demand for the fire property data. In order to satisfy this demand, four tests methods have been developed. The test methods are utilized in the following three most widely used apparatuses: 1) the Ohio State University (OSU) Heat Release Apparatus [1-3]; 2) the Flammability Apparatus at the Factory Mutual Research Corporation (FMRC) [4-7], and 3) the Cone Calorimeter [8-10].

FIRE PROPERTIES

The fire properties are associated with the processes of ignition, combustion, fire propagation and flame extinction.

Fire Properties Associated with the Ignition Process: the fire properties of a material associated with the ignition process are:

1) *Critical Heat Flux (CHF)*: it is the minimum heat flux at or below which there is no ignition. CHF is independent of the fire scale;

2) *Thermal Response Parameter (TRP)*: it represents resistance of a material to generate flammable vapor-air mixture. It consists of the density, specific heat, thickness, thermal conductivity; and ignition temperature above ambient. The TRP value is independent of the fire scale.

Fire Properties Associated with the Combustion Process: the combustion process can proceed with or without a flame. A combustion process without a flame, defined as *non-flaming combustion process*, proceeds as a result of the heat flux supplied to the material by external heat sources (*pyrolysis*) or by the heterogeneous reactions between the surface of the material and oxygen from air (*smoldering*). A combustion process with a flame, defined as *flaming combustion process*, proceeds as a result of the heat flux supplied by the flame of the burning material back to its own surface. The fire properties of a material associated with the combustion process are:

1) *Surface Re-Radiation Loss*: it is the heat loss to the environment by the hot material surface via radiation. Surface re-radiation loss is independent of the fire scale;

2) *Heat of Gasification*: it is the energy required to vaporize a unit mass of a material originally at the ambient temperature. Heat of gasification is independent of the fire scale;

3) *Flame Heat Flux*: it is the heat flux supplied by the flame of the burning material back to its own surface. Flame heat flux is dependent on the fire scale;

4) *Yield of a Product*: it is the mass of a product generated per unit mass of the material vaporized in non-flaming or flaming combustion process. The yields of products are independent of the fire size for the buoyant turbulent diffusion flames, but depend on the fire ventilation;

5) *Heat of combustion*: it is the energy generated in the flaming combustion process per unit mass of the material vaporized. If the material burns completely with water as a gas, it is defined as the *net heat of complete combustion*. The energy generated

in the actual combustion of the material is defined as the *chemical heat of combustion*. The chemical heat of combustion has a convective and a radiative component. The *convective heat of combustion* is the energy carried away from the combustion zone by the flowing product-air mixture. The *radiative heat of combustion* is the energy emitted to the environment from the combustion zone.

The heat of combustion is independent of the fire size for the buoyant turbulent diffusion flames, but depends on the fire ventilation;

6) *Corrosion Index*: it is the rate of corrosion per unit mass concentration of the material vapors. It is independent of the fire size.

Fire Properties Associated with the Fire Propagation Process: fire propagation process is associated with the movement of a vaporizing area on the surface of a material. The rate of the movement of the vaporizing area on the surface is defined as the fire propagation rate. The fire property associated with the fire propagation process is the:

Fire Propagation Index: it is related to the rate of fire propagation beyond the ignition zone and is expressed as the ratio of the heat flux from the flame transferred back to the surface of the material to the Thermal Response Parameter of the material. It is independent of the fire size.

Fire Properties Associated with the Flame Extinction Process: flame extinction is achieved by applying the agent in the gas phase such as Halon or alternates or on to the surface such as water. The fire property associated with the flame extinction process is the:

Flame Extinction Index: it is the mass fraction of an agent in the gas phase or on the surface of the burning material required for flame extinction. It is independent of the fire size for the buoyant turbulent diffusion flames, but depends on the fire ventilation.

TEST APPARATUSES

The most widely used apparatuses to measure the fire properties are: 1) the OSU Heat release Rate Apparatus, 2) the Flammability Apparatus, and 3) the Cone Calorimeter.

The OSU Heat Release Rate Apparatus: the apparatus is shown in Fig. 1. It was designed for the flaming fires by the Ohio State University in the early 70's. It is an ASTM standard test apparatus [1-3].

The Flammability Apparatus: the apparatus is shown in Figs. 2A and 2B. It was designed by the Factory Mutual Research Corporation's (FMRC) in the early 70's for non-flaming, flaming and propagating fires [4-7]. It is the FMRC standard test apparatus for cables and wall and ceiling insulation materials (replacing the 25 ft-Corner Test). It is being proposed as an apparatus for the FMRC standard test for conveyor belts. It is used extensively for the evaluation of composite and packaging materials, storage commodities, nonthermal damage assessment for various occupancies, and minimum concentrations of agents (water and Halon alternates) required for flame extinction. Nonthermal damage is defined as the damage associated with the toxic and corrosive products, reduced visibility and smoke damage [11].

Recently a Fire Growth and Spread (FSG) model has been incorporated in to the Flammability Apparatus to assess the fire propagation behavior of the materials under various fire scenarios. The FSG model operates concurrently with the test being performed and the FSG model results are available at the end of the test.

The Flammability Apparatus has a potential of being an advanced apparatus with model prediction capabilities for adoption by the ASTM, ISO, IEC, etc. for the examination of: a) flaming and non-flaming fires; b) upward and downward fire

propagation, b) nonthermal damage, and c) flame suppression and extinguishment by water, Halon alternates, inerts, dry powders, foams, water mist, etc.

The Cone Calorimeter: the apparatus is shown in Fig. 3. It was designed by the National Institute of Standards and Technology's in the 90's [8-10]. It is an ASTM standard test apparatus. Several design features and testing principles used in the Cone Calorimeter are taken from the Flammability Apparatus at FMRC, thus there are many similarities between the two apparatuses and equivalency of the data for ignition and combustion.

TEST CONDITIONS IN THE APPARATUSES

The test conditions used in the apparatus are listed in Table 1.

Environment: the apparatuses are designed for co-flow and natural air flow conditions with normal air as well as with air-nitrogen or oxygen gas mixtures, and extinguishing agents such as water, Halon and alternates, inerts, water mist, and foams. The gas velocity under co-flow is similar to one expected under natural air flow condition for a buoyant turbulent diffusion flame. Thus, results under well-ventilated co-flow condition are very similar to the results under natural flow condition.

The OSU Apparatus uses the co-air flow, the Flammability Apparatus uses the co-air flow with 0 to 60 % oxygen and natural air flow, and the Cone Calorimeter uses the natural air flow. The co-flow is used to examine the effects of ventilation, flame radiation, and gaseous flame extinguishing agents on the combustion and flame spread behaviors of the materials.

External Heat Flux Capabilities of the Apparatuses: different types of external radiant heaters are used. The tungsten-quartz heaters used in the Flammability Apparatus expose the sample to a constant external heat flux value instantaneously. The sample can also be exposed to increasing rate of heat flux, as the controller for the tungsten-quartz lamps can be computer programmed for any desired rate of power input.

In the OSU Apparatus (silicone carbide heater) and the Cone Calorimeter (electrical rod heater), power to the heaters is switched on prior to testing to achieve an equilibrium condition. The sample is inserted after the equilibrium condition has been achieved.

The maximum external heat flux that can be applied to the sample surface in the OSU Apparatus and the Cone Calorimeter is 100 kW/m^2 , whereas it is 65 kW/m^2 in the Flammability Apparatus.

The external heaters are adjusted in the OSU Apparatus and the Cone Calorimeter to obtain reasonably constant heat flux initially at the sample surface; no consideration is given for regression of the surface as the sample vaporizes with surface contraction or expansion. The external heaters in the Flammability Apparatus are adjusted to obtain reasonably constant heat flux within a $100 \times 100 \times 100 \text{ mm}$ three dimensional space. Thus the flux remains reasonably constant at the regressing or expanding surface as the sample vaporizes. The adjustment of the heaters for the three dimensional space, however, results in the reduction of the maximum value of the external heat flux.

For the measurements of the fire properties, it is necessary to know the external heat flux value absorbed by the sample fairly accurately. The effects of in-depth adsorption of external heat flux and surface emissivity of the sample thus need to be considered. These two factors are not considered in the OSU Apparatus and the Cone Calorimeter; in the Flammability Apparatus, their effects are reduced or eliminated by coating the sample surfaces with thin layers of fine graphite powder or they are painted black.

Table I. Test Conditions, and Measurements in the OSU Apparatus, The Flammability Apparatus and the Cone Calorimeter

Design and Test Conditions	OSU Apparatus ^a	Flammability Apparatus	Cone Calorimeter ^b
Design Features and Test Conditions			
Inlet gas flow	Co-flow	Co-& natural flow	Natural
Oxygen concentration (%)	21	0 to 60	21
Gas velocity (m/s)	0.49	0 to 0.146	NA
External heaters	Silicon Carbide	Tungsten-Quartz	Electrical Coils
External flux (kW/m ²)	0 to 100	0 to 65	0 to 100
Exhaust gas flow (m ³ /s)	0.04	0.035 to 0.364	0.012 to 0.035
Sample dimension (mm)			
horizontal	110 x 150	100 x 100	100 x 100
vertical	150 x 150	100 x 600	100 x 100
Ignition	Pilot flame	Pilot flame	Spark plug
Heat release capacity (kW)	8	50	8
Measurements			
Time to ignition	yes	yes	yes
Mass loss rate	no	yes	yes
Fire propagation rate	no	yes	no
Product generation rates	yes	yes	yes
Light obscuration	yes	yes	yes
Smoke property	no	yes	no
Gas phase corrosion	no	yes	no
Chemical heat release rate	yes	yes	yes
Convective heat release rate	yes	yes	no
Radiative heat release rate	no	yes	no
Flame Extinction : water and halon alternates	no	yes	no

^a: as specified in the ASTM E 906-83 [1-3]; ^b: as specified in the ASTM E 1354-90 [8-10].

Product Flow in the Apparatuses: the products generated in the tests are exhausted through the sampling ducts with forced flow. In the Flammability Apparatus and the Cone Calorimeter, products mixed with air are captured in a sampling duct, where measurements are made for the gas temperature, total flow, concentrations of fire products, optical transmission, etc. The maximum exhaust flow in the Flammability Apparatus is about 10 times the maximum flow in the Cone Calorimeter. The OSU Apparatus does not use the exhaust sampling duct, but measurements are made at the top of the sample exposure chamber.

Sample Configuration and Dimensions Used in the Apparatuses: samples in horizontal and vertical sheet (two dimensional) and box-like (three-dimensional) configurations are used. The sample dimensions used in the horizontal and vertical sheet configurations are: 1) about 110 x 150 mm and about 150 x 150 mm in the OSU Apparatus respectively, 2) about 100 x 100 mm in the Cone Calorimeter in both the configurations, and 3) about 100 x 100 mm in the horizontal configuration and about 100 mm wide and up to about 600 mm in the vertical configuration in the Flammability Apparatus.

The box-like (three-dimensional) configuration is used only in the Flammability Apparatus. One to eight, 100 mm cube box-like samples, in one to four layers with one to four boxes per layer are used. Each box and layer is separated by about 10 mm. The two- and three-dimensional vertical sample heights in the Flammability Apparatus are sufficient to perform the upward and downward fire propagation tests.

Measurements in the Apparatuses: measurements are made for the time to ignition, mass loss rate, heat release rate, generation rates of products, optical transmission through smoke, fire propagation rate, metal corrosion rate, smoke damage (color and odor) and flame extinction, utilizing the four test methods described in the next section.

THE IGNITION TEST METHOD

The Ignition Test Method is used to determine: 1) the *Critical Heat Flux (CHF)* and 2) the *Thermal Response Parameter (TRP)*. In the test, flammable vapor-air mixture is created by exposing the sample to various external heat flux values. The flammable mixture is ignited either by a small pilot flame (OSU and the Flammability Apparatuses) or by a spark plug (Cone Calorimeter).

Several tests are performed with variable external heat flux values and time-to-ignition is measured in each test. External heat flux value at which there is no ignition for 15 minutes, taken as the CHF value, is also determined, such as indicated in Fig. 4.

The inverse of the time-to-ignition and its square-root are plotted against the external heat flux as shown in Fig. 4. The plot which shows a linear relationship, away from the CHF value, is used to obtain the TRP value. The TRP value is obtained from the inverse of the slope by performing a linear regression analysis. In Fig. 4, the square-root of the inverse of the time-to-ignition shows a linear relationship, which is a relationship for the *thermally-thick materials* [6,7,12,13]:

$$\sqrt{\frac{1}{t_{ig}}} = \frac{\sqrt{4/\pi} (\dot{q}_e - CHF)}{(TRP)_{thick}} \quad (1)$$

where t_{ig} is the time to ignition (sec), \dot{q}_e is the external heat flux (kW/m²), CHF is the Critical Heat Flux (kW/m²), and $(TRP)_{thick}$ is the Thermal Response Parameter for thermally thick material (kW-s^{1/2}/m²). $(TRP)_{thick}$ is expressed as [6,7,12,13]:

$$(TRP)_{thick} = (k\rho c_p)^{1/2} (T_{ig} - T_a) \quad (2)$$

where k is the thermal conductivity (kW/m-K), c_p is the specific heat (kJ/kg-K), ρ is the density (kg/m³), T_{ig} is the ignition temperature (K), and T_a is the ambient temperature (K).

For a sample behaving as a *thermally-thin material*, the relationship between inverse of time to ignition and external heat flux is linear [6,7,12,13]:

$$\frac{1}{t_{ig}} = \frac{(\pi/4)(\dot{q}_c - CHF)}{(TRP)_{thin}} \quad (3)$$

where $(TRP)_{thin}$ is the Thermal Response Parameter for thermally-thin material (kJ/m^2). $(TRP)_{thick}$ is expressed as [6,7,12,13]:

$$(TRP)_{thick} = \rho c_p \delta (T_{ig} - T_a) \quad (4)$$

where δ is the thickness of the material (m).

The Ignition Test Method is routinely used in the Flammability Apparatus at FMRC. We have also used it to determine the TRP values from the time-to-ignition data measured in the Cone Calorimeter [14,15]. The CHF and TRP values for numerous materials, determined from the time-to-ignition data from the Flammability Apparatus and the Cone Calorimeter have been reported [6,7], an example is shown in Table 2. There is a reasonable agreement between the TRP values obtained from the time-to-ignition data from the Flammability Apparatus and the Cone Calorimeter for the materials for which surface emissivities are close to unity.

In general, physically thick materials behave as thermally-thick materials and physically thin and expanded materials (foams) as thermally-thin materials. Materials with higher CHF and TRP values have higher resistance to ignition and fire propagation. The effectiveness of the passive fire protection to resist ignition and fire propagation through fire retardancy, chemical structural changes, coatings, etc. can be assessed by the magnitude of the increase in the CHF and TRP values. In general, materials with CHF value $\geq 20 \text{ kW/m}^2$ and $(TRP)_{thick}$ value $\geq 450 \text{ kW-s}^{1/2}/\text{m}^2$ have a higher resistance to ignition and fire propagation.

The CHF and TRP values are used in the assessment of the fire propagation behavior of the materials. For example, they are used in the FPI concept and the complementary FSG model predictions at FMRC. It would be useful if the Ignition Test Method is adopted in the ASTM E 906-83 (the OSU Apparatus) and ASTM E 1354-90 (the Cone Calorimeter) such that model based assessments can be made for fire hazards and protection needs.

THE COMBUSTION TEST METHOD

The Combustion Test Method is used to determine: 1) surface re-radiation loss, 2) heat of gasification, 3) flame heat flux, 4) yields of products, 5) heats of combustion, and 6) Corrosion Index. In the test, the sample is exposed to various external heat values in a co-flowing inert environment or air with 10 to 60 % oxygen concentration or in natural air flow.

In the tests, measurements are made for the mass loss rate, heat release rate, generation rates of products, corrosion rate, optical transmission through the products, and smoke color and odor as functions of time and external heat flux.

Mass Loss Rate (Generation Rate of Fuel Vapors) in the Non-Flaming Combustion Process

The mass loss rate and its integrated value are measured as functions of time at three to four external heat flux values. The mass loss rate is plotted against the external heat flux value. From the inverse of the slope, the heat of gasification is determined using the linear regression analysis, as suggested by the following relationship for the steady state condition [4,6]:

$$\Delta H_g = \frac{\dot{q}_e - \dot{q}_{rr}}{\dot{m}''} \quad (5)$$

where \dot{m}'' is the mass loss rate ($\text{kg}/\text{m}^2\text{-s}$), \dot{q}_e is the external heat flux (kW/m^2), \dot{q}_{rr} is the surface re-radiation loss (kW/m^2) and ΔH_g is the heat of gasification (kJ/kg).

Table 2
Ignition Data for Materials

Material	CHF ^a (kW/m^2)	(TRP) ^{thick} ($\text{kW}\cdot\text{s}^{1/2}/\text{m}^2$)		(TRP) ^{thin} (kJ/m^2)
		Flamm. App. ^a	Cone ^b	
Thermally-Thin Materials				
100 % cellulose	13	-	-	159
Corrugated paper	13	-	-	385
News paper	11	-	-	175
Tissue paper	13	-	-	130
Polyester-1	11	-	-	161
Polyester-2	17	-	-	303
Polypropylene-1	12	-	-	278
Polypropylene-2	8	-	-	385
Rayon	17	-	-	227
Polyester & Rayon	11	-	-	286
Thermally-Thick Materials				
Polystyrene	13	162	-	-
Polypropylene	15	193	291	-
Styrene-butadiene	10	198	-	-
Polyvinyl ester	-	-	263	-
Polyoxymethylene	13	269	-	-
Nylon	15	270	-	-
Polymethylmethacrylate	11	274	380	-
High density polyethylene	15	321	364	-
Polycarbonate	15	331	-	-
Polyvinylchloride	10	194	285	-
Epoxy fiberglass	10	156	198	-
Phenolic fiberglass	33	105	172	-
Phenolic kevlar	20	185	258	-

a: from the Flammability Apparatus at FMRC; b: calculated from the data reported in Refs. 14 and 15.

For the transient conditions, the linear regression analysis is performed using the relationship between the integrated values of the mass loss rate and the external heat flux value [4,6]:

$$\Delta H_g = \frac{E_{ex}(t)}{W_f(t)} \quad (6)$$

where E_{ex} is the net external energy (kJ) and W_f is the total mass lost (kg). In Eq. 6, $E_{ex}(t)$ is determined from the following relationship:

$$E_{ex}(t) = A \sum_{n=t_0}^{n=t_f} (\dot{q}_c^* - \dot{q}_{rr}^*) \Delta t_n \quad (7)$$

where t_0 is the time at which the sample starts losing its mass (s) and t_f is the time at which the sample stops losing its mass (s). \dot{q}_{rr}^* value in Eqs. 5 and 7 is the external heat flux value at which there is no measurable mass loss rate. For higher accuracy, surface temperature is measured as a function of time to determine the \dot{q}_{rr}^* value. The $W_f(t)$ value in Eq. 6 is determined from the following relationship:

$$W_f(t) = A \sum_{n=t_0}^{n=t_f} \dot{m}_f(t) \Delta t_n \quad (8)$$

The heat of gasification and surface re-radiation loss values for numerous materials from the mass loss rate measurements for non-flaming fires in the Flammability Apparatus have been reported [4,6]; table 3 shows an example. The heat of gasification values from the mass loss rates for flaming fires at high external heat flux values in the Cone Calorimeter have also been calculated [4,6]. As can be noted in Table 3, the heat of gasification values from the data from the Flammability Apparatus, the Cone Calorimeter and the Differential Scanning Calorimeter show reasonable agreement.

Materials with higher values of surface re-radiation loss and heat of gasification have low intensity fires and generate lower amounts of products. The effectiveness of the passive fire protection through fire retardancy, chemical structural changes, coatings, and others can be assessed through the magnitude of the increase in the values of the surface re-radiation loss and heat of gasification.

The surface re-radiation loss and heat of gasification values are used as direct inputs to the FSG model in the Flammability Apparatus to predict the fire propagation rate. Alternately, the mass loss rate as a function of time at three external heat flux values is used directly by the FSG model in the Flammability Apparatus to predict the fire propagation rate.

It would be useful if the Combustion Test Method for the heat of gasification and surface re-radiation loss is adopted in the ASTM E 906-83 (the OSU Apparatus) and ASTM E 1354-90 (the Cone Calorimeter) such that model based assessments can be made for fire hazards and protection needs.

Mass Loss Rate (Generation Rate of Fuel Vapors) in the Flaming Combustion Process

The mass loss rate in the flaming combustion process is higher than in the non-flaming combustion process because of the additional heat flux from the flame:

$$\dot{m} = (\dot{q}_c^* + \dot{q}_{rr}^* + \dot{q}_{fc}^* - \dot{q}_{rr}^*) / \Delta H_g \quad (9)$$

where \dot{q}_{rr}^* is the radiative heat flux and \dot{q}_{fc}^* is the convective heat flux from the flame of the burning material transferred back to its own surface (kW/m²).

In the absence of the external heat flux, Eq. 9 becomes:

$$\dot{m}'' = (\dot{q}_{rr}'' + \dot{q}_{rc}'' - \dot{q}_{rr}'')/\Delta H_g \quad (10)$$

Results from numerous small- and large-scale fire tests show that as the surface area of the material increases, the radiative heat flux from the flame increases and reaches an asymptotic limit, whereas the convective heat flux from the flame decreases and becomes much smaller than the radiative heat flux at the asymptotic limit [6,16]. With increase in the surface area, however, there is an over all increase in the heat flux from the flame, resulting in the increase in the mass loss rate. In large fires, the flame heat flux and the mass loss rate per unit surface area both reach constant asymptotic values.

Table 3
Surface Re-Radiation and Heat of Gasification

Material ^a	Surface Re-Radiation Loss (kW/m ²)	Heat of Gasification (MJ/kg)			Large-Scale Flame Heat Flux (kW/m ²)
		Flamm. App	Cone	DSC ^b	
Water	1.0	2.58	-	2.59	-
Wood (Douglas fir)	10	1.8	-	-	-
Particle board	-	-	3.9	-	-
Polypropylene	15	2.0	1.4	2.0	67
Polyethylene (ld)	15	1.8	-	1.9	61
Polyethylene (hd)	15	2.3	1.9	2.2	61
Polyethylene/25% Cl	12	2.1	-	-	-
Polyethylene/36% Cl	12	3.0	-	-	-
Polyethylene/48% Cl	10	3.1	-	-	-
Polyvinylchloride (PVC)	15	2.5	2.3	-	50
PVC, LOI = 0.20	10	2.5	2.4	-	-
PVC, LOI = 0.30	-	-	2.1	-	-
PVC, LOI = 0.35	-	-	2.4	-	-
PVC, LOI = 0.50	-	-	2.3	-	-
Polyoxymethylene	13	2.4	-	2.4	50
Polymethylmethacrylate	11	1.6	1.4	1.6	60
ABS	10	3.2	2.6	-	-
Polystyrene	13	1.7	2.2	1.8	75
PU foams (flexible)	16-19	1.2-2.7	2.4	1.4	64-76

a: ld: low density; hd: high density; Cl: chlorine; OI: oxygen index; ABS: acrylonitrile-butadiene-styrene; PU: polyurethane; b: Differential Scanning Calorimeter

In small-scale fires, for a fixed area of the sample, the increase in the oxygen mass

fraction (Y_o) results in an increase in the radiative heat flux from the flame and decrease in the convective heat flux [6,16]. For $Y_o \geq 0.30$, the radiative heat flux from the flame reaches an asymptotic limit comparable to the limit for large-scale fires burning in the open [6,16]. The convective heat flux from the flame becomes much smaller than the radiative heat flux for $Y_o \geq 0.30$, similar to the value for the large-scale fires [6,16].

The dependency of the radiative and convective flame heat fluxes on the mass fraction of oxygen in co-flowing air in a small scale fire is shown in Fig. 5 for 100-x 100-mm x 25-mm thick slab of polypropylene, where data are from the Flammability Apparatus [6,16]. The increase in the flame radiative heat flux with Y_o is explained as due to the increase in the flame temperature and soot formation and decrease in the residence time in the flame [16]. The technique of Y_o variations to simulate large-scale flame radiative heat flux conditions in small-scale flammability experiments is defined as the *Flame Radiation Scaling Technique* [6,16].

In the Flame Radiation Scaling Technique, the heat flux from the flame is determined by performing the combustion tests at Y_o values in the range of 0.233 to 0.600, without the external heat flux and measuring the mass loss rate in each test and substituting the data in Eq. 10. Table 3 lists examples of the data obtained by the Flame Radiation Scaling Technique in the Flammability Apparatus.

The asymptotic values of the heat flux from the flame using the Flame Radiation Scaling Technique in the Flammability Apparatus show good agreement with the values obtained directly from the large-scale fire tests [6,16]. The asymptotic values of the heat flux from the flame vary from 22 to 77 kW/m², dependent primarily on the pyrolysis mode rather than on the chemical structures of the materials. For examples, for liquids, which vaporize primarily as monomers or as very low molecular weight oligomer, the asymptotic values of the heat flux from the flame are in the range of 22 to 44 kW/m², irrespective of their chemical structures. For polymers, which vaporize as high molecular weight oligomer, the asymptotic values of the heat flux from the flame increase substantially to the range of 49 to 71 kW/m², irrespective of their chemical structures. The independence of the asymptotic flame heat flux value from the chemical structure is consistent with the dependence of the flame radiation on optical thickness, soot concentration and flame temperature. The flame heat flux is one of the pertinent fire properties of materials used in the models to assess hazards and protection needs.

It would be useful if the Combustion Test Method for the Flame Radiation Scaling Technique is adopted in the ASTM E 906-83 (the OSU Apparatus) and ASTM E 1354-90 (the Cone Calorimeter) such that model based assessments can be made for fire hazards and protection needs.

Generation Rate of Products

The generation rates of major products (CO, CO₂, smoke and hydrocarbons) and depletion rate of oxygen and their integrated values are measured as functions of time at several external heat flux values in the non-flaming and flaming fires in the OSU Apparatus, in the Flammability Apparatus, and the Cone Calorimeter.

There is a direct proportionality between generation rate of a product and the mass loss rate or the total mass of the product generated to the total mass of the material lost [6,7]:

$$G_j = y_j \dot{m} \quad (11)$$

$$W_j = y_j W_t \quad (12)$$

where G_j is the generation rate of product j ($\text{kg}/\text{m}^2\text{-s}$), \dot{m} is the mass loss rate ($\text{kg}/\text{m}^2\text{-s}$), W_j is the total mass of the product generated (kg), W_f is total mass of the material lost (kg), which is determined from Eq. 8 and the proportionality constant y_j is defined as the yield of the product (kg/kg). W_j is determined from the following relationship:

$$W_j = A \sum_{t_1}^{t_2} G_j(t_n) \Delta t_n \quad (13)$$

The generation rates of products depend on the chemical structure of the material and additives, fire size, and ventilation. The yields of products for buoyant turbulent diffusion flames are independent of the fire size but depend on the fire ventilation [6]. For the model based assessments of hazards and protection needs, average yields of products are reported for the non-flaming and flaming combustion tests. The average yield of each product is determined from the ratio of the total mass of the product generated to the total mass of the material lost (Eq. 12). Extensive data tabulation for the average yields of products for variety of materials have been reported in Ref. 6; Table 4 shows an example of the data.

The yields of products associated with complete combustion such as CO_2 , are higher for materials with aliphatic, carbon-hydrogen-oxygen containing structures. The yields of products associated with incomplete combustion, such as CO and smoke, increase with increase in the chemical bond un-saturation, aromatic nature of the bonds, and introduction of the halogen atoms into the chemical structure of the material. The yields of products are used in fire models to assess hazards and protection needs in conjunction with the mass loss rate, such as the combination of Eqs. 9 and 11:

$$G_j = (y_j / \Delta H_g) (\dot{q}_c + \dot{q}_{rr} + \dot{q}_{rc} - \dot{q}_{rr}) \quad (14)$$

where $y_j / \Delta H_g$ is defined as the *Product Generation Parameter (PGP)*. PGP is a property of the material, its value for buoyant turbulent diffusion flame is independent of the fire size, but depends on the fire ventilation.

The hazards in fires are due to generation of heat and products. With increase in the generation rates of the products associated with the complete combustion, such as CO_2 , the heat release rate increases with enhancement of hazard due to heat (*thermal hazard*). On the other hand, with the increase in the generation rates of the products associated with incomplete combustion, such as CO and smoke, hazard due to toxicity, corrosivity, reduced visibility and smoke damage (nonthermal hazard) increases. Equation 14 shows that the generation rates of products can increase by changes in several factors, alone or in combination. The factors are: 1) yields of the products, 2) heat of gasification of the material; 3) surface re-radiation loss for the material, 4) radiative and convective heat fluxes from the flame of the burning material transferred back to its own surface, i.e., fire size, 5) external heat flux, and 6) extent of fire propagation, i.e., area.

The external and flame heat fluxes and extent of fire propagation are strongly dependent on the fire scenarios and are usually incorporated into the models through various heat flux correlations and/or heat flux data and fire propagation models, such as the FSG model at FMRC in the Flammability Apparatus. The yields of products and heats of gasification, separately or as ratios (Product Generation Parameter) are used as input parameters.

The PGP value of each product is quantified by measuring the generation rate of the product at three or four external heat flux values, plotting the generation rate against the external heat flux and determining the slope by the linear regression analysis. Figure 6 shows an example for the steady state condition. For fires, where

steady state condition cannot be achieved, PGP values are determined by plotting the values of W_j calculated from Eq. 13 and E_{ex} calculated from Eq. 7. The technique is used routinely in the Flammability Apparatus and can also be used in the OSU Apparatus and the Cone Calorimeter. Table 5 shows an example of the data for PGP values for CO and smoke from the Flammability Apparatus (see Tables 3 and 4).

Table 4
Yields of Major Products and Heats of Combustion of Materials^a

Material	Yield (kg/kg)			Heat of Combustion ^b (MJ/kg)		
	CO ₂	CO	Smoke	Chem	Con	Rad
Gases						
Ethylene	2.72	0.013	0.043	41.5	27.3	14.2
Propylene	2.74	0.017	0.095	40.5	25.6	14.9
1,3-Butadiene	2.46	0.048	0.125	33.6	15.4	18.2
Acetylene	2.60	0.042	0.096	36.7	18.7	18.0
Liquids						
Ethyl alcohol	1.77	0.001	0.008	25.6	19.0	6.5
Acetone	2.14	0.003	0.014	27.9	20.3	7.6
Heptane	2.85	0.010	0.037	41.2	27.6	13.6
Octane	2.84	0.011	0.038	41.0	27.3	13.7
Kerosene	2.83	0.012	0.042	40.3	26.2	14.1
Solids						
News paper	1.32	-	-	14.4	-	-
Wood (red oak)	1.27	0.004	0.015	12.4	7.8	4.6
Wood (Douglas fir)	1.31	0.004	-	13.0	8.1	4.9
Wood (pine)	1.33	0.005	-	12.4	8.7	3.7
Corrugated paper	1.22	-	-	13.2	-	-
Wood (hemlock) ^c	1.22	-	0.015	13.3	-	-
Wool 100 % ^c	1.79	-	0.008	19.5	-	-
ABS ^{e,d}	-	-	0.105	30.0	-	-
Polyoxymethylene	1.40	0.001	-	14.4	11.2	3.2
Polymethylmethacrylate	2.12	0.010	0.022	24.2	16.6	7.6
Polyethylene (PE)	2.76	0.024	0.060	38.4	21.8	16.6
Polypropylene	2.79	0.024	0.059	38.6	22.6	16.0
Polystyrene	2.33	0.060	0.164	27.0	11.0	16.0
Silicone	0.96	0.021	0.065	10.6	7.3	3.3
PE + 25 % Chlorine	1.71	0.042	0.115	22.6	10.0	12.6
PE + 36 % Chlorine	0.83	0.051	0.139	10.6	6.4	4.2

Material	Yield (kg/kg)			Heat of Combustion ^b (MJ/kg)		
	CO ₂	CO	Smoke	Chem	Con	Rad
PE + 48 % Chlorine	0.59	0.049	0.134	7.2	3.9	3.3
Polyvinylchloride (PVC)	0.46	0.063	0.172	5.7	3.1	2.6
PVC-1 ^c (LOI=0.50)	0.64	-	0.098	7.7	-	-
PVC-2 ^c (LOI=0.50)	0.69	-	0.076	8.3	-	-
PVC ^c (LOI = 0.20)	0.93	-	0.099	11.3	-	-
PVC ^c (LOI = 0.25)	0.81	-	0.078	9.8	-	-
PVC ^c (LOI = 0.30)	0.85	-	0.098	10.3	-	-
PVC ^c (LOI = 0.35)	0.89	-	0.088	10.8	-	-
PEEK-fiber glass (FG) ^{c,d}	1.88	-	0.042	20.5	-	-
Polyester1- FG ^c	2.52	-	0.049	27.5	-	-
Polyester2- FG ^c	1.47	-	-	16.0	-	-
Polyester3- FG ^c	1.18	-	-	12.9	-	-
Polyester4-FG	1.74	-	-	19.0	-	-
Polyester5-FG	1.28	-	-	13.9	-	-
Polyester6-FG	1.47	0.055	0.070	17.9	10.7	7.2
Polyester7-FG	1.24	0.039	0.054	16.0	9.9	6.1
Polyester8-FG	0.71	0.102	0.068	9.3	6.5	2.8
Epoxy1-FG ^c	2.52	-	0.056	27.5	-	-
Epoxy2-FG	1.10	0.166	0.128	11.9	-	-
Epoxy3-FG	0.92	0.113	0.188	10.0	-	-
Epoxy4-FG	0.94	0.132	0.094	10.2	-	-
Epoxy5-FG	1.71	0.052	0.121	18.6	-	-
Epoxy-FG-paint	0.83	0.114	0.166	11.3	6.2	5.1
Phenolic1-FG	0.98	0.066	0.023	11.9	-	-
Phenolic2-FG ^c	2.02	-	0.016	22.0	-	-
Phenolic-FG-paint	1.49	0.027	0.059	22.9	11.5	11.4
Epoxy-FG-Phenolic	1.06	0.134	0.089	11.5	-	-
Vinylester-FG	2.39	-	0.079	26.0	-	-
PPS ^d -FG	1.56	0.133	0.098	17.0	-	-
Phenolic-Kevlar	1.27	0.025	0.041	14.8	11.1	3.7
Epoxy-Kevlar-paint	0.873	0.091	0.126	11.4	6.3	5.1

a: Data from the Flammability Apparatus; b: Chem:chemical; Con: convective; Rad: radiative; c: from the Cone Calorimeter [14 and 15]; d: ABS- acrylonitrile-butadiene-styrene; PEEK: polyether-ether ketone; PPS- polyphenylene sulfide.

Table 5
Carbon Monoxide and Smoke Generation Parameters

Material ^a	Product Generation Parameter (g/MJ)	
	CO	Smoke
Wood (red oak)	2.2	8.3
Polypropylene	12	30
Polyethylene (ld)	13	33
Polyethylene (hd)	10	26
Polyethylene/25% Cl	20	55
Polyethylene/36% Cl	17	46
Polyethylene/48% Cl	16	43
Polyvinylchloride (PVC)	25	69
Polyoxymethylene	0.42	0
Polymethylmethacrylate	6.3	14
Polystyrene	35	96

It would be useful if the Combustion Test Method for the determination of the Product Generation Parameter be adopted in the ASTM E 906-83 (the OSU Apparatus) and ASTM E 1354-90 (the Cone Calorimeter) such that model based assessments can be made for fire hazards associated with the fire products and protection needs.

Heat Release Rate

The chemical, convective, and radiative heat release rates and their integrated values are measured as functions of time at several external heat flux values in the flaming fires. Heat release rate in combustion reactions, within a flame, is defined as the *chemical heat release rate* [6]. The chemical heat released within the flame is carried away from the flame by flowing product-air mixture and is emitted to the environment as radiation. The component of the chemical heat release rate carried away by the flowing products-air mixture is defined as the *convective heat release rate* [6]. The component of the chemical heat release rate emitted to the environment is defined as the *radiative heat release rate* [6].

The chemical heat release rate is determined from the *Carbon Dioxide Generation (CDG)* [6] and *Oxygen Consumption (OC) Calorimetry* [6,8]. In the CDG Calorimetry, the chemical heat release rate is determined from the mass generation rate of CO₂ corrected for CO [6]. In the OC Calorimetry, the chemical heat release rate is determined from the mass consumption rate of O₂ [6,8]. The convective heat release rate is determined from the *Gas Temperature Rise (GTR) Calorimetry* by measuring the gas temperature above ambient and the total mass flow rate [1,6]. The radiative heat release rate is determined from the difference between the chemical and convective heat release rates [6].

The OSU Apparatus is designed to use the GTR calorimetry [1-3], but now also uses the OC calorimetry. The Flammability Apparatus is designed to use CDG, OC, and GTR calorimetry [6]. The Cone Calorimeter is designed to use the OC Calorimetry [8].

The chemical heat release rate follows the same relationships as the generation

rates of products (Eqs. 11,12,14). The heat release rate relationship analogues to the relationships for the generation rates of products (Eqs. 11 and 12) are:

$$\dot{Q}_i = \Delta H_i \dot{m} \quad (15)$$

$$E_i = \Delta H_i W_f \quad (16)$$

where subscript i represents chemical, convective, or radiative, E_i is the chemical, convective, or radiative energy (MJ) and the proportionality constant ΔH_i is defined as the chemical, convective, or radiative heat of combustion (MJ/kg). E_i is determined from the following relationship:

$$E_i = \Lambda \sum_{n=1}^{n-1} \dot{Q}_i(t_n) \Delta t_n \quad (17)$$

The heat release rate depends on the chemical structure of the material and additives, fire size, and ventilation. The chemical, convective, and radiative heats of combustion for buoyant turbulent diffusion flames are independent of the fire size but depend on the fire ventilation [6]. For the model based assessments of hazards and protection needs, average heats of combustion are reported. The average heat of combustion is determined from the ratio of the energy to the total mass of the material lost (Eq. 16). Extensive data tabulation for the average chemical, convective, and radiative heats of combustion for variety of materials have been reported in Ref. 6; Table 4 shows an example of the data.

The chemical and convective heats of combustion are generally higher and the radiative heat of combustion is generally lower for materials with aliphatic, carbon-hydrogen-oxygen containing structures. The chemical and convective heats of combustion decrease with increase in the chemical bond un-saturation, aromatic nature of the bonds, and introduction of the halogen atoms into the chemical structure of the material. The heats of combustion are used in fire models to assess hazards and protection needs in conjunction with the mass loss rate, such as the combination of Eqs. 9 and 15:

$$\dot{Q}_i = (\Delta H_i / \Delta H_g)(\dot{q}_c + \dot{q}_{tr} + \dot{q}_{rc} - \dot{q}_{rr}) \quad (18)$$

where $\Delta H_i / \Delta H_g$ is defined as the *Heat Release Parameter (HRP)*. HRP is a property of the material, its value for buoyant turbulent diffusion flame is independent of the fire size, but depends on the fire ventilation.

The hazards in fires are due to generation of heat and products. With increase in the heat release rate, the thermal hazard increases. Equation 18 shows that the heat release rate increases by changes in several factors, alone or in combination. The factors are: 1) heat of combustion of the material, 2) heat of gasification of the material; 3) surface re-radiation loss for the material, 4) radiative and convective heat fluxes from the flame of the burning material transferred back to its own surface, i.e., fire size, 5) external heat flux, and 6) extent of fire propagation, i.e., area.

The external and flame heat fluxes and extent of fire propagation are strongly dependent on the fire scenarios and are usually incorporated into the models through various heat flux correlations and/or heat flux data and fire propagation models, such as the FSG model at FMRC in the Flammability Apparatus. The heat of combustion and heats of gasification, separately or as ratios (Heat Release Parameter) are used as input parameters.

The chemical, convective, and radiative HRP values are quantified by measuring

the chemical and convective heat release rates (radiative heat release rate by difference) at three or four external heat flux values, plotting the heat release rate against the external heat flux and determining the slope by the linear regression analysis. Figure 7 shows an example for the steady state condition. For fires, where steady state condition cannot be achieved, such as shown in Fig. 8, the HRP values are determined by plotting the values of E_i calculated from Eq. 17 and E_{ex} calculated from Eq. 7. The technique is used routinely in the Flammability Apparatus and can also be used in the OSU Apparatus and the Cone Calorimeter. Table 6 shows an example of the data for the chemical and convective HRP values from the OSU Apparatus, the Flammability Apparatus and the Cone Calorimeter taken from Ref. 6.

Table 6
The Chemical and Convective Heat Release Parameters^a

Materials	HRP-Chemical		HRP-Convective	
	Flamm.App.	Cone	Flamm.App.	OSU
ABS	-	14	-	-
Polyamide	21	21	-	-
Polypropylene	19	-	11	-
Polyethylene	17	21	12	-
Polystyrene	16	19	6	-
Polymethylmethacrylate	15	14	10	-
Nylon	12	-	7	-
Polyoxymethylene	6	-	5	-
Polyethylene /25 % Cl	11	-	5	-
PVC, LOI 0.25	-	5	-	-
PVC, LOI 0.30	-	5	-	-
PVC, LOI 0.30	-	5	-	-
Polyethylene/36 % Cl	4	-	-	-
PVC, LOI 0.50	-	3	-	-
Rigid PVC	2	3	1	-
Polyethylene/48 % Cl	2	-	-	-
ETFE (Tefzel)	6	-		
PFA (Teflon)	5	-		
FEP (Teflon)	2	-		
TFE (Teflon)	2	-		
Wood (Douglas fir)	7	-	5	-
Epoxy-FG	4	5	2	1
Epoxy/kevlar	4	4	2	2
Phenolic-FG	4	3	2	1

a: from Ref. 6.

The HRP values from the OSU Apparatus, the Flammability Apparatus, and the Cone Calorimeter are in reasonable agreement.

It would be useful if the Combustion Test Method for the determination of the Heat Release Parameter be adopted in the ASTM E 906-83 (the OSU Apparatus) and ASTM E 1354-90 (the Cone Calorimeter) such that model based assessments can be made for fire hazards associated with the fire products and protection needs.

THE FIRE PROPAGATION TEST METHOD

Fire propagation process is associated with the movement of a vaporizing area of a material on its surface. The rate of the movement of the vaporizing area on the surface is defined as the fire propagation rate. The vaporizing area is defined as the *pyrolysis front*.

Fire propagation tests are performed in the Flammability Apparatus, but not in the OSU Apparatus and the Cone Calorimeter. The fire propagation test in the Flammability Apparatus can be considered as a larger version of the ASTM D-2863 Oxygen Index test, with an ignition zone provided by four external heaters (Fig. 2B). In the test, downward and upward fire propagation are examined under co-flowing air with the oxygen mass fraction (Y_o) in the range 0 to 0.60 [6,7,12,13]. Materials as vertical slabs and cylinders of up to 600 mm in length and up to about 25-mm in thickness, 100-mm in width or 50-mm in diameter are used. Pyrolysis front, flame height, chemical, convective, and radiative heat release rates, and generation rates of products are measured during fire propagation.

The Downward Fire Propagation

Figures 9 and 10 show the fire propagation data for 25-mm thick, 100-mm wide, and 300-mm long vertical slab of polymethyl- methacrylate, taken from Ref.12. The slopes of the lines represent the fire propagation rate. Figure 9 shows the pyrolysis front for $Y_o = 0.334$. Figure 10 shows the chemical heat rate accompanying the pyrolysis front for the downward fire propagation for $Y_o = 0.446$ and for the burning of the entire slab after the flame reaches the bottom of the slab for $Y_o \leq 0.233$. The flame extinction occurs at $Y_o = 0.178$, in excellent agreement with the predicted value of 0.18 and values measured by other researchers for larger samples [12]. The Y_o value for flame extinction in the Flammability Apparatus (buoyant turbulent diffusion flame) is lower than from the Oxygen Index (laminar flame) as expected.

Numerous studies have been performed to examine the effects of Y_o on fire propagation (reviewed in Ref. 12). An example is shown in Fig. 11 for the downward fire propagation rates versus Y_o for the polymethylmethacrylate slab with width ≤ 25 -mm and length ≤ 300 mm (data from the studies reviewed in Ref. 12). The data show that for $Y_o < 0.30$, fire propagation rate decreases rapidly and approaches the flame extinction zone for $Y_o = 0.178$, in excellent agreement with the flame extinction value in Fig. 10 and predicted value of $Y_o = 0.18$ [12].

The Upward Fire Propagation

Figure 12 shows the pyrolysis front for the upward fire propagation for 25-mm diameter, 600-mm long vertical cylinder of polymethyl- methacrylate in co-flowing air with $Y_o = 0.233, 0.279, \text{ and } 0.446$. The data are from the Flammability Apparatus at FMRC [12]. The upward fire propagation is much faster than the downward fire propagation as expected due to differences in the heat flux transferred by the flame.

The slopes of the lines in Fig. 12 represent the fire propagation rate, which

increases with the increase in the mass fraction of oxygen. This behavior is not a surprise as Flame Radiation Scaling Technique shows that flame heat flux transferred back to the surface of the material increase with Y_o .

The upward fire propagation rate in the direction of air flow for thermally thick materials is expressed as [6]:

$$u^{1/2} = \frac{\delta_f^{1/2} \dot{q}_f}{\Delta T_{i,s} \sqrt{k\rho c_p}} \quad (18)$$

where u is the fire propagation rate in m/s; δ_f is an effective flame heat transfer distance (m) generally assumed to be a constant, \dot{q}_f is the heat flux transferred from the propagating flame ahead of the pyrolysis front (kW/m^2), and $\Delta T_{i,s} \sqrt{k\rho c_p}$ is the Thermal Response Parameter (TRP) for the thermally thick materials in $\text{kW}\cdot\text{s}^{1/2}/\text{m}^2$ (Eq. 2).

Through data correlations, it has been shown that the heat flux transferred from the propagating flame ahead of the pyrolysis front satisfies the following relationship [6]:

$$\dot{q}_f \propto (0.42 Q_{c,h})^{1/3} \quad (19)$$

where $Q_{c,h}$ is the chemical heat release rate per unit width or circumference of the material as a slab or a cylinder respectively (kW/m). From Eqs. 18 and 19:

$$u^{1/2} \propto \frac{(0.42 Q_{c,h})^{1/3}}{\Delta T_{i,s} \sqrt{k\rho c_p}} \quad (20)$$

The right hand side of Eq. 20, with a proportionality constant assumed to be 1000, $Q_{c,h}$ in kW/m and $\Delta T_{i,s} \sqrt{k\rho c_p}$ in $\text{kW}\cdot\text{s}^{1/2}/\text{m}^2$, is defined as the *Fire Propagation Index (FPI)* [6,7,17]:

$$\text{FPI} = 1000 \frac{(0.42 Q_{c,h})^{1/3}}{\text{TRP}} \quad (21)$$

Classification of Materials Based on Their Fire Propagation Behavior

The following FPI values, based on the data from the Flammability Apparatus with validation in the large-scale fires, have been found to characterize the general fire propagation behavior of materials [6,7,17]:

1) $\text{FPI} \leq 7$: no fire propagation beyond the ignition zone. Materials are identified as *non-propagating Group N-1 materials*. Flame is at the critical extinction condition;

2) $7 < \text{FPI} < 10$: decelerating fire propagation beyond the ignition zone. Materials are identified as Group D-1 materials. Fire propagates beyond the ignition zone although in a decelerating fashion. Fire propagation beyond the ignition zone is limited;

3) $10 \leq \text{FPI} < 20$: fire propagates slowly beyond the ignition zone. Materials

are identified as *propagating Group P-2 materials*;

4) $FPI \geq 20$: Fire propagates rapidly beyond the ignition zone. Materials are identified as *propagating Group P-3 materials*.

For the classification of material for their fire propagation behavior, the Fire Propagation Index Test is performed and materials are classified as Group 1, 2, or 3 materials.

The Fire Propagation Index (FPI) Test

Two sets of tests are performed:

1) *Thermal Response Parameter Test*: ignition test is performed for up to 100- x 100-mm or 100-mm diameter and up to 25-mm thick sample in the Flammability Apparatus (Fig. 2A) and the Thermal Response Parameter (TRP) value is determined from the time to ignition versus external heat flux relationship (Eqs. 1 or 3).

2) *Upward Fire Propagation Test*: fire propagation test is performed for vertical slabs, sheets, or cylinders in the Flammability Apparatus (Fig. 2B). About 25-mm thick, 100-mm wide slabs or 50-mm diameter cylinders with lengths of up to about 600-mm long are used. The bottom 120- to 200-mm of the sample is kept in the ignition zone, where it is exposed to 50 kW/m² of external heat flux in the presence of a pilot flame. Beyond the ignition zone, fire propagates by itself, under co-air flow condition with $Y_o = 0.40$. During upward fire propagation, measurements are made for the chemical heat release rate and generation rates of the fire products as functions of time.

The TRP value and the chemical heat release rate are used in Eq. 21 to calculate the Fire Propagation Index (FPI) value as a function of time and determine the propagating and non-propagating fire behavior of the material. An example is shown in Fig. 13 for five composite systems [17]. In the tests, there was no fire propagation beyond the ignition zone for all the systems, the FPI values are less than 5, and thus the composites are identified as non-propagating, Group 1N materials.

The FPI test procedure for electrical cables is the FMRC cable standard [18], where cables are classified as Group 1 ($FPI < 10$)- non-propagating or decelerating, Group 2 ($10 \leq FPI < 20$) - slowly propagating, and Group 3 ($FPI \geq 20$)- rapidly propagating. The FPI test procedure has also been adopted as a FMRC standard for conveyor belts [19, to be issued shortly]. It is also being used to classify wall and ceiling insulation panels with modifications [20,21], ducts, chutes, clean room materials, and others. Table 7 lists examples of the FPI values quantified in the Flammability Apparatus.

Fire Propagation Index (FPI) is one of the most important fire properties of materials to assess fire hazards and protection needs. Increasing the TRP value and decreasing the heat release rate for materials by various passive fire protection techniques would decrease the FPI value and change the fire propagation behavior from propagating to decelerating to non-propagating. Passive fire protection techniques could involve modifications of chemical structures, incorporation of fire retardants, and changes in the shape, size, and arrangements of the materials, use of coatings, inert barriers. Heat release rate could also be reduced by the application of active fire protection agents such as water, foam, inert, dry powders, Halon and alternates, etc.

Recently the Fire Spread and Growth (FSG) model has been incorporated into the Flammability Apparatus at FMRC to assess the fire propagation behavior of the materials under various fire scenarios, complementing the FPI based classification of materials. The FSG model operates concurrently with the test being performed and the FSG model results are available at the end of the test. The fire propagation rate

predictions by the FSG model so far supports the FPI classification.

In the future, it is anticipated that the FPI test classification will be replaced by the Flammability Apparatus based test methodology using the FSG model assessments with risk profile predictions using a FMRC risk model currently under development.

The Flammability Apparatus with FSG and risk models has a potential of being considered as an apparatus with advance test procedures for adoption by the ASTM, ISO, IEC, and others.

Table 7
Fire Propagation Index Values for Materials^a

Materials ^b	Diameter/ Thickness (mm)	FPI	Group	Fire Propagation ^c
Synthetic Polymers				
Polymethylmethacrylate	25	30	3	P
Fire retarded polypropylene	25	>>10	3	P
Electrical Cable Insulation and Jacket				
PVC/PVC (power)	4-13	11-28	2-3	P
PVC/PVC (communications)	4	36	3	P
PE/PVC (power)	11	16-23	3	P
PE/PVC (communications)	4	28	3	P
PVC/PE (power)	34	13	2	P
PVC/PVF (communications)	5	7	1	N
Silicone/PVC (power)	16	17	2	P
Silicone/XLPO (power)	55	6-8	1	N-D
Si/XLPO (communications)	28	8	1	D
EP/EP (power)	10-25	6-8	1	N-D
XLPE/XLPE (power)	10-12	9-17	1-2	D-P
XLPE/XLPO (communications)	22-23	6-9	1	N-D
XLPE/EVA (power)	12-22	8-9	1	D
XLPE/Neoprene (power)	15	9	1	D
XLPO/XLPO (power)	16-25	8-9	1	D
XLPO,PVF/XLPO (power)	14-17	6-8	1	N-D
EP/CLP (power)	4-19	8-13	1-2	D-P
EP,FR/None (power)	4-28	9	1	D
EP-FR/none (communications)	28	12	2	P
ETFE/EVA (communications)	10	8	1	D
FEP/FEP (communications)	8-10	4-5	1	N

Materials ^b	Diameter/ Thickness (mm)	FPI	Group	Fire Propagation ^c
Composite Systems				
Polyester 1-70%FG	4.8	13	2	P
Polyester 2-70%FG	4.8	10	2	P
	19	8	1	D
	45	7	1	D
Epoxy 1-65%FG	4.4	9	1	D
Epoxy 2-65%FG	4.8	11	2	P
Epoxy 3-65%FG	4.4	10	2	P
Epoxy 4-76%FG	4.4	5	1	N
Phenolic-80%FG	3.2	3	1	N
Epoxy-82%FG-Phenolic	-	2	1	N
Phenolic-84%Kevlar	4.8	8	1	D
Cyanate-73%Graphite	4.4	4	1	N
PPS-84 %FG	4.4	2	1	N
Epoxy-71%FG	4.4	5	1	N
Conveyor Belts				
Styrene-Butadiene Rubber (SBR)	-	8-11	1-2	D-P
Chloroprene Rubber (CR)	-	5	1	N
CR/SBR	-	8	1	D
PVC		4-10	1-2	N-P

a: table from Ref. 6;

b: PVC-polyvinylchloride; PE-polyethylene; PVF-polyvinylidene fluoride; XLPO-cross-linked polyolefin; Si- silicone; EP-ethylene-propylene; XLPE-cross-linked polyethylene; EVA-ethylvinyl acetate; CLP- chlorosulfonated polyethylene; FEP-fluorinated ethylene-propylene; FG- fiber glass; PPS- polyphenylene sulfide;

c: P: propagating; D: decelerating propagation; N: non-propagating.

NONTHERMAL DAMAGE TEST METHOD

Damage due to heat is defined as thermal damage and damage due to smoke, toxic, and corrosive products is defined as nonthermal damage [11]. Nonthermal damage depends on the chemical nature and deposition of products on the walls, ceilings, building furnishings, equipment, components, etc., and the environmental conditions. The severity of the nonthermal damage increases with time. Some examples of nonthermal damage to property are corrosion damage, electrical malfunctions, damage due to discoloration and odors, etc. Toxic effects of fire products on human body resulting in an injury or loss of life is an example of nonthermal damage of residential occupancies. The subject of toxicity has been discussed in detail in Ref. 22.

The subject of corrosion for commercial and industrial occupancies has been reviewed based on the knowledge derived from the telephone central office (TCO) experience for the deposition of atmospheric pollutants and fire products on equipment, severity of corrosion damage and ease of cleaning the equipment [23,24].

In TCO fires involving PVC based electrical cables, contamination levels in the range of about 5 to 900 microgram/cm² have been observed [23,24]. In general, an electronic switch would be expected to accumulate zinc chloride levels in the range of about 5 to 9 microgram/cm² from the interaction with the environment over its expected lifetime of 20 + years. A clean equipment is expected to have less than about 2 microgram/cm² of chloride contamination, whereas, contaminated equipment can have as high as 900 microgram/cm². Thus, equipment contamination levels due to chloride ions and ease of restoration have been classified into four levels [23], which are listed in Table 8.

Table 8
Contamination Levels for the Surface Deposition of
Chloride Ions for Electronic Equipment ^a

Chloride Ion (microgram/cm ²)	Level	Damage/Cleaning/Restoration
2	One	No damage expected. No cleaning and restoration required.
<30	Two	Equipment can be easily restored to service by cleaning without little impact on long-term reliability.
30 to 90	Three	Equipment can also be restored to service by cleaning, as long as no unusual corrosion problems arise, and the environment is strictly controlled soon after the fire.
>90	Four	The effectiveness of cleaning the equipment dwindles and the cost of cleaning quickly approaches the replacement cost. Equipment contaminated with high chloride levels may require severe environmental controls even after cleaning in order to provide potentially long-term reliable operation.

a: from Ref. 23

Currently the nonthermal damage is assessed by toxicity tests [22] and by smoke and corrosion tests [11].

The Corrosion Test Method

The corrosion test method is used in the Flammability Apparatus. Corrosion damage is assessed in terms of rate of corrosion of a material exposed to a unit concentration of material (fuel) vapors, defined as the *Corrosion Index* (CI) [6]:

$$CI = \{ \delta_{loss} / \Delta t_{exposure} \} / \{ W_f / \dot{V}_T \Delta t_{test} \} \quad (22)$$

where CI is in (Å/min)/(g/m³), δ_{loss} is the metal loss due to corrosion (Å), $\Delta t_{exposure}$ is the time the corrosive product deposit is left on the surface of the metal (min), W_f is the total mass of the material lost (Eq.7) for the test duration (g), \dot{V}_T is the total volumetric flow rate of the mixture of fire products and air (m³/min) and Δt_{test} is the test duration (min).

In the corrosion test method, a Rohrback Cosasco [RC] atmospheric metal corrosion probe, designed for the Flammability Apparatus, is placed inside the sampling duct of the Apparatus (Fig. 2B). The probe consists of two metal strips

(5,000 Å), embedded in epoxy- fiber glass plates. One metal strip is coated and acts as a reference and the other un-coated metal strip acts as a sensor. As the sensor strip corrodes and loses its thickness, its resistance changes. The change in the resistance, which represents the extent of corrosion of the metal, is measured as a function of time, by the difference in the resistance between the two strips. The probe readings remain reliable up to about half the thickness of the metal strip (2500 Å), the probe is thus identified as 2500 Å probe.

In the test, corrosion is measured every minute for first three hours and every hour after that up to a maximum of 16 hours. Figure 14 shows an example of the metal corrosion from the combustion products of the polyvinylchloride (PVC) homopolymer and PVC commercial materials, as measured in the Flammability Apparatus. The metal corrosion is faster in the initial stages and becomes slower in later stages due to protective oxide film formation on the surface, within the test duration of about 20 minutes. The data in Fig. 22 show that the metal corrosion from the combustion products of the PVC homopolymer is significantly higher than the metal corrosion from the products of the PVC commercial materials, indicating dilution and/or partial neutralization of HCl by the pyrolysis products of non-halogenated additives in the commercial materials.

The metal corrosion in Fig. 14 is quite fast as it occurs within the test duration of 20 minutes. For less corrosive products, for the same test duration, the metal corrosion process takes about 12 to 14 hours to complete. Thus a maximum of 16 hour exposure is used for products showing slow corrosion.

In the corrosion test method, three types of measurements are made: 1) mass loss rate as a function of time and total mass of the material lost and its duration, 2) total volumetric flow rate of the mixture of the products with air as a function of time, and 3) metal corrosion as a function of time. The average corrosion rate is obtained from the difference between the initial and final corrosion values divided by the time duration. The data are used in Eq. 22 to calculate the CI value.

The CI values have been reported in Ref. 6. Typical CI value for a highly halogenated material with hydrogen atoms in the structure, such as PVC, is 4×10^3 (Å/min)/(kg/m³) and for a highly halogenated polymer with no hydrogen atoms in the structure, such as TFE, it is 0.6×10^3 (Å/min)/(kg/m³), indicating importance of the formation of water in the combustion and inefficiency of the hydrolysis process with water from the ambient air to generate acids.

The Smoke Damage Test

Smoke is a mixture of black carbon (soot) and aerosol. Smoke damage is considered in terms of reduction in the visibility, discoloration and odor of the property exposed to smoke, interference in the electric conduction path and corrosion of the parts exposed to smoke.

In the tests, measurements are made for the optical density in the sampling duct of the Flammability Apparatus and the Cone Calorimeter and above the sample exposure chamber in the OSU Apparatus. Tests are also performed to quantify the odor, color, and electrical properties of smoke in the Flammability Apparatus [6].

FLAME EXTINCTION TEST METHOD

Flame extinction process is associated with the interference with the chemical reactions and/or heat removal and/or dilution by liquids, gases, solid powders, or foams within the flame and/or on the surface of the burning material. The most commonly used liquid and gaseous chemical inhibition agents at the present time are: Halon- 1211 (CBrClF₂), 1301 (CBrF₃), and 2402 (CBrF₂CBrF₂). (The numbers represent: *First*- number of

carbon atoms; *Second*- number of fluorine atoms; *Third*- number of chlorine atoms; *Fourth*- number of bromine atoms).

Because of the contribution of Halons to depletion of the stratospheric ozone layer, they will, however, not be used in the future [25]. There is thus an intense effort underway to develop alternative fire suppressants to replace ozone layer depleting Halon [25]. The Halon alternatives belong to one of the following classes:

- 1) Hydrobromofluorocarbons (HBFC);
- 2) Chlorofluorocarbons (CFC);
- 3) Hydrochlorofluorocarbons (HCFC);
- 4) Perfluorocarbons (FC);
- 5) Hydrofluorocarbons (HFC);
- 6) Inert gases and vapors.

The Environmental Protection Agency (EPA) has provided the following information for the use of the Halon alternates [26]:

Acceptable Total Flooding Agents Feasible in Normally Occupied Areas

- 1) HFC-23: CHF_3 (Du Pont (FE13))
- 2) HFC-227ea: $\text{CF}_3\text{CHFCF}_3$ (Great Lakes FM 200)
- 3) FC-3-1-10: C_4F_{10} (3M PFC 410) {restricted use}
- 4) [HCFC Blend] A (NAF S III) (N.A.Fire Guardian)
- 5) [Inert Gas Blend] A (Inergen).

Other Acceptable Total Flooding Agents

- 1) HBFC-22B1: CHF_2Br (Great Lakes FM100)
- 2) HCFC-22: CHClF_2 (Du Pont FE 232)
- 3) HCFC-124: CF_3HClF
- 4) HFC-125: CF_3CHF_2 (Du Pont FE-25)
- 5) HFC-134a: $\text{CF}_3\text{CH}_2\text{F}$
- 6) Powdered Aerosol (Spectrex)
- 7) Solid Propellant Gas Generator (Rocket Research).

Streaming Agents: Commercial and Military Uses Only

- 1) [HCFC Blend]B (Halotron I)
- 2) HCFC-123: CF_3CHCl_2 (Du Pont FE-241)
- 3) FC-5-1-14: C_6F_{14} (3M PFC 614)-(restricted use)
- 4) HBFC-22B1: CHF_2Br (Great Lakes FM 100).

Total Flooding Agents (Pending)

- 1) Water Mist (Securiplex; Yates)
- 2) Powder Aerosols (Spectrex; Service)
- 3) Inert Gas Blends (Securiplex; Minimax)
- 4) SF_6 (Discharge test agent)
- 5) C_3F_8 (3M CEA-308; PFC-218)
- 6) Fluoroiodocarbons (CF3I)

Streaming Agents (Pending)

- 1) HCFC-124: CF_3HClF
- 2) HFC-134a: $\text{CF}_3\text{CH}_2\text{F}$
- 3) HFC-227ea: $\text{CF}_3\text{CHFCF}_3$ (Great Lakes FM-200)
- 4) HCFC/HFC Blend (NAF P III)

- 5) HCFC Blend (NAF Blitz III)
- 6) Powdered Aerosol/HFC or /HCFC Blend (Powsus).

The most common test to screen the Halon alternates is the "Cup Burner" test, where concentrations of Halons or alternates required for extinction of a small laminar diffusion flame are determined [25]. Table 9 lists the concentrations of Halon 1301 and alternates required for heptane flame extinction in the "Cup Burner" test, where the values are taken from Refs. 25 and 27. Acceptable total flooding agents in normally occupied areas are indicated in the table.

The Flammability Apparatus operates under principles very similar to the "Cup Burner", where both laminar and buoyant turbulent diffusion flames are examined [28]. An example of the flame extinction data for Halon 1301 is shown in Fig. 15, where initially there is a rapid decrease in the chemical heat release rate followed by an increase between 5.40 and 6.25 %, due to increase in the flame luminosity and flame heat flux transferred back to the fuel surface. Flame extinction occurs at 6.25 %.

Figure 16 shows a rapid increase in the generation efficiencies of CO, mixture of hydrocarbons, and smoke with increase in the Halon concentration. Generation efficiency is the ratio of the experimental yield of the product to the maximum possible stoichiometric yield of the product [6].

The effect of Halon on the generation efficiencies in Fig. 16 is strong for CO and the mixture of hydrocarbons and weak for smoke. This type of combustion behavior is similar to one found with the decreasing ventilation by decreasing the amount of oxygen. The behavior is postulated to be due to the increasing preference of fuel carbon atom to convert to CO and to the mixture of hydrocarbons rather than to smoke [29]. It thus appears that the chemical interruption processes in the oxidation zone for flame extinction are very similar with increasing amounts of Halon and decreasing amounts of oxygen. This experimental finding is consistent with the concept that a critical Damkohler number exists at the flame extinction condition [26].

The existence of the critical conditions at flame extinction has also been postulated by the "Fire Point Theory" [6] and supported by the experimental data for the critical mass pyrolysis and heat release rates [6].

The extinction test method in the Flammability Apparatus is performed in a fashion very similar to the Combustion Test Method, except that air with different amounts of the gaseous agent is used to determine the minimum concentration for flame extinction. Water is applied directly the surface as large drops and its application rate for flame extinction is determined. Nonthermal damage due to corrosive products and smoke is also determined.

Currently the Flammability Apparatus is being used quite extensively to determine the flame extinction concentrations of halon alternates and water, heat release rate, the types of products generated and the nonthermal damage potential for flame extinction conditions.

SUMMARY

1. The most widely used apparatuses are the OSU Apparatus, the Flammability Apparatus at FMRC, and the Cone Calorimeter. These apparatuses are capable of providing the necessary input combustion data needed for the model based assessments of fire hazards and protection needs;
2. The Flammability Apparatus is capable of providing additional input data to the models for the assessment of hazards due to fire propagation, corrosion and smoke damage, and concentrations of agents required for flame extinction;

3. A Flame Spread and Growth (FSG) model has been incorporated into the Flammability Apparatus and operates as the test is being performed in the Apparatus, providing the fire propagation assessment at the end of the test. It is planned to combine this effort with a risk model currently under development at FMRC. It is anticipated that this tool (the Flammability Apparatus, the FSG model, and the risk model) would be a powerful tool for the assessment of hazards and protection needs in various types of fire scenarios. The tool will be available for adoption by the ASTM, ISO, IEC, and others in the very near future.

Table 9
Concentrations of Halon 1301 and Alternates Required for
Flame Extinction in the "Cup Burner" Test^a

Agent Name	Formula	Concentration (Volume %)	Relative Concentration
Halon 1301	CF ₃ Br	2.9	1.0
Trifluoromethyl Iodide 1311	CF ₃ I	3.0	1.03
FC-14	CF ₄	13.8	4.76
HCFC-22 (Du Pont FE 232)	CHClF ₂	11.6	4.00 ^b
HBFC-22B1 (Great Lakes FM100)	CHBrF ₂	4.4	1.52
HFC-23 (Du Pont FE13)	CHF ₃	12.4	4.28
HFC-32	CH ₂ F ₂	8.8	3.03
FC-116	CF ₃ CF ₃	7.8	2.69
HCFC-124	CHClFCF ₃	8.2	2.83
HBFC-124B1	CF ₃ CHBrF ₃	2.8	0.97
HFC-125 (Du Pont FE 25)	CF ₃ CHF ₂	9.40	3.24
HFC-134	CHF ₂ CHF ₂	11.2	3.86
HFC-134a	CF ₃ CH ₂ F	10.5	3.62
HFC-142b	CClF ₂ CH ₃	11.0 (calc)	3.79
HFC-152a	CHF ₂ CH ₃	27.0 (calc)	9.31
HFC-218	CF ₃ CF ₂ CF ₃	6.1	2.10
HFC-227ea (Great Lakes FM 200)	CF ₃ CHFCF ₃	6.1	2.10 ^b
C318	C ₄ F ₈	7.3	2.52
FC-5-1-14 (3M PFC 614)	C ₄ F ₁₀	5.5	1.90 ^b

a: from Refs. 25 and 27; b: acceptable total flooding agents in normally occupied areas.

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FIGURE CAPTIONS

Figure 1. The Ohio State University (OSU) Heat Release Rate Apparatus [1-3].

Figure 2A. The Flammability Apparatus for Horizontal Sample Configuration at the Factory Mutual Research Corporation (FMRC) [4-7].

Figure 2B. The Flammability Apparatus for Vertical Sample Configuration at the Factory Mutual Research Corporation (FMRC) [4-7].

Figure 3. The Cone Calorimeter [8-10].

Figure 4. Time to Ignition Versus External Heat Flux for a Silicone Based Polymer. Data Measured in the Flammability Apparatus. Data Satisfy the *Thermally-Thick* Behavior but Not the *Thermally-Thin* Behavior Away from the Critical Heat Flux Value.

Figure 5. Flame Radiative and Convective Heat Fluxes at Various Oxygen Mass Fractions in the Co-Flowing Air for the Steady-State Combustion of 100 x 100 x 25 mm Thick Slab of Polypropylene. Data are from the Combustion Tests using the Flame Radiation Scaling Technique in the Flammability Apparatus at FMRC [6,16]. Numbers Within the Bars are Oxygen Mass Fractions.

Figure 6. CO Generation Rate Versus the External Heat Flux. The Slopes of the Lines Represent the CO Generation Parameter for Polyethylene and Polystyrene. The Data are from the Flammability Apparatus at FMRC.

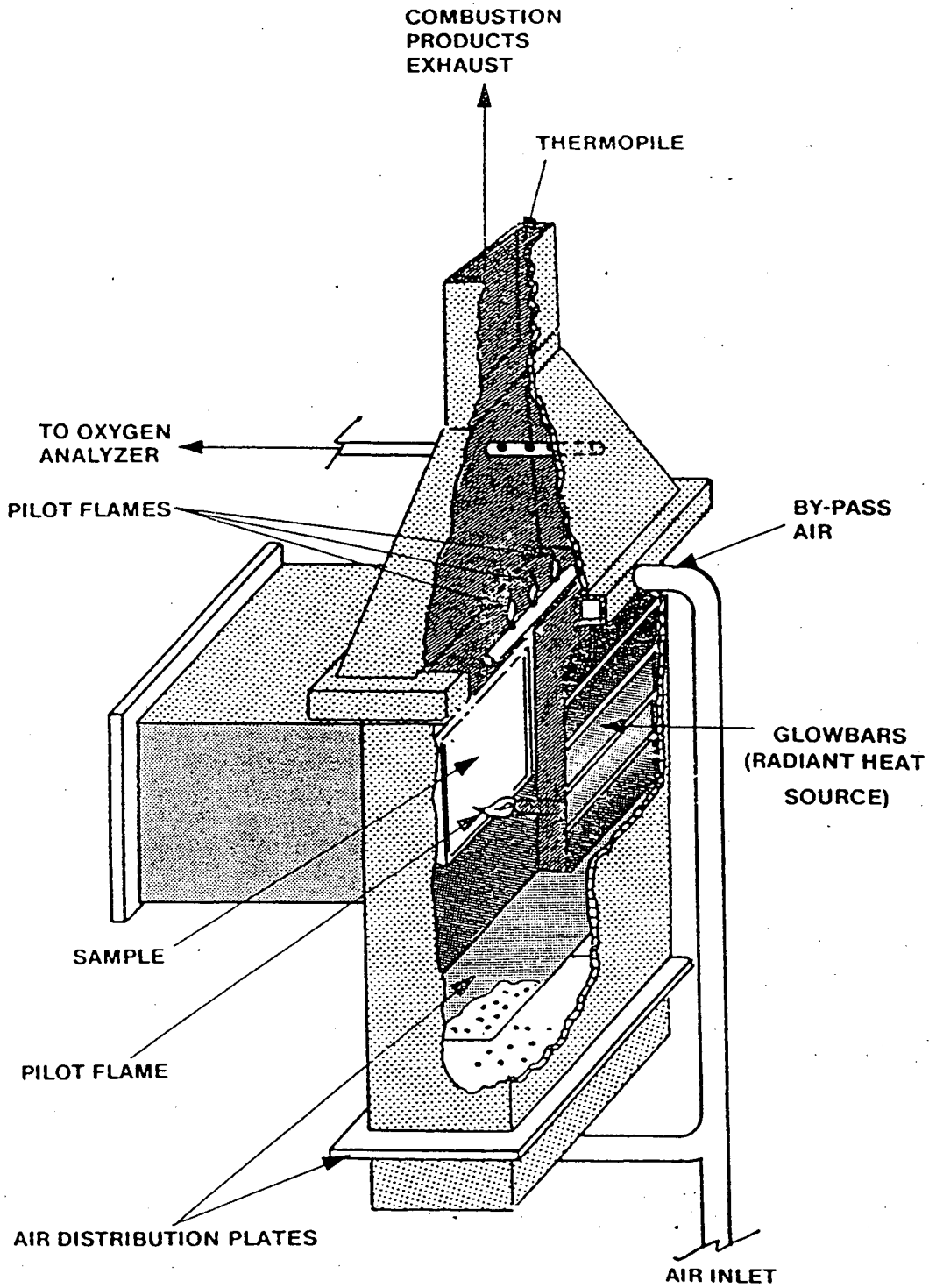
Figure 7. Chemical Heat Release Rate Versus the External Heat Flux. The Slopes of the Lines Represent the Chemical Heat Release Parameter for Polyethylene and Polystyrene. The Data are from the Flammability Apparatus at FMRC.

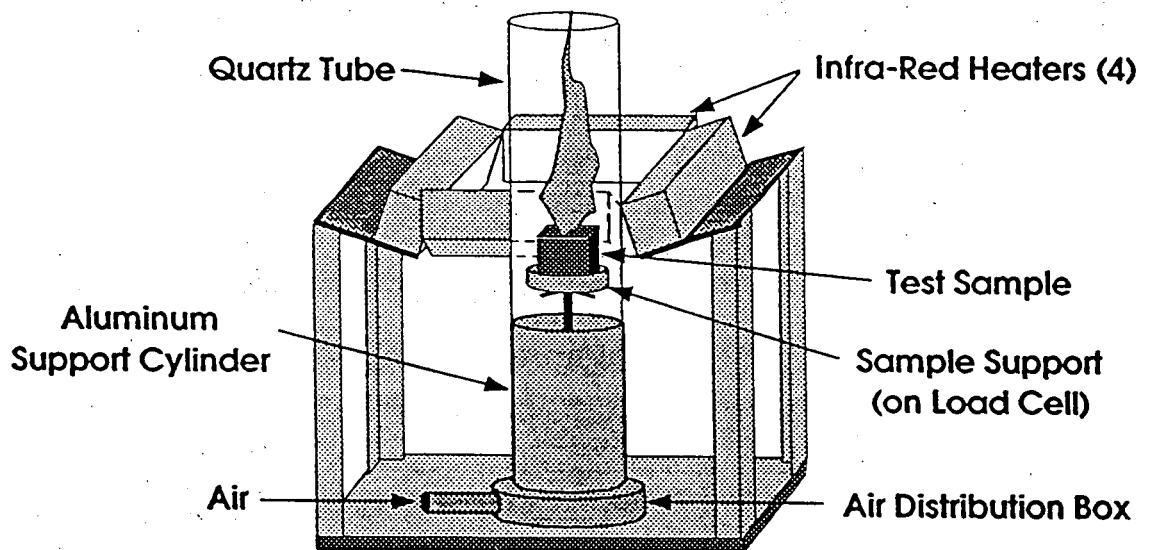
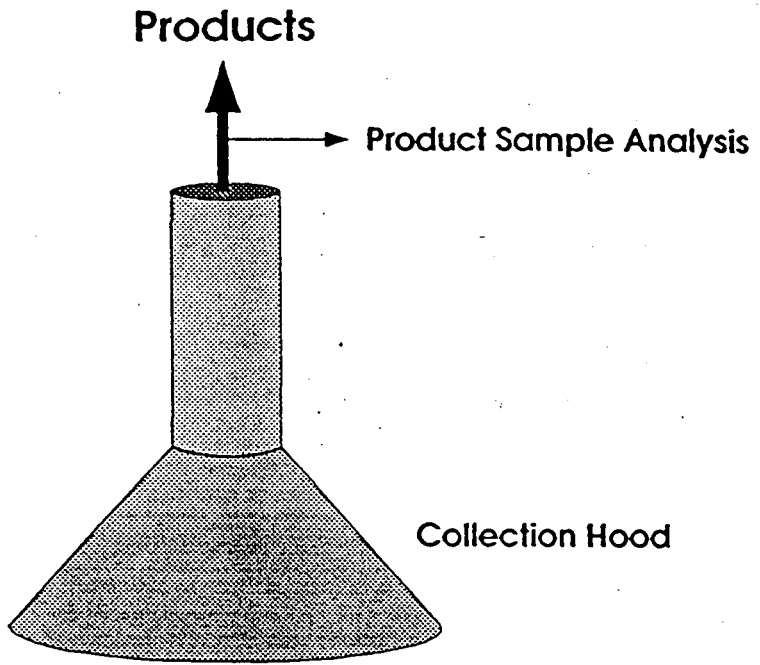
Figure 8. Chemical Heat Release Rate for 100-mm Diameter and 25 mm Thick Slab of Polypropylene Exposed to an External Heat Flux of 50 kW/m² for 0.09 m/s Co-Flowing Normal Air in the Flammability Apparatus at FMRC. The Theoretical Prediction is Based on Eq.18 and Data from Tables 3 and 4. OC: Oxygen Consumption Calorimetry; CDG: Carbon Dioxide Generation Calorimetry.

Figure 9. Pyrolysis Front Versus Time for the Downward Fire Propagation for 300-mm Long, 100-mm Wide and 25-mm Thick Polymethylmethacrylate Vertical Slab Under Opposed Air Flow Condition in the Flammability Apparatus at FMRC. Air Flow Velocity = 0.09 m/s. Oxygen Mass Fraction = 0.334 [12].

Figure 10. Chemical Heat Release Rates Versus Time for the Downward Fire Propagation, Combustion, and Flame Extinction for 300-mm Long, 100-mm Wide and 25-mm Thick Polymethylmethacrylate Vertical Slab Under Opposed Air Flow Condition in the Flammability Apparatus at FMRC. Air Flow Velocity = 0.09 m/s. Numbers in the Figure are the Oxygen Mass Fractions [12].

Figure 11. Downward Fire Propagation Rate Versus Oxygen Mass Fraction for Vertical Polymethylmethacrylate Slabs with Width \leq 25 mm and Lengths \leq 300 mm. Data are Taken from Various Studies Reported in the Literature (Reviewed in Ref. 12).





BLAST GATE & LINEAR ACTUATOR CONTROL

THREE PORTS - 120° APART,
ONE - PARTICULATE SAMPLING,
TWO - PRESSURE MEASUREMENT,
THREE - CORROSION MEASUREMENT

TWO PORTS - 180° APART,
ONE & TWO - OPTICAL
TRANSMISSION MEASUREMENT

THREE PORTS - 120° APART,
ONE - GAS TEMPERATURE MEASUREMENT,
TWO - PRODUCT SAMPLING,
THREE - NOT IN USE

152mm ID TEFLON COATED
STAINLESS STEEL DUCT

VERTICAL SLAB

162mm ID, 260mm LONG
ALUMINUM EXTENSION

162mm ID, 432mm LONG
QUARTZ TUBE

FOUR INFRA-RED HEATERS

METAL SCREEN PLATFORM

ALUMINUM CYLINDER

ALUMINUM AIR
DISTRIBUTION BOX

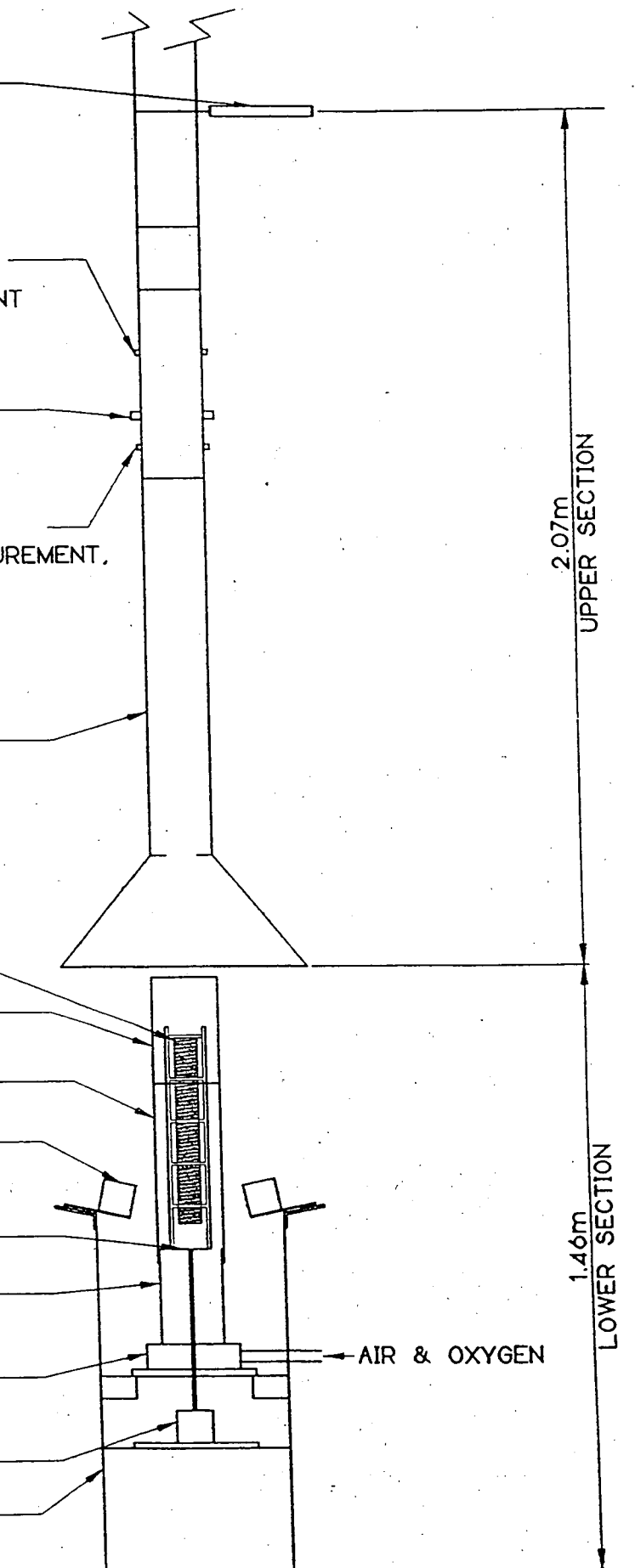
LOAD CELL

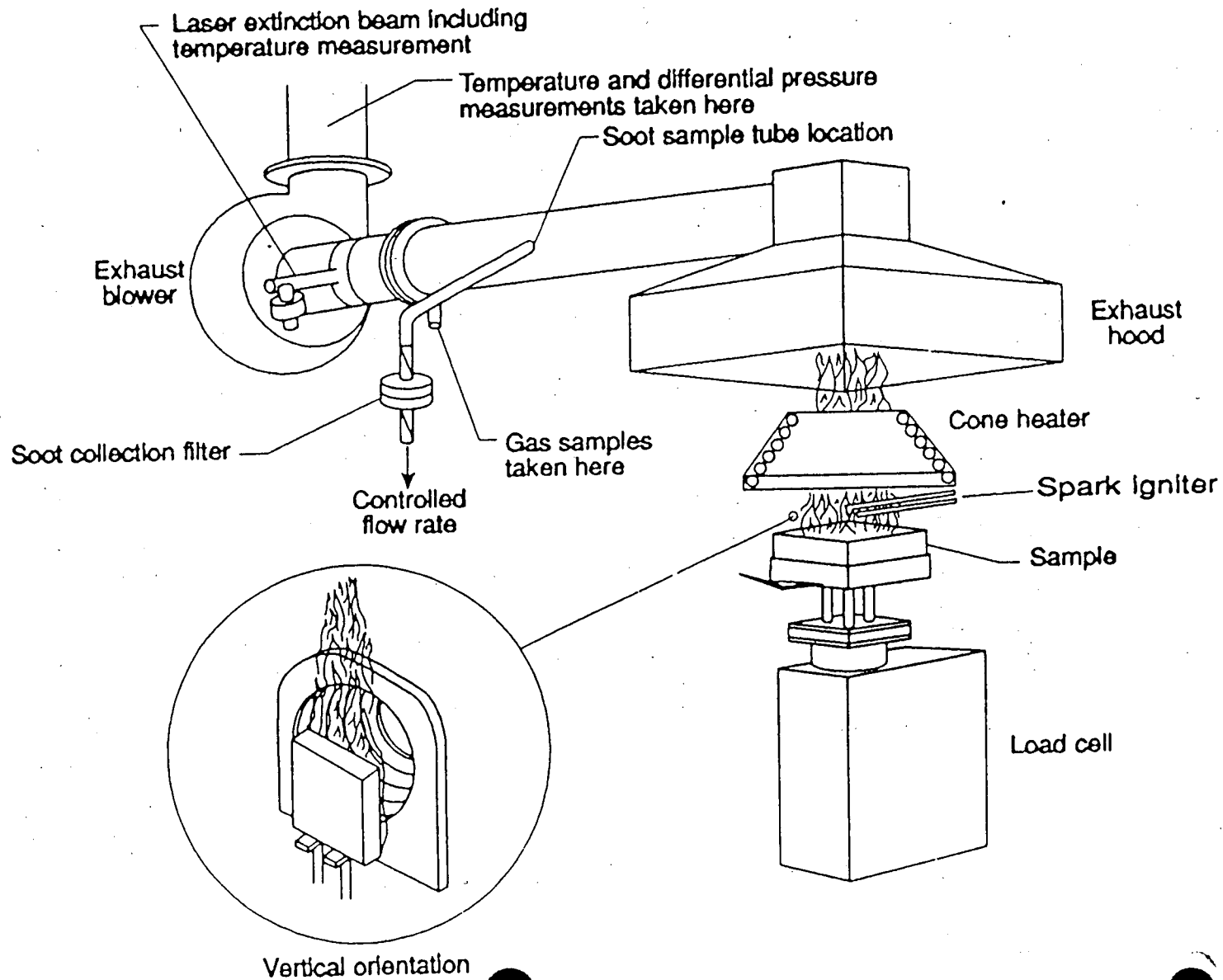
UNISTRUT STEEL FRAME

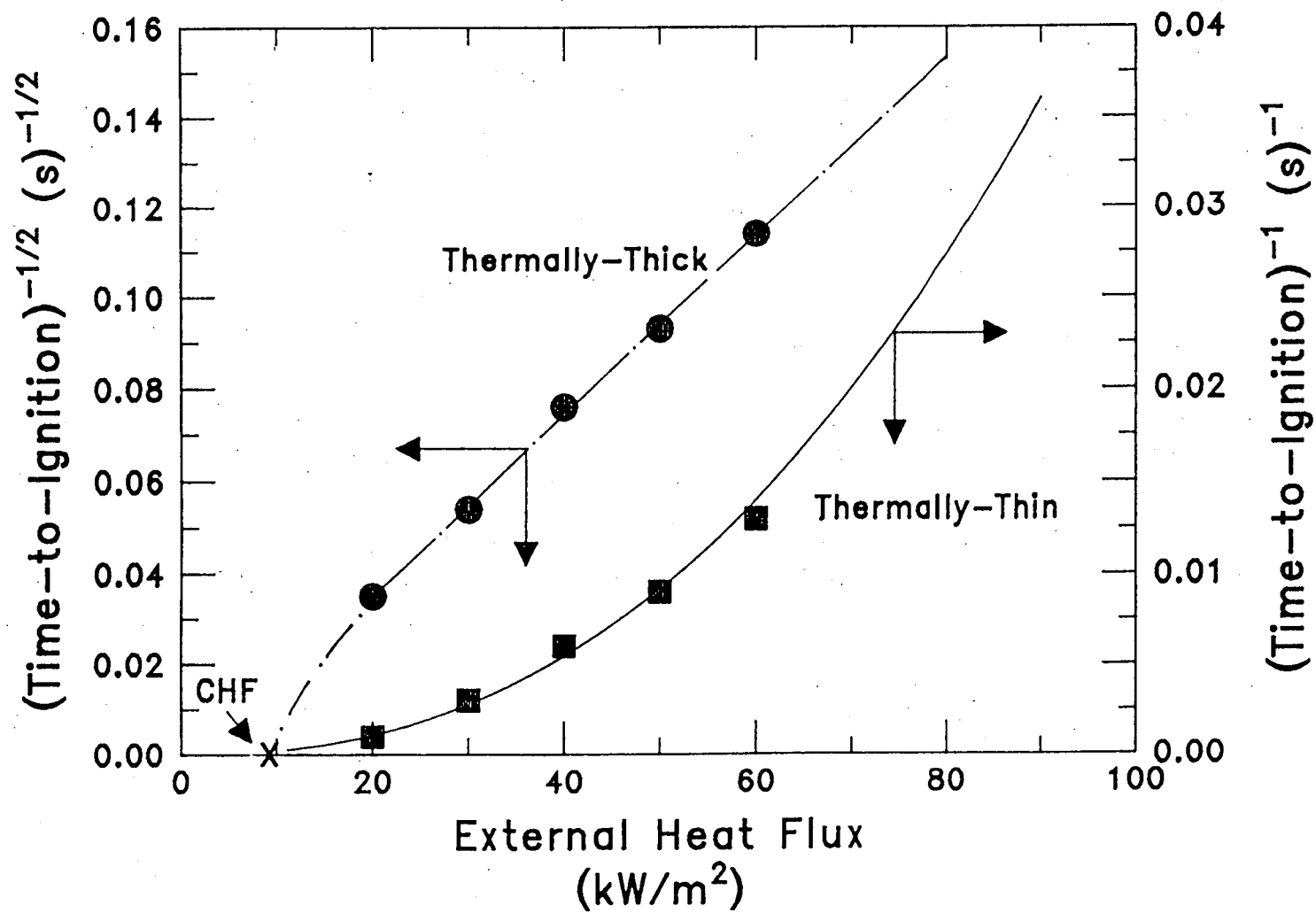
AIR & OXYGEN

2.07m
UPPER SECTION

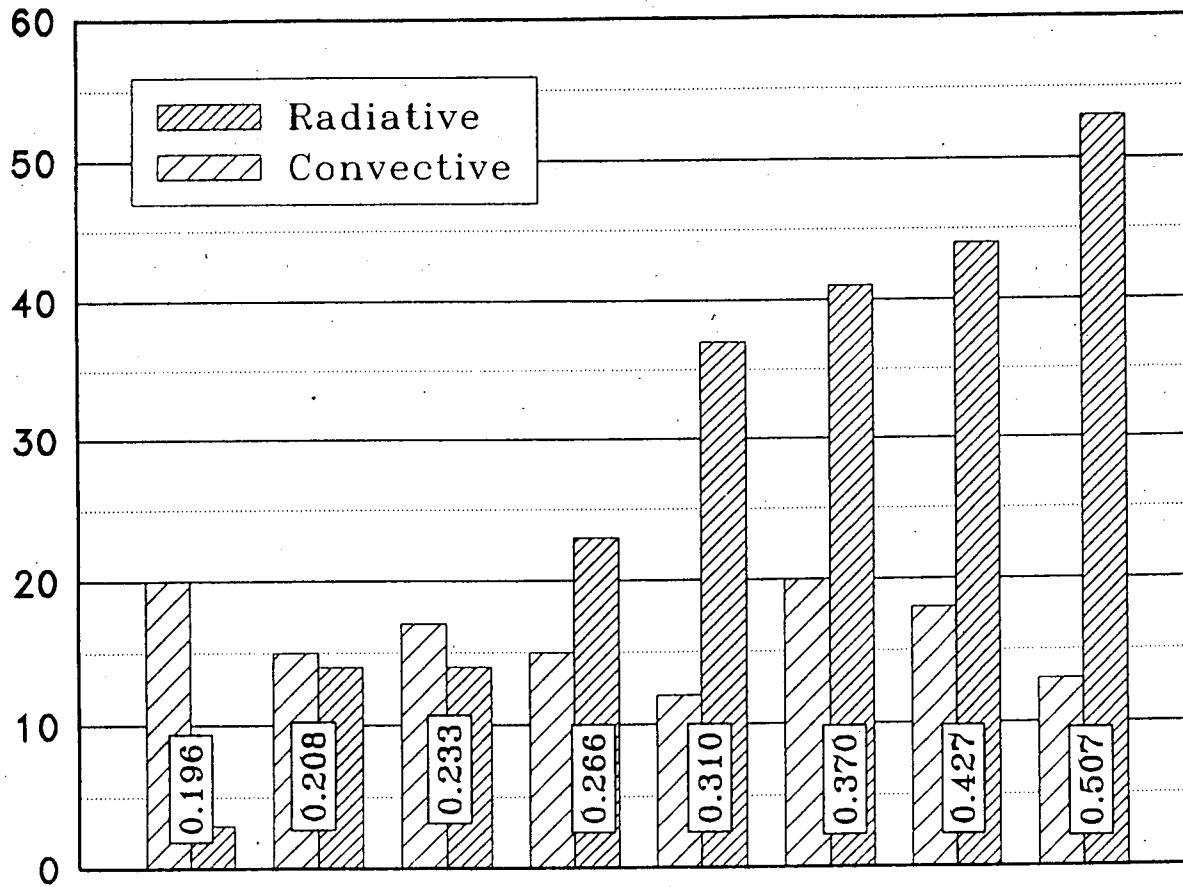
1.46m
LOWER SECTION

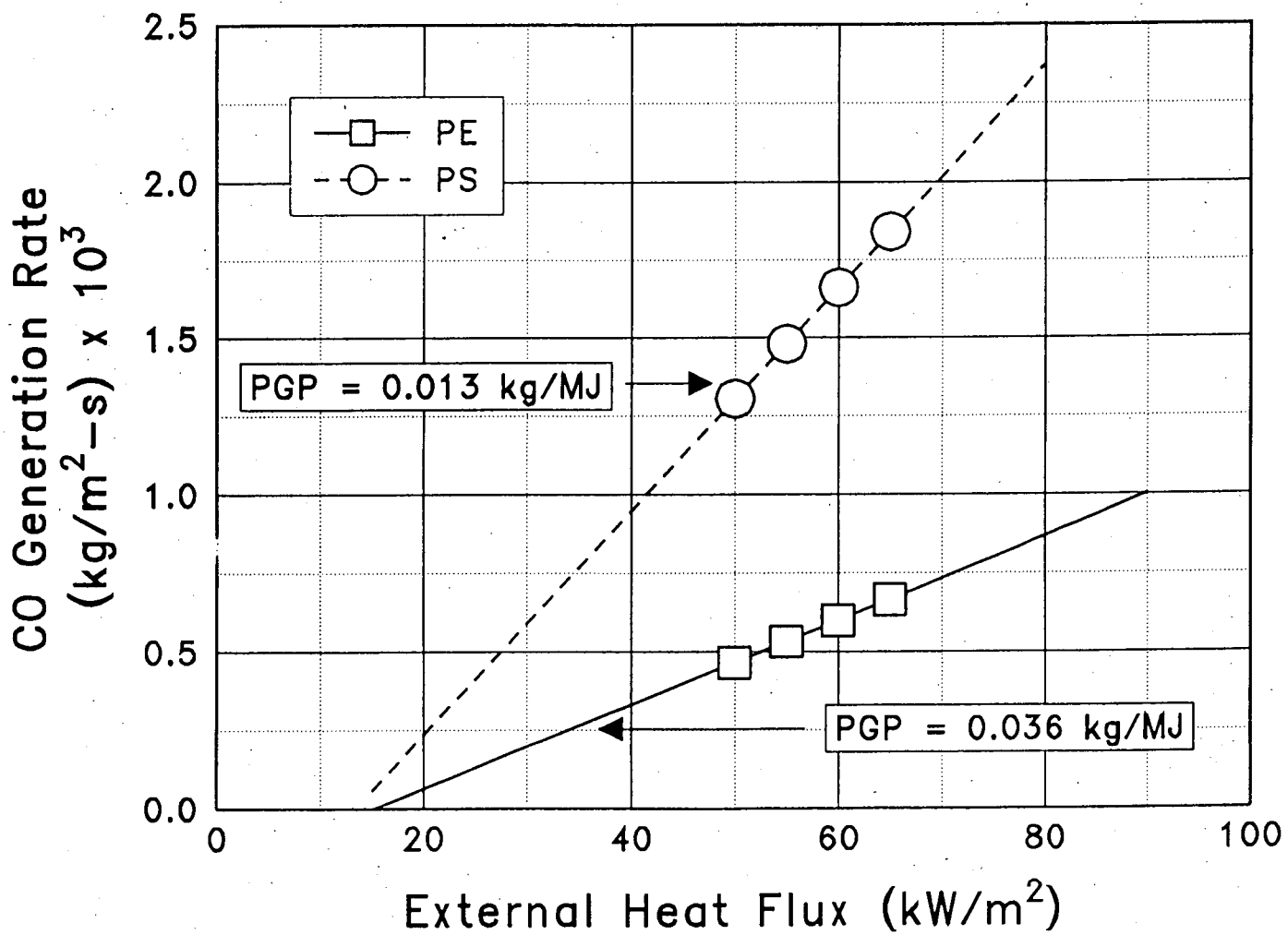


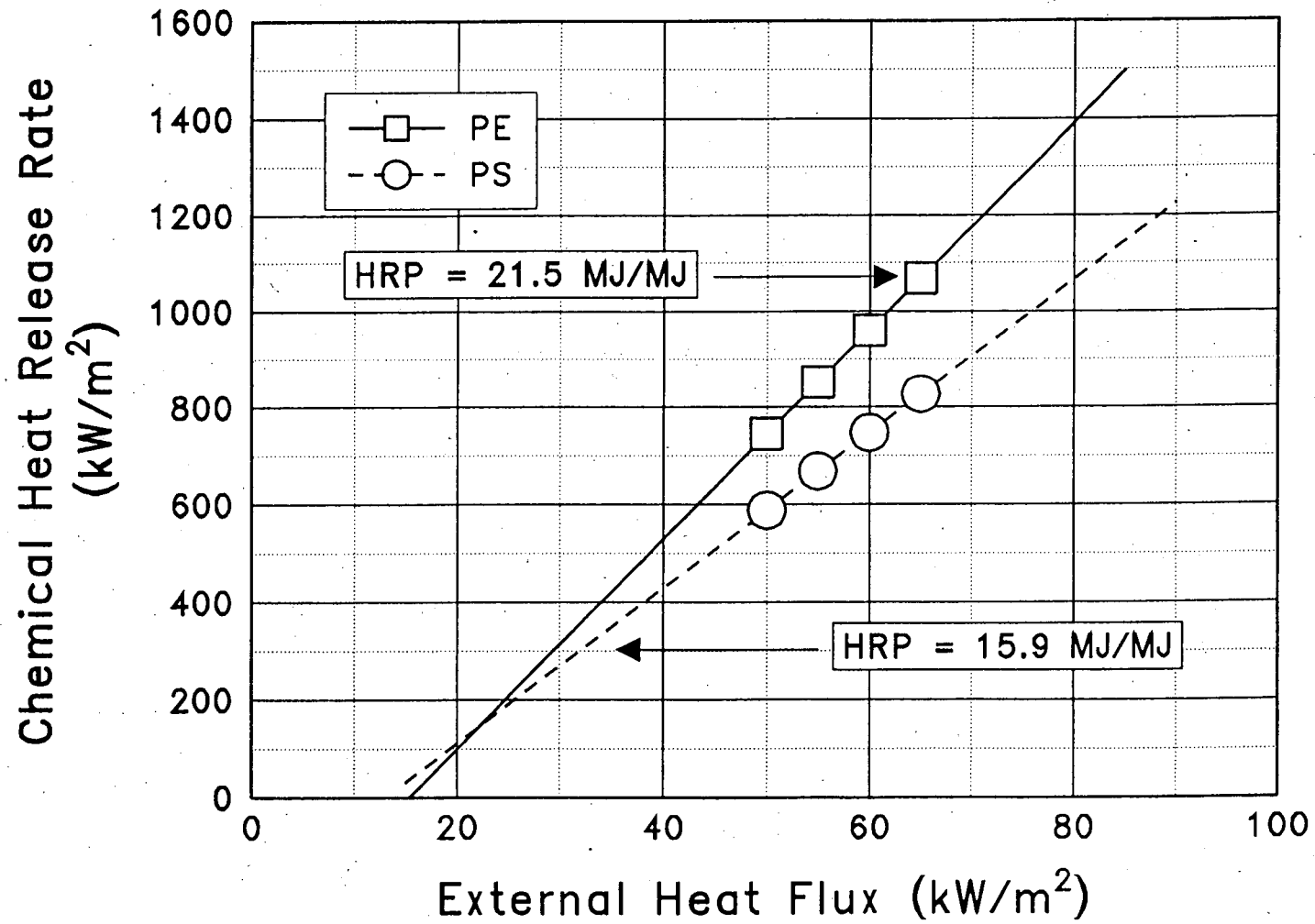


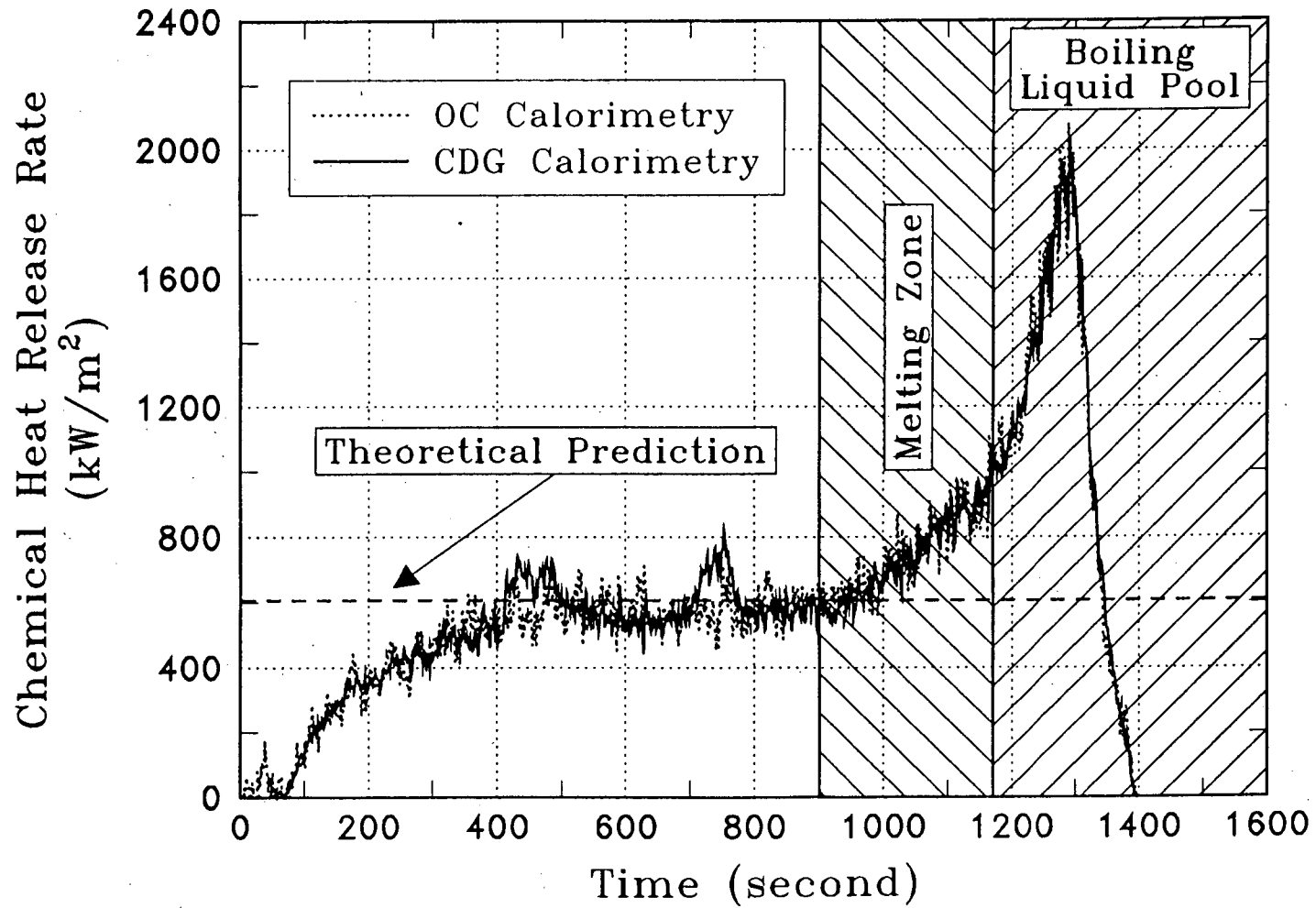


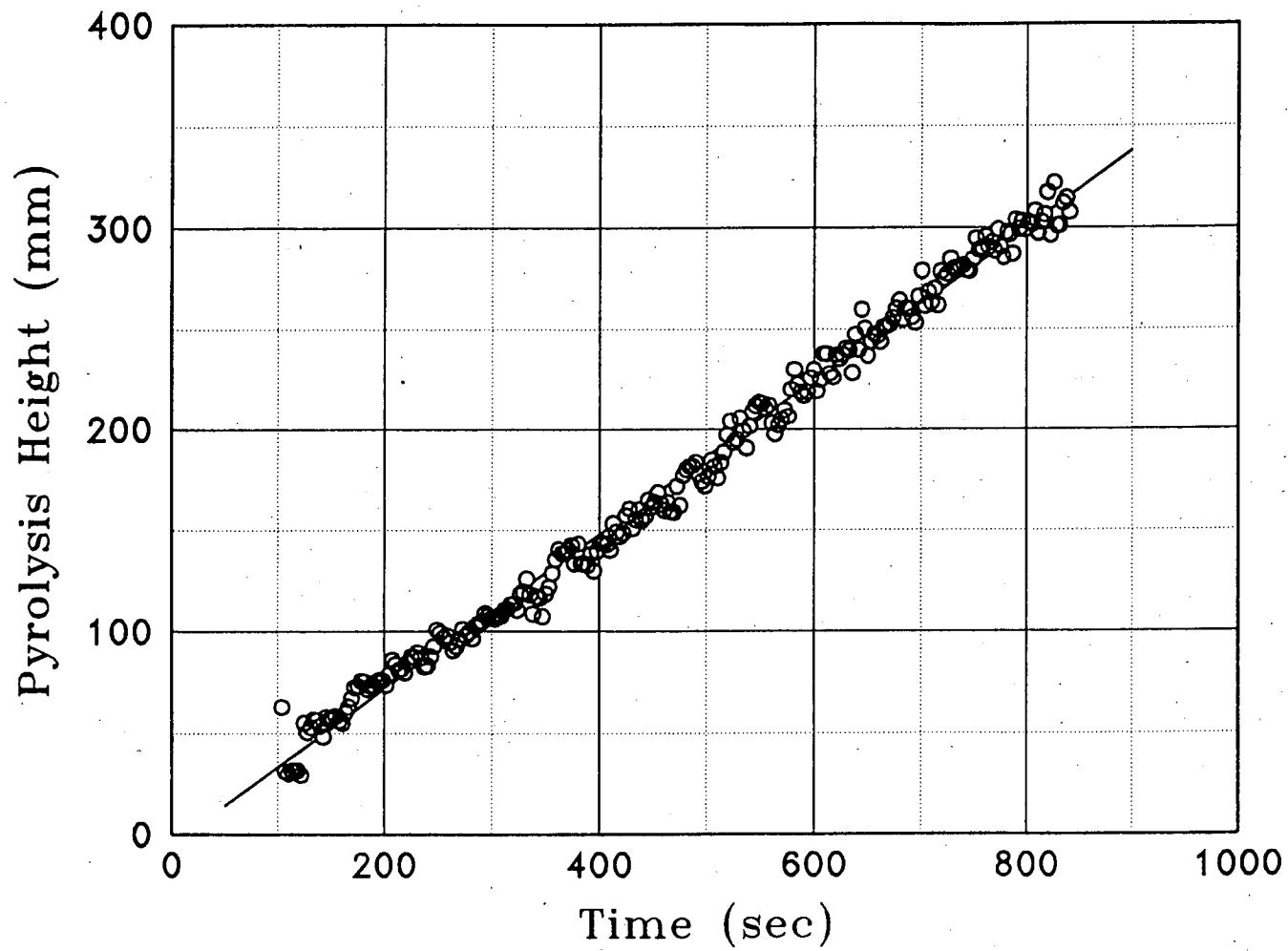
Flame Heat Flux
(kW/m²)

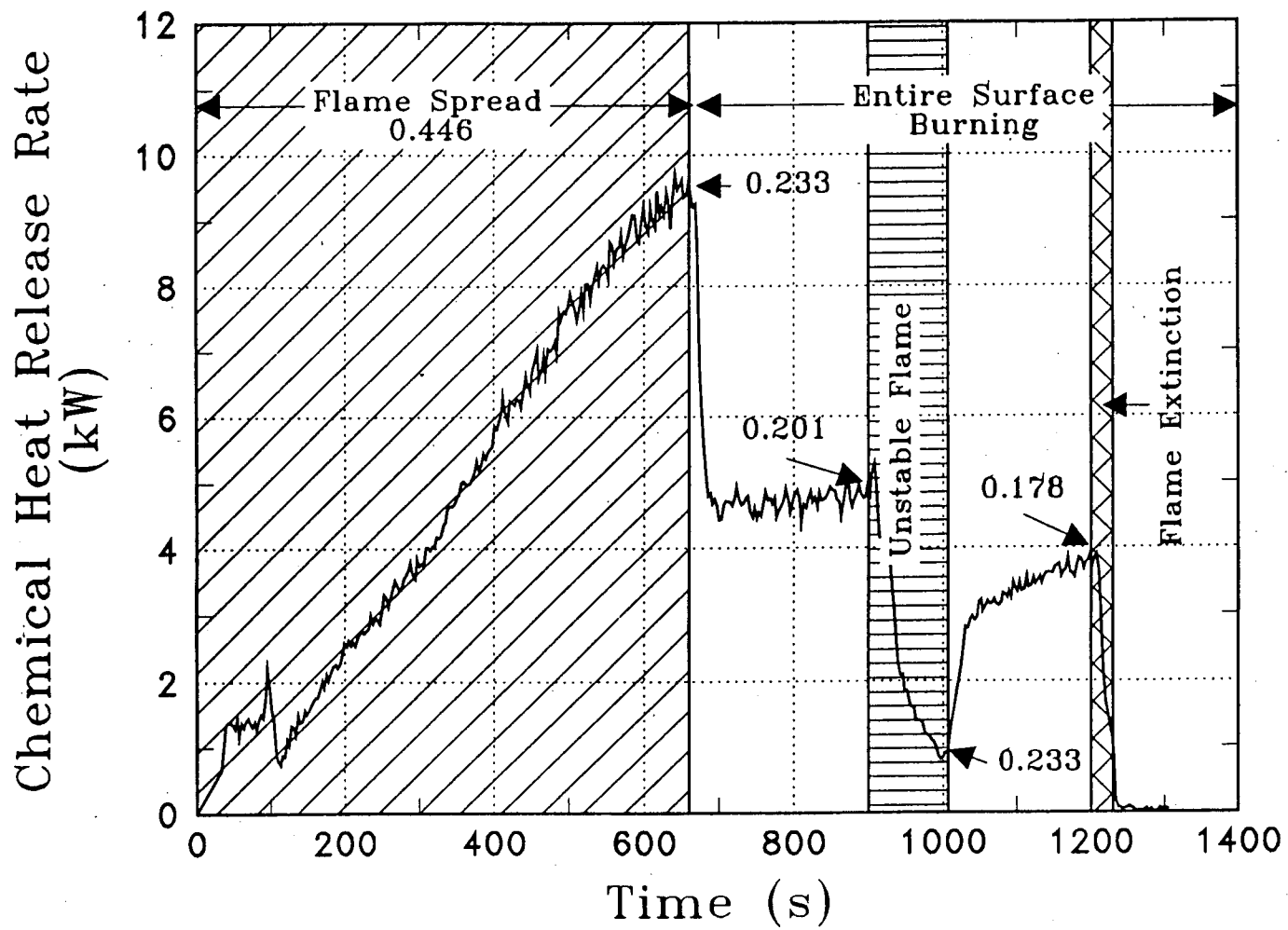


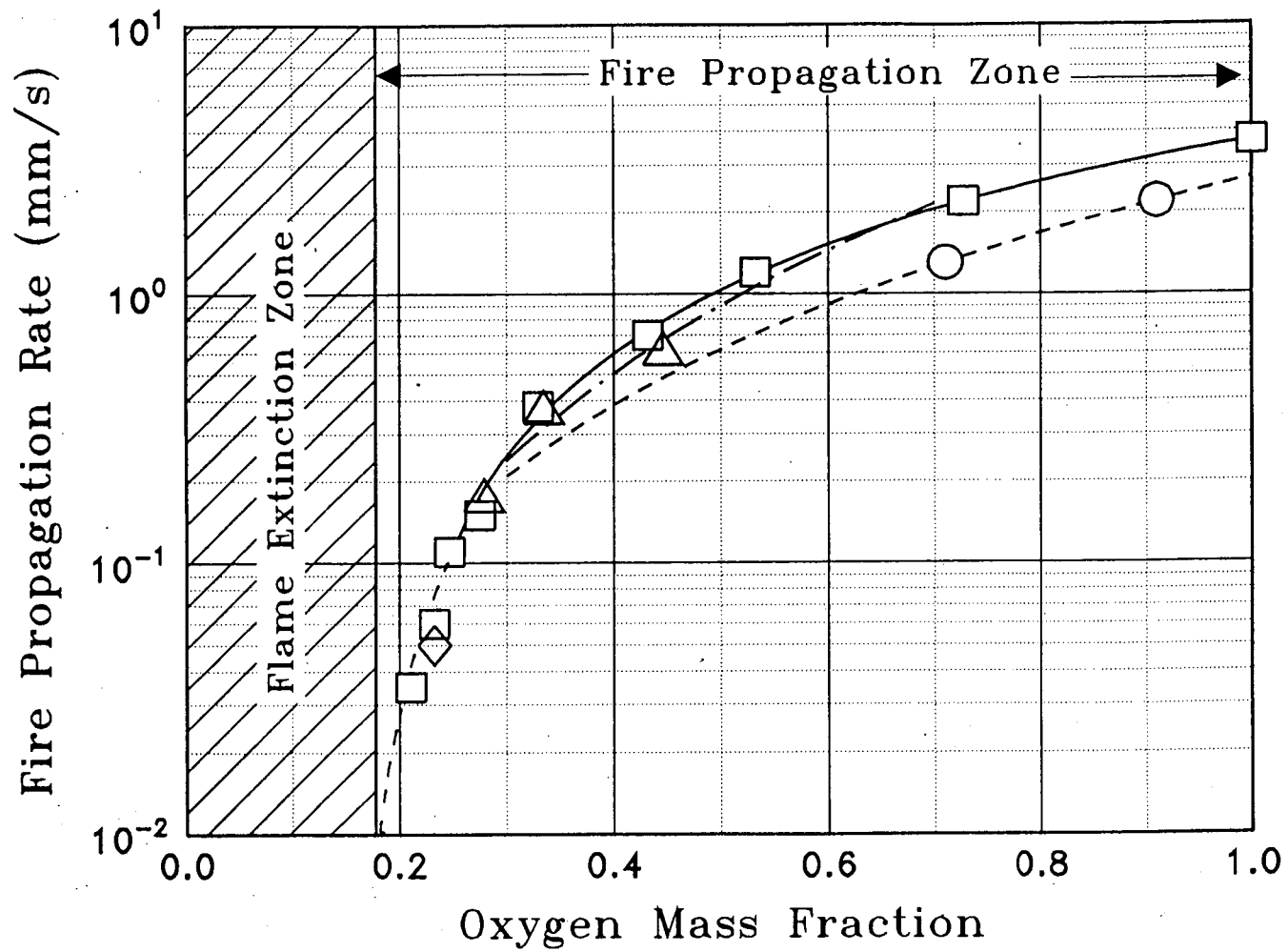


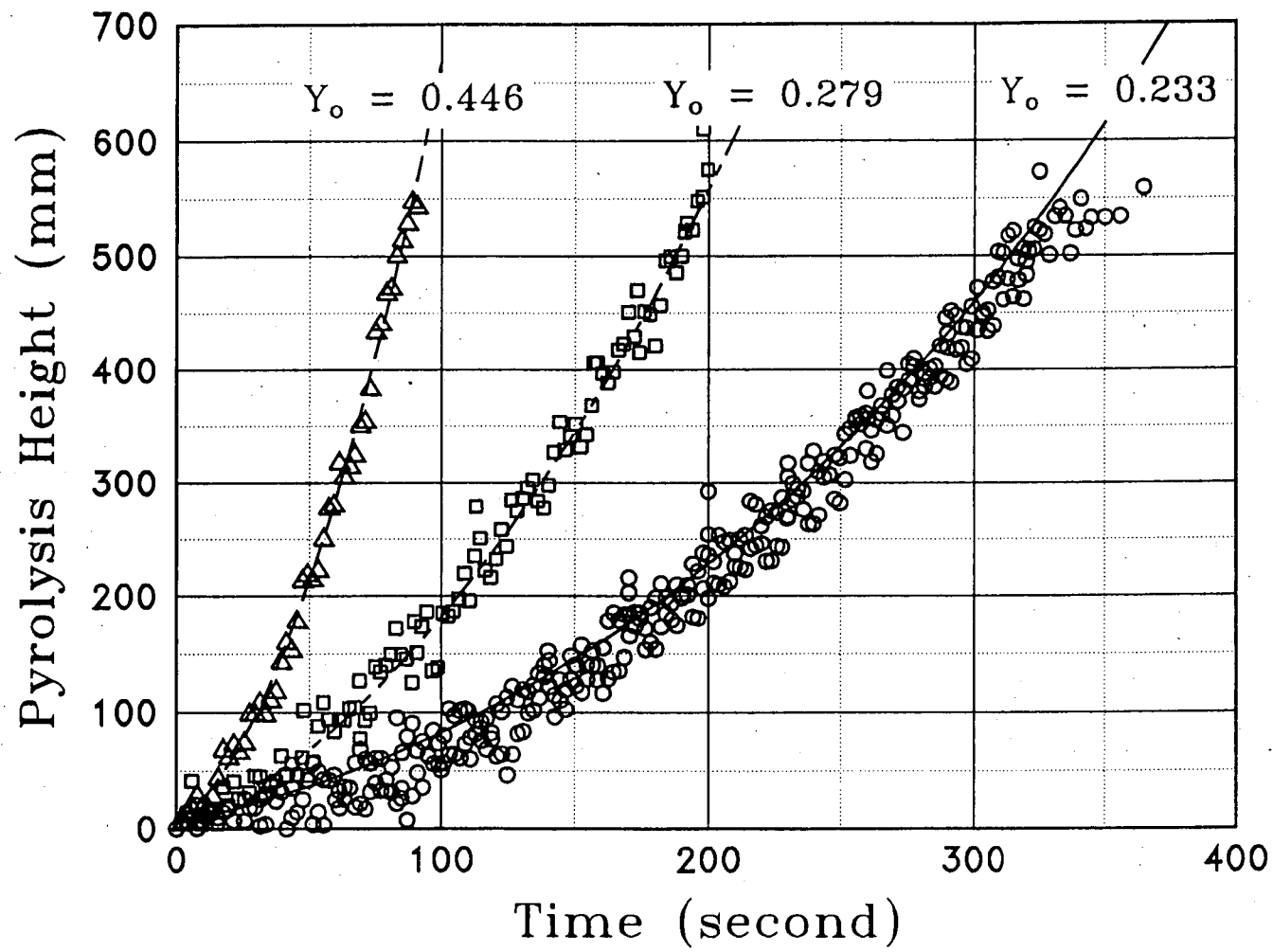












Sample Number :

Sample :

Cable Type : Power

Manufacturer/Supplier :

Cable Insulation : Cross-Linked Polyethylene (XPE).

Cable Jacket : Cross-Linked Polyethylene (XPE).

Conductor Size : 12 AWG

Number of Conductors/Volts : 3/ 600.

Diameter : 0.012 m.

Critical Heat Flux : 24 kW/m².

Chemical Heat of Combustion : 14,000 kJ/kg.

Fire Propagation Test Conditions

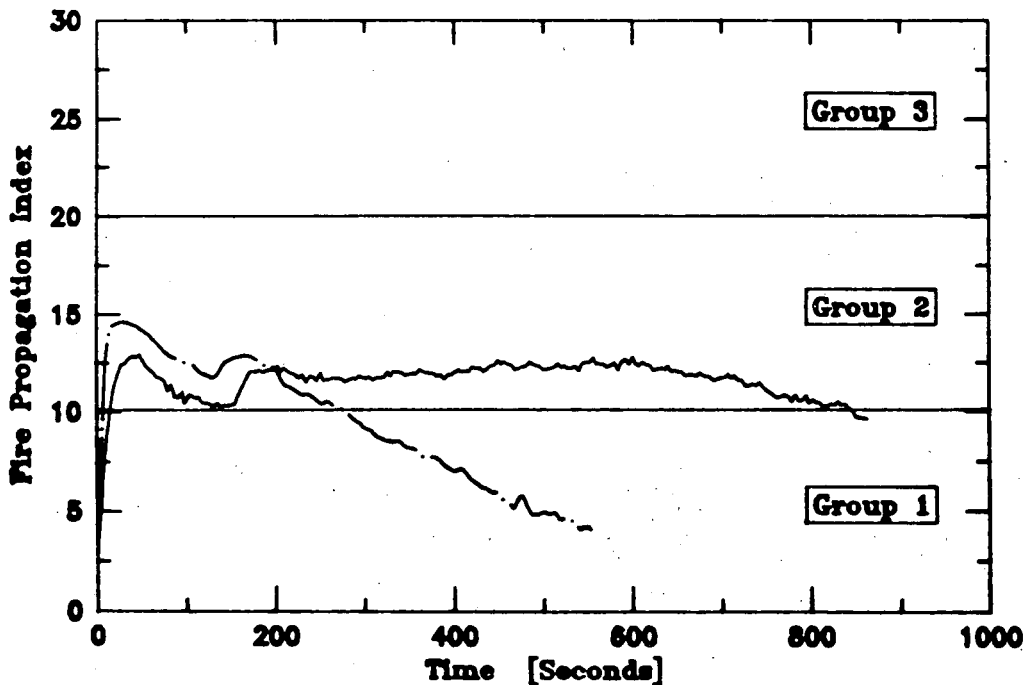
Apparatus : 500 kW-Scale.

Cable Length : 1.29 & 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : NAVY SHIP

Manufacturer/Supplier :

Cable Insulation : Silicone.

Cable Jacket : Poly(vinyl chloride) (PVC).

Conductor Size : 16 AWG.

Number of Conductors/Volts : 10 / Not Known.

Diameter : 0.016 m.

Critical Heat Flux : 19 kW/m².

Chemical Heat of Combustion : 15,100 kJ/kg.

Fire Propagation Test Conditions

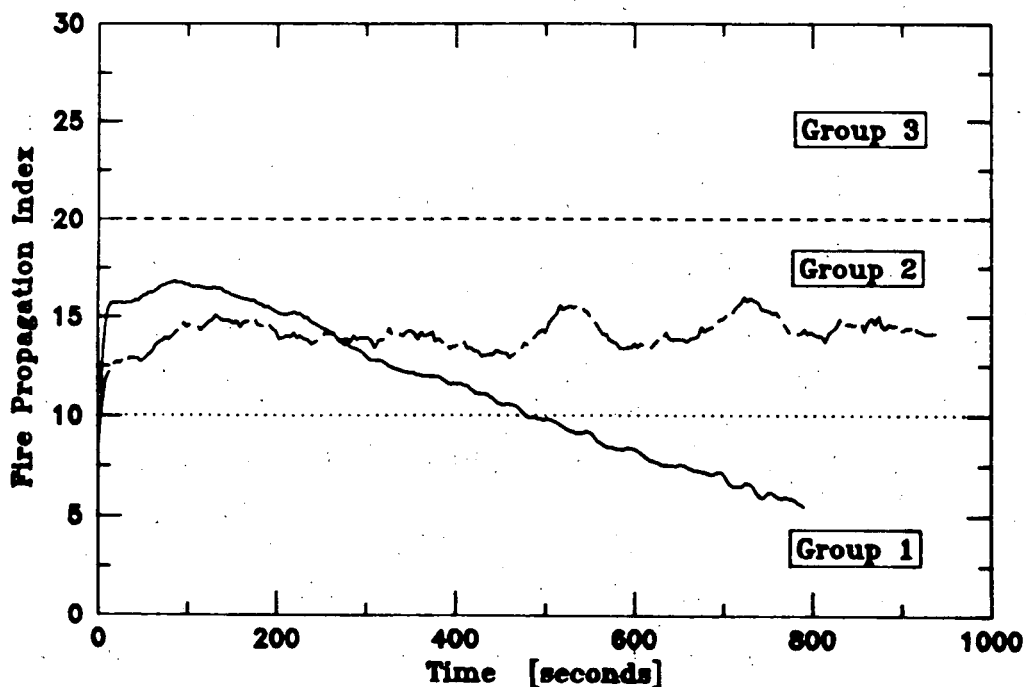
Apparatus : 500 kW-Scale.

Cable Length : 0.508 & 1.29 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

Sample Number :

Sample :

Cable Type : *CONTROL*

Manufacturer/Supplier :

Cable Insulation : Polyethylene-Polypropylene(EP).

Cable Jacket : Poly(vinyl chloride) (PVC).

Conductor Size : 12 AWG.

Number of Conductors/Volts : 3 / 600.

Diameter : 0.011 m.

Critical Heat Flux : 15 kW/m².

Chemical Heat of Combustion : 13,400 kJ/kg.

Fire Propagation Test Conditions

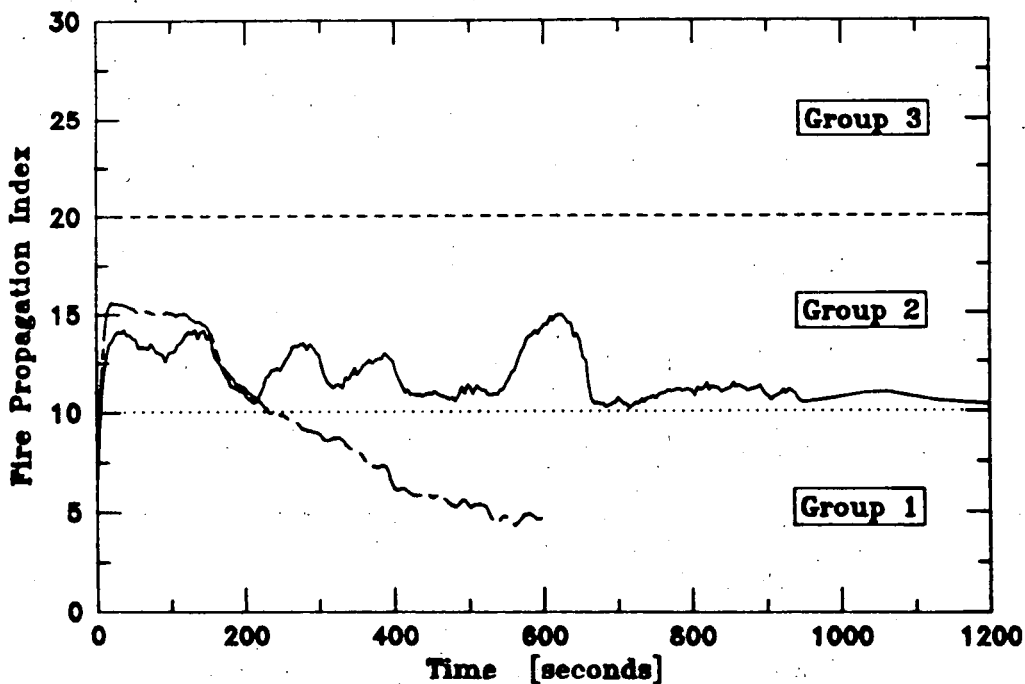
Apparatus : 500 kW-Scale.

Cable Length : 0.508 & 1.29 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : NOT KNOWN

Manufacturer/Supplier :

Cable Insulation : Poly(vinyl chloride) (PVC).

Cable Jacket : Poly(vinyl chloride) (PVC).

Conductor Size : 12 AWG.

Number of Conductors/Volts : 7 / 600.

Diameter : 0.013 m.

Critical Heat Flux : 25 kW/m².

Chemical Heat of Combustion : 16,500 kJ/kg.

Fire Propagation Test Conditions

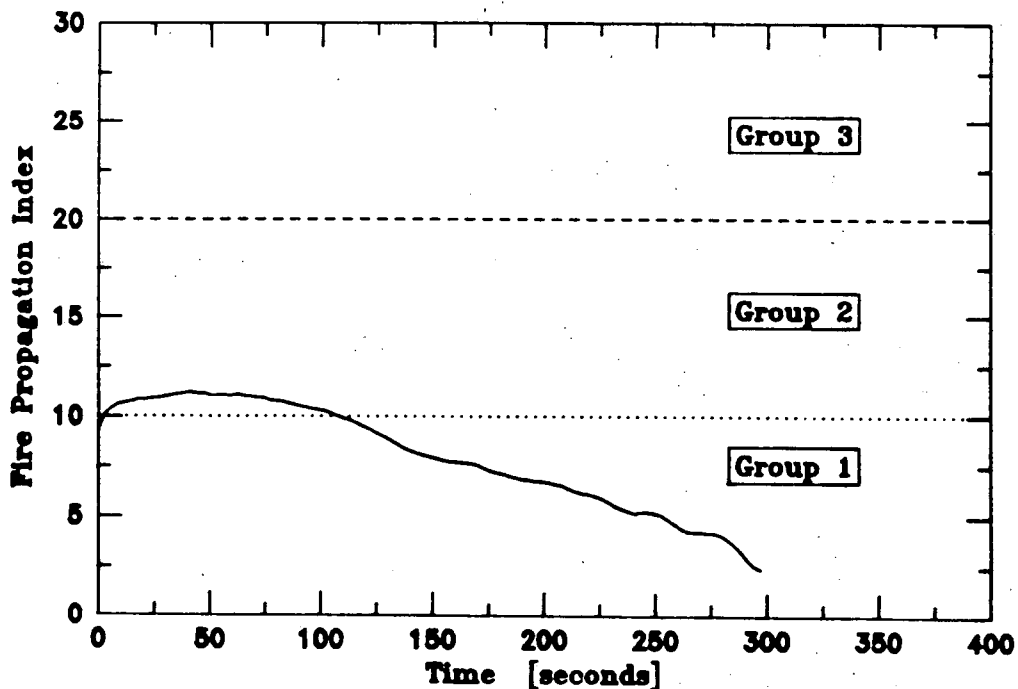
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : POWER

Manufacturer/Supplier :

Cable Insulation : Poly(vinyl chloride) (PVC).

Cable Jacket : Polyethylene-Polypropylene (EP).

Conductor Size : 2/0 AWG.

Number of Conductors/Volts : 3 / 600.

Diameter : 0.034 m.

Critical Heat Flux : 15 kW/m².

Chemical Heat of Combustion : 12,600 kJ/kg.

Fire Propagation Test Conditions

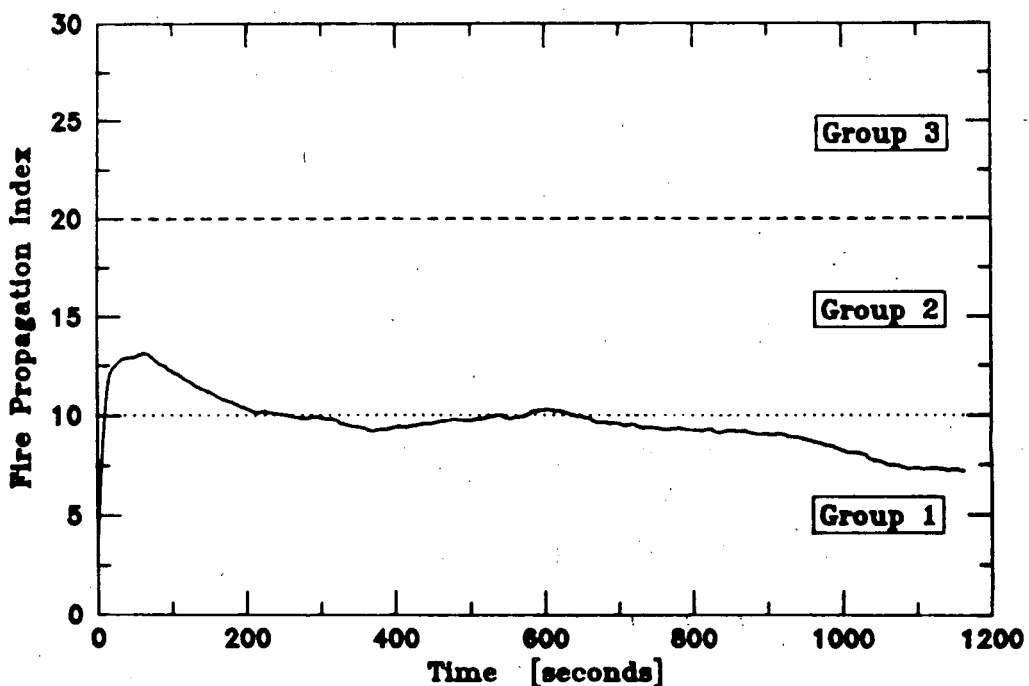
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

Sample Number :

Sample :

Cable Type : POWER & CONTROL

Manufacturer/Supplier :

Cable Insulation : Poly(vinyl chloride) (PVC).

Cable Jacket : Poly(vinyl chloride) (PVC).

Conductor Size : 12 AWG.

Number of Conductors/Volts : 3 / 600.

Diameter : 0.0092 m.

Critical Heat Flux : 13 kW/m².

Chemical Heat of Combustion : 12,600 kJ/kg.

Fire Propagation Test Conditions

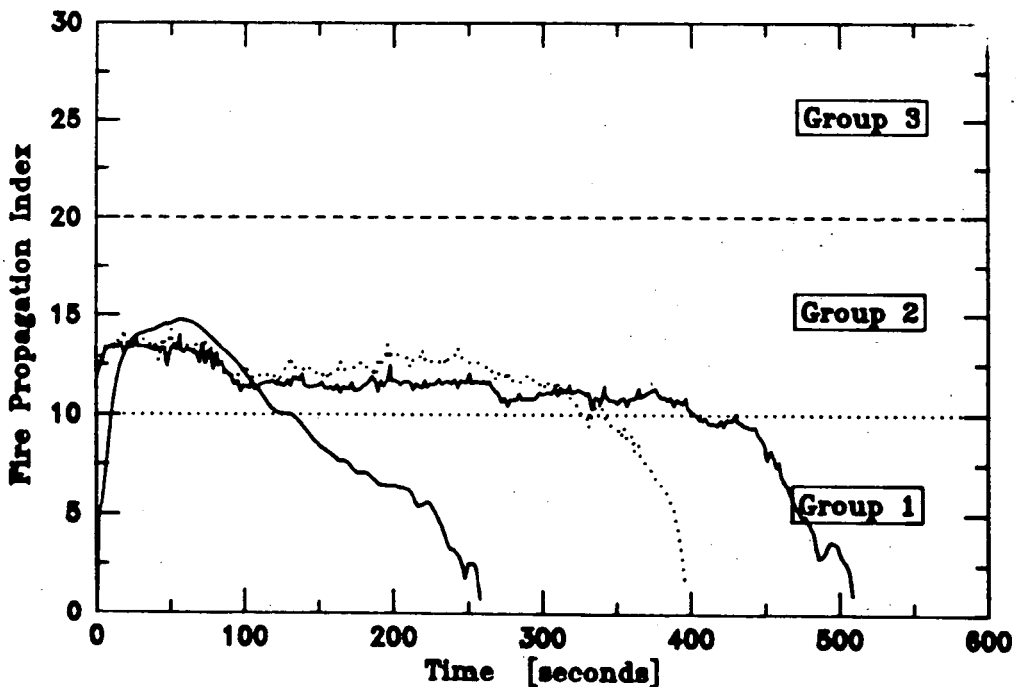
Apparatus : 500 kW-Scale.

Cable Length : 0.508 & 1.29 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %

Factory Mutual Classification :



Sample Number :

Sample :

Cable Type : Armored/Shielded Type CMB

Manufacturer/Supplier :

Cable Insulation : Unknown

Cable Jacket : Unknown

Conductor Size : 24 AWG

Number of Conductors/Volts : 100/Unknown

Diameter : 0.023m

Critical Heat Flux : 15 kW/m².

Chemical Heat of Combustion : 16,240 kJ/kg.

Fire Propagation Test Conditions

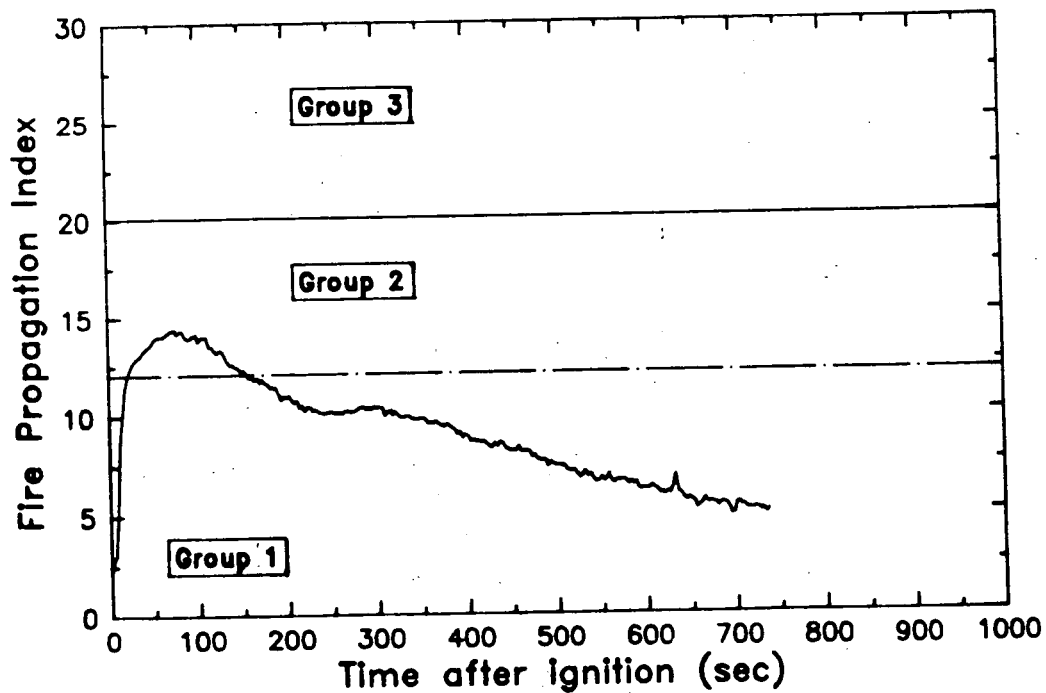
Apparatus : 500 kW-Scale.

Cable Length : 0.61m

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %

Factory Mutual Classification :



Sample Number :

Sample :

Cable Type : Control

Manufacturer/Supplier :

Cable Insulation : Ethylene-Propylene (EP), Fire Retarded (FR).

Cable Jacket : None.

Conductor Size : 14 AWG.

Number of Conductors/Volts : 1 / Unknown.

Diameter : 0.0035 m.

Critical Heat Flux : 25 kW/m².

Chemical Heat of Combustion : 30,900 kJ/kg.

Fire Propagation Test Conditions

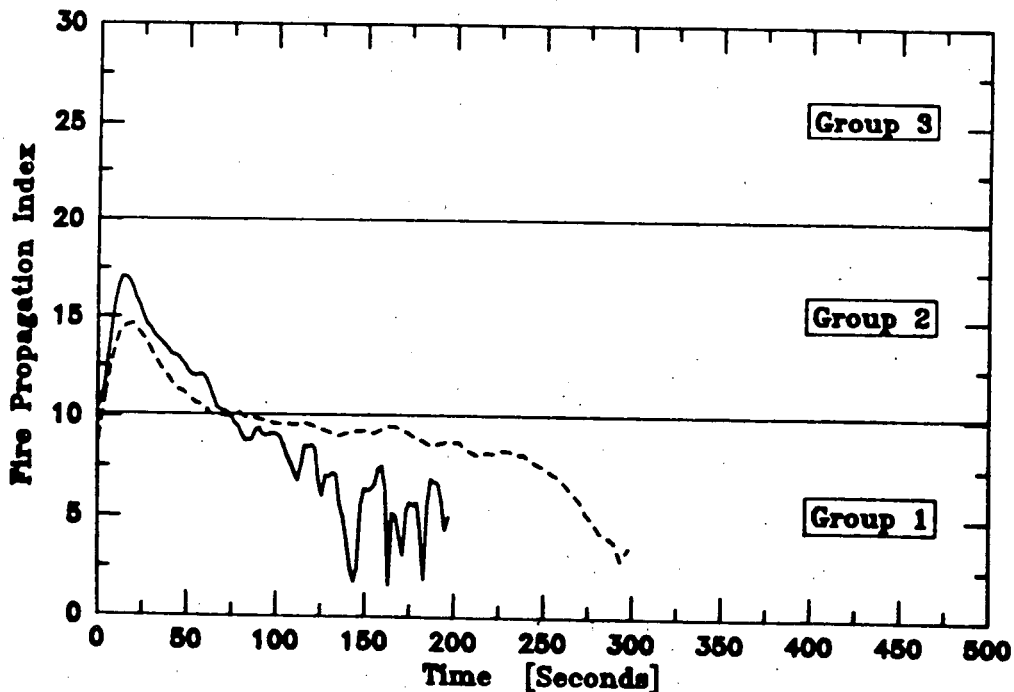
Apparatus : 500 kW-Scale.

Cable Length : 1.29 & 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : Signal

Manufacturer/Supplier :

Cable Insulation : Ethylene-Propylene (EP), Fire Retarded (FR).

Cable Jacket : None.

Conductor Size : 14 AWG.

Number of Conductors/Volts : 37 / Unknown.

Diameter : 0.028 m.

Critical Heat Flux : 19 kW/m².

Chemical Heat of Combustion : 14,600 kJ/kg.

Fire Propagation Test Conditions

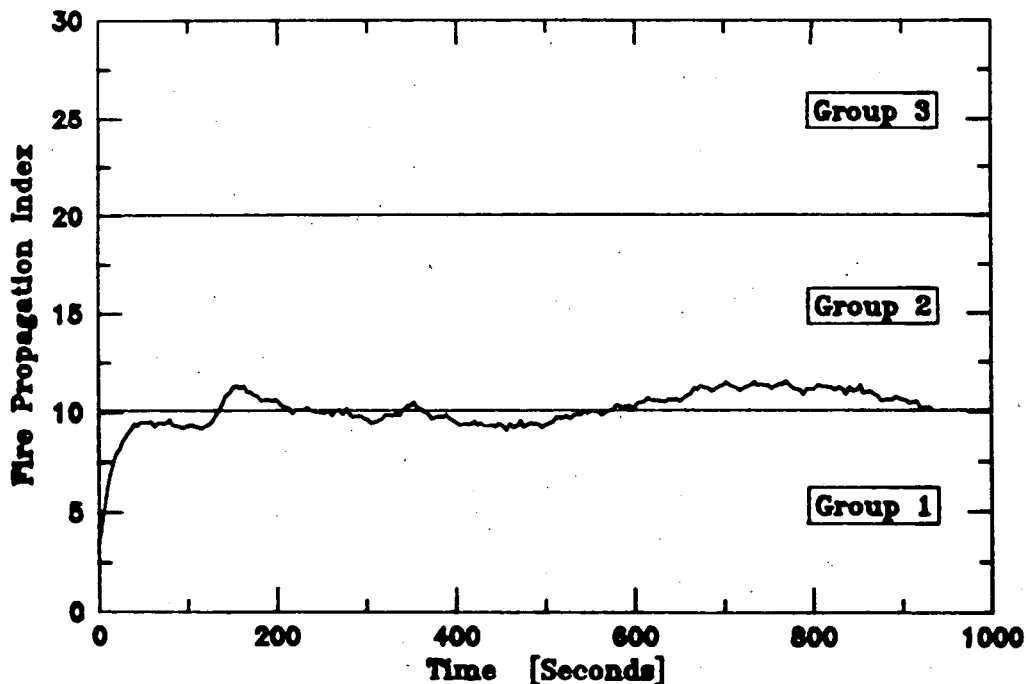
Apparatus : 500 kW-Scale.

Cable Length : 1.29 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : *POWER*

Manufacturer/Supplier :

Cable Insulation : Thermoplastic Elastomer (TPE).

Cable Jacket : Thermoplastic Elastomer (TPE).

Conductor Size : 12 AWG.

Number of Conductors/Volts : 3 / 600.

Diameter : 0.0084 m.

Critical Heat Flux : 15 kW/m².

Chemical Heat of Combustion : 12,000 kJ/kg.

Fire Propagation Test Conditions

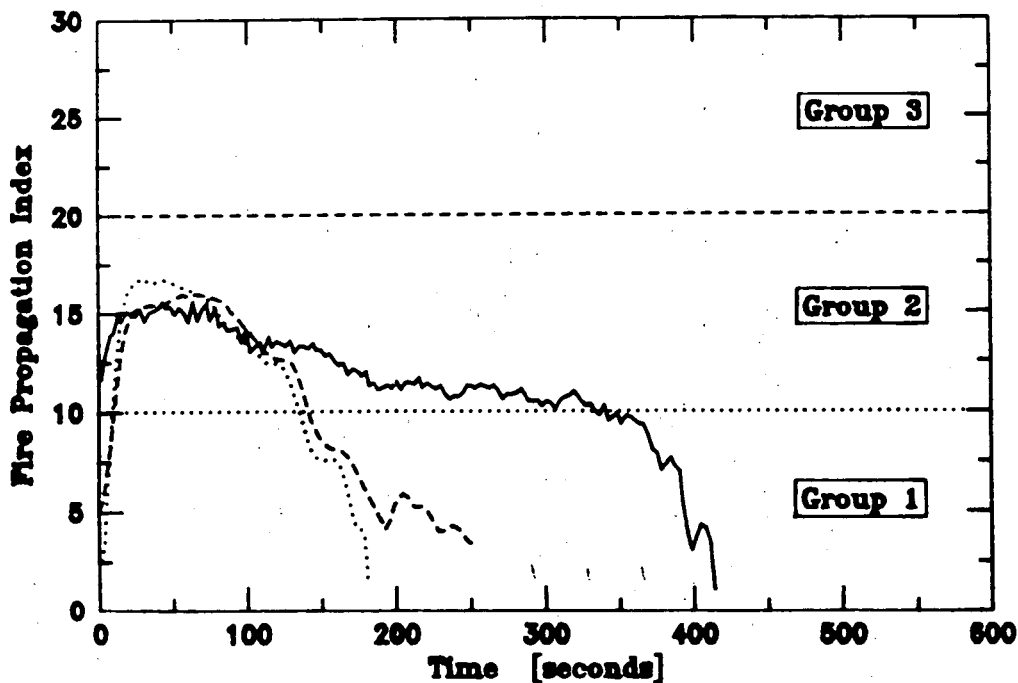
Apparatus : 500 kW-Scale.

Cable Length : 0.508 & 1.29 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30, 35 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : *POWER*

Manufacturer/Supplier :

Cable Insulation : Thermoplastic Elastomer (TPE).

Cable Jacket : Chlorinated Polyethylene (CPE).

Conductor Size : 12 AWG.

Number of Conductors/Volts : 3 / 600.

Diameter : 0.0094 m.

Critical Heat Flux : 25 kW/m².

Chemical Heat of Combustion : 11,200 kJ/kg.

Fire Propagation Test Conditions

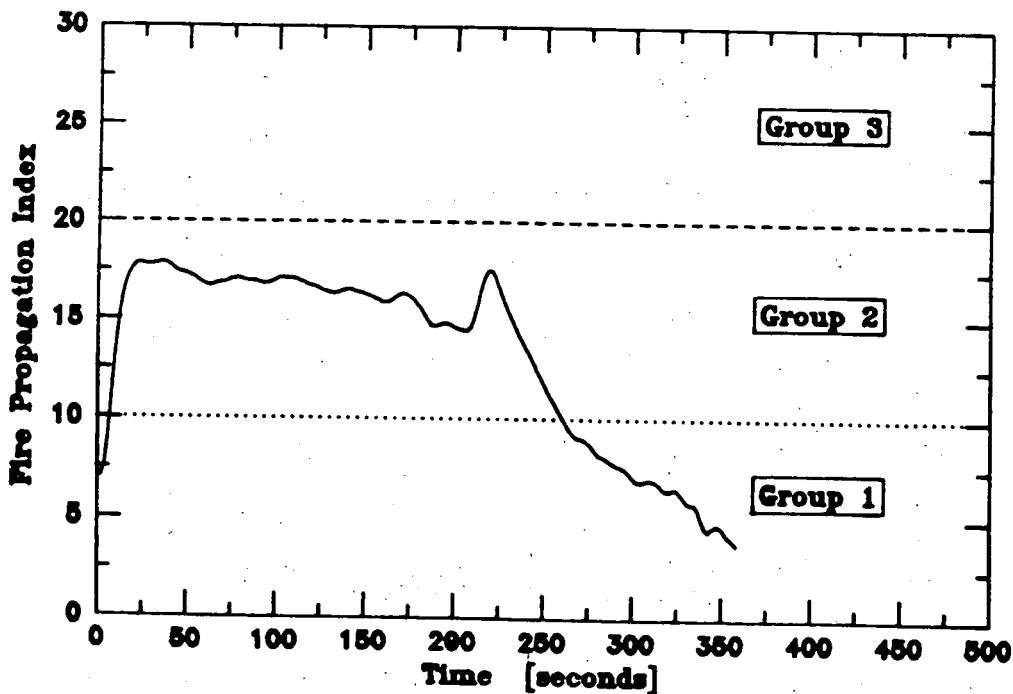
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : Control & Lighting.

Manufacturer/Supplier :

Cable Insulation : Ethylene-Propylene (EP).

Cable Jacket : Polyethylene-Chloro-Sulfonated (PE-Cl-S)

Conductor Size : 14 AWG.

Number of Conductors/Volts : 1 / 600.

Diameter : 0.0043 m.

Critical Heat Flux : 20 kW/m².

Chemical Heat of Combustion : 15,900 kJ/kg.

Fire Propagation Test Conditions

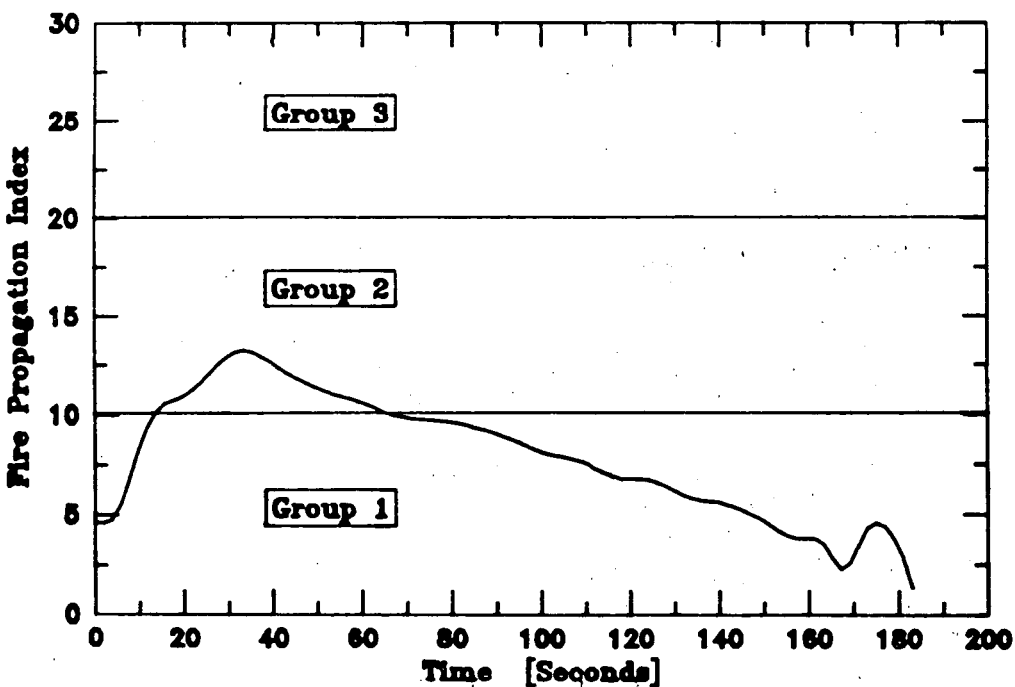
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

Sample Number :

Sample :

Cable Type : Power.

Manufacturer/Supplier :

Cable Insulation : Ethylene-Propylene (EP).

Cable Jacket : Polyethylene-Chloro-Sulfonated (PE-Cl-S)

Conductor Size : 12 AWG.

Number of Conductors/Volts : 3 / 600.

Diameter : 0.011 m.

Critical Heat Flux : 18 kW/m².

Chemical Heat of Combustion : 18,900 kJ/kg.

Fire Propagation Test Conditions

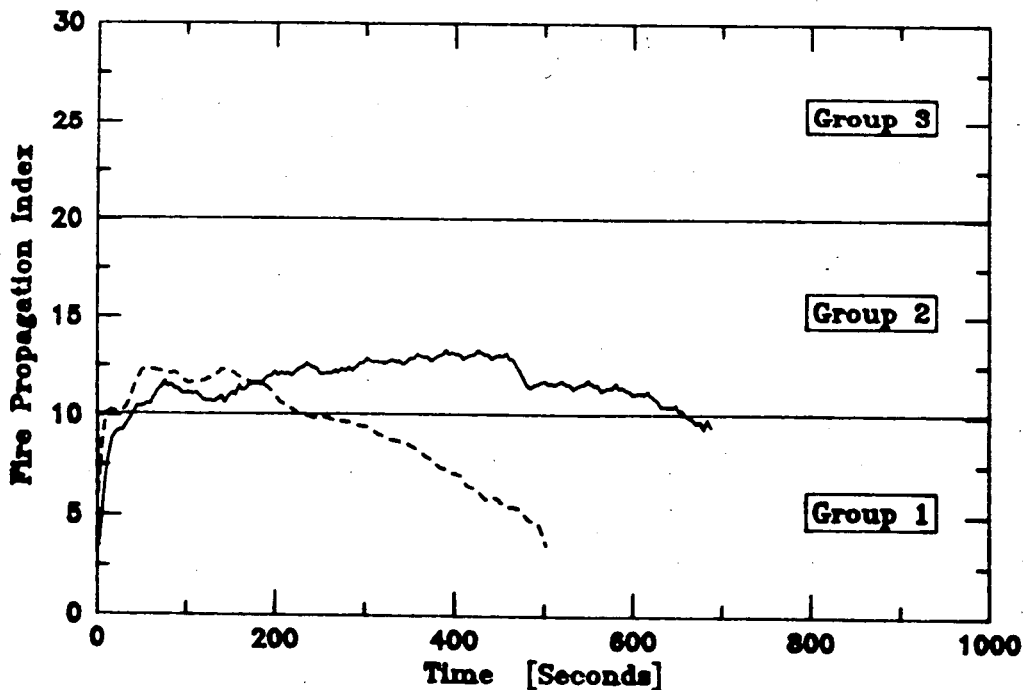
Apparatus : 500 kW-Scale.

Cable Length : 1.29 & 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : Control

Manufacturer/Supplier :

Cable Insulation : Polyethylene-Chlorinated (PE-Cl).

Cable Jacket : None.

Conductor Size : 1/0 AWG.

Number of Conductors/Volts : 1 / Unknown.

Diameter : 0.015 m.

Critical Heat Flux : 12 kW/m².

Chemical Heat of Combustion : 11,600 kJ/kg.

Fire Propagation Test Conditions

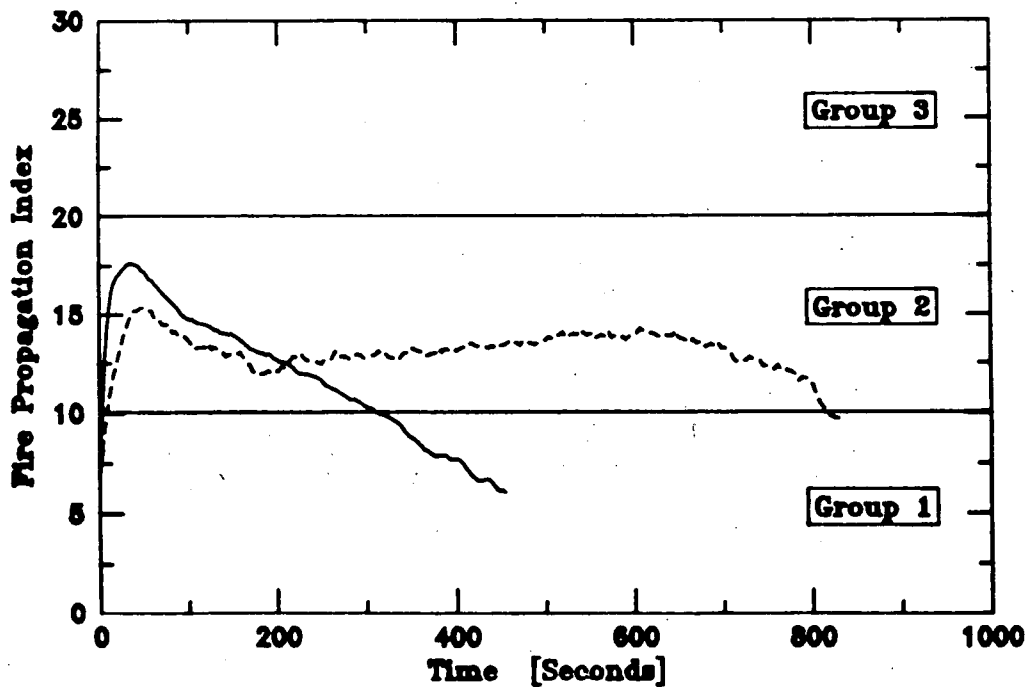
Apparatus : 500 kW-Scale.

Cable Length : 1.29 & 0.508 m.

Ignition Flux : 60 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

GROUP 3 CABLES

FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

Sample Number :

Sample :

Cable Type : RESIDENTIAL AND IN CONDUITS

Manufacturer/Supplier :

Cable Insulation : Polyethylene (PE).

Cable Jacket : Poly(vinyl chloride) (PVC).

Conductor Size : 22 AWG.

Number of Conductors/Volts : 4 / Not Known.

Diameter : 0.0037 m.

Critical Heat Flux : 20 kW/m².

Chemical Heat of Combustion : 20,900 kJ/kg.

Fire Propagation Test Conditions

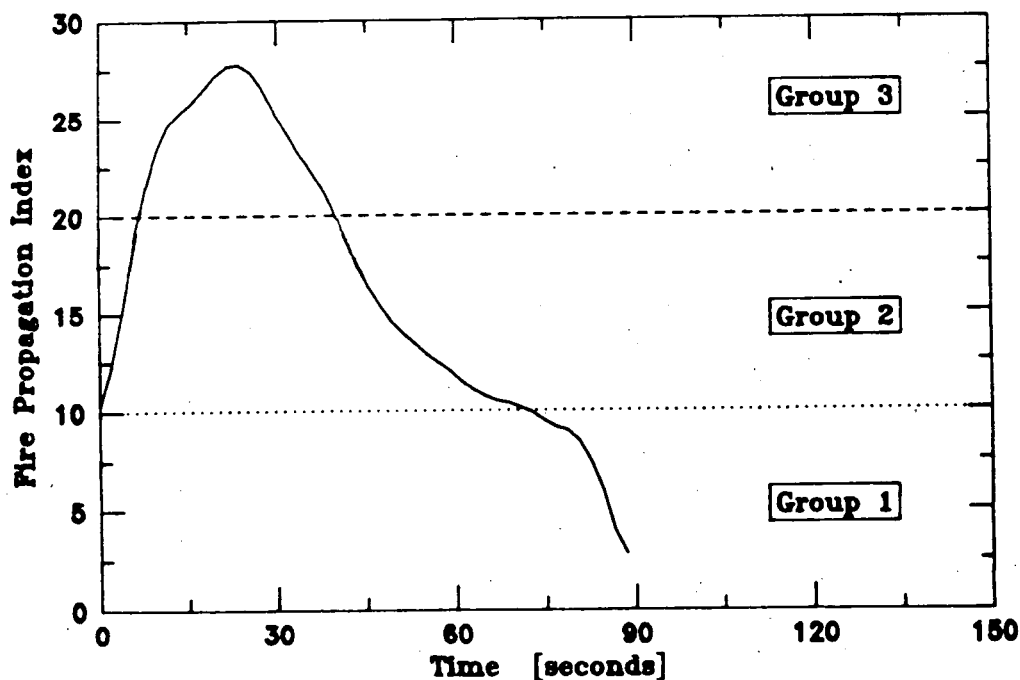
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

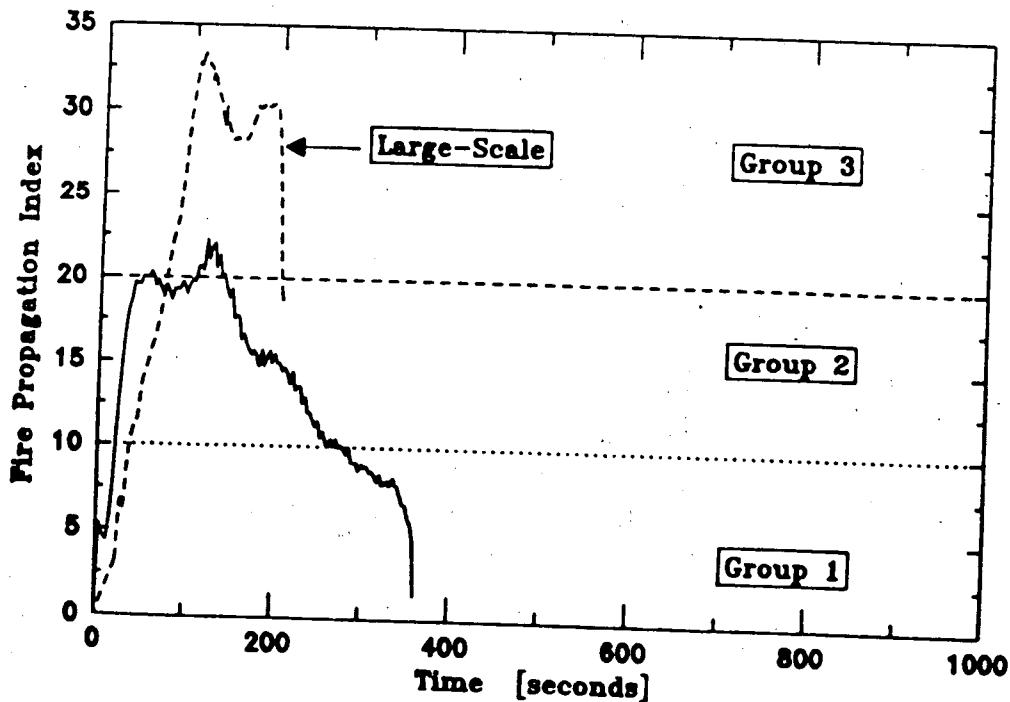
Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



Sample Number :
 Sample :
 Cable Type : NOT KNOWN
 Manufacturer/Supplier :
 Cable Insulation : Polyethylene (PE).
 Cable Jacket : Poly(Vinyl Chloride) (PVC).
 Conductor Size : 12 AWG.
 Number of Conductors/Volts : 3 / Not Known.
 Diameter : 0.011 m.
 Critical Heat Flux : 10 kW/m².
 Chemical Heat of Combustion : Not Determined.
Fire Propagation Test Conditions
 Apparatus : 500 kW-Scale.
 Cable Length : 0.508 m.
 Ignition Flux : 50 kW/m².
 Oxygen Concentration : 40 %.
 Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

Sample Number :

Sample :

Cable Type : Signal

Manufacturer/Supplier :

Cable Insulation : Fluorinated ethylene propylene (FEP).

Cable Jacket : Fluorinated ethylene propylene (FEP).

Conductor Size : Unknown.

Number of Conductors/Volts : 10 / Unknown.

Diameter : 0.0079 m.

Critical Heat Flux : 36 kW/m².

Chemical Heat of Combustion : 6,200 kJ/kg.

Fire Propagation Test Conditions

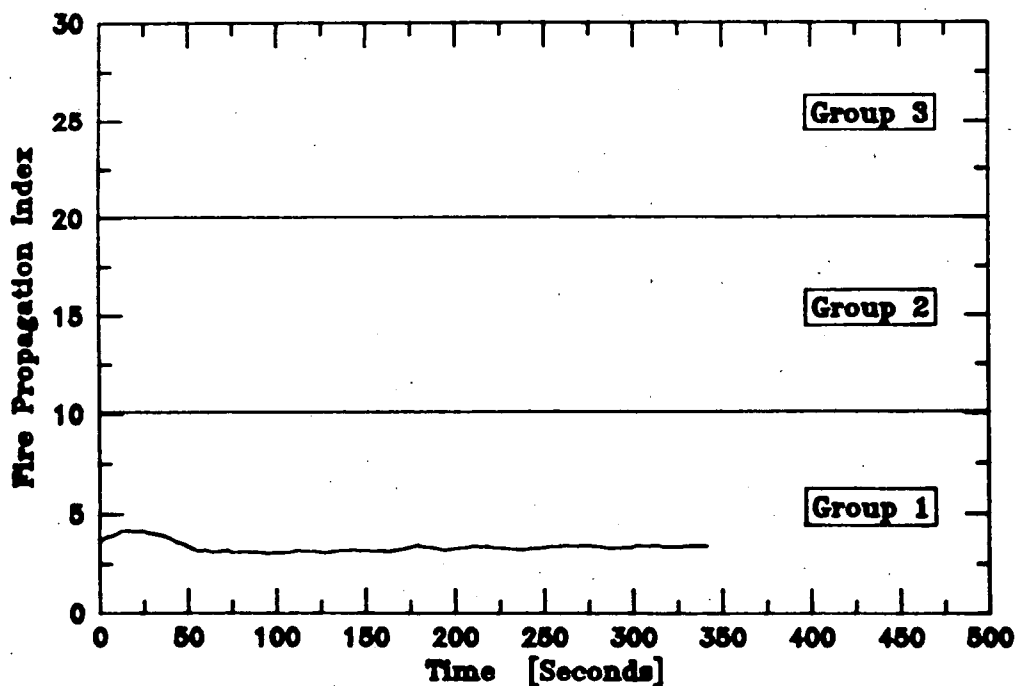
Apparatus : 500 kW-Scale.

Cable Length : 1.29 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : Power limited circuit.

Manufacturer/Supplier :

Cable Insulation : Fluorinated ethylene propylene (FEP).

Cable Jacket : Fluorinated ethylene propylene (FEP).

Conductor Size : 22 AWG.

Number of Conductors/Volts :12 / Unknown.

Diameter : 0.0097 m.

Critical Heat Flux : 30 kW/m².

Chemical Heat of Combustion : 6,200 kJ/kg.

Fire Propagation Test Conditions

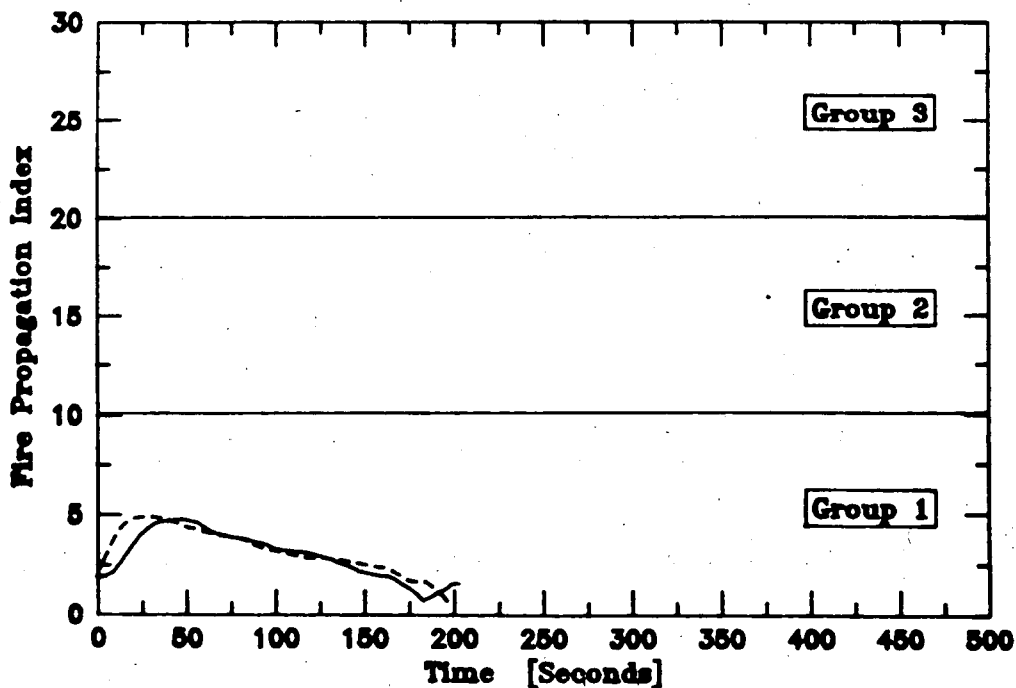
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 & 45 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : *PLENUM*.

Manufacturer/Supplier :

Cable Insulation : Poly(vinyl chloride) (PVC).

Cable Jacket : Poly(vinylidene fluoride) (PVF).

Conductor Size : 24 AWG.

Number of Conductors/Volts : 8 (pair) / Not Known.

Diameter : 0.0050 m.

Critical Heat Flux : 30 kW/m².

Chemical Heat of Combustion : 5,300 kJ/kg.

Fire Propagation Test Conditions

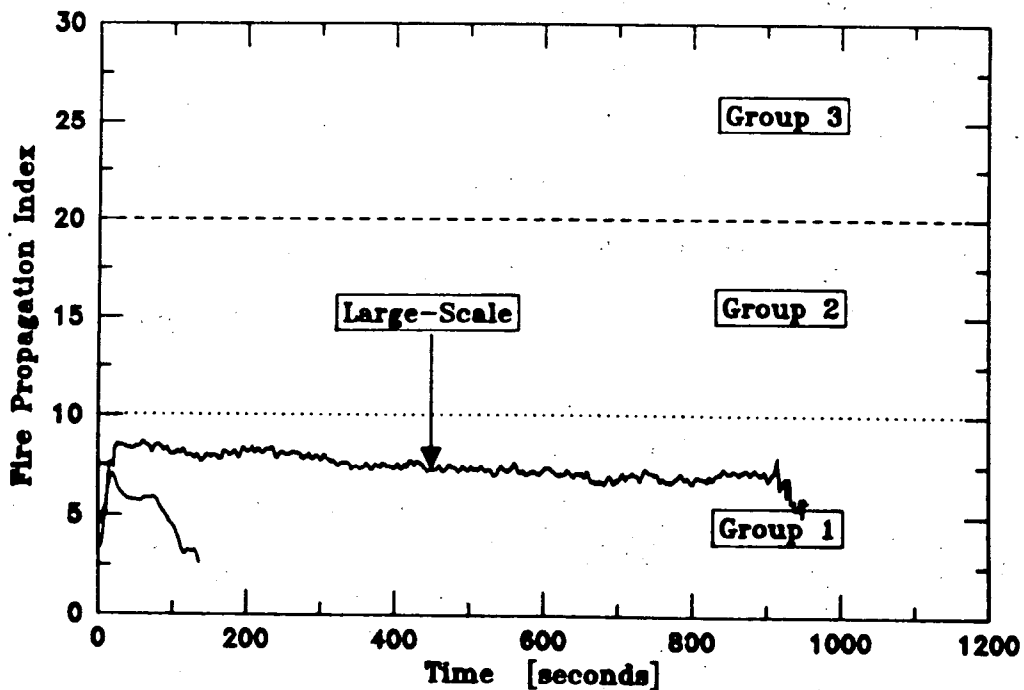
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : Control

Manufacturer/Supplier :

Cable Insulation : Ethylene-tetra fluoroethylene (ETFE).

Cable Jacket : Ethylene-acrylic (EA).

Conductor Size : Unknown.

Number of Conductors/Volts : 10 / Unknown.

Diameter : 0.010 m.

Critical Heat Flux : 12 kW/m².

Chemical Heat of Combustion : 11,200 kJ/kg.

Fire Propagation Test Conditions

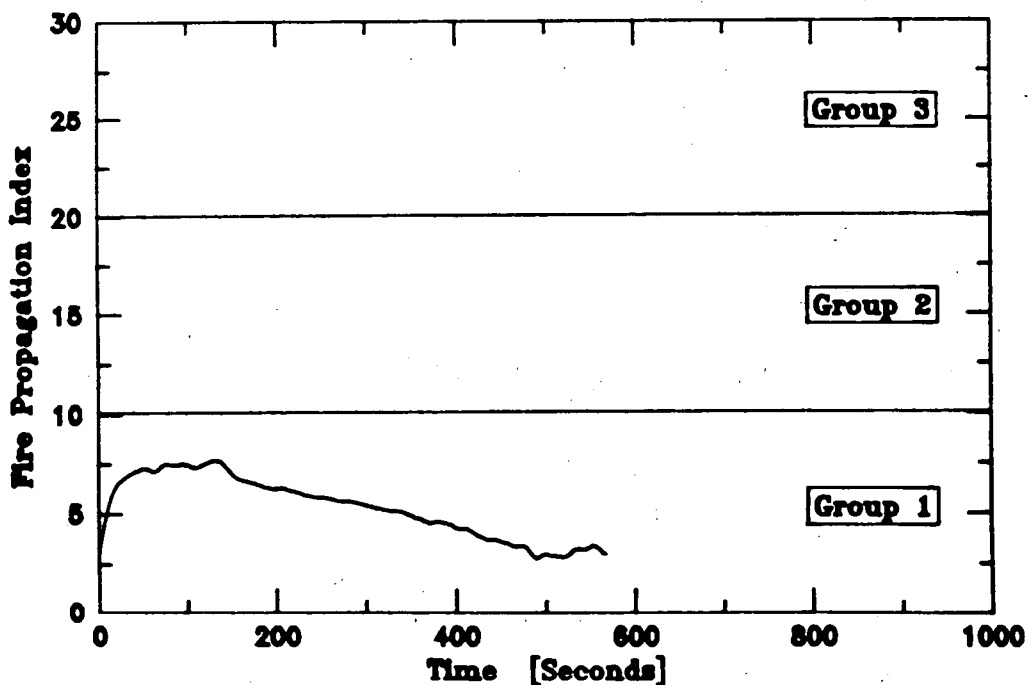
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : *NOT KNOWN*

Manufacturer/Supplier : 1

Cable Insulation : Cross-Linked Polyethylene (XPE).

Cable Jacket : Ethylene Vinyl-Acetate (EVA).

Conductor Size : 12 AWG.

Number of Conductors/Volts : 3 / Not Known.

Diameter : 0.012 m.

Critical Heat Flux : 25 kW/m².

Chemical Heat of Combustion : 17,200 kJ/kg.

Fire Propagation Test Conditions

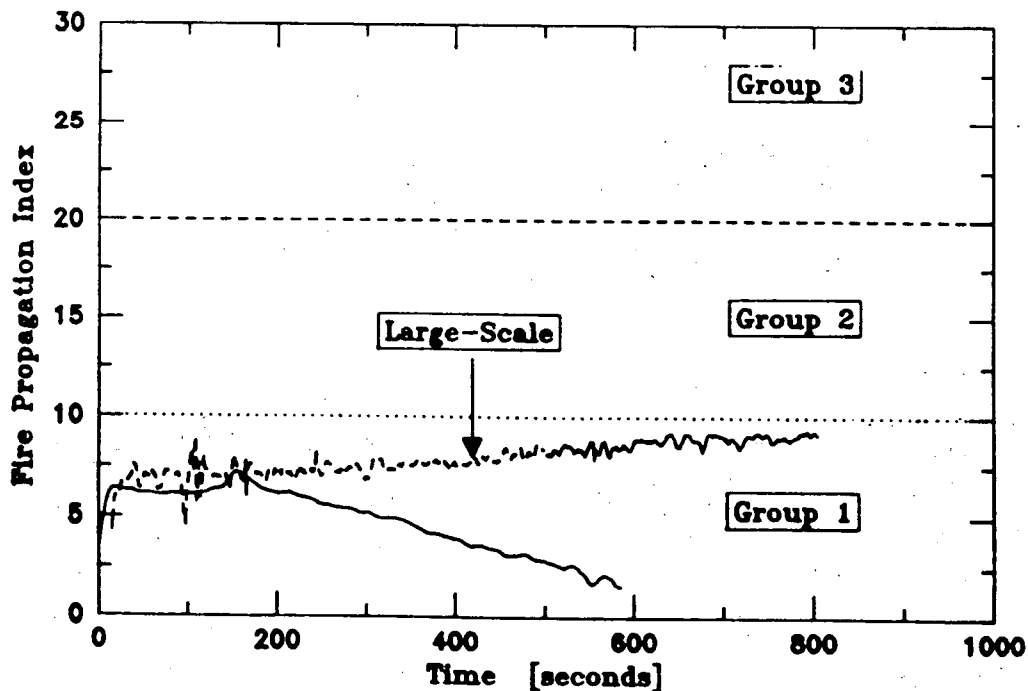
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

Sample Number :

Sample : 1

Cable Type : Power

Manufacturer/Supplier :

Cable Insulation : Cross-Linked Polyethylene (XPE).

Cable Jacket : Ethylene-vinyl acetate (EVA).

Conductor Size : 2/0 AWG

Number of Conductors/Volts : 1 / 1000.

Diameter : 0.017 m.

Critical Heat Flux : 25 kW/m².

Chemical Heat of Combustion : 21,600 kJ/kg.

Fire Propagation Test Conditions

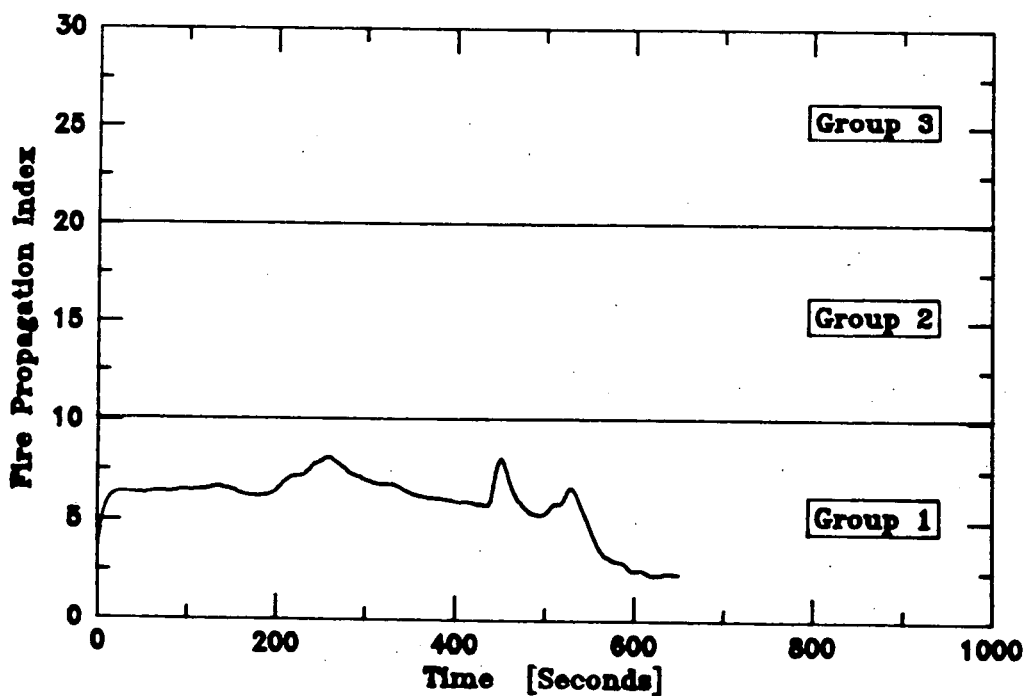
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

Sample Number :

Sample :

Cable Type : Power

Manufacturer/Supplier :

Cable Insulation : Cross-Linked Polyethylene (XPE).

Cable Jacket : Ethylene-vinyl acetate (EVA).

Conductor Size : 500 MCM

Number of Conductors/Volts : 1 / 2000.

Diameter : 0.022 m.

Critical Heat Flux : 20 kW/m².

Chemical Heat of Combustion : 22,000 kJ/kg.

Fire Propagation Test Conditions

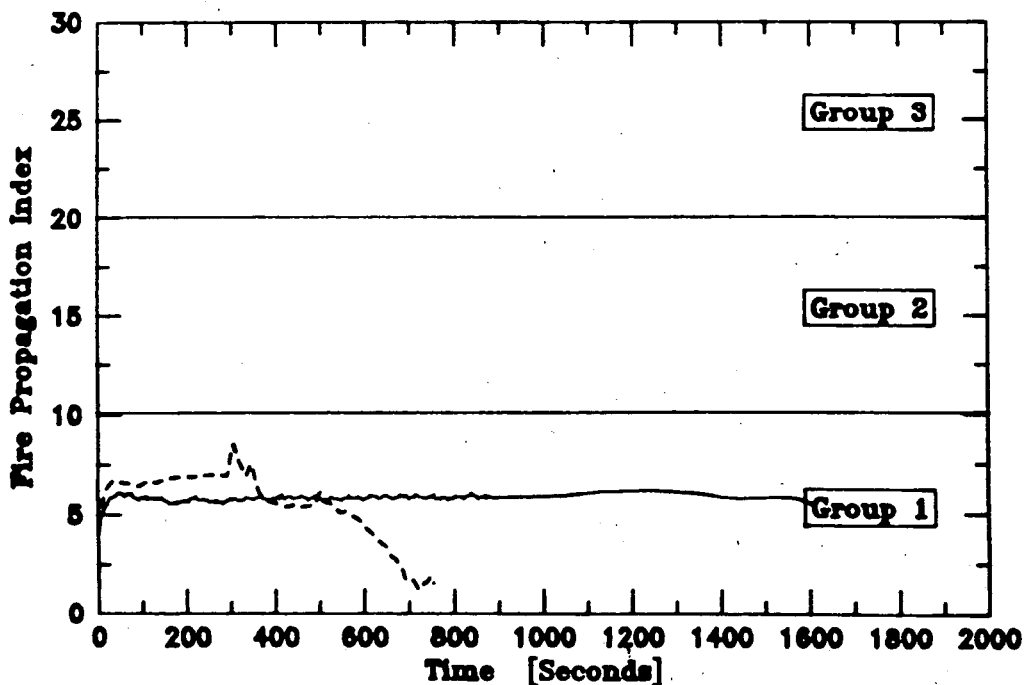
Apparatus : 500 kW-Scale.

Cable Length : 1.29 & 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

Sample Number :

Sample :

Cable Type : *NOT KNOWN*

Manufacturer/Supplier :

Cable Insulation : Cross-Linked Polyethylene (XPE).

Cable Jacket : Neoprene.

Conductor Size : 12 AWG.

Number of Conductors/Volts : 7 / Not Known.

Diameter : 0.015 m.

Critical Heat Flux : 20 kW/m².

Chemical Heat of Combustion : 12,900 kJ/kg.

Fire Propagation Test Conditions

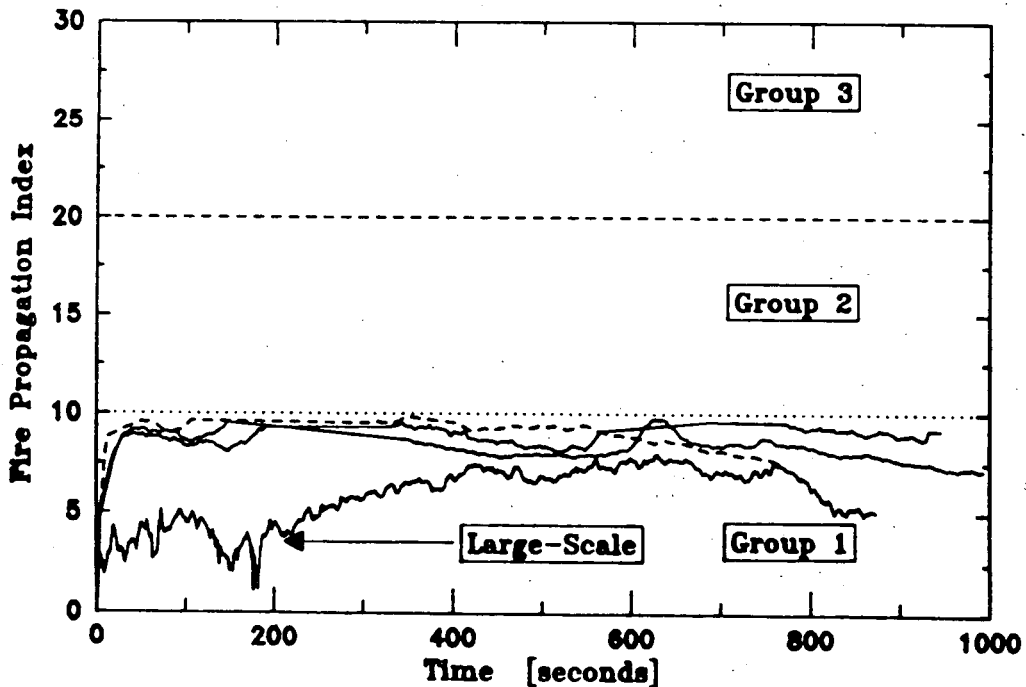
Apparatus : 500 kW-Scale.

Cable Length : 0.508 and 1.29 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30, 35 and 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

Sample Number :

Sample :

Cable Type : Control & Power

Manufacturer/Supplier :

Cable Insulation : Cross-Linked Polyethylene (XPE).

Cable Jacket : Cross-Linked Polyethylene (XPE).

Conductor Size : Unknown

Number of Conductors/Volts : 10/ 600.

Diameter : 0.0099 m.

Critical Heat Flux : 25 kW/m².

Chemical Heat of Combustion : 18,200 kJ/kg.

Fire Propagation Test Conditions

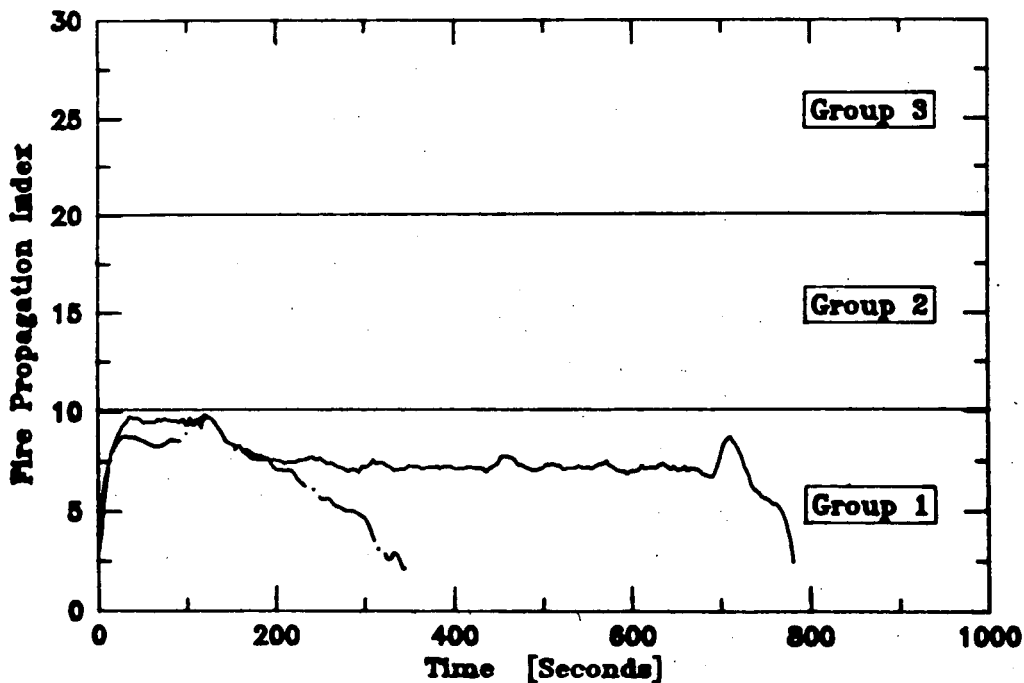
Apparatus : 500 kW-Scale.

Cable Length : 1.29 & 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : Control & Power

Manufacturer/Supplier :

Cable Insulation : Cross-Linked Polyethylene (XPE).

Cable Jacket : Cross-Linked Polyethylene (XPE).

Conductor Size : Unknown

Number of Conductors/Volts : 10/ 600.

Diameter : 0.011 m.

Critical Heat Flux : 22 kW/m².

Chemical Heat of Combustion : 19,400 kJ/kg.

Fire Propagation Test Conditions

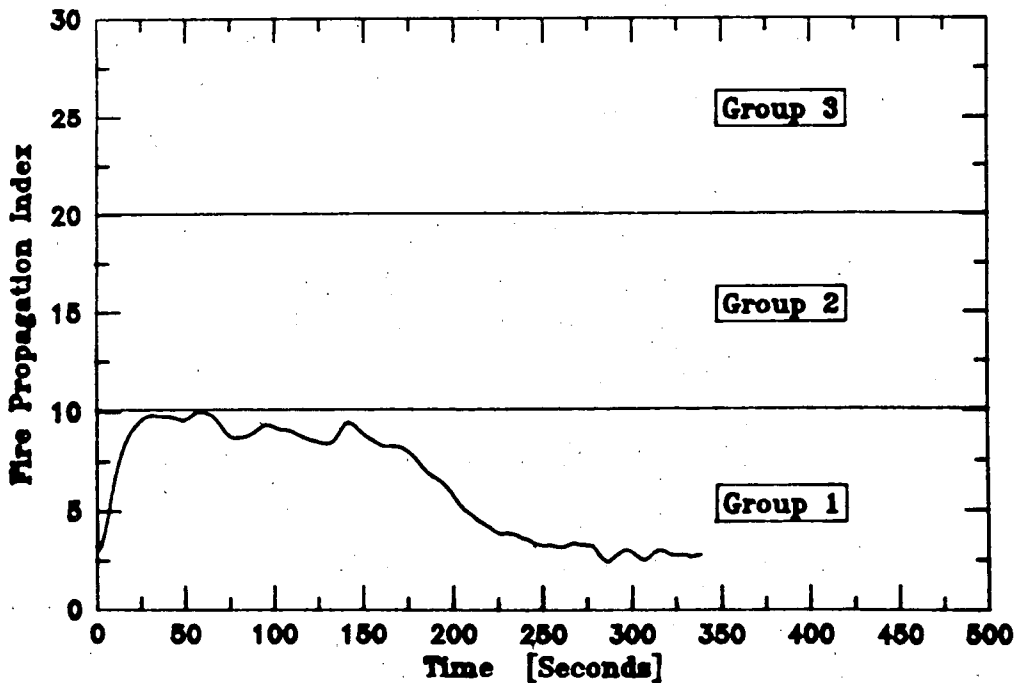
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : TRAY CABLE

Manufacturer/Supplier :

Cable Insulation : Cross-Linked Polyolefin (XPO).

Cable Jacket : Cross-Linked Polyolefin (XPO).

Conductor Size : 12 AWG.

Number of Conductors/Volts : 9 / 600.

Diameter : 0.016 m.

Critical Heat Flux : 20 kW/m².

Chemical Heat of Combustion : 14,000 kJ/kg.

Fire Propagation Test Conditions

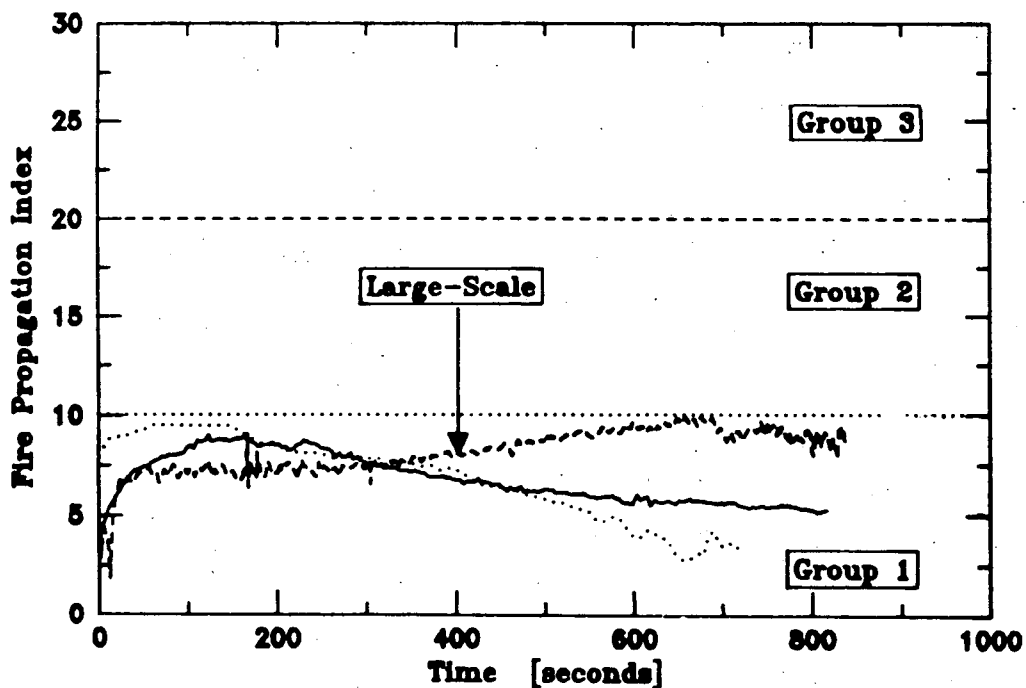
Apparatus : 500 kW-Scale.

Cable Length : 1.29 & 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

Sample Number :

Sample :

Cable Type : *POWER*

Manufacturer/Supplier :

Cable Insulation : Polyethylene-Polypropylene (EP).

Cable Jacket : Polyethylene-Polypropylene (EP).

Conductor Size : 14 AWG.

Number of Conductors/Volts : 5 / 2000.

Diameter : 0.016 m.

Critical Heat Flux : 23 kW/m².

Chemical Heat of Combustion : 16,600 kJ/kg.

Fire Propagation Test Conditions

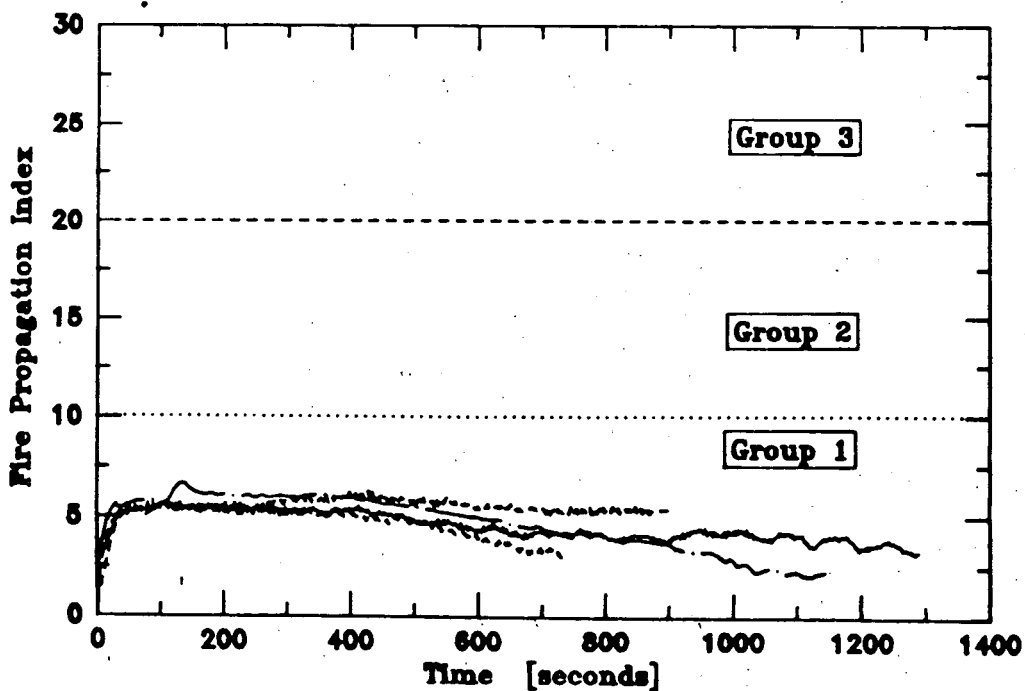
Apparatus : 500 kW-Scale.

Cable Length : 0.508 & 1.29 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 21, 30, 35 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1.RC

Sample Number :

Sample :

Cable Type : Power.

Manufacturer/Supplier :

Cable Insulation : Ethylene-Propylene (EP), Fire Retarded (FR).

Cable Jacket : None.

Conductor Size : 2/0 AWG.

Number of Conductors/Volts : 1 / Unknown.

Diameter : 0.015 m.

Critical Heat Flux : 25 kW/m².

Chemical Heat of Combustion : 14,800 kJ/kg.

Fire Propagation Test Conditions

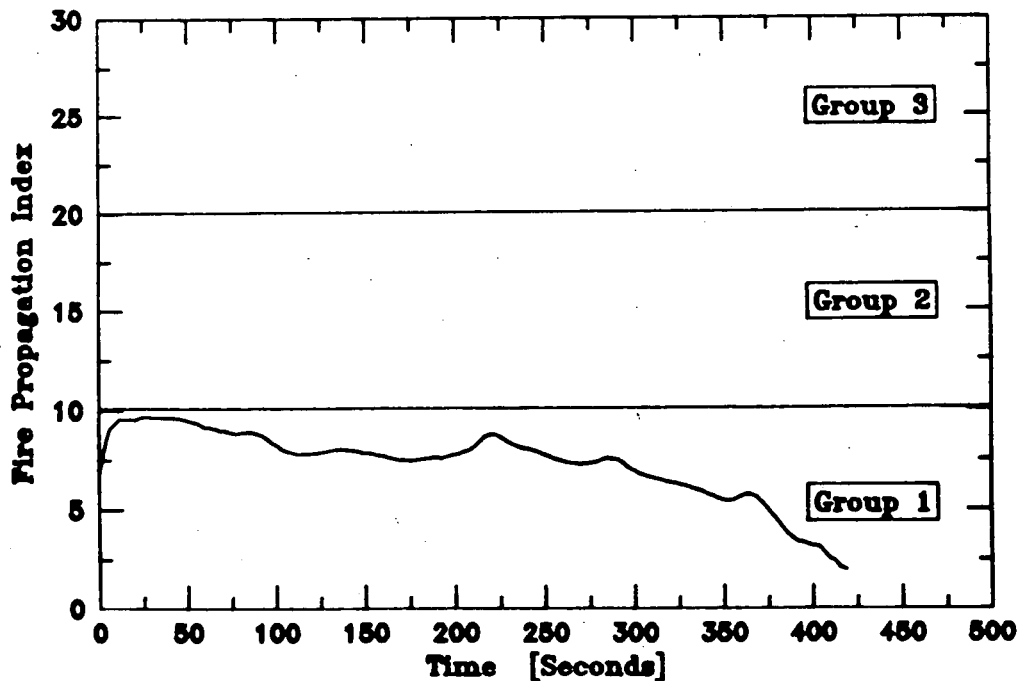
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : Power.

Manufacturer/Supplier :

Cable Insulation : Ethylene-Propylene (EP), Fire Retarded (FR).

Cable Jacket : None.

Conductor Size : 4/0 AWG.

Number of Conductors/Volts : 1 / Unknown.

Diameter : 0.018 m.

Critical Heat Flux : 20 kW/m².

Chemical Heat of Combustion : 15,100 kJ/kg.

Fire Propagation Test Conditions

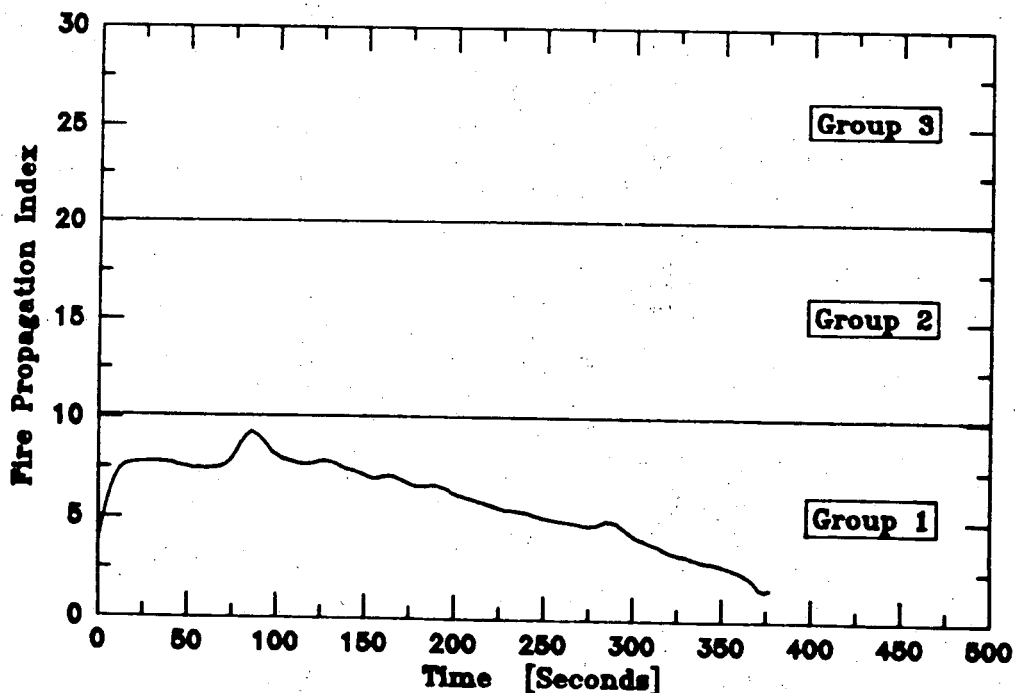
Apparatus : 500 kW-Scale.

Cable Length : 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : *POWER*

Manufacturer/Supplier :

Cable Insulation : Polyethylene-Polypropylene (EP).

Cable Jacket : Polyethylene-Polypropylene (EP).

Conductor Size : 250 MCM.

Number of Conductors/Volts : 1 / 2000.

Diameter : 0.025 m.

Critical Heat Flux : 23 kW/m².

Chemical Heat of Combustion : 19,700 kJ/kg.

Fire Propagation Test Conditions

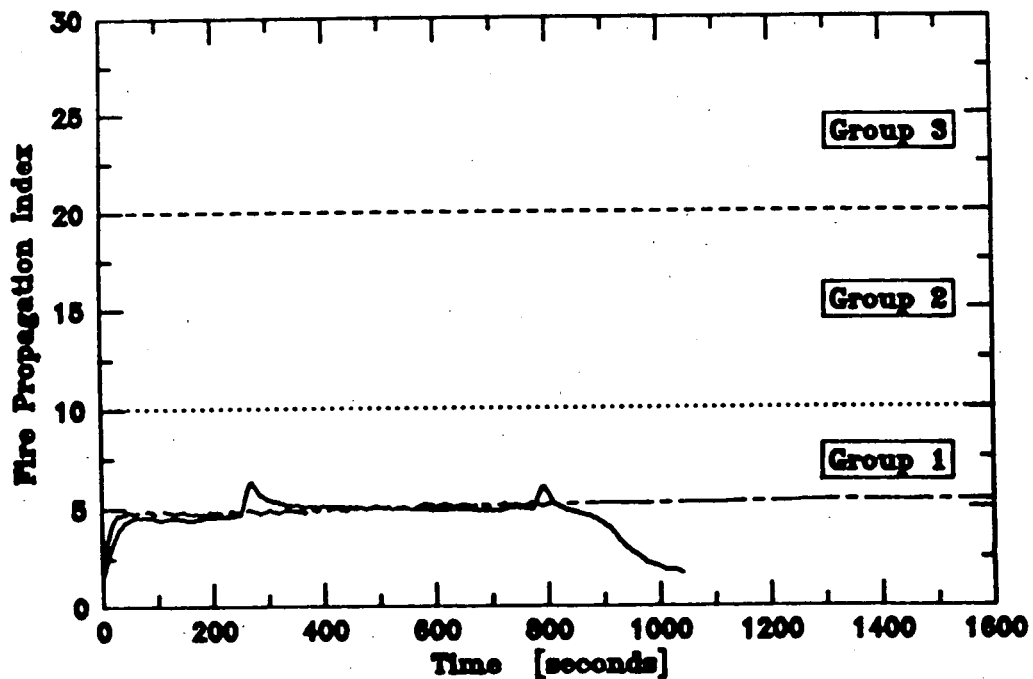
Apparatus : 500 kW-Scale.

Cable Length : 0.508 & 1.29 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

OM2E1:RC

Sample Number :

Sample :

Cable Type : Power.

Manufacturer/Supplier :

Cable Insulation : Ethylene-Propylene (EP).

Cable Jacket : Polyethylene-Chloro-Sulfonated (PE-Cl-S).

Conductor Size : 2/0 AWG.

Number of Conductors/Volts : 1 / 600.

Diameter : 0.016 m.

Critical Heat Flux : 20 kW/m².

Chemical Heat of Combustion : 19,300 kJ/kg.

Fire Propagation Test Conditions

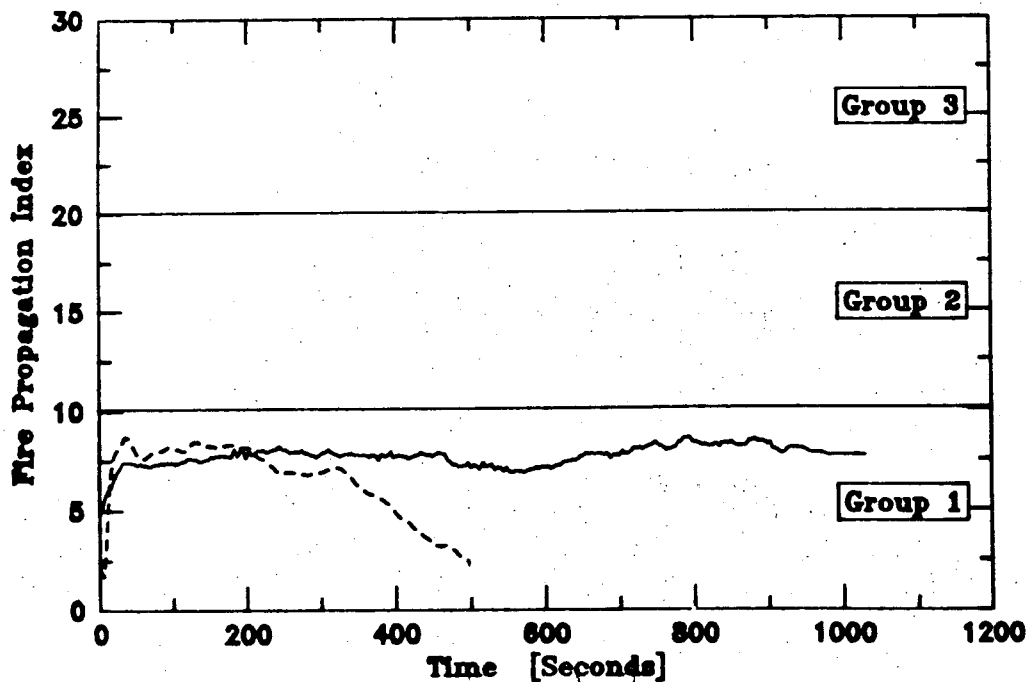
Apparatus : 500 kW-Scale.

Cable Length : 1.29 & 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number :

Sample :

Cable Type : POWER

Manufacturer/Supplier :

Cable Insulation : Polyethylene-Polypropylene (EP).

Cable Jacket : Polyethylene-Polypropylene (EP).

Conductor Size : 6 AWG.

Number of Conductors/Volts : 1 / 600.

Diameter : 0.010 m.

Critical Heat Flux : 20 kW/m².

Chemical Heat of Combustion : 17,100 kJ/kg.

Fire Propagation Test Conditions

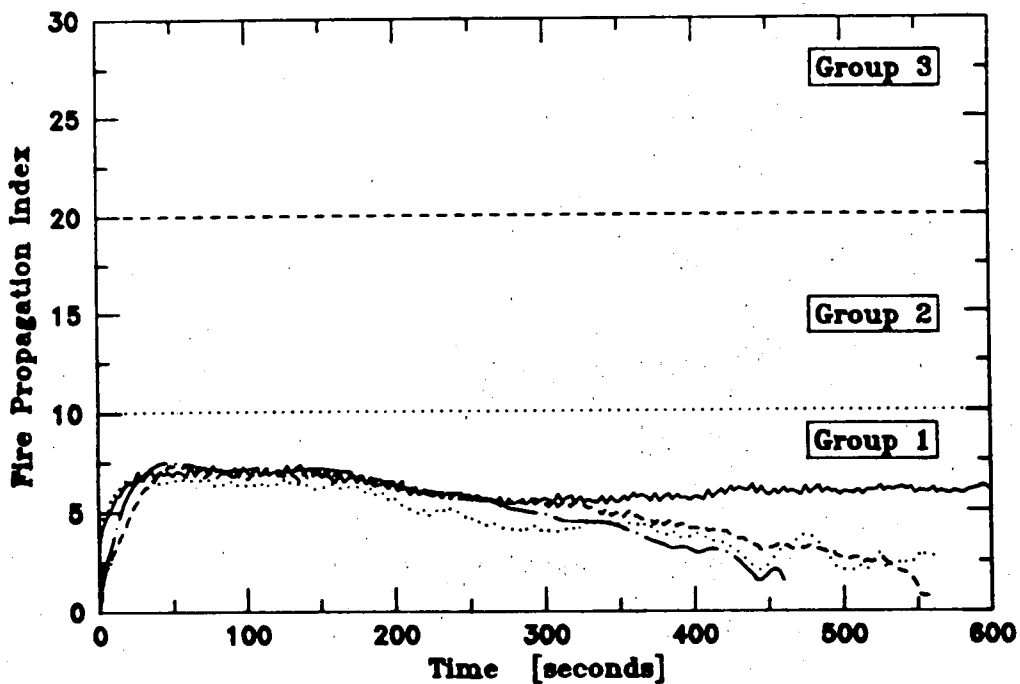
Apparatus : 500 kW-Scale.

Cable Length : 0.508 & 1.29 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 21, 30, 35 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

QM2E1.RC

Sample Number

Sample :

Cable Type : Powert.

Manufacturer/Supplier :

Cable Insulation : Ethylene-Propylene (EP).

Cable Jacket : Polyethylene-Chloro-Sulfonated (P-Cl-S).

Conductor Size : 4/0 AWG.

Number of Conductors/Volts : 1 / 600.

Diameter : 0.019 m.

Critical Heat Flux : 20 kW/m².

Chemical Heat of Combustion : 20,100 kJ/kg.

Fire Propagation Test Conditions

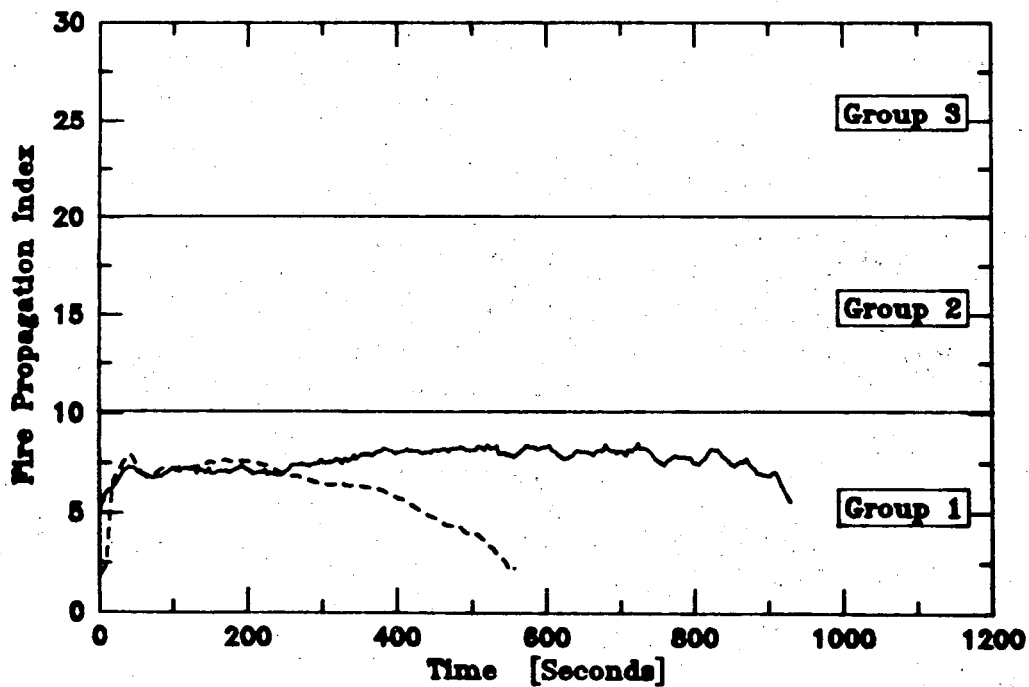
Apparatus : 500 kW-Scale.

Cable Length : 1.29 & 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



FACTORY MUTUAL RESEARCH CORPORATION

0M2E1.RC

GROUP 2 CABLES

Sample Number :

Sample :

Cable Type : Control & Power

Manufacturer/Supplier :

Cable Insulation : Cross-Linked Polyethylene (XPE).

Cable Jacket : Cross-Linked Polyethylene (XPE).

Conductor Size : 12 AWG.

Number of Conductors/Volts : 3 / 600.

Diameter : 0.0095 m.

Critical Heat Flux : 20 kW/m².

Chemical Heat of Combustion : 12,400 kJ/kg.

Fire Propagation Test Conditions

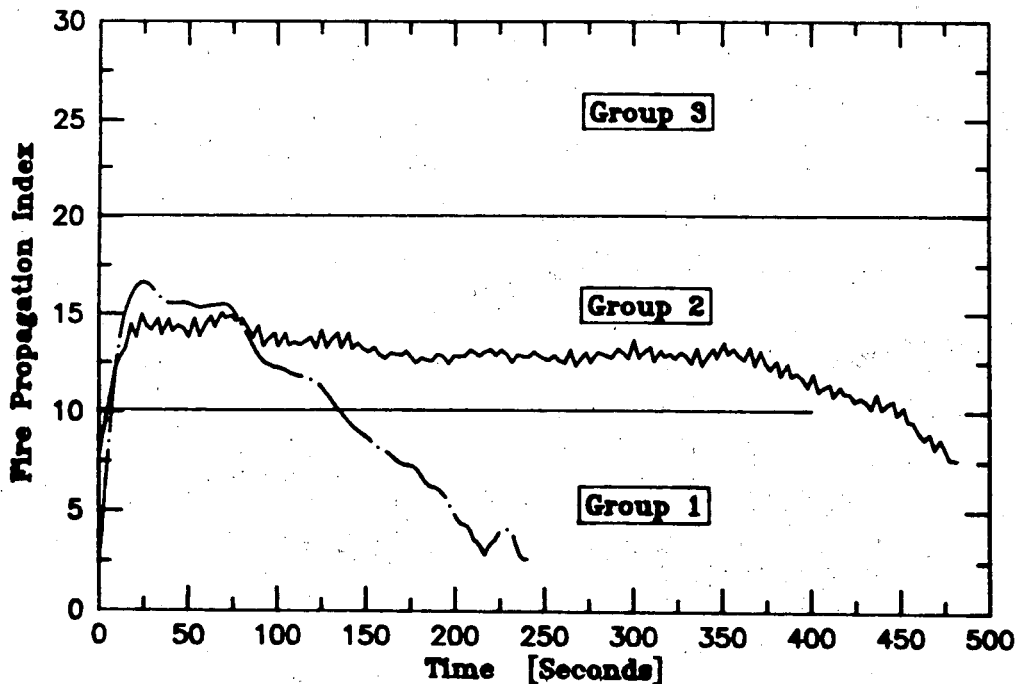
Apparatus : 500 kW-Scale.

Cable Length : 1.29 & 0.508 m.

Ignition Flux : 50 kW/m².

Oxygen Concentration : 30 & 40 %.

Factory Mutual Classification :



OM2E1.RC

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30. Tewarson, A., "Flame-Retardant Polymeric Materials (M. Lewin, S.M. Atlas and E.M. Pearce, Eds.), Vol. 3, Chapter 3, p. 97, Plenum Press, New York, NY, 1982.
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APPENDIX A

NATIONAL ELECTRICAL CODE 1987

Cable Designations Based on Insulation and Jacketing Materials

(Taken from Reference 3)

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Trade Name	Type Letter	Insulation	Jacket
Heat-Resistant Rubber	RH	Heat Resistance Rubber	Moisture Resistant, Flame Retardant, Non-metallic
	RHH		
Moisture and Heat-Resistance Rubber	RHW	Moisture & Heat Resistance Rubber	Same as above
Moisture Resistant Thermoplastic	TW	Flame Retardant, Resistant, Thermoplastic	None
Heat Resistant Thermoplastic	THHN	Flame Retardant, Heat Resistant Thermoplastic	Nylon
Moisture and Heat Resistant Thermoplastic	THW	Flame Retardant, Moisture & Heat Resistant Thermoplastic	None
Same as above	THWN	Same as above	Nylon
Moisture & Heat Resistant Cross Linked Synthetic Polymer	XHHW	Flame Retardant Cross Linked Synthetic Polymer	None

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APPENDIX B

FIRE PROPAGATION

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Fire propagation is one of the major processes through which hazardous environments are created in fires. Numerous studies have been performed to understand the fire propagation process [29]. The fire propagation rate is expressed as a ratio of the heat transfer rate to the material surface to the thermal response of the material for both concurrent and opposed flow spread. Concurrent flow spread is defined as the fire propagation in the direction of the flow; the opposed flow spread is defined as the fire propagation in the direction opposite to the gas flow. For concurrent flow spread for thermally thick solids, the fire propagation velocity, V , is expressed as [35],

$$V^{1/2} = \dot{q}_{fs}'' \delta_{fs}^{1/2} / (k \rho c_p)^{1/2} \Delta T, \quad (B-1)$$

where V is in m/s; \dot{q}_{fs}'' is the maximum flame heat flux to fuel surface ahead of the flame front (kW/m^2); δ_{fs} is an effective flame heat transfer distance estimated to be about 0.16 m; k is the thermal conductivity (kW/m-K); ρ is the density (g/m^3); c_p is the specific heat (kJ/g-K); and ΔT is the difference between the ignition temperature and initial surface temperature in K.

The heat conduction theory shows that the thermal response of a thermally thick material (denominator in Eq. (B1)) can be expressed as a function of time to ignition, t_{ig} :

$$t_{ig}^{-1/2} \propto \dot{q}_i'' / (k \rho c_p)^{1/2} \Delta T, \quad (B-2)$$

where t_{ig} is in seconds; and \dot{q}_i'' is the heat flux absorbed by the material (kW/m^2). The time to gasification can also be expressed in a similar fashion, in which case ΔT is the difference between the gasification temperature and the ambient temperature in K. $(k\rho c_p)^{1/2} \Delta T$ is defined as thermal response parameter in this report.

Eqs. (B-1) through (B-2) suggest that the fire propagation process is affected by factors which influence the heat transfer rate to the surface of the material and its thermal response; the factors are: 1) external heat flux; 2) flame heat flux; 3) initial surface temperature of the material; 4) O_2 concentration in the gas flow; and 5) chemical structures, which influence decomposition, gasification and combustion of materials. Other

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important factors are gas velocity and pressure, sample orientation and thickness. The effects of these factors have been examined in numerous studies and theories, and engineering relationships have been developed for the flame propagation process [29].

Extent of Flame Propagation

The fire propagation on a surface is a process associated with the consumption of material vapors and generation of heat and chemical compounds. The heat release rate and generation of chemical compounds can be expressed as [26]:

$$E_{Ch}(t) = \int_{t_{ig}}^t \dot{Q}_{Ch}(t) dt = \int_{t_{ig}}^t x_{Ch} \Delta H_T \dot{w}(t) dt = \Delta H_{Ch} W, \quad (B-3)$$

$$M_j(t) = \int_{t_{ig}}^t \dot{G}_j(t) dt = \int_{t_{ig}}^t Y_j \dot{w}(t) dt = Y_j W, \quad (B-4)$$

where $E_{Ch}(t)$ is the chemical energy in kJ and $M_j(t)$ is the mass of compound j in gm generated between t_{ig} and t ; $\dot{w}(t)$ is the mass generation rate of material vapors during the flame propagation process at time t (g/s); ΔH_{Ch} is the average chemical heat of combustion (kJ/g); W is the total mass of material generated (g); $\dot{G}_j(t)$ is the generation rate of compound j at time t (g/s) and Y_j is the average yield of compound j (g/g). All these quantities can be measured experimentally.

For the vertical fire propagation process, if it is assumed that the total chemical energy and total mass of each compound generated and total mass of material consumed during the flame propagation process, per unit total area, are conserved, then the following relationships should be valid at any time during the flame propagation process [26]:

$$E_{Ch}(t)/A(t) = \xi, \quad (B-5)$$

$$M_j(t)/A(t) = \eta, \quad (B-6)$$

$$W(t)/A(t) = \mu, \quad (B-7)$$

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where t refers to any specified time; A is the surface area (m^2); ξ , n and μ are constants within each generic group of polymers. ξ is in kJ/m^2 , n and μ are in g/m^2 ; A is equal to $\pi d l$ for a single cable, where d is the diameter of the cable (m) and l is the effective combustion length (m). A is equal to $\pi d n h$ for grouped cable (cables attached diameter-to-diameter to a support of inert material), n is the number of cables and h is the effective combustion height (m).

From Eqs. (B-5) to (B-7), the following relationships can be derived for the extent of fire propagation [26]:

Single Cable

$$l(t) = E_{Ch}(t) / \pi d \xi = M_j(t) / \pi d n = W(t) / \pi d \mu. \quad (B-8)$$

Grouped Cables with Vertical Configuration

$$h(t) = E_{Ch}(t) / (\pi d n \xi) = M_j(t) / (\pi d n \mu) \\ = W(t) / (\pi d n \mu). \quad (B-9)$$

The fire propagation rate then can be expressed as:

$$V(t) = dl(t)/dt = dh(t)/dt. \quad (B-10)$$

Since $E_{Ch}(t)$, $M_j(t)$ or $W(t)$ depend on burn out, pyrolysis and combustion, the computed values of l and h will vary accordingly. $V(t)$ in Eq. (B-10) thus may be considered as an average fire propagation rate.

From Eq. (B-1), assuming 1) cable width to be equal to $n\pi d$, where n is the number of cables and d is the overall cable diameter, and 2) radiative component of the chemical heat release rate, χ_R , to be 0.40 [26]:

$$V^{1/2} \propto (0.40 \dot{Q}_{Chem} / n\pi d)^{1/3} / \Delta T (k\rho c_p)^{1/2} \quad (B-11)$$

Cable data satisfy Eq. (11) as shown in Figure 1B, where χ_R is assumed to equal to 0.40.

Vertical Fire Propagation for Electrical Cables

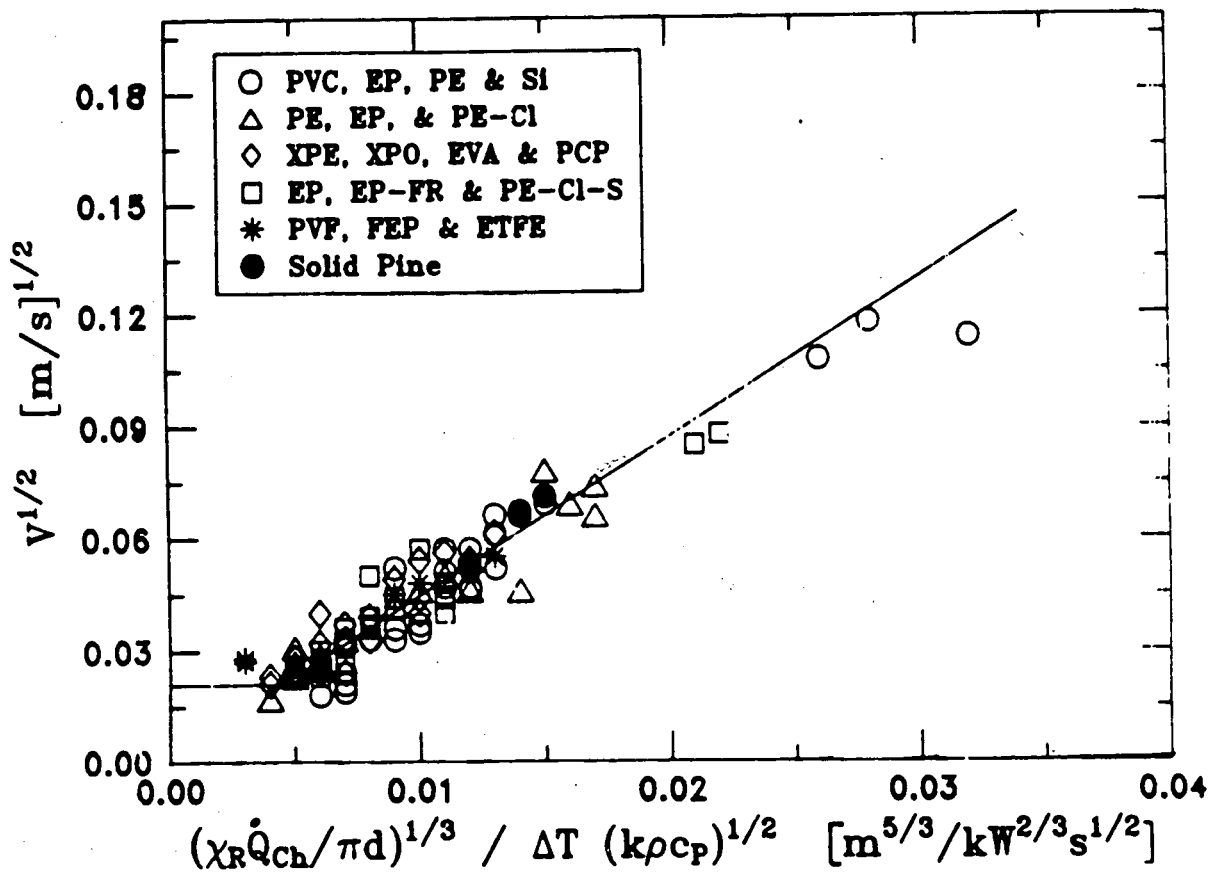


Figure 1B. Relationship between Fire Propagation Rate and the Ratio of Flame Heat Flux to the Thermal Response of the Cable. χ_R assumed to be equal to 0.40.

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For a cable under two different heat flux values, from Eq. (B-1),

$$(v_1/v_2)^{1/2} \propto \dot{q}_1''/\dot{q}_2'' \quad (B-12)$$

It is thus possible to correct fire propagation velocity for the enhancement of flame heat flux, under specific geometrical arrangements.

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APPENDIX C

RELATIONSHIPS FOR THE CALCULATION OF TOTAL MASS AND
VOLUMETRIC FLOW RATES, GENERATION RATES OF FIRE PRODUCTS
(SMOKE, CHEMICAL COMPOUNDS AND HEAT) AND LIGHT OBSCURATION
(TAKEN FROM REFERENCE 13)

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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 in g/s are calculated from the relationship given in Reference 40:

$$\dot{m} = 34.783 K d^2 F_a (\Delta p_m \rho)^{1/2} \quad (C-1)$$

where \dot{m} is the mass flow rate; K = flow coefficient of the orifice in the duct; d = orifice opening diameter (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:

$$\rho = 11.798 (p_d/T_d) MW \quad (C-2)$$

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. (C-1) and (C-2)

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

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. (C-3) can be written as:

$$\dot{m} \text{ (kg/s)} = 0.6426 K d^2 [\Delta p_m (p_d/T_d)]^{1/2} \quad (C-4)$$

In the FM Small-Scale Flammability Apparatus, the orifice plate diameter, d , is 5.08 cm. To determine the value of the flow coefficient K , the funnel (Figure 1A) was replaced by a calibration orifice plate. Experiments were

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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:

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

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 H₂O and p_d is measured in kg/cm². Using these units and the values of K_m and d_m in Eq. (C-4), the mass flow rate can be expressed as:

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

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

$$\dot{v} \text{ (m}^3\text{/s)} = \dot{m}/\rho = 0.00005953 K_m d_m^2 (\Delta p_m)^{1/2} (T_d/p_d)^{1/2} \quad (C-7)$$

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. (C-6) and (C-7), together with the values of K_m and d_m .

GENERATION RATES OF FIRE PRODUCTS - HEAT, SMOKE AND CHEMICAL COMPOUNDS

GENERATION OF FIRE PRODUCTS

Fire products consist of heat and mixture of smoke and chemical compounds.

Smoke and chemical compounds can be generated in both nonflaming and flaming fires. The mass generation rate of a chemical compound per unit sample surface area, \dot{G}_j'' , can be expressed as:

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APPENDIX D

HEAT FLUX CALCULATIONS FOR SUSTAINED
ELECTRICAL OVERLOADING OF POWER CABLES

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$$\dot{G}_j'' = \dot{v} c_j \rho_j / A \quad (C-8)$$

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

From Eqs. (C-2), (C-7) and (C-8), if c_j is expressed in ppm,

$$\dot{G}_j'' = 0.07025 \times 10^{-5} K_m (d_m)^2 c_j (MW) (\Delta p_m)^{1/2} (p_d / T_d)^{1/2} \quad (C-9)$$

In the experiments, concentrations of CO_2 , CO , smoke 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. (C-9). The data for the generate rates are time shifted to account for delays with the gas sampling lines and the instrument responses.

Heat Release Rate

In flaming fires, heat is generated in chemical reactions where CO and CO_2 are the main products and combustible vapors and O_2 are the main reactants. In our studies heat generated in chemical reactions in fires is defined as chemical heat (32). For the calculation of the chemical heat release rate, the following relationships, based on generation rates of CO and CO_2 and depletion rate of O_2 , have been developed (30):

$$\dot{Q}_{\text{Ch}}'' = (\Delta H_T / k_{\text{CO}_2}) \dot{G}_{\text{CO}_2}'' + [(\Delta H_T - \Delta H_{\text{CO}} k_{\text{CO}}) / k_{\text{CO}}] \dot{G}_{\text{CO}}'' \quad (C-10)$$

$$\dot{Q}_{\text{Ch}}'' = (\Delta H_T / k_{\text{O}_2}) \dot{D}_{\text{O}_2}'' \quad (C-11)$$

where \dot{Q}_{Ch}'' is the chemical heat release rate (kW/m^2); ΔH_T is the net heat of complete combustion (kJ/g); ΔH_{CO} is the heat of combustion of CO (kJ/g); \dot{G}_{CO_2}'' and \dot{G}_{CO}'' are the generation rates of CO and CO_2 , respectively, and \dot{D}_{O_2}'' is the depletion rate of O_2 ($\text{g/m}^2\text{s}$); k_{CO_2} is the theoretical yield of CO_2 when all the carbon initially present in the material is converted to CO_2 (g/g); k_{CO} is the theoretical yield of CO when all the carbon initially present in the

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material is converted to CO (g/g); and k_{O_2} is the mass stoichiometric oxygen to fuel ratio (g/g). The net heat of complete combustion can be measured in an Oxygen Bomb Calorimeter; the values of k_{CO_2} , k_{CO} and k_{O_2} can be calculated from the elemental composition of the material, which can also be measured. For less accurate results, average values of $\Delta H_T/k_{CO_2}$, $\Delta H_T/k_{CO}$ and $\Delta H_T/k_{O_2}$, reported in the literature (30), can be used. Thus, for the determination of \dot{Q}_{Ch} , measurements for the generation rates of CO and CO_2 and depletion rate of O_2 are needed.

LIGHT OBSCURATION

The fraction of light transmitted through smoke, I/I_0 , can be expressed as,

$$\ln(I_0/I) = \ell \sigma c \quad (C-12)$$

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). $\ln(I_0/I)$ is defined as the optical density, D (also expressed as \log rather than \ln).

In the experiments, I and I_0 are recorded at 1-s intervals (or longer) and D is calculated, for 0.10 m optical path length, as a function of time for three wavelengths: 0.458, 0.624, and 1.06 μ .

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According to the Ohm's law, relationship between voltage (V), current (I) and resistance (R) is given by,

$$V = IR \quad (D-1)$$

where V is in volts, I is in ampers and R is in ohms.

The electrical power, P (in watt) delivered to the conductor due to the imposed current is given by,

$$P = IV \quad (D-2)$$

From Eq. (D-1),

$$P = I^2R \quad (D-3)$$

which is the heat dissipation from the conductor.

Now, assuming uniform energy conversion within the conductor and disregarding end effects,

$$\dot{q}_I'' = \frac{I^2R}{A_{\text{cond}}} \times 10^{-3} \quad (D-4)$$

where \dot{q}_I'' is the heat flux due to imposed current, per unit conductor surface area (kW/m^2) and A_{cond} is the surface area of the conductor (m^2) and is given by

$$A_{\text{cond}} = \pi d \ell \quad (D-5)$$

where d is the diameter of the conductor (m) and ℓ is the length of the conductor (m).

The energy for vapor formation from a cable, due to overload current, can be expressed as,

$$E_I = \dot{q}_I'' \times t_v \quad (D-6)$$

where t_v is the time to vaporization (sec). E_I is in kJ/m^2 .

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APPENDIX E

CABLE CLASSIFICATION BASED
ON FIRE PROPAGATION INDEX

GROUP 1 CABLES

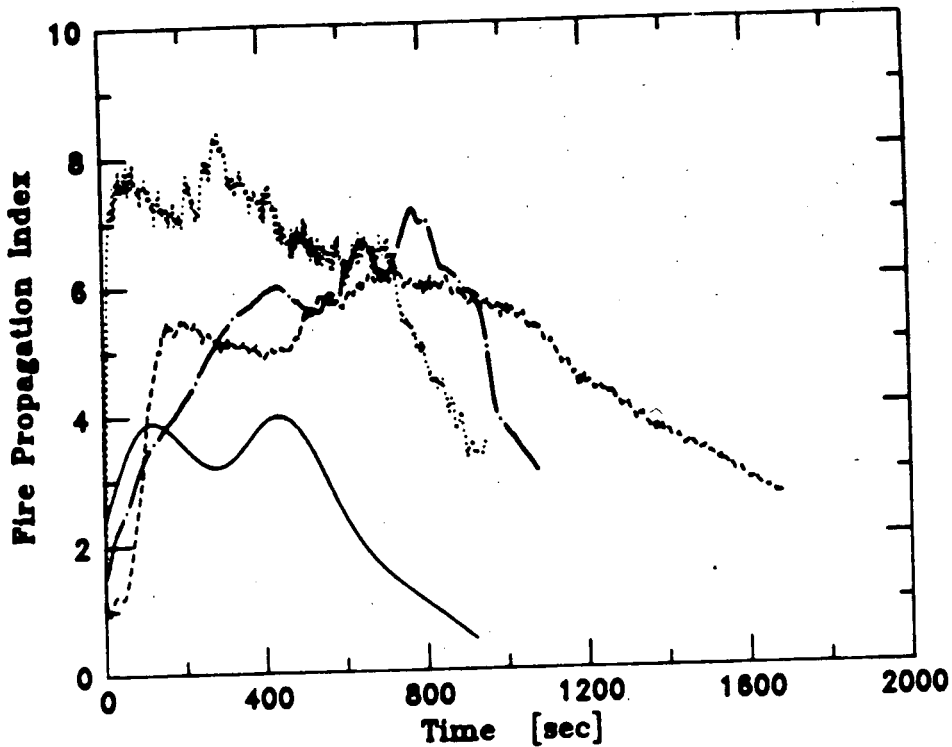


Figure 17. Vertical Fire Propagation for Ethylene Propylene Rubber or Crosslinked Polyethylene-Crosslinked Polyolefin Cable. Conditions: Number of Cables, Cable Length (m), Oxygen (%) and External Heat Flux (kW/m^2) respectively:: 1, 0.61, 40 and 50; - - - - -: 3B, 0.61, 40, and 50; — — —: 1, 0.38, 40 and 0; — — — —: 1, 0.10, 21 and 50. (3B: Bundle of Three Cables).

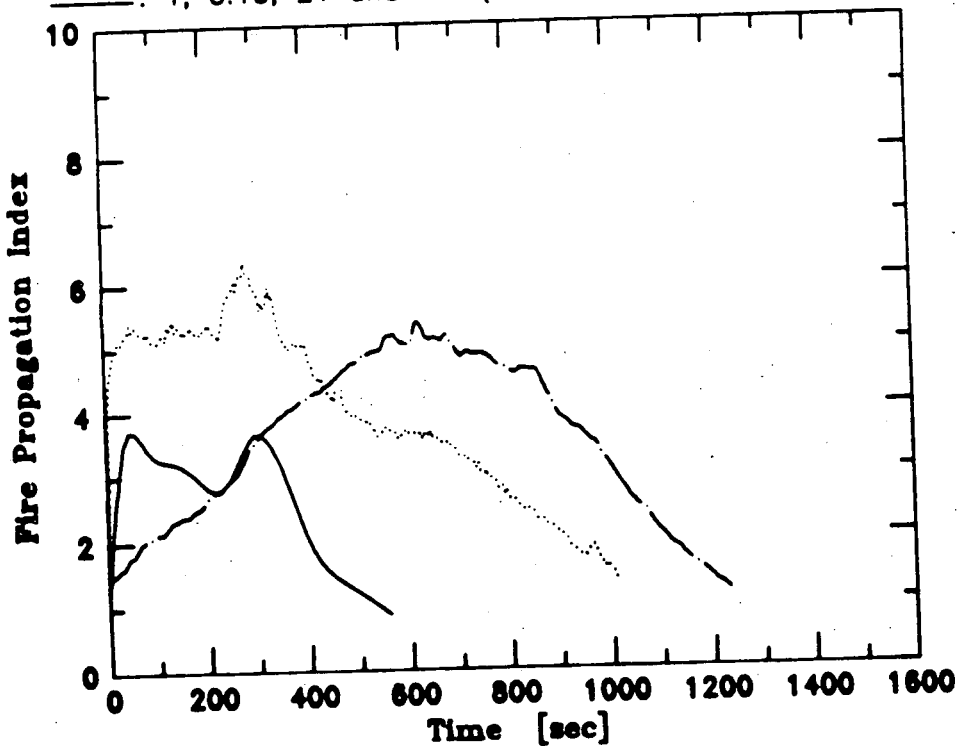


Figure 18. Vertical Fire Propagation for Crosslinked Polyethylene-Crosslinked Polyolefin Cable. Conditions: Number of Cables, Cable Length (m), Oxygen (%) and External Heat Flux (kW/m^2) respectively:: 1, 0.61, 40, and 50; — — —: 1, 0.38, 40, and 0; — — — —: 1, 0.10, 21 and 50.

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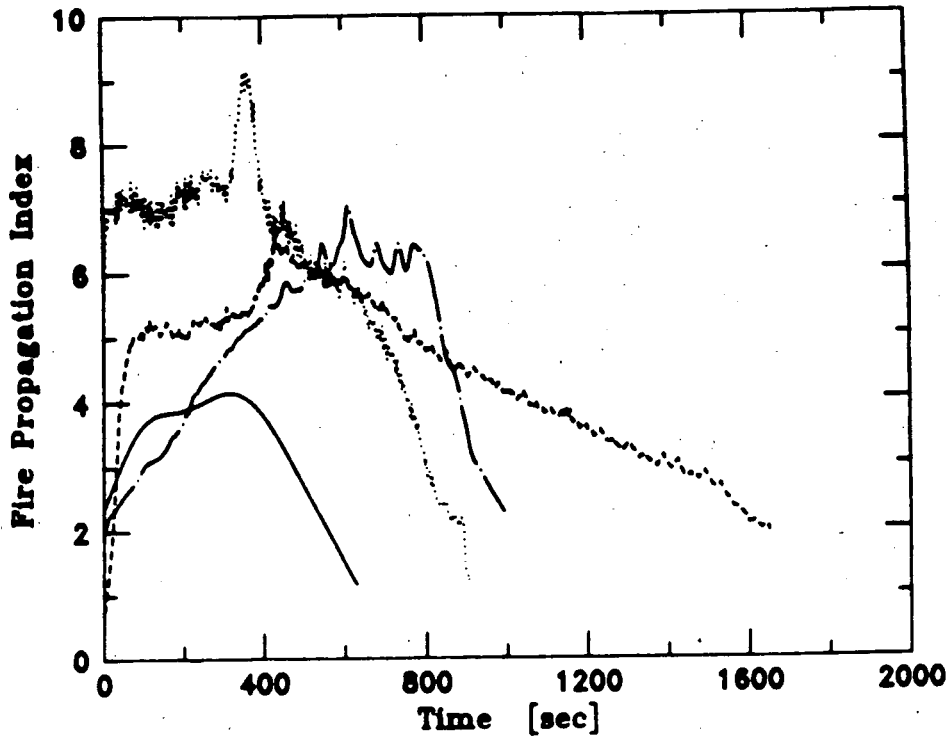


Figure 19. Vertical Fire Propagation for Crosslinked Polyethylene-Crosslinked Polyolefin Cable. Conditions: Number of Cables, Cable Length (m), Oxygen (%) and External Heat Flux (kW/m^2) respectively:: 1, 0.61, 40 and 50;-----: 3B, 0.61, 40 and 50;-----: 1, 0.38, 40 and 0;———: 1, 0.10, 21 and 50. (3B: Bundle of Three Cables).

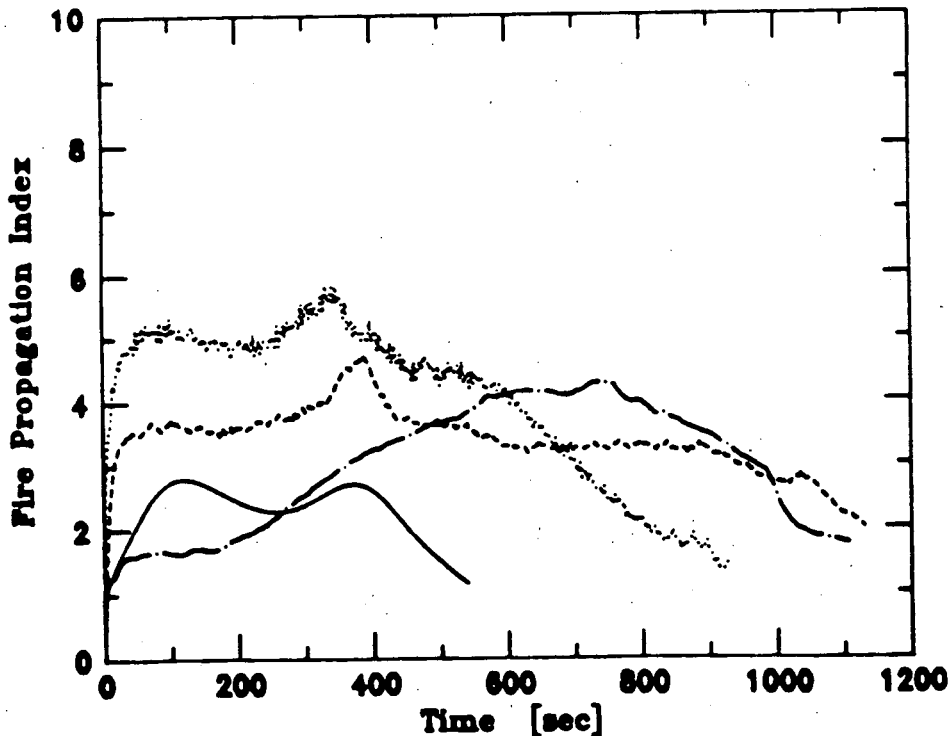


Figure 20. Vertical Fire Propagation for Crosslinked Polyolefin/Polyvinylidene Fluoride-Crosslinked Polyolefin Cable. Conditions: Number of Cables, Cable Length (m), Oxygen (%) and External Heat Flux (kW/m^2) respectively:: 1, 0.61, 40 and 50;-----: 3B, 0.61, 40, and 50;-----: 1, 0.38, 40 and 0;———: 1, 0.10, 21 and 50. (3B: Bundle of Three Cables).

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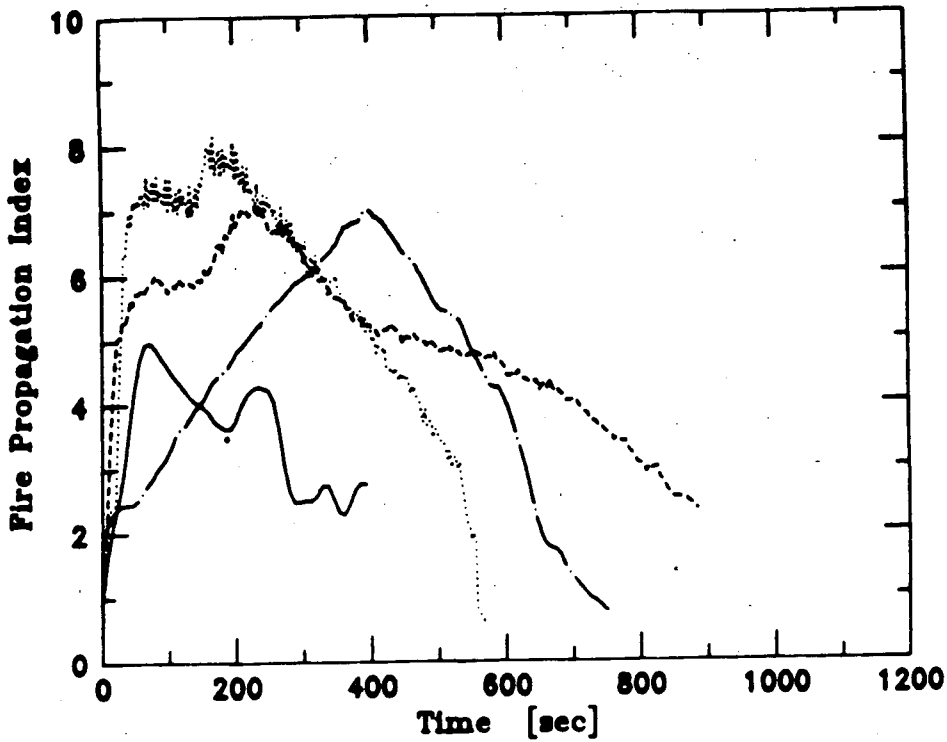


Figure 21. Vertical Fire Propagation for Crosslinked Polyolefin/Polyvinylidene Fluoride-Crosslinked Polyolefin Cable. Conditions: Number of Cables, Cable Length (m), Oxygen (%) and External Heat Flux (kW/m^2) respectively:: 1, 0.61, 40 and 50; -----: 3B, 0.61, 40, and 50; ———: 1, 0.38, 40 and 0; - · - · - : 1, 0.10, 21 and 50. (3B: Bundle of Three Cables).

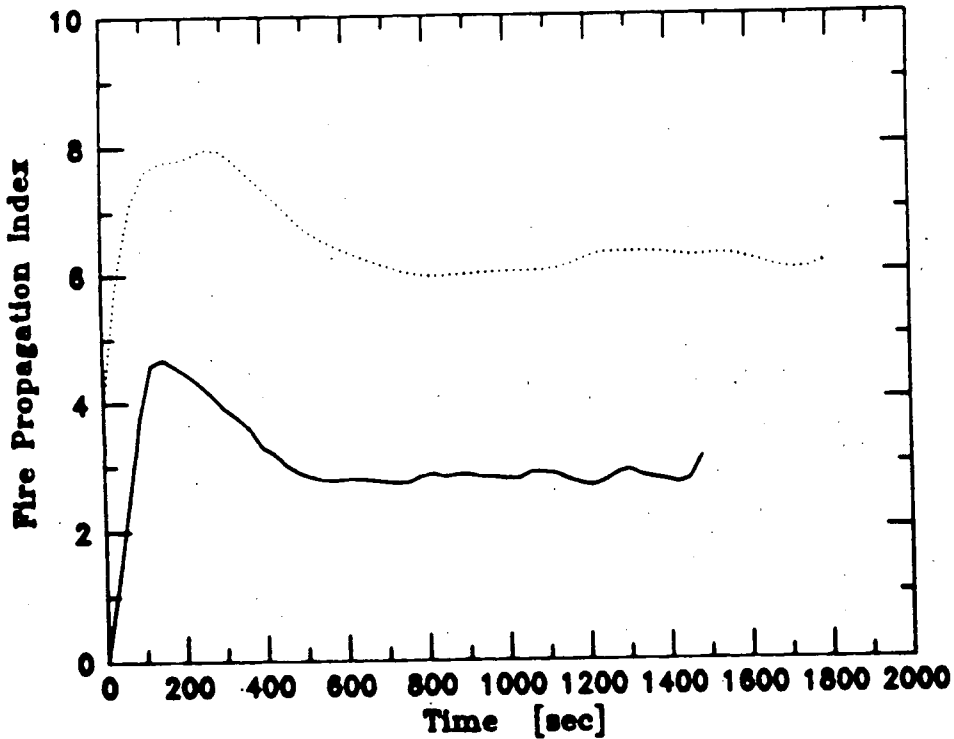


Figure 22. Vertical Fire Propagation for Silicone Rubber-Cross Linked Polyolefin Cable. Conditions: Number of Cables, Cable Length (m), Oxygen Concentration (%) and External Heat Flux (kW/m^2) respectively:: 1, 0.61, 40, and 50 and ———: 1, 0.10, 21 and 50.

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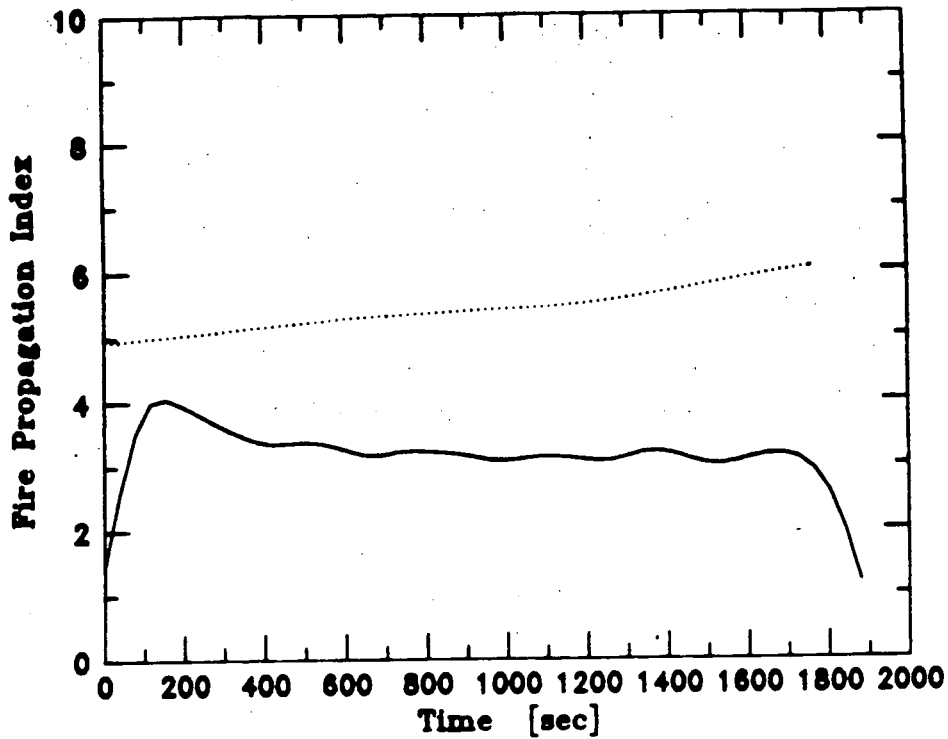


Figure 23. Vertical Fire Propagation for Silicone Rubber-Cross Linked Polyolefin/Metal Armor Cable. Conditions: Number of Cables, Cable Length (m), Oxygen Concentration (%) and External Heat Flux (kW/m^2) Respectively:: 1, 0.61, 40, and 50 and ———: 1, 0.10, 21 and 50.

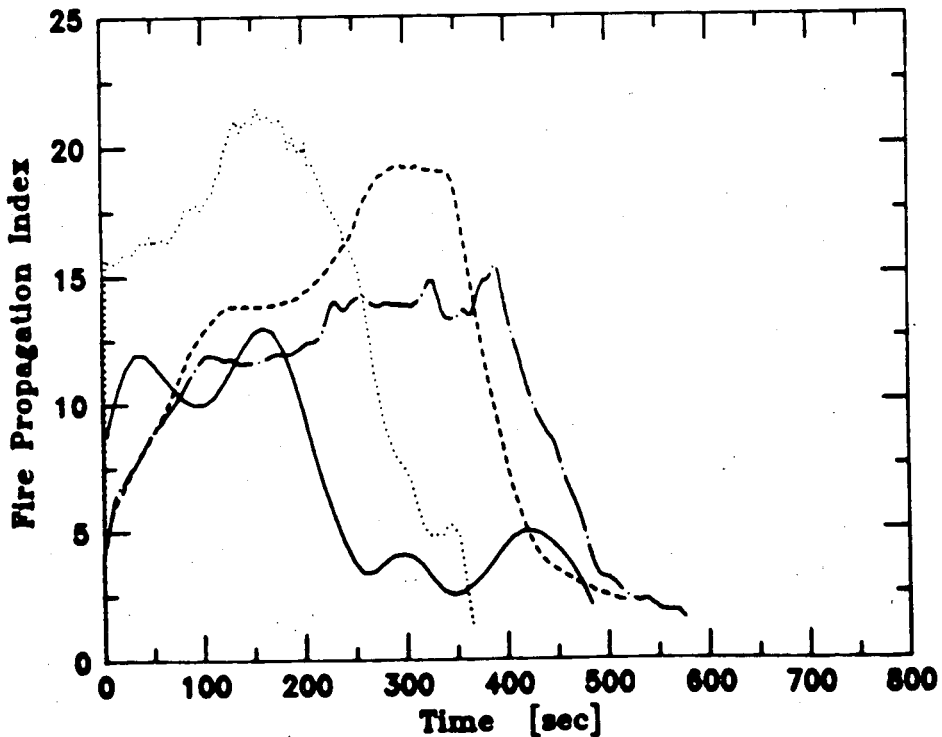


Figure 24. Vertical Fire Propagation for Polypropylene/Polyester-Polyvinyl Chloride Cable. Conditions: Number of Cables, Cable Length (m), Oxygen Concentration (%) and External Heat Flux (kW/m^2) respectively:: 1, 0.61, 40 and 50; ———: 1, 0.38, 40, and 0; - - - - -: 1, 0.25, 40 and 0 and — · — · —: 1, 0.10, 21 and 50.

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sample. Cables for which FPI values were equal to or greater than 20, showed very rapid fire propagation, taking a few minutes to reach to the top of the 0.61 m (2 ft) long cable sample. Cables for which the FPI values were equal to or greater than 10 but less than 20, showed that the fire propagation was self-sustained; the rate was not very rapid, increasing linearly with time. Based on these experimental results, cables thus were classified into three groups as shown in Table III:

1) Group 1: Cables with FPI values less than 10 belong to this group. Cables in Group 1 are not expected to have self-sustained fires. Group 1 cables are not expected to require protection in the absence of extended external heat sources and with adequate electrical protection to prevent sustained overloading and arcing due to thermal damage threat (such as sprinklers). Based on the data from this study and our other study [24], it may be possible to divide Group 1 cables into two subgroups: 1) Group 1A cables for which non-thermal damage (damage due to smoke; toxic and corrosive compounds) is expected to be negligibly small, and 2) Group 1B cables for which non-thermal damage (damage due to smoke, toxic and corrosive compounds) is expected.

Several cables belong to Group 1, as can be noted in Figures 15 to 24 and in Appendix E. Group 1 classification of cables, which are "less flammable" cables, has satisfied the objective of this study.

2) Group 2: Cables with FPI values equal to or greater than 10 but less than 20 belong to this group. Fires are expected to be self-sustained, and fire growth rates are expected to increase linearly. For Group 2 cables, fire protection would be required. Electrical protection will be required for Group 2 cables. Several cables belong to Group 2, as can be noted in Appendix E.

3) Group 3: Cable with FPI values equal to or greater than 20 belong to this group. Fires are expected to be self-sustained, and the fire propagation rates are expected to increase very rapidly. Fire protection would be required. Several cables belong to Group 3, as can be noted in Figure 24 and in Appendix E.

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3.4 LARGE-SCALE VALIDATION TESTS FOR THE FIRE PROPAGATION INDEX

Large-scale validation tests were performed in the Factory Mutual Large-Scale Flammability Apparatus (Fire Products Collector), shown in Figure 1C. This Apparatus works under the same principles as the Factory Mutual Small- (10 kW-) and Intermediate-Scale 500 kW-Scale) Flammability Apparatuses.

In the large-scale tests, two 4.9 m (16 ft) long and 0.61 m (2 ft) wide vertical sheets of Marinite, separated by about 0.30 m (1 ft), were used. A single layer of cables, touching each other, was attached to both Marinite sheets. For ignition, a 61 kW (210,000 Btu/hr) propane air sand burner with a flame height of about 0.60 m (2 ft) was used. The burner was placed at the bottom between the two sheets as shown in Figure 1C. Under this geometry, flame radiation is enhanced by about 50% [26] and is expected to assist in the self-sustained fire propagation extending it beyond the heat flux zone of the propane burner*.

All the fire products generated during fire propagation were captured in the sampling duct of the Apparatus with air and measurements made in the duct to determine the chemical heat release rate, very similar to the determination in the Factory Mutual Small- (10 kW-) and Intermediate-Scale 500 kW-Scale) Flammability Apparatuses. In these tests, five cable types were tested (Appendix E): 1) Group 3 cable: polyethylene/polyvinylchloride (PE/PVC) cable (diameter = 0.011 m); 2) Group 1 cables: a) PVC/polyvinylidene fluoride (PVF), UL Type CMP, UL 910 approved, plenum cable (diameter = 0.005 m); b) crosslinked polyethylene (XLPE)/ethylene vinyl-acetate (EVA) cable (diameter = 0.012 m); c) XLPE/neoprene cable (diameter = 0.015 m) and d) crosslinked polyolefin/crosslinked polyolefin (XLPO/XLPO) (diameter = 0.016 m).

*This geometry was selected as it is expected to present a fairly severe challenge to the cable due to flame radiation exchange between the parallel cable surfaces. Heat losses due to surface reradiation is essentially zero. In large-scale fires, flame heat flux to the surface is in the range of about 50 to 60 kW/m² for the type of plastics used in cable construction [33]. The surface reradiation is very close to the critical heat flux value, which is in the range of about half the flame heat flux value (Table III).

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After ignition and during fire propagation, all the fire products were collected in the sampling duct of the FM Large-Scale (5000 kW-Scale) Flammability Apparatus, also called the Fire Products Collector. In the duct, measurements were made for the chemical heat release rate, very similar to those made in the FM Small- (10 kW-) and Intermediate-Scale (500 kW-Scale) Flammability Apparatuses. The data were used to calculate; 1) the fire propagation velocity (using Eq. B13 in Appendix B), and 2) the Fire Propagation Index using chemical heat release rate during fire propagation and thermal response parameter values from Table III. Visual observations for the large-scale cable fire tests are reported in Table IV.

In the large-scale tests, fire propagation was very rapid for Group 3 cable (PE/PVC), as can be noted in Table IV. The fire reached the top of the cable sheets in about 2 minutes. For Group 1 cables, for test durations of 30 minutes, the extent of fire propagation beyond the heat flux zone of the propane burner was about 0.9 m (3 ft) for PVF/PVC cable; 1.5 m (5 ft) for XLPE/neoprene cable; 3.0 m (10 ft) for XLPE/EVA cable and 3.7 m (12 ft) for the XLPO/XLPO cable. For Group 1 cables, fire propagation beyond the heat flux zone of the propane burner is assisted by the enhancement of the flame heat flux (by about 50%), because of the two parallel vertical plate geometry of cables used in the test [26]. This was confirmed by turning off the burner, at which point the fire extinguished and repropagated as the burner was turned on (example given for XLPO/XLPO cable in Table IV).

Figure 25 (taken from Reference 26) shows the calculated fire propagation rate as a function of time for the large-scale cable fire tests. As can be noted, for PE/PVC cable, which is a Group 3 cable, fire propagation rate is very rapid. In the actual test, fire reached the top of the cable sheets about 2 minutes after the cable was ignited (Table IV). The fire burned very intensely and extended into the sampling duct of the apparatus; it was extinguished immediately with water hoses. For Group 1 cables, the fire propagation rates are less than 5 mm/s for about 20 minutes for all the cables, with fire reaching a maximum of about 3.0 m (10 ft) (XLPO-XLPO cable) beyond the burner heat flux zone. Beyond 20 minutes, the rate increases to about 7 mm/s. As discussed before, the fire propagation rates are expected to be higher for these tests, because of the test geometry of the cables where flame heat flux is enhanced (by about 50%) [26]. Using heat flux enhancement

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TABLE IV

VISUAL OBSERVATIONS IN LARGE-SCALE CABLE FIRE TESTS^a

Time (m)	Cable Samples (Insulation/Jacket) ^b				
	PE/PVC	XLPE/Neoprene	PVC/PVF	XLPO/XLPO	XLPE/EVA
Burner Turned On	Burner flame height = 0.6 m (2 ft)	Burner flame height = 0.6 m (2 ft)	Burner flame height = 0.6 m (2 ft)	Burner flame height = 0.6 m (2 ft)	Burner flame height = 0.6 m (2 ft)
2	Very rapid fire propagation. Reached the top in 2 min, thick greyish black smoke.	No fire propagation beyond the heat flux zone of the burner. Black smoke.	No fire propagation beyond the heat flux zone of the burner. Very light white smoke.	No fire propagation beyond the heat flux zone of the burner. Grey smoke.	No fire propagation beyond the heat flux zone of the burner. Very light bluish smoke
4	Very intense fire. Used water hose to extinguish both cable sheets. Damage: 4.9 m (16 ft)	Fire propagated to 0.3 m (1 ft) beyond the heat flux zone of the burner. Thick black smoke.	Same as above.	Same as above.	Same as above.
6		Fire propagated to 0.9 m (3 ft) beyond the burner heat flux zone. Thick black smoke.	Same as above.	Fire propagated to 0.2 m (0.5 ft) beyond the burner heat flux zone. Thick black smoke.	Same as above.
8		Fire propagated to 1.5 m (5 ft) beyond the burner heat flux zone. Flickering flames. Thick black smoke.	Same as above.	Fire propagated 0.3 m (1 ft) beyond the burner heat flux zone. Thick grey smoke.	Same as above.
10		Flames at 1.5 m (5 ft) beyond the burner heat flux zone. Flickering flames. Thick black smoke.	Fire propagated to 0.1 m (0.3 ft) beyond the burner heat flux zone. Flickering flames. Very light white smoke.	Fire propagated to 1.2 m (4 ft) beyond the burner heat flux zone. Thick dark grey smoke.	Fire propagated to 0.1 m (0.3 ft) beyond the burner heat flux zone. Light bluish smoke.
12		Flames at 1.5 m (5 ft) beyond the burner heat flux zone. Flickering flames. Light grey smoke.	Fire propagated to 0.2 m (0.5 ft) beyond the burner heat flux zone. Flickering flame. Very light white smoke.	Fire propagated to 1.5 m (5 ft) beyond the burner heat flux zone. Thick dark grey smoke.	Fire propagated to 0.2 m (0.5 ft) beyond the burner heat flux zone. Light bluish smoke.
14		Flames at 1.5 m (5 ft) beyond the burner heat flux zone. Flickering flames. Light grey smoke.	Same as above. Burner turned off. Flames extinguished. Extent of damage 0.9 m (3 ft).	Fire propagated to 1.8 m (6 ft) beyond the burner heat flux zone. Thick very dark grey smoke.	Fire propagated to 0.3 m (1 ft) beyond the burner heat flux zone. Light bluish smoke.
16		Same as above		Flames at 1.8 m (6 ft) beyond the burner heat flux zone. Thick very dark grey smoke.	Fire propagated to 0.9 m (3 ft) beyond the burner heat flux zone. Light bluish smoke.

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TABLE IV (cont.)

VISUAL OBSERVATIONS IN LARGE-SCALE CABLE FIRE TESTS^a

Time (m)	Cable Samples (Insulation/Jacket) ^b				
	PE/PVC	XLPE/Neoprene	PVC/PVF	XLPO/XLPO	XLPE/EVA
18		Flames at 0.9 m (3 ft) beyond the burner heat flux zone. Flickering flames. Light grey smoke.		Fire propagated to 3.0 m (10 ft) beyond the burner heat flux zone. Thick very dark grey smoke. Flickering flames.	Flames at 0.9 m (3 ft) beyond the burner heat flux zone. Light bluish smoke.
20		Burner turned off. Flames extinguished. Whitish grey smoke at the end. Extent of damage: 0.9 m (3 ft).		Flames at 3.0 m (10 ft) beyond the burner heat flux zone. Flickering flames. Burner turned off. Flames extinguished with light grey smoke.	Same as above
22				Burner off.	Fire propagated to 1.8 m (6 ft) beyond the burner heat flux zone. Light bluish smoke.
24				Burner turned on. Fire propagation on only one side surface to 2.1 m (7 ft) beyond the burner heat flux zone. Grey smoke.	Fire propagated to 3.0 m (10 ft) beyond the burner heat flux zone. Light bluish smoke.
26				Same as above.	Flames at 3.0 m (10 ft) beyond the burner heat flux zone. Light bluish smoke.
28				Flames at 0.9 m (3 ft) beyond the burner heat flux zone. Grey smoke.	Same as above
30				Flames within the burner heat flux zone. Burner turned off. Flame extinguished. Extent of damage 3.7 m (12 ft).	Burner turned off. Cable kept burning. Used water hose to extinguish. Extent of damage 3.0 m (10 ft)

a: Two 4.9 m (16 ft) long, 0.61 m (2 ft) wide single layer of cables, touching each other and attached to Marinite Sheets separated by 0.30 m (1 ft); cables facing each other. Ignition source: 61 kW (210,000 Btu/hr) propane sand burner at the bottom between the two sheets. In this geometry flame heat flux enhanced by about 50%. Apparatus: Factory Mutual Large-Scale (5000 kW-scale) Flammability Apparatus (Fire Products Collector).

b: All the length measurements given in the columns are estimated based on visual observation:
 PE: polyethylene; PVC: polyvinylchloride; XLPE: cross-linked polyethylene; PVF: polyvinylidene fluoride; XLPO: cross linked polyolefin; EVA: ethyl vinyl acetate.

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correction (Eq. B-14 in Appendix B), the average fire propagation rates from the large-scale cable fire tests show very good agreement with the peak average fire propagation rates from the small-scale cable fire tests, as shown in Figure 26, taken from Reference 26.

Figures 27 through 31 show the Fire Propagation Index (FPI) profiles in the small- and large-scale cable fires for the five cables, where the large-scale FPI values have not been corrected for the 50% flame heat flux enhancement. The FPI values from small-scale and large-scale fires for each cable remain within the boundaries of the cable for at least up to 1000 s. The FPI value for PE/PVC cable (Figure 27) is higher in the large-scale test than in the small-scale test, suggesting that PE/PVC cable, which is a Group 3 cable, has higher sensitivity to the enhancement of flame heat flux. The large-scale FPI values for XLPO/XLPO and XLPE/EVA cables (Figures 30 and 31) show increase with time, when the propane-air sand burner is left on. The data thus suggest that these two Group 1 cables are also very sensitive to the enhancement of flame heat flux. XLPE/Neoprene and PVC/PVF cables (Figures 28 and 29) which are Group 1 cables, on the other hand, appear to be less sensitive to the enhancement of flame heat flux.

3.5 ELECTRICAL FAULTS AND FIRE PROPAGATION

As discussed in the Introduction Section, the objective of this study was to develop cable classification to identify "less flammable" cables which can be accepted without fire protection in occupancies such as control rooms, cable spreading rooms and others where cables are the only combustibles. The Factory Mutual Ad Hoc Committee on Cable Flammability considered various ignition scenarios. The Committee concluded that cables subjected to external ignition by combustible construction or occupancy were not within the scope of the assignment as such areas should normally be protected. In areas of noncombustible occupancies and constructions, several ignition modes were discussed by the Committee. They were:

- (1) Ignition of continuous combustible deposit, dust, oil, etc.
- (2) Ignition from minor sources (e.g., welding slag, small items of trash, etc.); and
- (3) Electrical ignition from arcing or overload.

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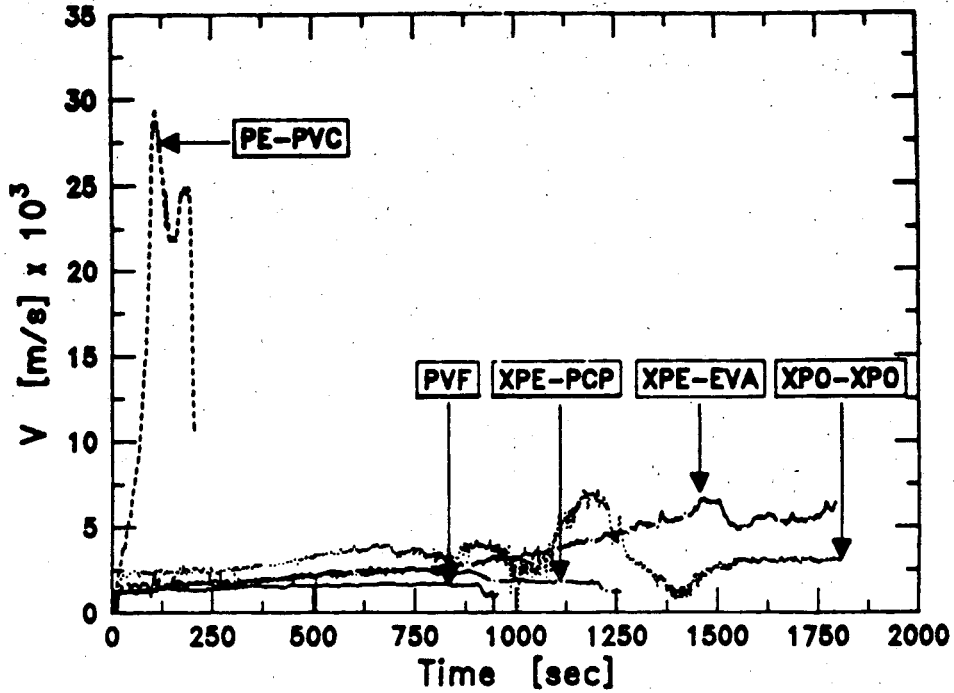


Figure 25. Fire Propagation Rate in Large-Scale Cable Fire Tests Performed in the Factory Mutual Large-Scale (5000kW-Scale) Flammability Apparatus (Fire Products Collector). PE: Polyethylene; PVC: Polyvinylchloride; PVF: Polyvinylidene Fluoride; XPE: Crosslinked Polyethylene; PCP: Neoprene; EVA: Ethylvinyl Acetate; XPO: Crosslinked Polyolefin.

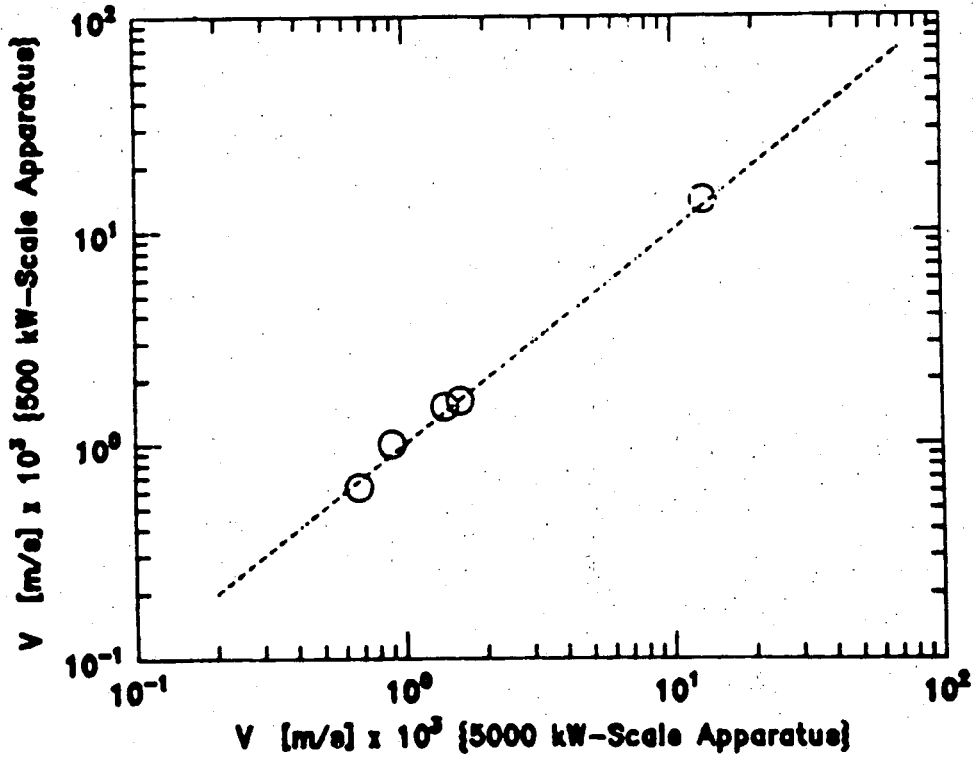


Figure 26. Correlation Between Small-Scale and Large-Scale Cable Fire Test Data for Fire Propagation Rate. Large-Scale Data Have Been Corrected for 50% Enhancement of the Flame Heat Flux.

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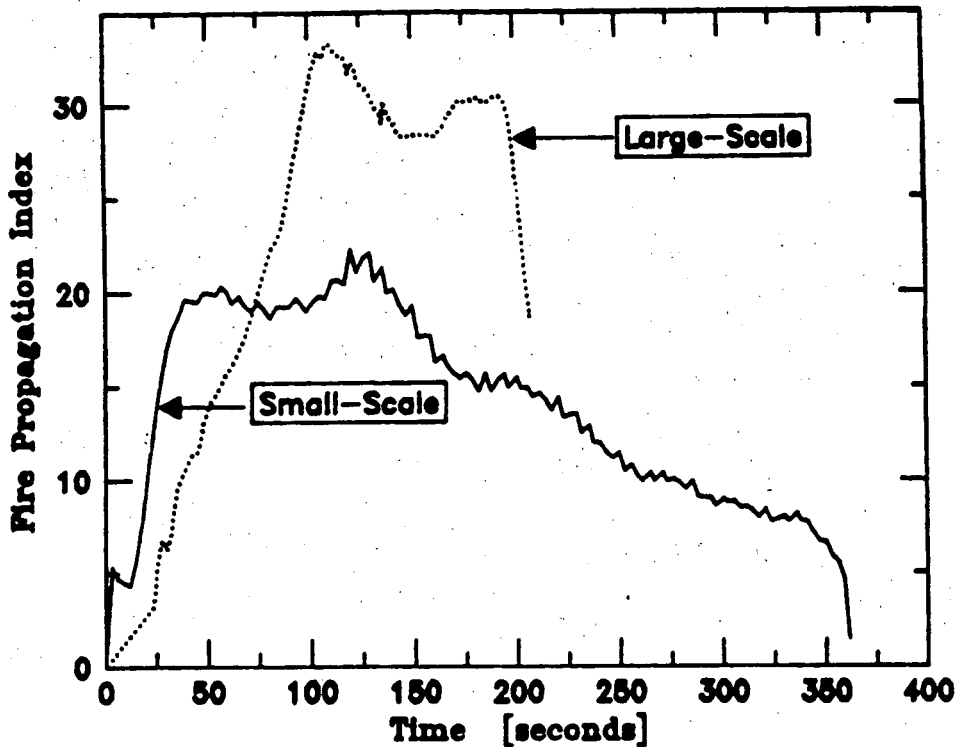


Figure 27. Fire Propagation Index for Polyethylene-Polyvinyl Chloride Cable (Diameter = 0.011 m) in Small- and Large-Scale Cable Fire Tests.

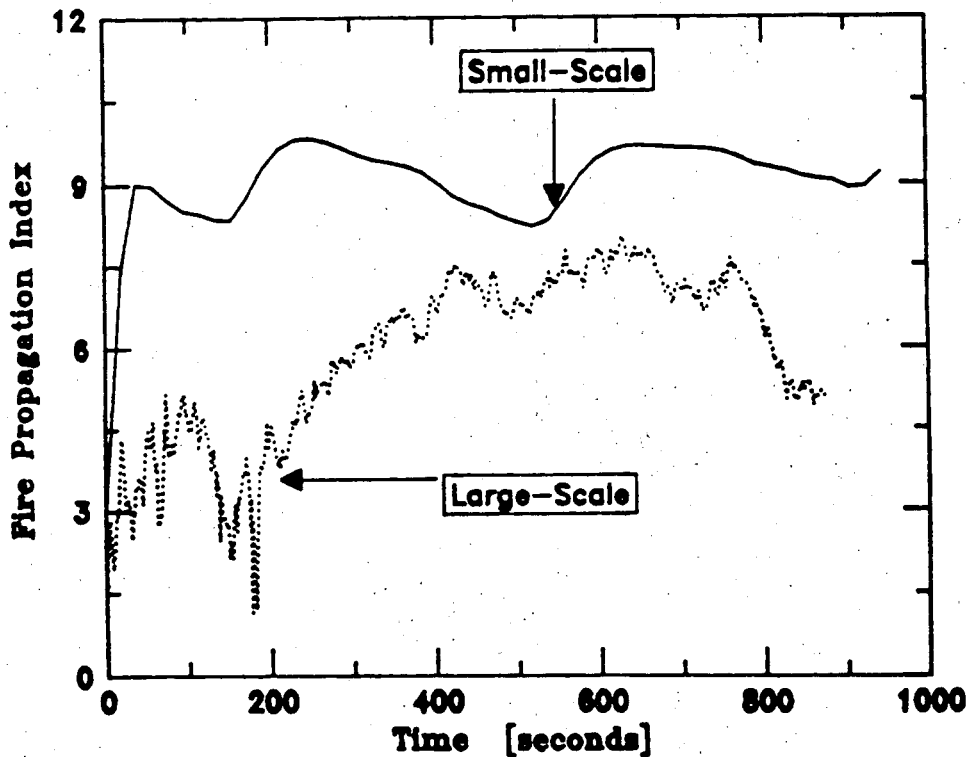


Figure 28. Fire Propagation Index for Crosslinked Polyethylene-Neoprene Cable (Diameter = 0.015 m) in Small- and Large-Scale Cable Fire Tests.

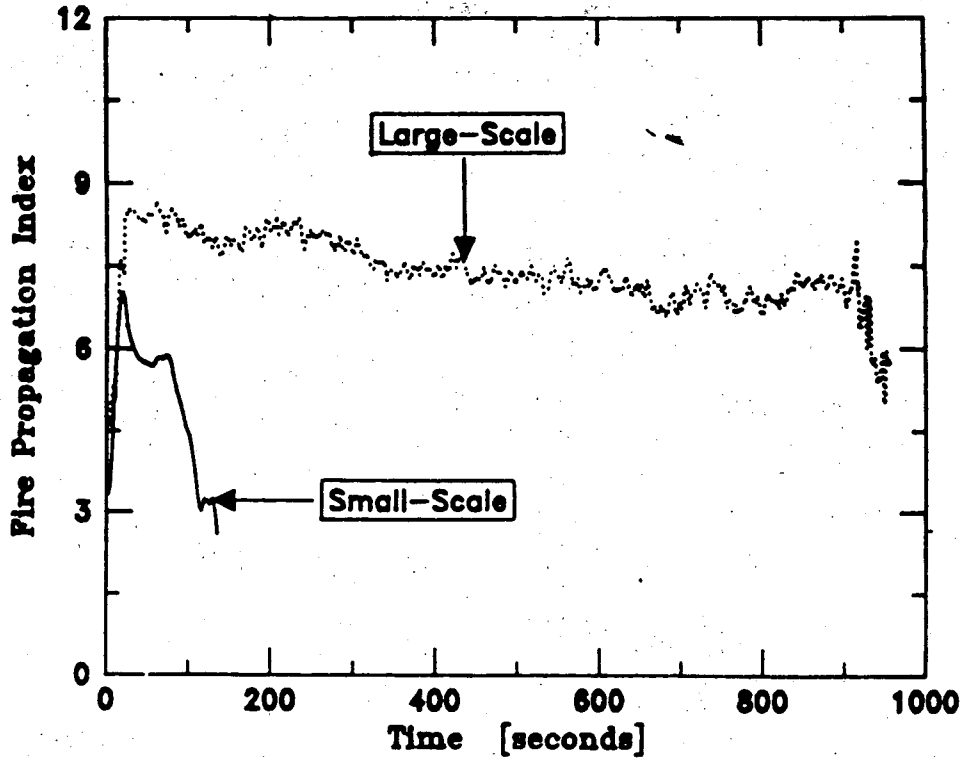


Figure 29. Fire Propagation Index for Polyvinylchloride-Polyvinylidene Fluoride Cable (Diameter = 0.005 m) in Small- and Large-Scale Cable Fire Tests.

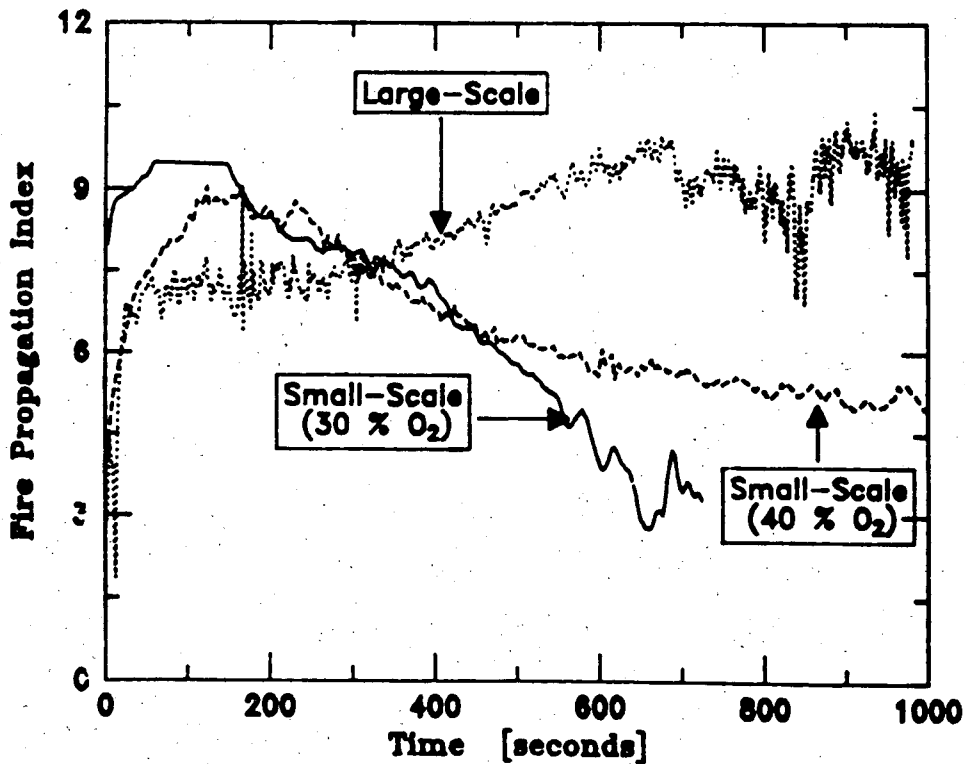


Figure 30. Fire Propagation Index for Crosslinked Polyolefin-Crosslinked Polyolefin Cable (Diameter = 0.016 m) in Small- and Large-Scale Cable Fire Tests.

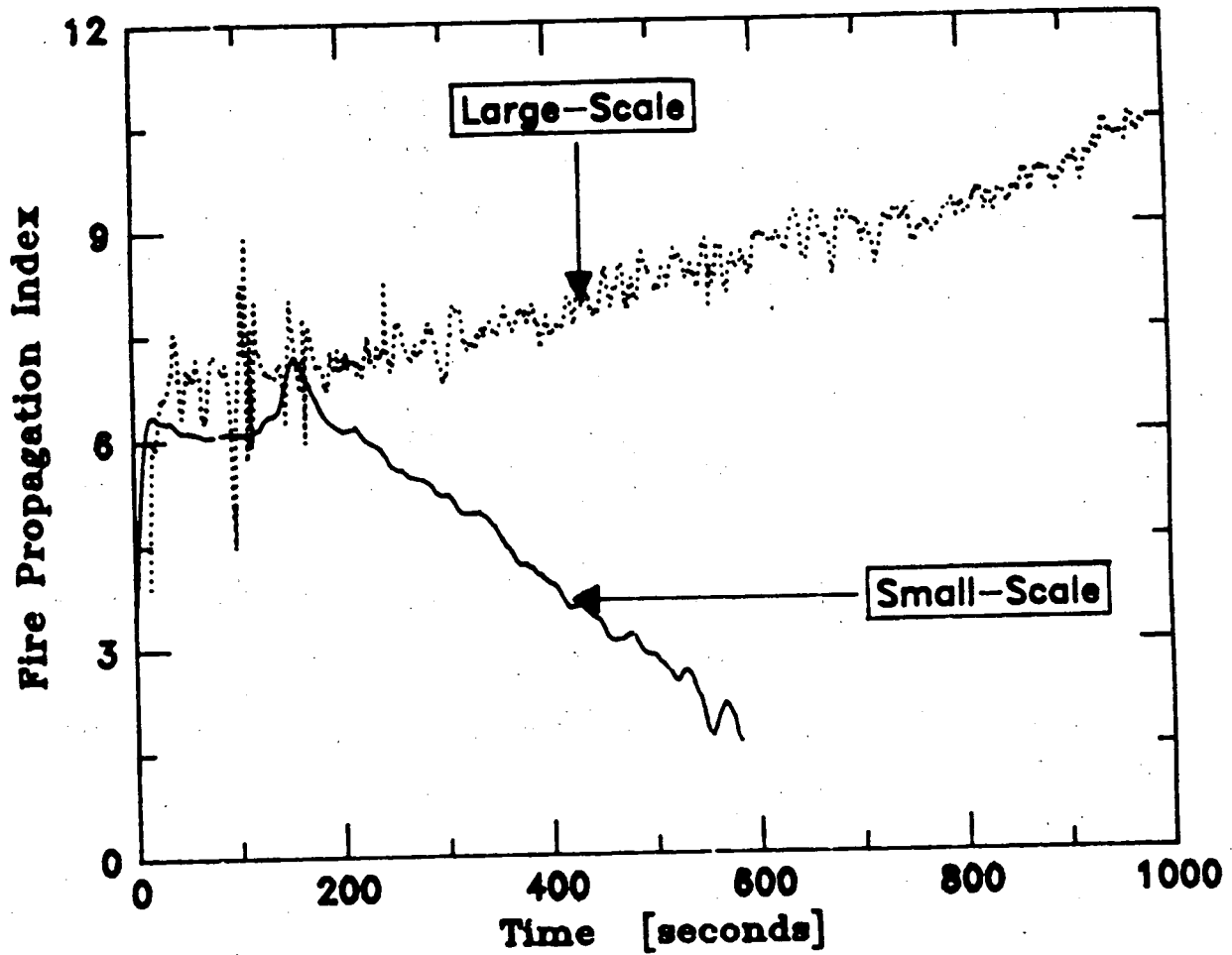


Figure 31. Fire Propagation Index for Crosslinked Polyethylene-Ethyl Vinyl Acetate Cable (Diameter = 0.012 m) in Small- and Large-Scale Cable Fire Tests.

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The Committee agreed that areas having combustible deposits, oil accumulations, etc., were areas where the deficiency permitting the accumulations should be corrected or protection be provided [4]. Ignition from welding slag or a minor trash fire was considered to be analogous to ignition from sustained electrical arcing. A cable resistant to arcing ignition was considered to also exhibit reasonable resistance to minor fires or welding ignition.

Ignition by electrical arcing and/or overload was considered the key parameter. The Committee referred to the work done by the Sandia National Laboratories [6]. This laboratory investigated cable flammability for nuclear stations and determined that arcing was not a significant ignition source of cables used in those applications. Some simple bench-scale tests on various types of cables confirmed that arcing ignition on cable samples was an unlikely ignition source by itself. In these evaluations (in which burning metal was used to simulate the arc), heat was radiated to the environment and ignition was not sustained.

The Factory Mutual Hazards Laboratory also reviewed bench-scale test results [4], where it was found that cables did exhibit different ignition characteristics. Once the conductor became hot, however, all of the cables propagated a fire. Under conditions of electrical overload, elevated conductor temperatures were likely. This introduced the possibility that the worst condition affecting cable flammability could occur during an overload condition.

The Committee reviewed the literature and contacted several cable manufacturers regarding fire testing under conditions of electrical overload. Except for single conductor overload tests done by Sandia [6], no other documented test results could be found. The Sandia results indicated overload was not a major problem. The Committee believed the reason for this absence of data is that almost all cable testing has been done for nuclear stations. Electrical protection design and maintenance in nuclear stations are much more rigorous than in the average industrial or fossil-fuel power plant [4]. In these plants, breaker failures can and have occurred and represent a hazard which must be considered in establishing cable flammability parameters [4].

A series of overload tests were conducted at Factory Mutual [4]. These tests confirmed that overload could result in ignition of even the least

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flammable cables, as well as one cable coated with an FM-Approved coating. Ignition was often accompanied by rupture of cable jacket/insulation and the release of gaseous flammable degradation products.

Since the recommendations of the FM Ad Hoc Committee on Cable Flammability, several studies and loss investigations dealing with cable fires with ignition of electrical origin have been and are continuing to be performed at Factory Mutual [37-39]. In this study, exploratory testing dealing with sustained electrical overloading conditions was undertaken to investigate its effects on fire propagation.

3.5.1 Exploratory Testing of Sustained Electrical Overloading of Power Cables

For the application of sustained electrical overloading, the Factory Mutual Multi-Amp Circuit Breaker Tester (Model CB-225) was used. This tester can provide up to 4500 amperes with very low voltage (about 5 to 7.5 volts).

In the study, a single vertical cable, 1.37 m (4.5 ft) in length, was used with the arrangement very similar to the one used in the fire propagation tests in the Factory Mutual Intermediate-Scale (500 kW-Scale) Flammability Apparatus. No glass tube was used and the tests were performed under free air flow conditions. Both ends of the cable conductors were connected to special aluminum wire connectors (ILSO, PB3-600). The FM Multi-Amp Tester was connected to the special aluminum wire connectors through two 1.5 m (5 ft) long parallel cables (4/0 AWG, flexible welding cable). In the tests, measurements were made for: 1) voltage across the cable sample, 2) surface temperature using a cement on foil thermocouple located at about 0.69 m (2.3 ft) from the bottom of the cable, and 3) conductor temperature using an ungrounded junction thermocouple probe, located very close to the surface thermocouple and introduced perpendicularly through the insulation/jacket materials.

In the tests, the load current applied to the cable was held constant and surface temperature and conductor temperature were measured as functions of time. Visual observations were also made for time to vapor formation. After the surface and conductor temperatures reached conditions for ignition, a butane burner was used to ignite the cable vapor air mixture. This procedure was repeated for different load currents.

The experimental data for load current and surface and conductor temperatures were used to calculate the heat flux to the cable and temperature to vapor formation. The time to vaporization was very close to time to

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ignition at the critical heat flux. The details of the heat flux calculations are described in Appendix D.

Figure 32 shows the experimental data for time to vaporization at various sustained overload current values. Figure 33 shows inverse of the energy for vaporization (Eq. (D-6) in Appendix D) at various sustained overload current values. By extrapolation, a critical overload current (or critical heat flux, Eq. (D-4) in Appendix D) at or below which vaporization of the cable is not expected can be determined. The critical overload current values determined in this fashion are listed in Column 5 in Table V. Data for wire size, ampacity and vaporization temperature are also included in this Table. The data in Table V suggest that under sustained overload conditions, if the overload current is in the range of 1.4 to 2.2 times the ampacity of the cable or above this range, the cable insulation/jacket materials are expected to vaporize.

Figure 34 shows a plot of the inverse of time to vaporization versus heat flux due to current (calculated from Eq. (D-4) in Appendix D). The vaporization relationships shown in Figure 34 for internal cable heating is very similar to the ignition relationships shown in Figures 3 to 12, as expected, because vapor formation and ignition are very similar processes in terms of heat transfer considerations.

In the study it was found that once the current overload was set to give the critical heat flux for ignition, fire propagation was instantaneous, irrespective of the cable classification. This is shown in Figure 35 for a cable, where time to ignition using external heat flux and time to vaporization using internal heat flux are shown. The internal and external heat flux data follow each other, as expected, in terms of energy requirements.

The exploratory test results thus suggest that all cables, irrespective of their classification, are expected to have fire propagation in the presence of electrical faults and cable overheating. At the critical heat flux conditions, fire propagation would be very rapid, irrespective of cable classification. The data from the study suggest that if the overload current is in the range of 2.9 to 3.3 times the ampacity of the cable or above,

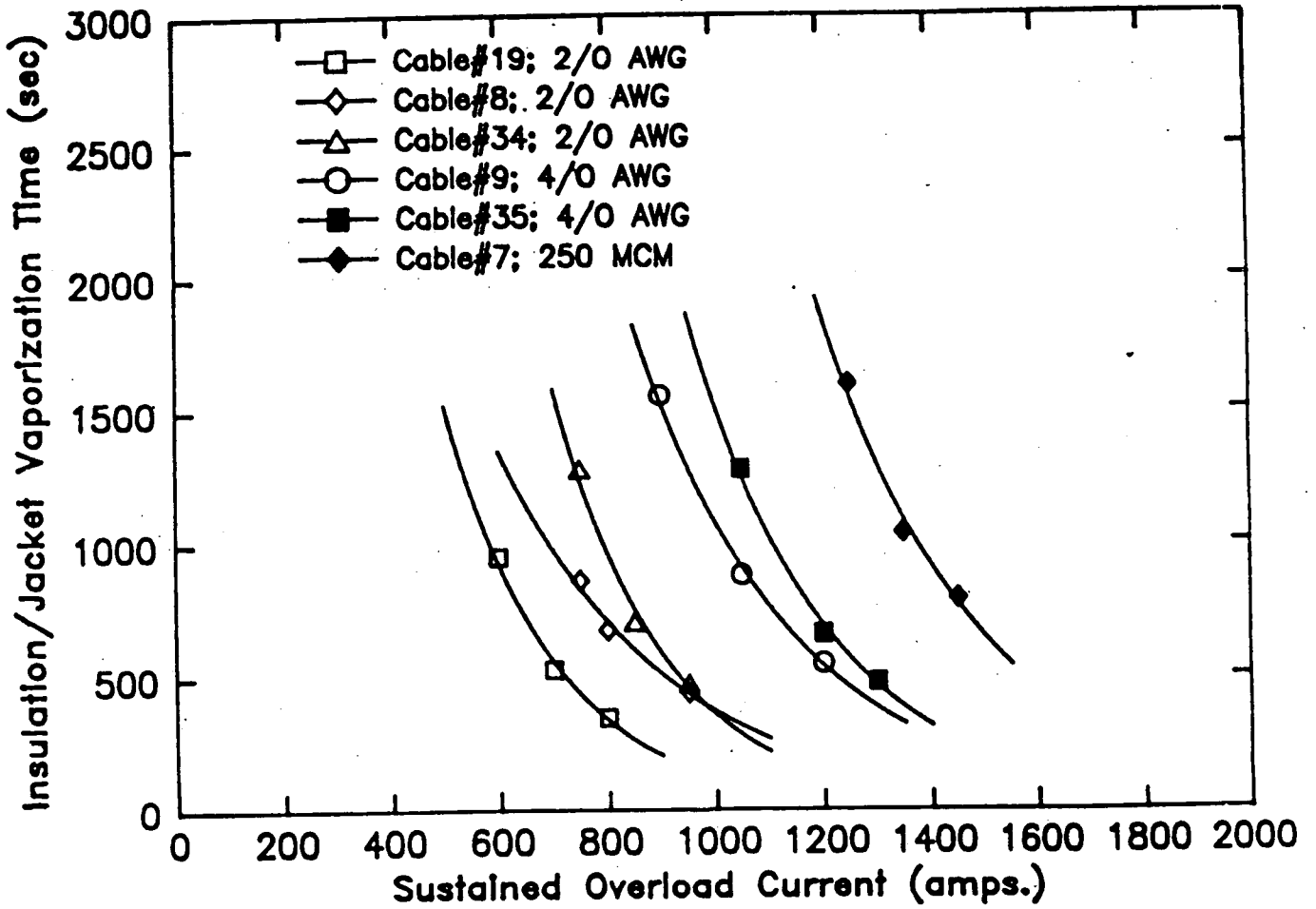


Figure 32. Time to Vapor Formation from Cables as a Result of Sustained Electric Overload Current.

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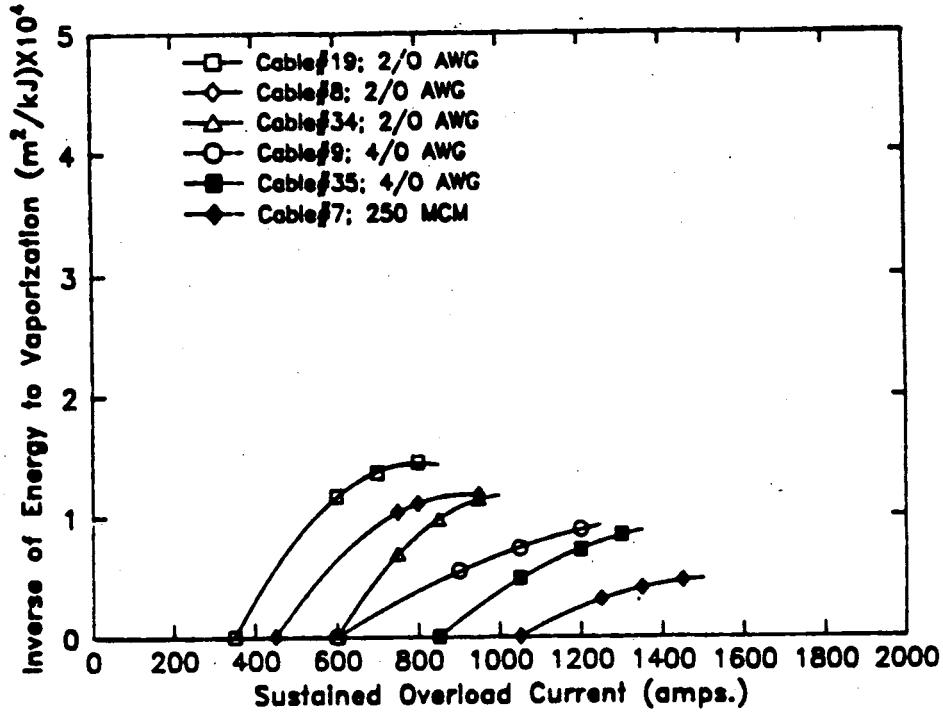


Figure 33. Relationship Between Energy Required for Vaporization of Cable Insulation/Jacket Materials and Sustained Electrical Overload Current.

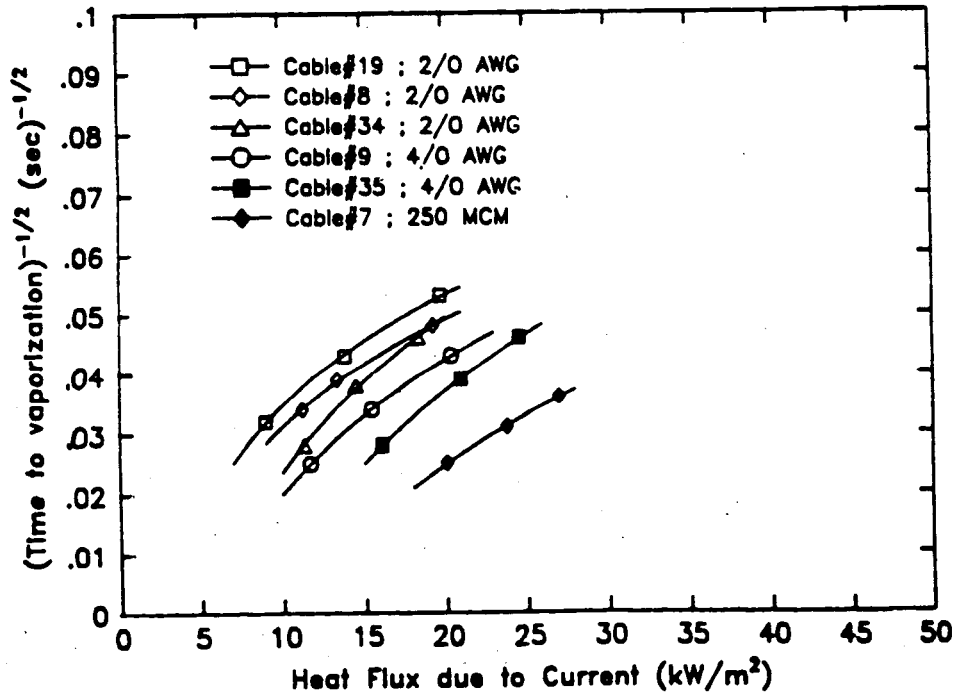


Figure 34. Relationship Between Time to Vaporization of Cable Insulation/Jacket Materials and Heat Flux Exposure of the Conductor as a Result of Sustained Electrical Overload Current.

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TABLE V

CABLE VAPOR FORMATION DATA UNDER
SUSTAINED ELECTRICAL OVERLOAD^a

Insulation/ Jacket	Wire Size (AWG)	Ampacity ^b @ 90°C (Amps)	Vaporization Temperature, (°C)	Critical Overload at or Below which the Cable is Not Expected to Vaporize (Amp)
EP/PE-C1-S	4/0	421	126	600
EP/PE-C1-S	2/0	312	129	450
XLPE/EVA	2/0	245	143	350
FR-EP	2/0	312	150	600
FR-EP	4/0	421	150	850
PE-C1-S	250 MCM	473	-	1050

^a: Single 1.37 m (4.5 ft) long vertical cable in free air initially at ambient temperature (21°C).

^b: Taken from Reference 3.

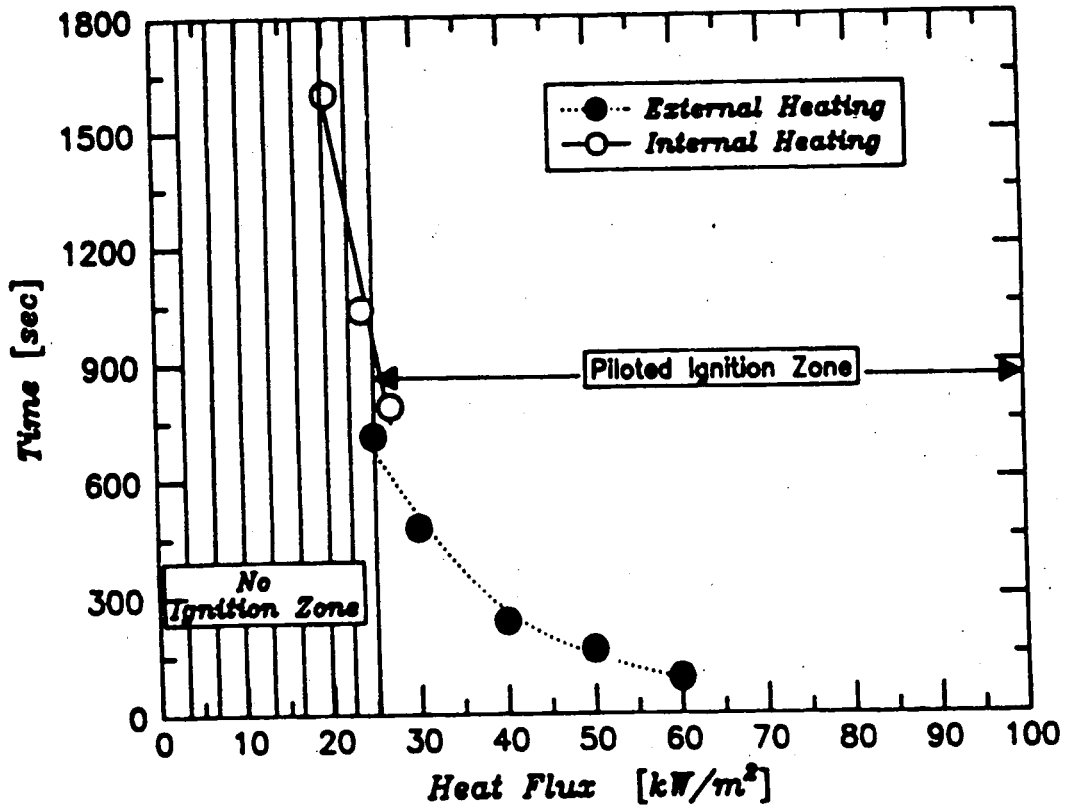


Figure 35. Relationship Between Time to Ignition and Vaporization and Heat Flux Using External and Internal Heat Sources.

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critical conditions for instantaneous fire propagation are expected to be present. Thus electrical protection for Groups 1, 2 and 3 cables is very important, such that cable overheating does not reach the critical heat flux conditions for ignition and instantaneous fire propagation.

3.6 CABLE CLASSIFICATION BASED ON THE FIRE PROPAGATION INDEX, THE IEEE-383 TEST AND THE NATIONAL ELECTRICAL CODE FOR FIRE RESISTANCE OF TELECOMMUNICATION CABLES

Table VI lists cable group classifications based on FPI values, IEEE-383 and NEC fire resistance tests for telecommunication cables. The data in the table show inconsistencies in the IEEE-383 classification, as cables which pass the test belong to either Group 1, 2 or 3 based on the FPI values. Inconsistencies are also found with the classification of telecommunication cables based on the NEC fire resistance test. The CM, CMR and CMX cables belong to Group 3, except for the CMP cable, a highly halogenated cable, which belongs to Group 1. Note that CM cable passes the UL Vertical Tray Test (same as the IEEE-383 Test); CMR cable passes the UL 1666 Riser Cable Fire Test, CMX cable passes the UL VW-1 Flame Test, and CMP cable passes the UL 910 test.

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TABLE VI

CABLE CLASSIFICATION BASED ON THE FIRE PROPAGATION INDEX,
THE IEEE-383 TEST AND NEC FIRE RESISTANCE TESTS FOR
TELECOMMUNICATION CABLES

Cable (AWG, diameter mm)	Cable Classification		
	Group Based on FPI	IEEE 383 Test	NEC Fire Resistance Tests ^a
PE/PVC (24, 0.0036)	3	Passed	CM
PE/PVC (24, 0.0044)	3	NA	CMR
PE/PVC (22, 0.0037)	3	NA	CMX
EP/PVC (12, 0.011)	2	Passed	NA
PVC/EP (2/0, 0.034)	2	Passed	NA
XLPE/Neoprene (12, 0.015)	1	Passed	NA
XLPO/XLPO (12, 0.016)	1	Passed	NA
XLPE/XLPO (20, 0.022)	1	Passed	NA
XLPE/XLPO (18, 0.022)	1	Passed	NA
XLPE/XLPO (10, 0.023)	1	Passed	NA
XLPE/XLPO (12, 0.025)	1	Passed	NA
Si/XLPO (18, 0.028)	1	Passed	NA
XLPO, PVF/XLPO (20, 0.014)	1	Passed	NA
XLPO, PVF/XLPO (22, 0.017)	1	Passed	NA
Si/XLPO (400#MCM, 0.055)	1	Passed	NA
Si/XLPO (400#MCM, 0.055)	1	Passed	NA
EP/PE-C1-S (12, 0.011)	2	Passed	NA
PVC/PVF (24, 0.0050)	1	NA	CMP

a: CM: General purpose; CMR: Riser; CMX: Ordinary; CMP: Plenum.

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IV

CONCLUSIONS

1. Cables can be classified by their fire propagation behavior using the Fire Propagation Index, which combines the chemical heat release rate and thermal response parameter based on theoretical arguments.
2. Three types of fire propagation behaviors can be identified for cables: i) fire propagation rate is very rapid (Group 3); ii) fire propagation rate increases linearly with time (Group 2); and iii) fire propagation is not self-sustained (Group 1).
3. In the presence of electrical faults leading to cable overheating, fire propagation initiated by an arc or an external flame is instantaneous, irrespective of cable group, when the critical heat flux for ignition condition is satisfied.
4. Inconsistencies are present in cable classification based on the IEEE-383 Test and fire resistance tests of the National Electrical Code for Telecommunication Cables.
5. In general, for some insulation and jacket materials, the Fire Propagation Index decreases with increase in the overall cable diameter, as a result of increase in the conductor diameter.
6. Damage due to heat (thermal damage) is expected from Groups 2 and 3 cables, but not from Group 1 cable. Thus, fire protection against thermal hazard would be required.
7. Damage due to smoke, toxic and corrosive products (non-thermal damage) is expected from some of the Group 1, 2 and 3 cables. It may thus be possible to classify cables into Subgroup A for which non-thermal damage is expected to be negligibly small and Subgroup B for which non-thermal damage is expected.
8. Based on this research effort, it is recommended that Factory Mutual and IEEE develop a specified testing standard for cable fire propagation.

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TABLE II
STANDARD CABLE FIRE TESTS

<u>Cable Test</u>	<u>Ignition Source Strength Btu/hr (kW)</u>	<u>Exposure Duration (minutes)</u>	<u>Cable Fire Resistance Level</u>
UL 910	300,000 (88)	20	First Level [*]
UL 1666	495,000 (145)	30	Second Level [*]
IEEE 383 (UL Vertical-Tray)	70,000 (21)	20	Third Level ^{**&***}
	210,000 (62)	20	Not Known ^{**}
	400,000 (118)	20	Not Known ^{**}
VW-1	3,400 (1)	1/4 each (Total 1 min 15 sec)	Fourth Level [*]

^{*} Communications cables [20, 28].

^{**} Power and instrument cables [5].

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2.2 FIRE PROPAGATION

Numerous studies have been performed to understand the fire propagation processes [29]. Theoretically, the fire propagation rate is expressed as a ratio of the heat transfer rate from the flame to the material surface to the thermal response parameter of the material. In this study, the heat transfer rate from the flame to the material surface is assumed to be proportional to the chemical heat release rate. The thermal response parameter of the material is derived from the relationship between time to ignition and heat flux exposure of the sample [8,25,26]. These concepts are briefly described in Appendix B. The ratio of the heat transfer rate from the flame to the material surface to the thermal response parameter of the material multiplied by 1000 is defined as the Fire Propagation Index (FPI):

$$FPI = \left(\frac{0.40 \times \text{Chemical Heat Release Rate}}{\pi \times \text{Number of Cables} \times \text{Cable Diameter}} \right)^{1/3} \times 1000 / \text{Thermal Response Parameter}$$

where chemical heat release rate is in kW and thermal response is in $\text{kW s}^{1/2}/\text{m}^2$. The radiative fraction of the chemical heat release rate is assumed to be equal to 0.40. Chemical heat release rate is defined as the heat released during chemical reactions in a fire generating CO and CO₂ with the consumption of O₂.

In this study, FPI has been used to classify the fire propagation behavior of cables. Although smoke and other products were also measured, the data were not used in the cable classification.

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III

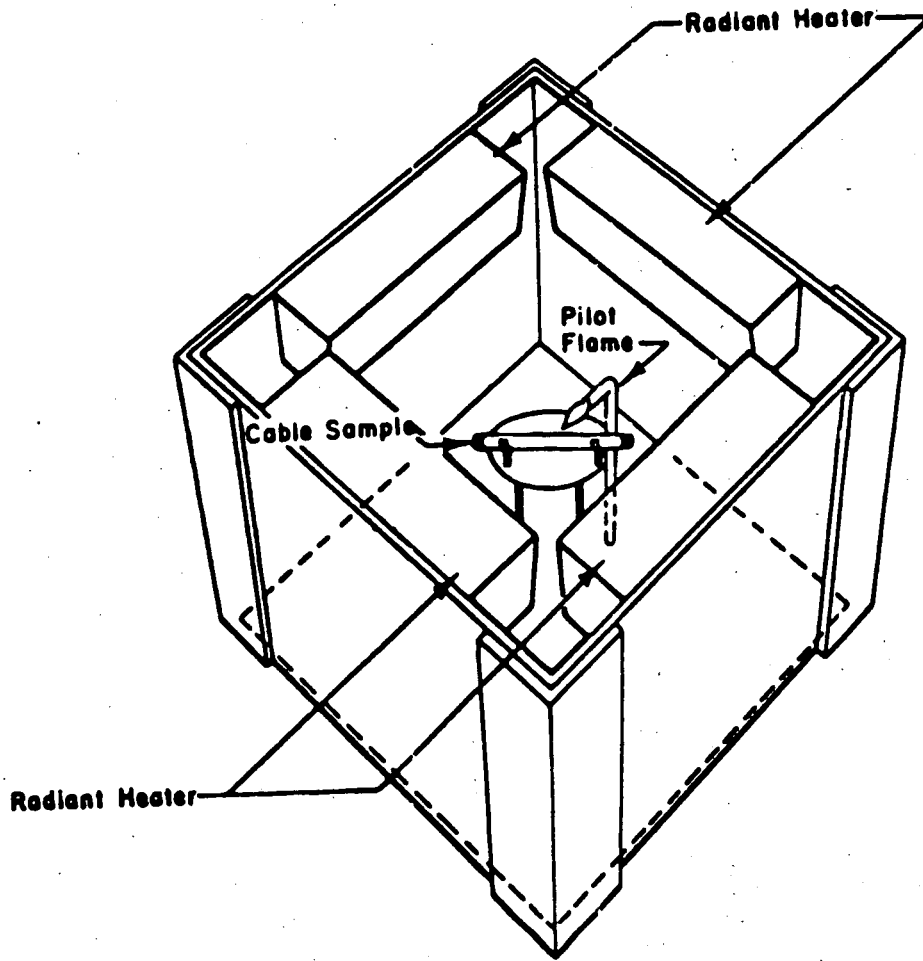
EXPERIMENTS

In the study, tests were performed to quantify the Fire Propagation Index (FPI) for the classification of cables. Three types of tests were performed: 1) ignition tests to determine the thermal response of the cables; 2) fire propagation tests to determine the chemical heat release rate and 3) large-scale validation tests.

3.1 IGNITION TESTS

Ignition tests were performed in the Factory Mutual Small-Scale (10 kW-Scale) Flammability Apparatus, shown in Figure 1A. The details of the ignition setup are shown in Figure 2, where the sample is located horizontally. Exploratory ignition tests were performed with 0.10 m (4 in.) long vertical and horizontal cable samples with and without the covered edges, and with and without spraying the surface with a thin layer of flat black paint (and drying with a hot air gun) to reduce errors due to surface absorptivity differences. After examining the data from this study, as well as data for over 100 cables from our other studies [8, 12-14, 18, 21, 24], it was found that there were strong effects on ignition due to edges and surface absorptivity differences; the cable sample orientation, however, was found to have minor effects on ignition. For reducing errors due to edge effects and surface absorptivity differences, thus the sample length was increased to 0.13 m (5 in.) with 0.5 in. (0.013 m) of both ends tightly covered with heavy duty aluminum foil. The sample was used in a horizontal configuration and attached to a holder/platform as shown in Figure 2. Cables with non-black jackets were spray painted with a thin layer of flat black paint and dried with a hot air gun before the test.

The cable sample on the holder/platform in the Apparatus was surrounded with four radiant heaters to expose the sample to external radiant heat flux in the range of 0 to 60 kW/m² (317 Btu/ft²/min). When cables were exposed to the heat flux, vapors were generated and mixed with air, producing combustible mixtures. For igniting this mixture, a premixed ethylene-air horizontal pilot flame about 0.01 m (0.39 in.), located about 0.010 m (0.39 in.) from the cable surface, as shown in Figure 2, was used. The pilot flame was established on a 0.006 m (0.25 in.) diameter copper tube with a ceramic tip. The tests were performed in the open under natural ventilation.



Piloted Ignition Experiment

Figure 2. Piloted Ignition Experiment Test Setup.

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In the test, the samples were exposed to several values of the external heat flux, and time to ignition was measured visually using a stop watch at each flux, including the flux at or below which there was no ignition. From the data for the inverse of the square root of time to ignition against the external heat flux and from the inverse of the slope, thermal response parameter was calculated (Eq B5 in Appendix B, where proportionality constant is assumed to be unity). The external heat flux value at or below which there is no ignition is defined as the critical heat flux. Figures 3 to 12 show some selected examples of the ignition behavior of the cables. All the cables that have been tested at Factory Mutual (in this study as well as in our other studies [8, 12-14, 18, 21, 24]), follow the relationships shown in Figures 3 to 12. The data calculated from such relationships for the critical heat flux and thermal response parameter are listed in Table III for the cables examined in this study.

The higher the critical heat flux and thermal response parameter values the slower is the fire propagation rate and the lower is the FPI value expected. The lower the FPI value the better the cable in terms of resistance to self-sustained fire propagation.

3.2 FIRE PROPAGATION TESTS TO DETERMINE THE CHEMICAL HEAT RELEASE RATE

Exploratory fire propagation tests were performed with single 0.10 m (4 in.), 0.25 m (10 in.), 0.38 m (15 in.), 0.61 m (2 ft) and 1.25 m (4 ft) long cable samples and 0.61 m (2 ft) long bundles of three cable samples in both Small (10 kW-) and Intermediate (500 kW-Scale) Apparatuses. The cable sample was attached to a support and was surrounded by an air tight glass tube connected on the top to an aluminum tube as shown in Figure 13. Based on the exploratory tests, the Intermediate-Scale (500 kW-Scale) Flammability Apparatus, shown in Figure 1B was selected for the fire propagation tests. The details of the fire propagation setup are shown in Figure 13. The glass and the aluminum tubes were 0.25 m (10 in.) in diameter and 0.61 m (2 ft) in length. The bottom 0.20 m (8 in.) of the cable sample was in the external heat flux zone as shown in Figure 13. The critical heat flux values for cables are found to be in the range of about 10 to 40 kW/m² [8, 12-14, 18, 21, 24]; an external heat flux value of 50 kW/m² was thus selected to expose the

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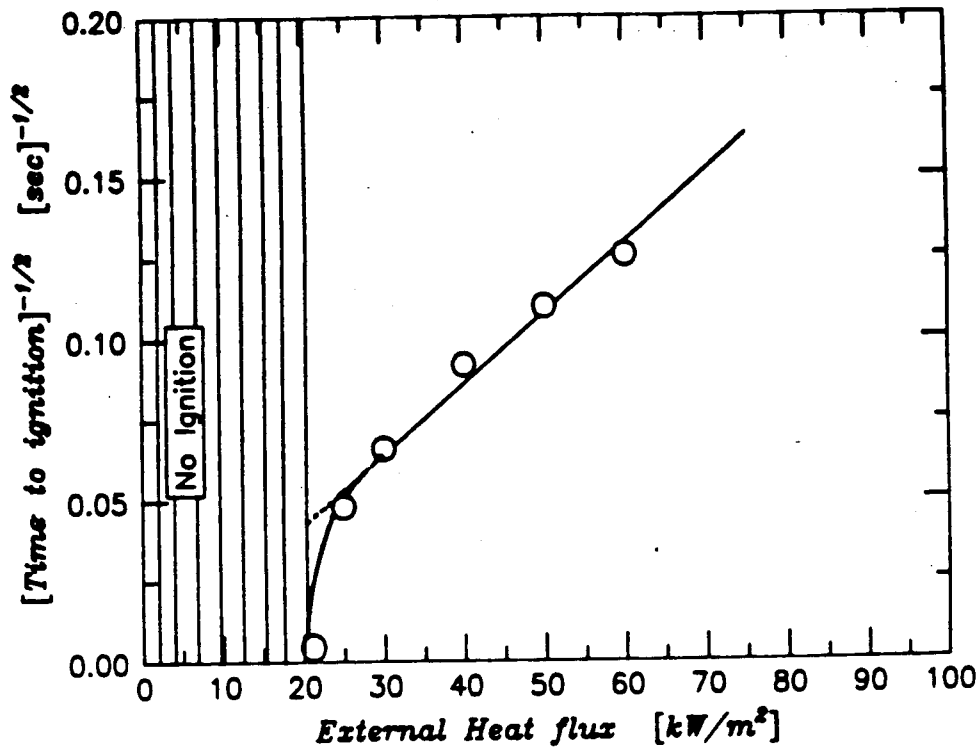


Figure 3. Relationship between Time to Piloted Ignition and External Heat Flux for Silicone Rubber-Crosslinked Polyolefin Cable.

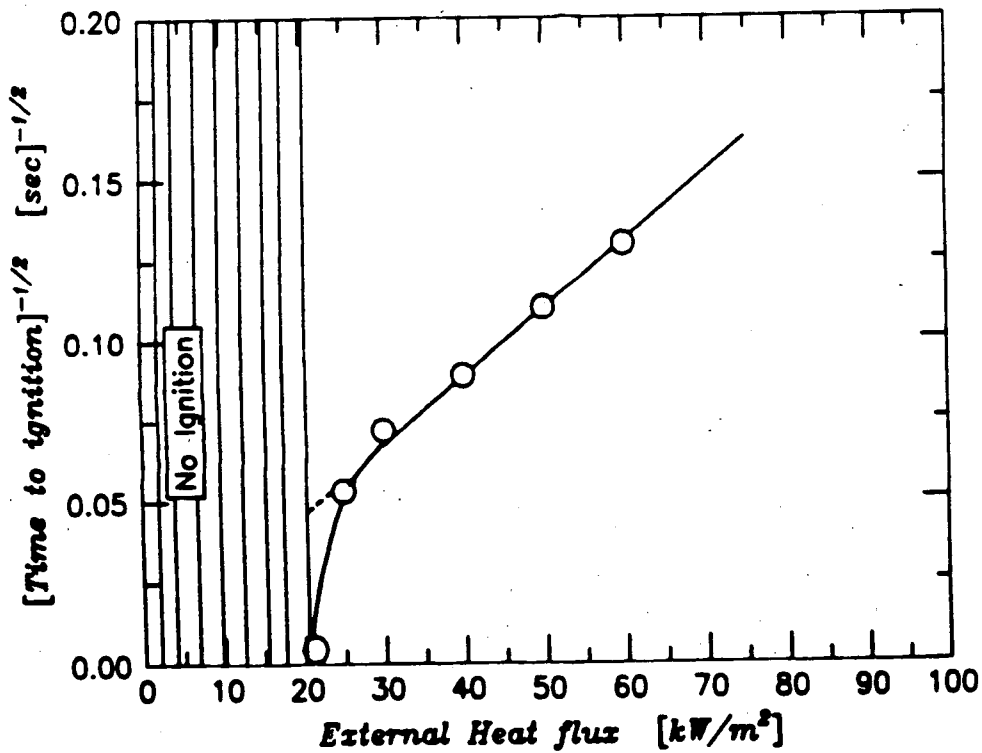


Figure 4. Relationship between Time to Piloted Ignition and External Heat Flux for Crosslinked Polyethylene-Crosslinked Polyolefin Cable.

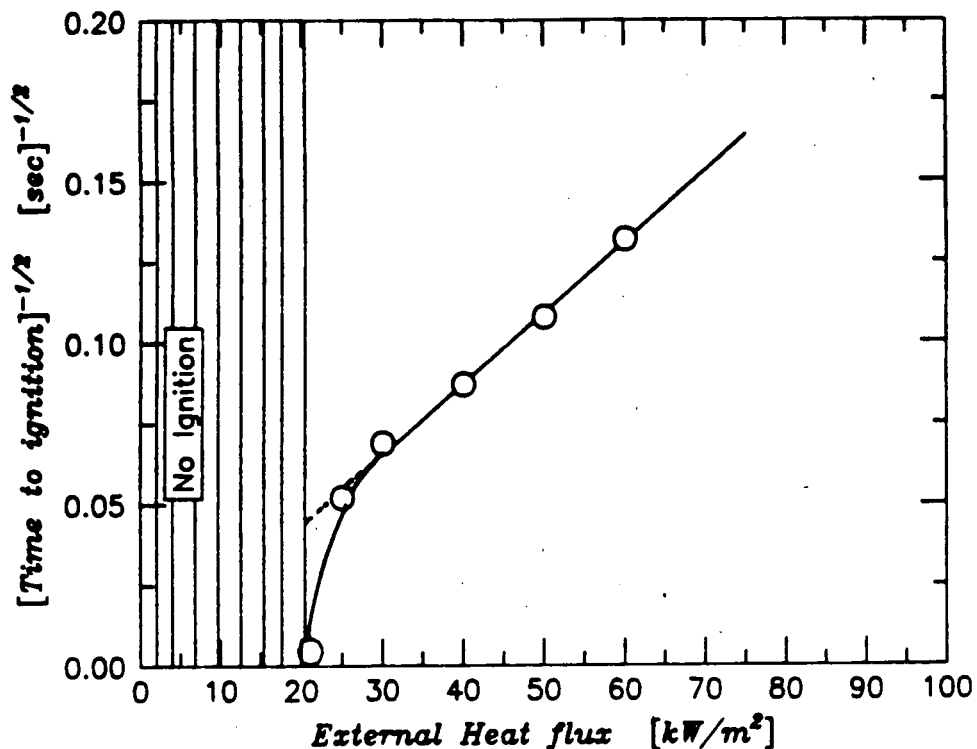


Figure 5. Relationship between Time to Piloted Ignition and External Heat Flux for Crosslinked Polyolefin Cable.

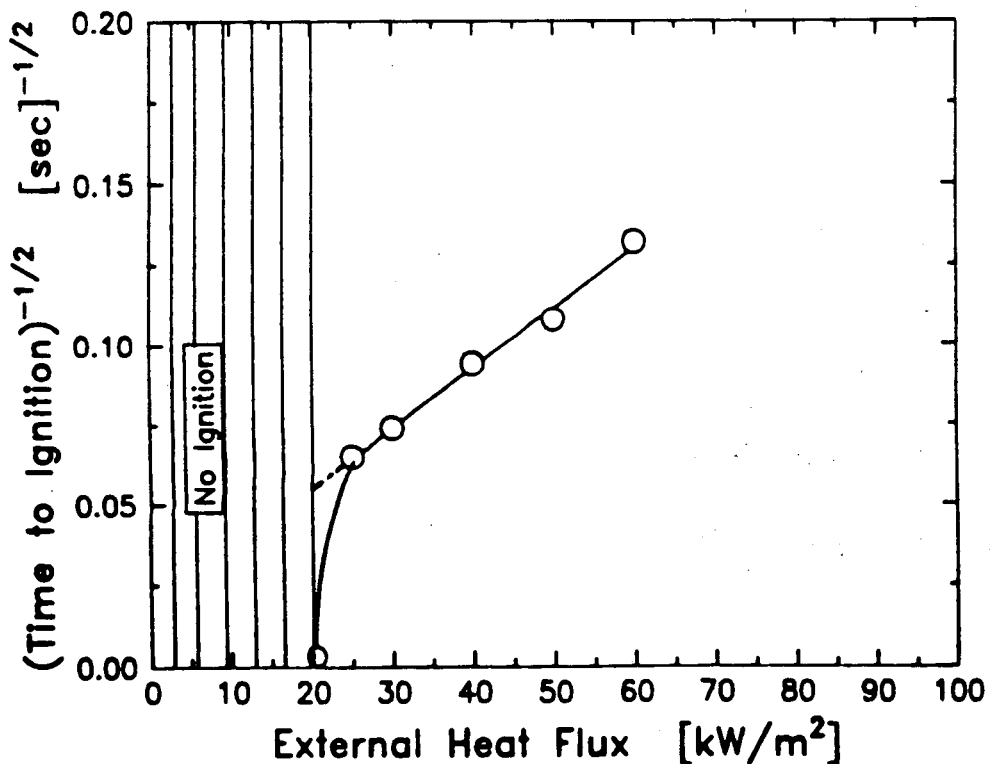


Figure 6. Relationship between Time to Piloted Ignition and External Heat Flux for Crosslinked Polyethylene-Crosslinked Polyolefin Cable.

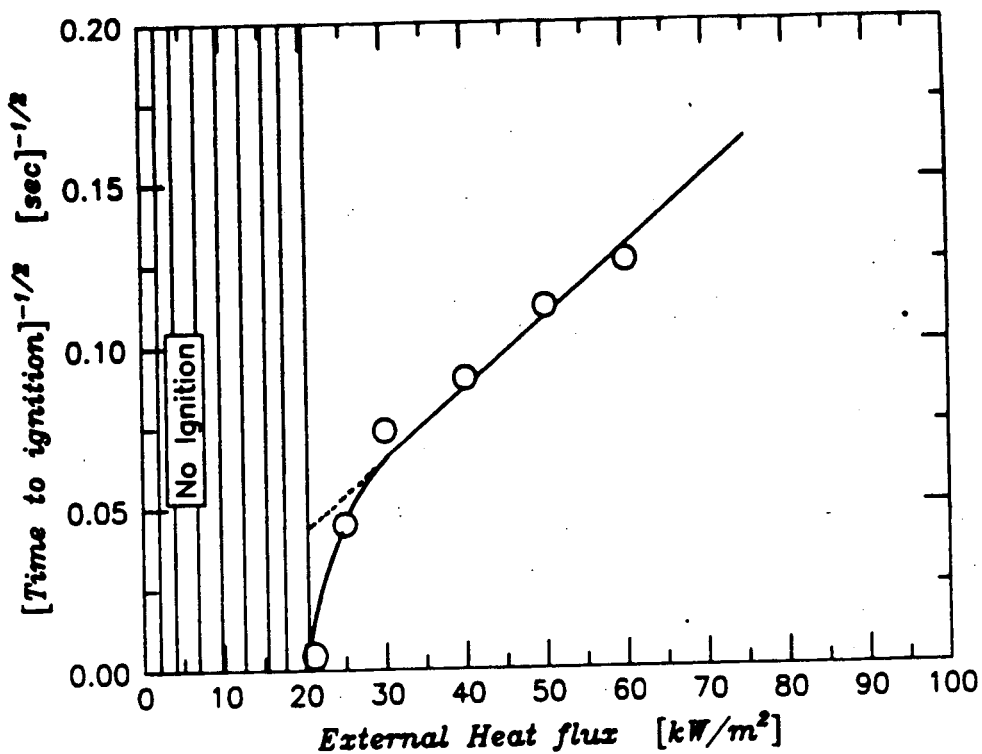


Figure 7. Relationship between Time to Piloted Ignition and External Heat Flux for Crosslinked Polyethylene-Crosslinked Polyolefin Cable.

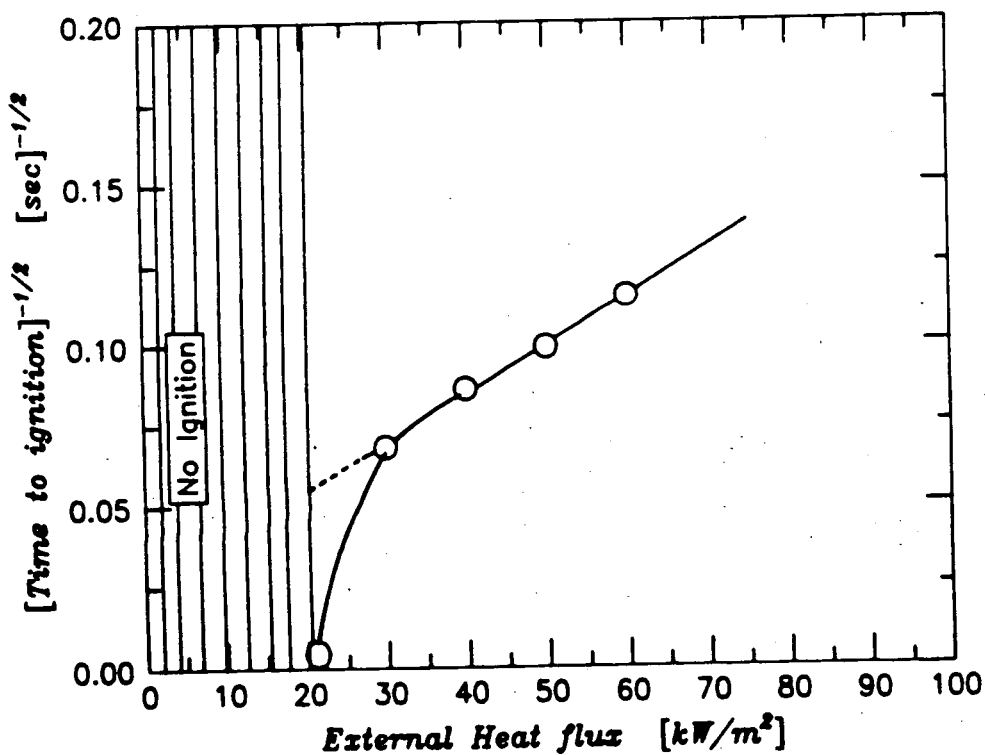


Figure 8. Relationship between Time to Piloted Ignition and External Heat Flux for Crosslinked Polyethylene/Polyvinylidene Fluoride-Crosslinked Polyolefin Cable.

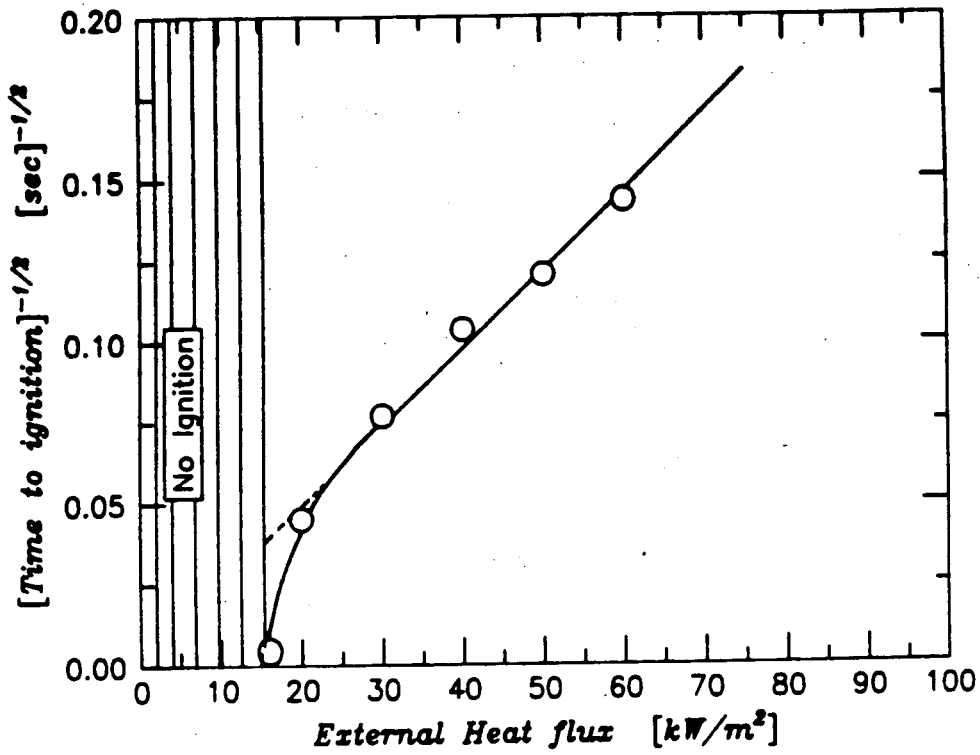


Figure 9. Relationship between Time to Piloted Ignition and External Heat Flux for Crosslinked Polyethylene/Polyvinylidene Fluoride-Crosslinked Polyolefin Cable.

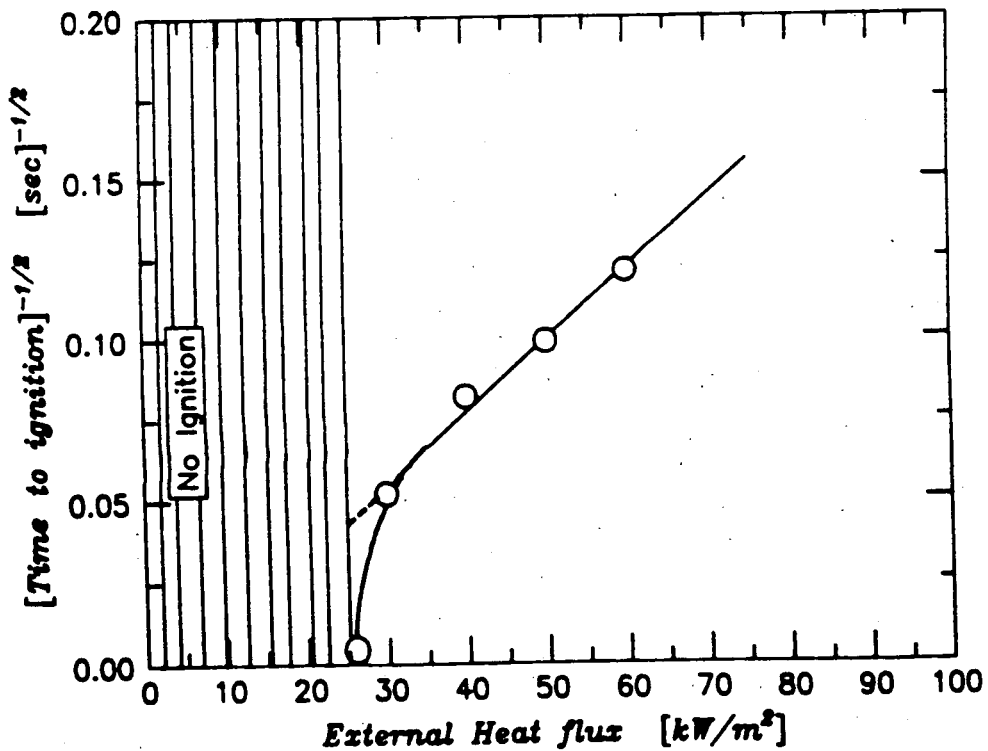


Figure 10. Relationship between Time to Piloted Ignition and External Heat Flux for Silicone Rubber-Crosslinked Polyolefin Cable.

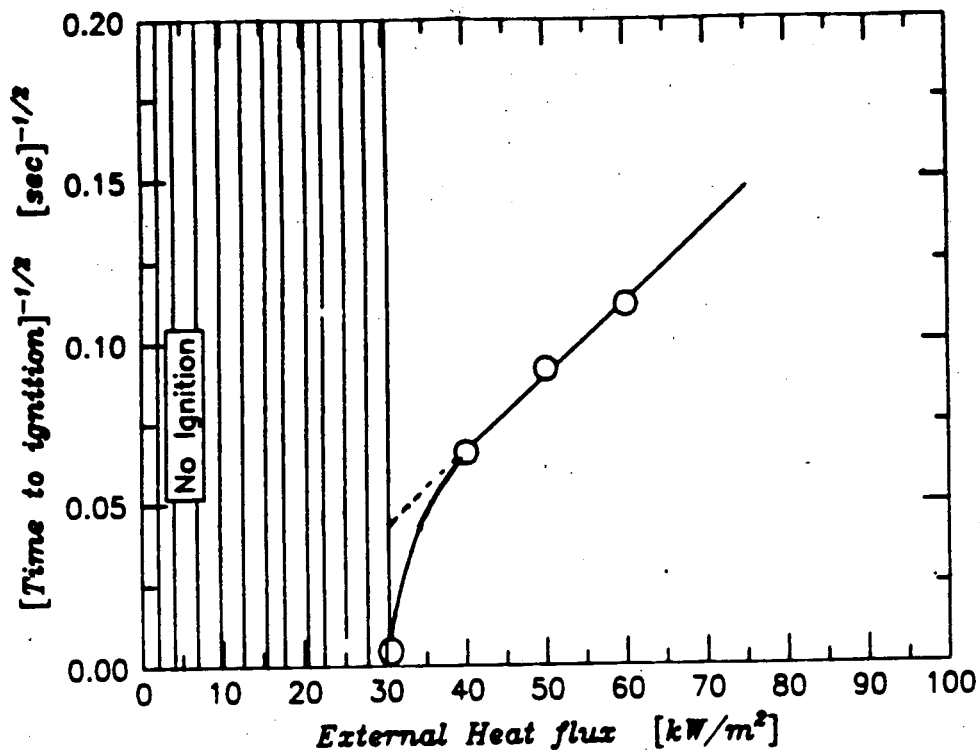


Figure 11. Relationship between Time to Piloted Ignition and External Heat Flux for Silicone Rubber-Crosslinked Polyolefin/Metal Armor Cable.

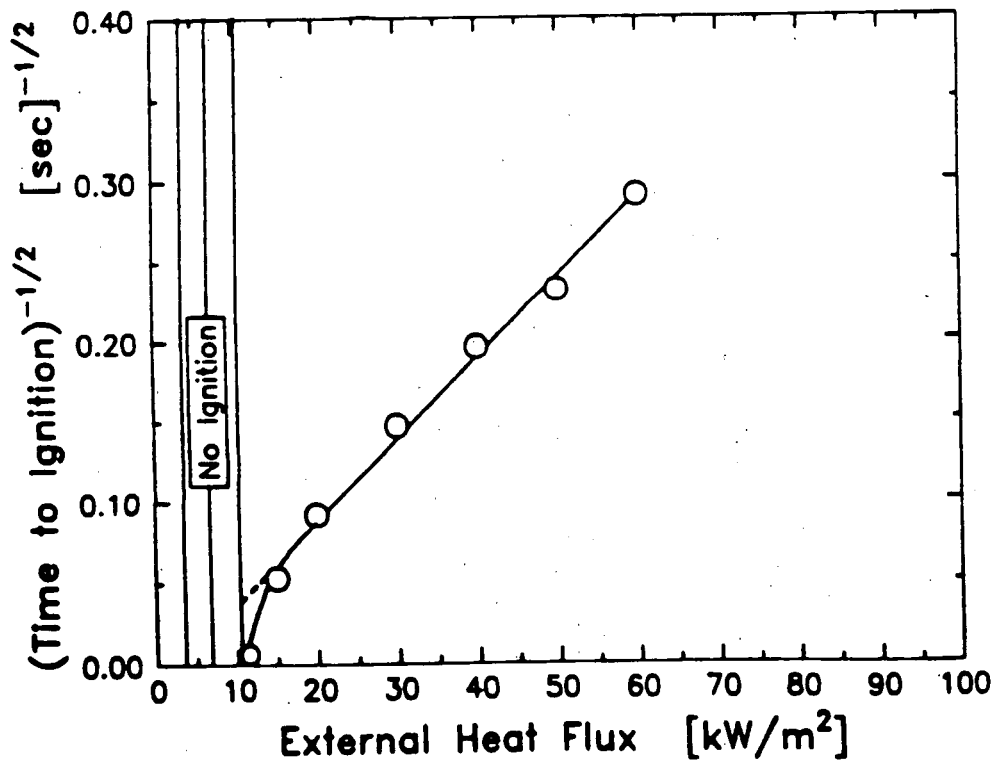


Figure 12. Relationship between Time to Piloted Ignition and External Heat Flux for Polypropylene/Polyester-Polyvinyl Chloride Cable.

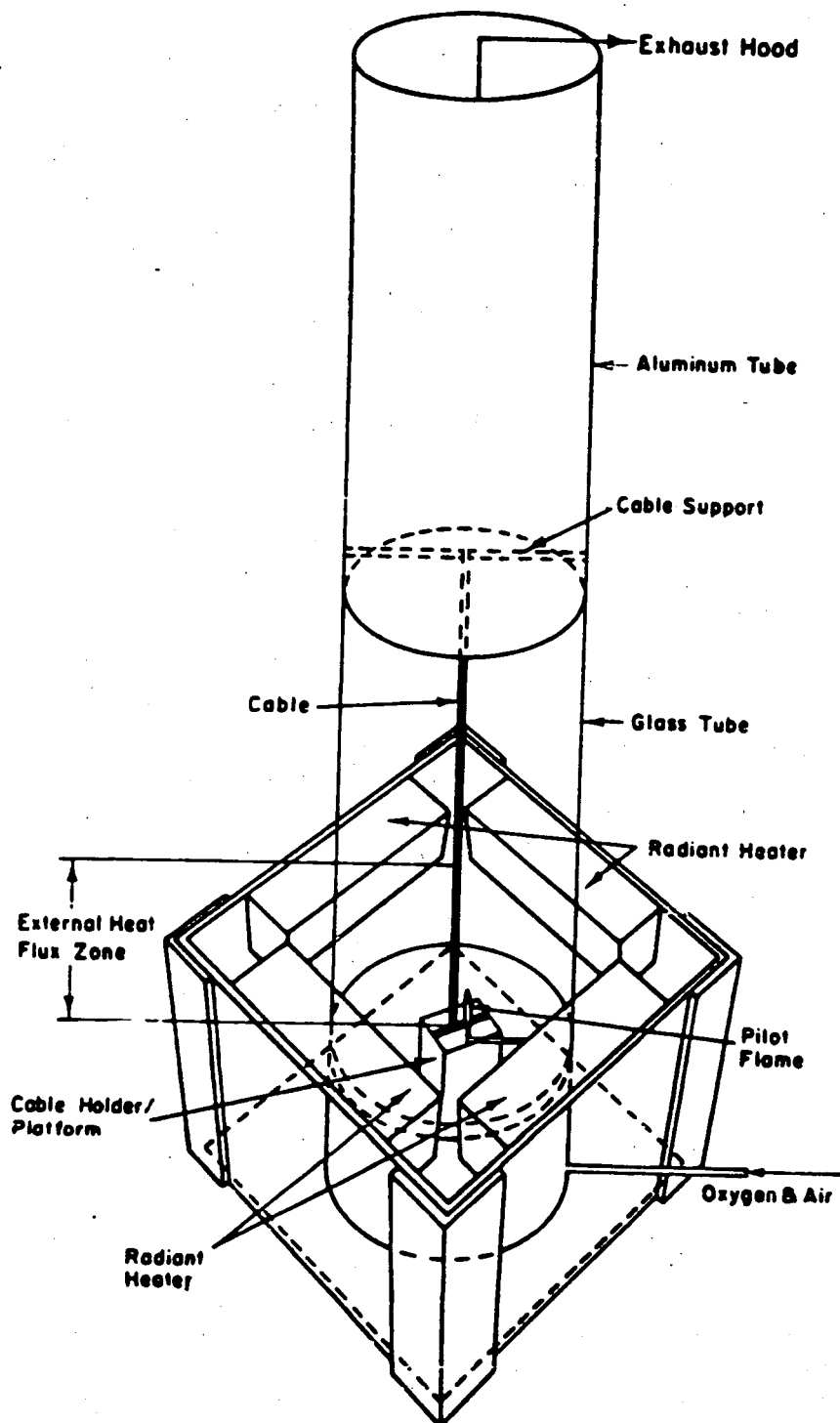


Figure 13. Factory Mutual Flammability Apparatus - Lower Part.

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bottom 0.20 m (8 in.) of the cable sample to make sure that the cable vapor air mixture would ignite. For the ignition of the combustible cable vapor air mixture, a pilot flame located 0.15 m (6 in.) from the bottom end of the cable was used. The pilot flame consisted of a vertical ethylene air premixed flame, established at the ceramic tip of a 0.006 m (0.25 in.) diameter copper tube. The pilot flame was about 0.010 m (0.39 in.) in length and was located about 0.010 m (0.39 in.) from the cable surface, as shown in Figure 13.

In the tests, air with a flow rate of $0.005 \text{ m}^3/\text{s}$ (11 cfm) was introduced at the bottom of the glass tube, as shown in Figure 1B. For the simulation of large-scale flame radiation conditions [30-34], exploratory tests were performed with air having oxygen concentrations in the range of 21 to 50%. Figure 14 shows an example of the data. Based on the analysis of the large-scale flame radiation simulation data from the exploratory tests, oxygen concentrations of 30% and above were found to be the limits for peak flame radiation and fire propagation rate. All the fire propagation tests thus were performed at 40% oxygen concentration.

After the cable was ignited, fire propagated vertically on the cable surface, generating heat, smoke and other compounds, all of which were captured along with air in the sampling duct of the Apparatus as shown in Figure 1B. Smoke and other compounds generated in fires could be toxic and corrosive and reduce visibility. In the sampling duct of the Factory Mutual Intermediate-Scale (500 kW-Scale) Flammability Apparatus, all the hot fire products were well mixed before the measurements were made for determination of the generation rate of smoke and other compounds, heat release rate and light obscuration by smoke.

For the determination of the generation rate of smoke and other compounds, heat release rate and light obscuration by smoke, the following measurements were made:

- 1) Total flow rate of fire products and air mixture through the sampling duct using pressure transducers across a calibrated orifice plate and gas temperature in the sampling duct and ambient temperature (Appendix C).

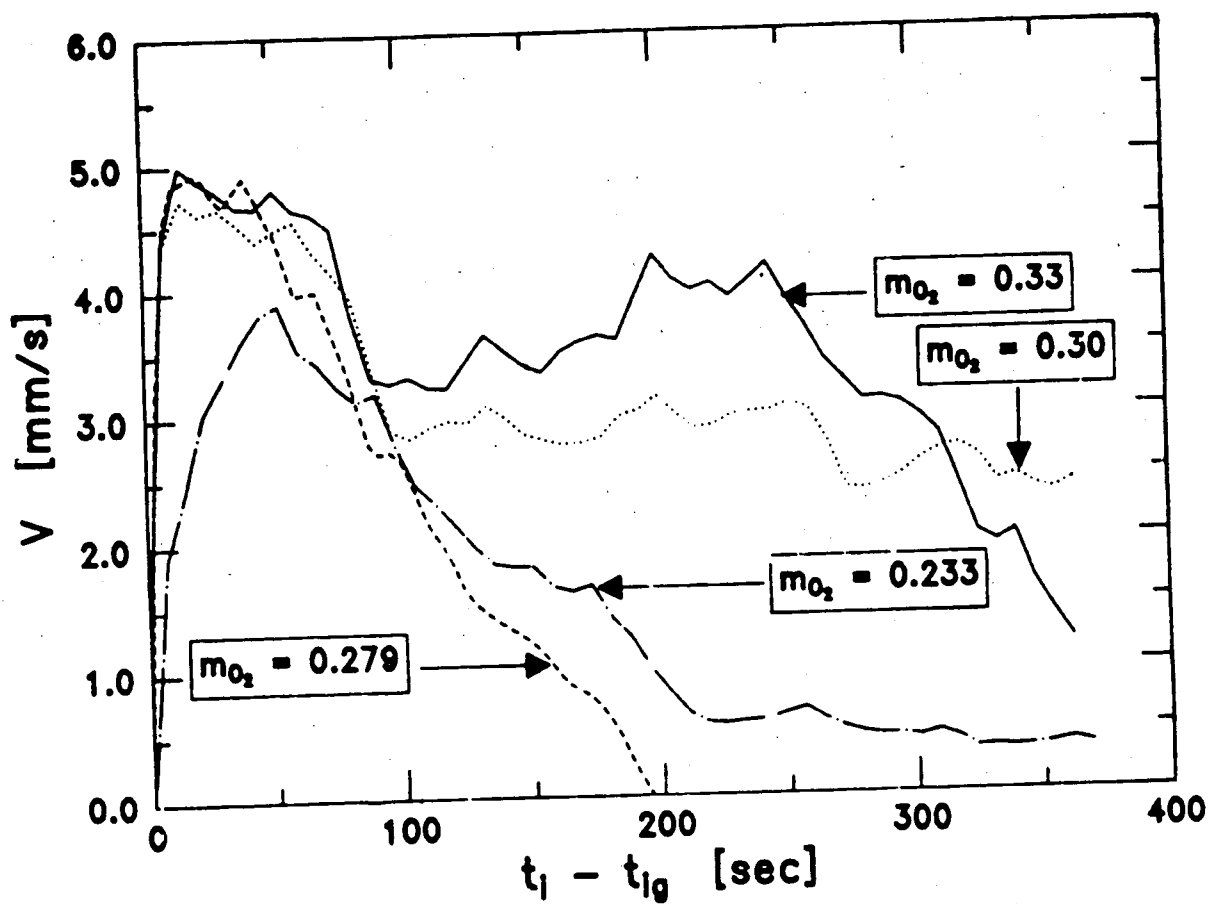


Figure 14. Increase in the Fire Propagation Rate Due to Increase in Oxygen Concentration for a Vertical, 1.29 m (4 ft) Long Cable. m_{O_2} Represents Mass Fraction of Oxygen.

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2) Concentrations* of CO, CO₂, total gaseous hydrocarbons, smoke and oxygen using the following analyzers: a) Infrared CO and CO₂ Analyzers (Beckman Models 864); b) Servomex O₂ Analyzer (Sybron/Taylor Model OA-540); c) Flame Ionization Hydrocarbon Gas Analyzer (Beckman Model 400) and d) TEOM Particle Mass Monitor (Rupprecht & Patashnick).

The CO, CO₂, total gaseous hydrocarbon and O₂ analyzers were calibrated using standard gas-nitrogen mixtures in the concentration range expected in the test. No calibration procedure was used for the total volumetric flow rate in the sampling duct and the Particle Mass Monitor; instead, a checking procedure was used. In the tests, the initial and final weights of the filter used to collect the smoke in the Particle Mass Monitor were measured by a high sensitivity chemical balance and compared with the data calculated on the basis of total volumetric flow rate based on pressure and temperature in the sampling duct and the Particle Mass Monitor measurements. With very few exceptions, the data based on total volumetric flow rate and Particle Mass Monitor and the chemical balance were in excellent agreement.

Relationships for the calculations of generation rates of chemical compounds are given in Appendix C.

3) Light obscuration by smoke was measured by using the Factory Mutual Smoke Turbidimeter. The relationship for the calculation of light obscuration is given in Appendix C.

The chemical heat release rate was calculated from the generation rates of CO and CO₂; relationships for the calculations are given in Appendix C.

Although the generation rates of smoke and other chemical compounds and light obscuration were determined, for the classification of the cable, only chemical heat release rate was used.

The chemical heat release rate and its radiative component depend on the chemical structure of the plastics and fire size; the radiative component is in the range of about 0.35 to 0.45 with some exceptions [30-34]. For simplification, we have assumed the radiative component of the chemical heat release rate to be equal to 0.40 for all the cables for fire propagation in higher oxygen concentrations in the Flammability Apparatus and in the large-scale cable fire tests in normal air.

* Concentrations of HCl and HCN were measured for some limited number of cable samples and are reported in Reference 24.

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The cables were classified on the basis of the Fire Propagation Index expressed as FPI,

$$FPI = \left(\frac{0.40 \times \text{Chemical Heat Release Rate}}{n \times \text{Number of Cables} \times \text{Cable Diameter}} \right)^{1/3} \times 1000 / \text{Thermal Response Parameter}$$

where chemical heat release rate is in kW and the thermal response parameter is expressed in $\text{kWs}^{1/2}/\text{m}^2$.

3.3 EXPLORATORY TESTS FOR THE FIRE PROPAGATION INDEX

Exploratory tests were performed using 0.10 m (4 in.), 0.25 m (10 in.), 0.38 m (15 in.), 0.61 m (2 ft) and 1.25 m (4 ft) long single vertical cable samples and 0.61 m (2 ft) long vertical bundle of three cables. Single cables with lengths of 0.25 m (10 in.) and 0.38 m (15 in.) were examined in the absence of external heat flux and oxygen concentration of 40%. Single cables with lengths of 0.10 m (4 in.), 0.61 m (2 ft) and 1.25 m (4 ft) and 0.61 m (2 ft) long bundles of three cables were examined in the presence of 50 kW/m^2 of external heat flux and oxygen concentrations in the range of 21 to 45%.

The chemical heat release rate was determined as a function of time during fire propagation using the generation rates of CO and CO₂. The chemical heat release rate profiles were used in conjunction with the thermal response data from Table III to calculate the FPI profiles for the cables. Figures 15 to 24 show these profiles under various conditions for some selected cable samples; for other cables the profiles are included in Appendix E.

The FPI profiles in Figures 15 through 24 show that the data are very repeatable. As the length of cable sample and oxygen concentration are increased, FPI increases; however, for lengths of 0.61 m (2 ft) and 1.25 m (4 ft) and oxygen concentrations of 30% and above, the profiles do not show significant variations.

For the cables examined in this study, large differences were found in the FPI values. Cables for which FPI values were less than 10 showed that the fire propagation had difficulty in sustaining itself and conditions were close to flame extinction conditions, taking as much as 30 minutes or longer depending on the cable to reach the top of the 0.61 m (2 ft) long cable

TABLE III

CRITICAL HEAT FLUX, THERMAL RESPONSE PARAMETER AND CABLE CLASSIFICATION

Cable No.	Insulation/ Jacket	Overall Diameter (m)	Thermal Response Parameter (kW/m ²) s ^{1/2}	Chemical Heat of Combustion (kJ/kg) x 10 ⁻³	Critical Heat Flux (kW/m ²)	Cable Classification (Group)	FPI (Peak Values)
1	PVC/PVC	0.0036	131	18.9	15	3	36
2	PVC/PVC	0.0044	156	18.1	15	3	28
3	PVC/PVC	0.0092	267	12.6	13	2	15
4	PVC/PVC	0.013	341	16.5	25	2	11
5	PE/PVC	0.0037	183	20.9	20	3	28
6	EP/PVC	0.011	244	13.4	15	2	16
6A	PE/PVC	0.011	221	-	15	3	23
7	PVC/EP	0.034	263	12.6	15	2	13
8	SI/PVC	0.016	212	15.1	19	2	17
9	TPE/TPE	0.0094	270	12.0	15	2	17
10	TPE/PE-Cb	0.0094	219	11.2	25	2	18
11	EP/EP	0.010	467	17.1	20	1	8
12	EP/EP	0.016	499	16.6	23	1	7
13	EP/EP	0.025	567	19.7	23	1	6
14	XLPE/XLPE	0.0095	273	12.4	20	2	17
15	XLPE/XLPE	0.0099	382	18.2	25	1	9
16	XLPE/XLPE	0.011	386	19.4	22	1	9
17	XLPE/XLPE	0.012	276	14.0	24	2	15
18	XLPE/EVA	0.012	503	17.2	25	1	8
19	XLPE/EVA	0.017	460	21.6	25	1	8
20	XLPE/EVA	0.022	442	22.0	20	1	9
21	XLPE/Neoprene	0.015	291	12.9	20	1	9
22	XLPO/XLPO	0.016	463	14.0	20	1	9
23	XLPE/XLPO	0.022	461	14.4	20	1	9

TABLE III (Continued)

CRITICAL HEAT FLUX, THERMAL RESPONSE PARAMETER AND CABLE CLASSIFICATION

Cable No.	Insulation/ Jacket	Overall Diameter (m)	Thermal Response Parameter ($\text{kW/m}^2 \text{ s}^{1/2}$)	Chemical Heat of Combustion ($\text{kJ/kg} \times 10^{-3}$)	Critical Heat Flux (kW/m^2)	Cable Classification (Group)	FPI (Peak Values)
24	XLPE/XLPO	0.022	474	20.6	20	1	9
25	XLPE/XLPO	0.023	535	13.8	20	1	6
26	XLPE/XLPO	0.025	456	12.4	20	1	8
27	SI/XLPO	0.028	457	15.9	20	1	8
28	XLPO, PVF/XLPO	0.014	413	14.3	15	1	8
29	XLPO, PVF/XLPO	0.017	639	14.0	20	1	6
30	SI/XLPO	0.055	448	18.9	25	1	8
31	SI/XLPO, Metal Armor	0.055	435	19.6	30	1	6
32	PP, Polyester/PVC	0.020	197	19.3	10	3	21
34	EP/PE-C1-S	0.0043	343	15.9	20	2	13
35	EP/PE-C1-S	0.011	283	18.9	18	2	13
36	EP/PE-C1-S	0.016	415	19.3	20	1	9
37	EP/PE-C1-S	0.019	416	20.1	20	1	8
38	EP-FR/None	0.0035	289	30.9	25	2	17
39	EP-FR/None	0.015	370	14.8	25	1	9
40	EP-FR/None	0.018	448	15.1	20	1	9
41	EP-FR/None	0.028	295	14.8	19	2	12
42	PE-C1/None	0.015	217	11.6	12	2	18
43	ETFE/EA	0.010	454	11.2	22	1	8
44	PVC/PVF	0.0050	264	6.0	30	1	7
45	FEP/FEP	0.0079	652	6.2	36	1	4
46	FEP/FEP	0.0097	638	9.8	30	1	5

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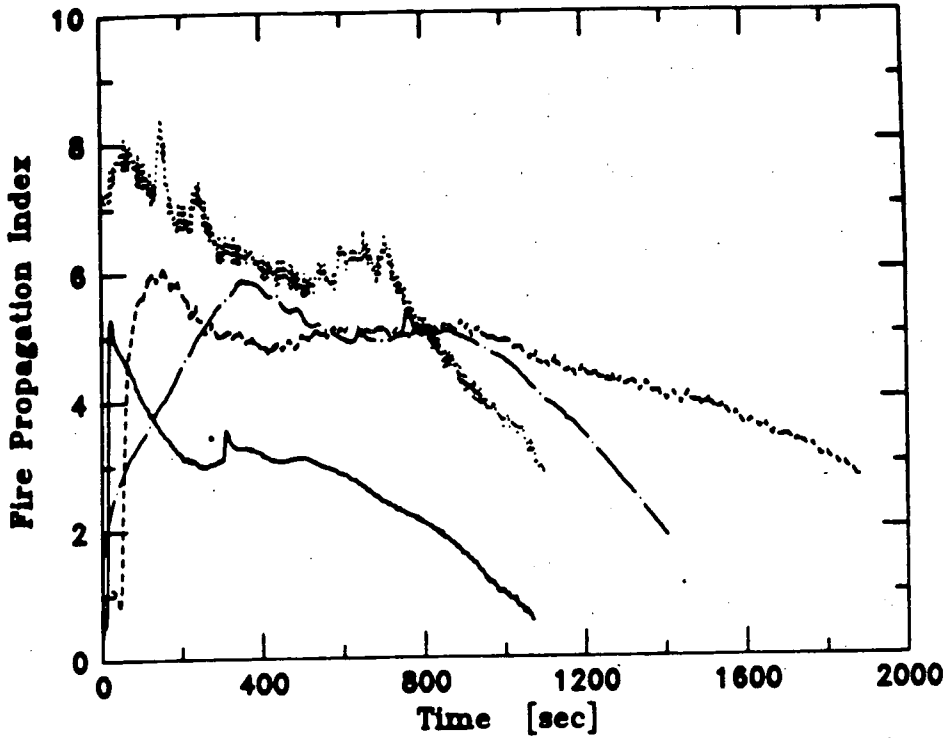


Figure 15. Vertical Fire Propagation for Silicone Rubber-Crosslinked Polyolefin Cable. Conditions: Number of Cables, Cable Length (m), Oxygen (%) and External Heat Flux (kW/m^2) respectively:
 - - - - - : 1, 0.61, 40, and 50;
 - - - - - : 3B, 0.61, 40, and 50;
 - - - - - : 1, 0.38, 40 and 0;
 - - - - - : 1, 0.10, 21 and 50. (3B: Bundle of Three Cables).

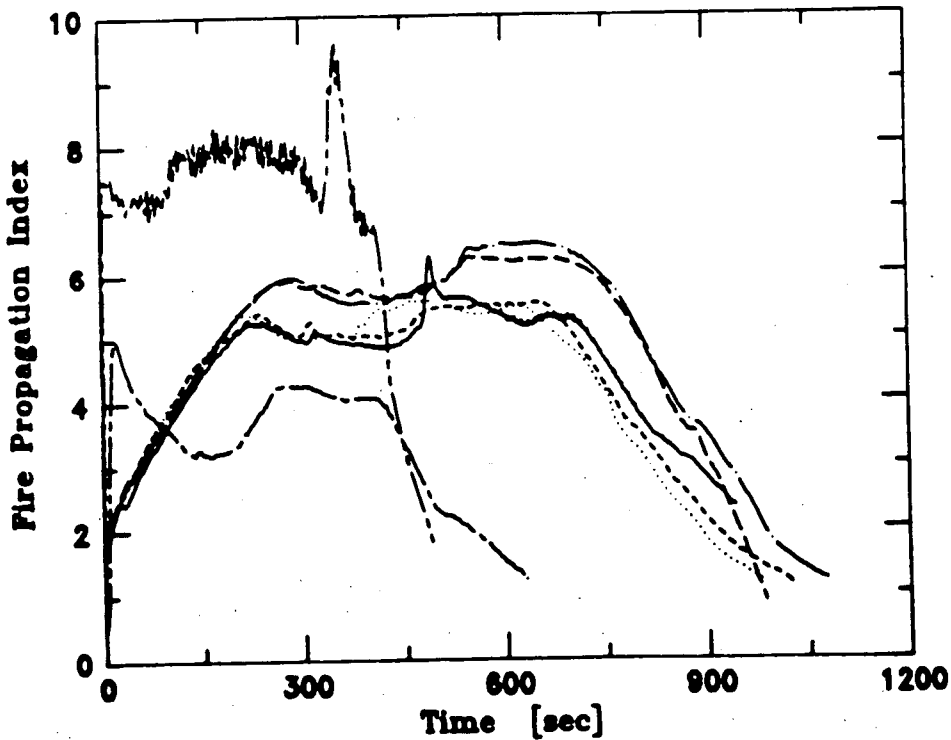


Figure 16. Vertical Fire Propagation for Crosslinked Polyethylene-Crosslinked Polyolefin Cable. Conditions: Number of Cables, Cable Length (m), Oxygen (%) and External Heat Flux (kW/m^2) respectively:
 - - - - - : 1, 0.61, 40, and 50;
 - - - - - : 1, 0.38, 40, and 0;
 - - - - - : 1, 0.38, 40 and 0 (Repeat);
 - - - - - : 1, 0.25, 40 and 0;
 - - - - - : 1, 0.25, 40 and 0 (Repeat);
 - - - - - : 1, 0.25, 40 and 0 (Repeat);
 - - - - - : 0.10, 21, 50.

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I

INTRODUCTION

A cable is an insulated conductor or group of individually insulated conductors in twisted or parallel configuration used for carrying electrical power and signals. The most commonly used conductors are made from copper and aluminum in the form of wire. Wire is a slender rod or filament of drawn metal. In addition to copper and aluminum, glass fibers in fiber optic cables are also used to carry signals.

The conductors are designed to conform to a range of nominal areas in graduated steps [1]. The American usage is based on American Wire Gauge (AWG), a standard system for designating wire diameter. AWG is used for smaller conductor sizes, i.e., 40 AWG to 0000 (4/0). Larger conductor sizes are expressed in thousand circular mils (MCM). A mil is 1/1000 in.; a circular mil is the area of a circle one mil in diameter. Countries outside of North and South America use the metric system; the conductor diameter is expressed in mm [1]. Cables are used as single and multiconductor cables. A coaxial cable consists of two cylindrical conductors with a common axis separated by a dielectric.

The metallic conductors or glass fibers in cables are insulated by covering them with various types of plastics having high resistance to the flow of electric current. For the protection of cable insulation, mainly against the environment, an outer covering over the insulation is used. This outer covering, usually made of plastics, is called a jacket. For added mechanical protection, metal armors consisting of braids, wrapping or interlocking, including continuously corrugated welded seam construction, are used. The common metals are galvanized steel, aluminum and bronze. For the protection of cable core, such as protection from moisture and chemicals, electrical short circuiting, etc., sheaths or tapes are used. The sheaths consist of metals such as aluminum. The tapes are made of plastics or plastic and metal combinations such as thin sheets of aluminum, copper, or lead laminated to an adhesive ethylene copolymer. In multiconductor cables, spaces are formed by the assembled conductors and are filled with inert materials or plastics. For shielding against outside interferences as well as interferences between cable pairs in the same core, metal or metal and plastic

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combinations are used such as twisted pairs, steel conduit or armor, aluminum/mylar, thermosetting semi-conducting polyolefin compound, etc. Cables thus are complex structures of metals and plastics.

Cables are used for various applications [2]: 1) 0-300 volts (instrument cables; audio cables; computer cables, etc.); 2) 600 volt class (building wire and single conductor power cable; multiconductor power cable; composite cables; control cables, etc.); 3) 5 kV Class (single conductor power cable for a) conduit or underground duct installations and b) tray, aerial or direct burial applications; three conductor power cable for tray, aerial or direct burial applications; 4) 8 to 35 kV Class (single conductor cable for conduit, duct, aerial, tray or direct burial applications and three conductor power cables for use in trays and racks); and 5) 69 to 138 kV Class.

For cable insulation and jacket, thermoplastics are generally used. A thermoplastic is a material which softens when heated or reheated and becomes firm on cooling. The most commonly used plastics for cable insulation and jackets are [1,2]: polyvinylchloride (PVC), polyethylene (PE), polypropylene (PP), polyolefins (PO), nylon, polyurethanes, fluorinated polymers: polytetrafluoro-ethylene (PTFE), FEP (TFE copolymer with hexafluoropropylene) Tefzel (TFE copolymer with ethylene), Halar (ethylene copolymer with chlorotrifluoroethylene), PFA (perfluoroalkoxy branched polymers), Dyflor (polyvinylidene fluoride), styrenebutadiene rubber (SBR), butyl rubber (copolymer of isobutylene (97%) and isoprene (3%)), ethylene propylene rubber (EPR) including EPM (copolymers of ethylene and propylene) and EPDM (copolymers of ethylene, propylene and a non-conjugated diene such as dicyclopentadiene (DCPD), cyclooctadiene (COD), ethylidene norbornene (ENB) and 1,4-hexadiene (HD)), crosslinked polyethylene (XLPE), ethyl vinyl acetate (EVA), chloroprene rubber (CR or PCP), polyethyleneterephthalate (PET, Melinex or Mylar), chlorosulfonated polyethylene rubber (Hypalon, CSP, CSM), acrylonitrilebutadiene rubber (NBR/PVC blends), fluorocarbon rubbers such as copolymer of vinylidene fluoride and hexafluoropropylene (Viton). The National Electrical Code 1987 (National Fire Protection) [3] has established cable designations based on the types of plastics used for insulation and jacket; these designations are listed in Appendix A.

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Numerous fires have occurred in cables used as bundles or in trays, because plastics used in the cables are combustible. Cable fires can be started by any number of ignition sources such as electrical arcing, cable overheating, nearby burning material, spilled liquid pool fire, etc. After ignition, the fire will spread over the cable surfaces accompanied by the generation of heat, smoke, corrosive and toxic compounds and creation of hazardous environments. Generation of heat in cable fires is expected to create hazardous thermal environments; generation of smoke, corrosive and toxic compounds is expected to create hazardous non-thermal environments. Cable fire prevention and protection thus are one of the major concerns for Factory Mutual (FM) as well as for the general fire community.

In order to investigate the problems associated with cable fire prevention and protection, an Ad Hoc Committee on Cable Flammability was formed at FM [4]. The Committee's responsibility was to investigate the feasibility of: 1) determining conditions under which "less flammable" cables might be accepted without fire protection and 2) developing an approval criteria for "less flammable" cables. Based on the extensive review of the available information on cable fires and data from cable fire tests and cable fire research, the Ad Hoc Committee concluded that:

- 1) All power cables, including those which passed the IEEE-383 test [5], tested by the Factory Mutual Research Corporation (FMRC) ignited and propagated in a "small bench-scale pipe" test. In the test, cable samples were placed inside a pipe, to reduce heat losses.
- 2) The conductor temperature affected the flammability of the cables. Fire propagation rate increased with increase in the conductor temperature as a result of simulated and actual electrical overloading.
- 3) Differences in ignition resistance were found for cables. The size of the cable was important. Larger cables showed higher resistance to ignition with slower fire propagation than the smaller cables. The differences due to cable size, however, became less important as the temperature of the conductor was increased.
- 4) The IEEE-383 test [5] is a screening test and does not simulate actual installations in terms of cable loading, multiple cable arrangements, etc. Thus, reliance on the IEEE-383 test for establishing permanent acceptance criteria is not advisable.

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5) The existing FM Flammability Apparatus is a promising tool for developing relative flammability measurements for cables. It may be possible to correlate the flammability results to predict fire spread in various cable configurations.

Based on the conclusions, the Ad Hoc Committee recommended that FMRC should develop test criteria including correlations with large-scale tests representative of actual installations to determine if "less flammable" cables exist which can be accepted without fire protection in occupancies where combustibles other than cables are present in negligibly small amounts such as control rooms, cable spreading rooms and others.

This report describes the results and analysis of a three year study program undertaken by FMRC based on the recommendations of the FM Ad Hoc Committee on Cable Flammability. The objectives of the study was to develop test criteria for the classification of cables based on fire propagation, utilizing the FM Small-Scale (10 kW-Scale)* and Intermediate-Scale (500 kW-Scale) Flammability Apparatuses, shown in Figures 1A and 1B. The results from the small-scale tests were validated by performing the large-scale cable fire tests in the FM Large-Scale Flammability Apparatus (Fire Products Collector), shown in Figure 1C. A cable classification was developed for identifying "less flammable" cables for which protection is not required due to thermal damage.

For the study, a total of 46 cables of various types were used as listed in Table I. Thirty-six of the cables were donated by the cable industry. Most of the cables passed IEEE-383 cable tray test and the fire resistance tests specified in the National Electrical Code for the communication cables. Of the 46 cables, 52% were power cables; 31% were control cables and 17% were communication, signal and special and general purpose cables. Twenty-seven percent of the cables were small cables (diameters in the range of 0.0035 to 0.0099 m (0.14 to 0.39 in.) while 73% of the cables were larger cables (diameters in the range of 0.010 to 0.055 m (0.40 to 2.2 in.).

*The FM 10 kW-Scale Apparatus is currently being modified to 50 kW-Scale so that vertical propagation tests for cables up to 0.60 m (2 ft) length can be performed.

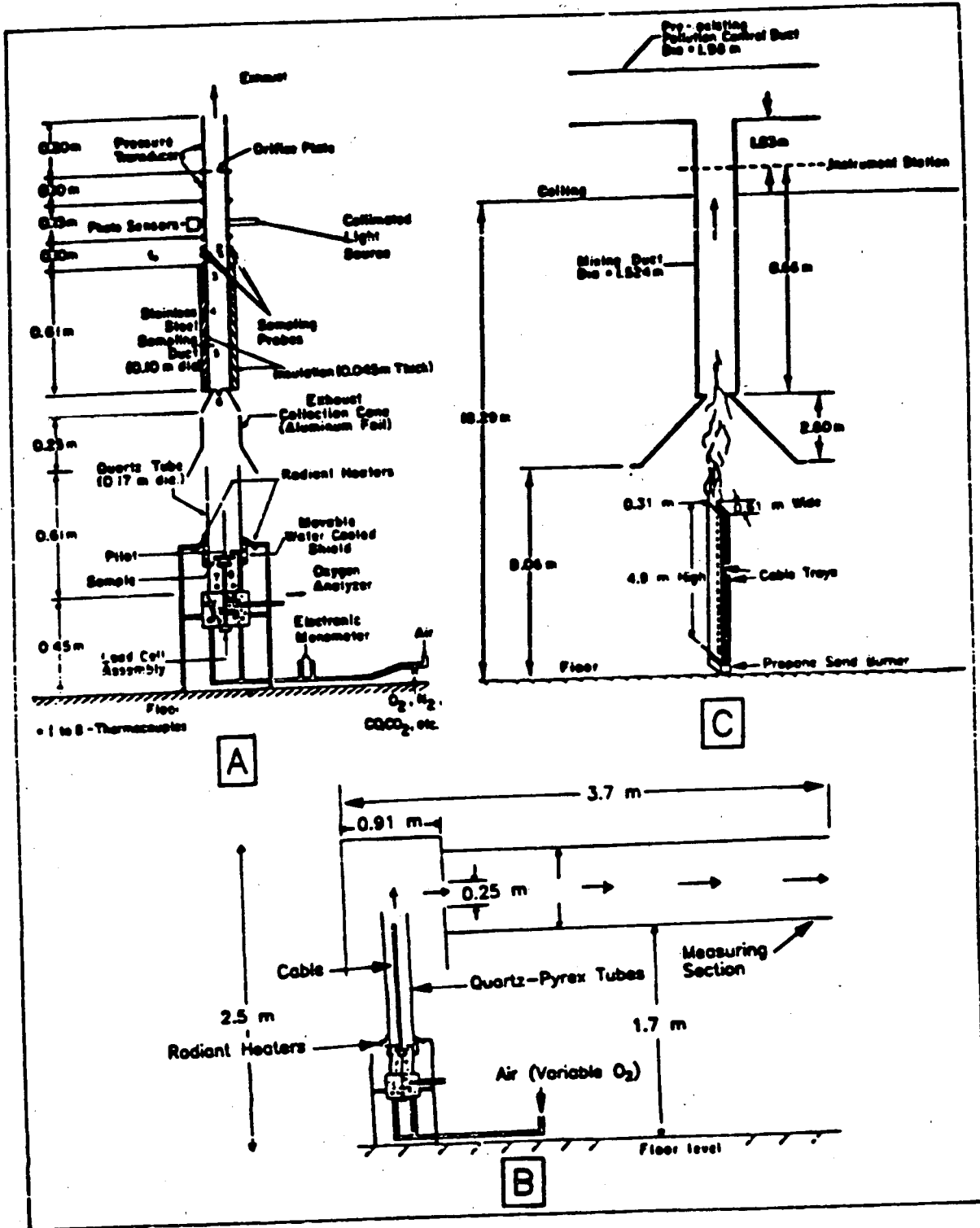


Figure 1. Flammability Apparatuses Used in the Experiments: A) 10 kW-Scale; B) 500 kW-Scale; and C) Fire Products Collector.

TABLE I
CABLE SAMPLES USED IN THE STUDY

Cable No.	Insulation/Jacket	Conductor Size	No. of Conductors	Overall Diameter (m)	Linear Density g/m		Cable Type
					Cable (incl. cond.)	Insulation/Jacket	
1	PVC/PVC	24 AWG	6 (pair)	0.0036			Vertical Tray (UL Type CM, IEEE 383)
2	PVC/PVC	24 AWG	8	0.0044			General Purpose & Riser (UL Type CMR)
3	PVC/PVC	12 AWG	3	0.0092	151.10	61.10	Power & Control (600V Type TC Tray Cable, NEMA K2, 600V)
4	PVC/PVC	12 AWG	7	0.013			
5	PE/PVC	22 AWG	4	0.0037			Control & Lighting (UL Type CMX LADSW D Station)
6	EP/PVC	12 AWG	3	0.011	201.0	110.50	Power & Control (600V, IEEE 383)
7	PVC/EP	2/0 AWG	3	0.034	2740.0	750.0	Power (600V, IEEE 383)
8	SI/PVC	16 AWG	10	0.016			Navy Ship (MIL-C-915)
9	TPE/TPE	12 AWG	3	0.0094	156.10	66.80	Power (600V, R/RK-12F-3Cu)
10	TPE/PE-Cl	12 AWG	3	0.0094	165.0	78.0	Power (600V, R/CPEK-12F-3Cu)
11	EP/EP	6 AWG	1	0.010	207.30	90.80	Power (600V)
12	EP/EP	14 AWG	5	0.016	386.0	288.50	Power (600V)
13	EP/EP	250 MCM	1	0.025	1655.0	515.0	Power (2kV)
14	XLPE/XLPE	12 AWG	3	0.0095	166.60	69.60	Control & Power 600V
15	XLPE/XLPE		10	0.0099			Power & Control PMS-400-881 (600V)
16	XLPE/XLPE		10	0.011			Power & Control PMS-400-881 (600V);
17	XLPE/XLPE	12 AWG	3	0.012	241.30	152.7	Power 600V
18	XLPE/EVA	12 AWG	3	0.012	270.0	157.20	Control & Lighting Cu Cond.; 1kV
19	XLPE/EVA	2/0 AWG	1	0.017	397.0	223.30	Power Alum. Cond.; 1kV
20	XLPE/EVA	500 MCM	1	0.022	1474.40	257.80	Power 2kV; 110C
21	XLPE/Neoprene	12 AWG	7	0.015	431.40	219.70	Control 600V; IEEE 383
22	XLPO/XLPO	12 AWG	9	0.016			Control Tray Cable; 90C
23	XLPE/XLPO	20 AWG	6 (pair)	0.022	704.80	528.60	Communication IEEE 383

TABLE 1 (Continued)

CABLE SAMPLES USED IN THE STUDY

Cable No.	Insulation/Jacket	Conductor Size	No. of Conductors	Overall Diameter (m)	Linear Density g/m		Cable Type
					Cable (incl. cond.)	Insulation/Jacket	
24	XLPE/XLPO	18 AWG	44	0.022	815.70	416.0	Power & Lighting IEEE 383
25	XLPE/XLPO	10 AWG	10 (pair)	0.023			Communication and Instrumentation; IEEE 383
26	XLPE/XLPO	12 AWG	19	0.025	1435.70	703.50	Special Purpose; IEEE 383
27	S1/XLPO	18 AWG	44	0.028	1313.60	919.50	Control; IEEE 383
28	XLPO,PVF/XLPO	20 AWG	6 (pair)	0.014	380.20	178.70	- IEEE 383
29	XLPO,PVF/XLPO	22 AWG	14 (pair)	0.017	607.70	370.70	- IEEE 383
30	S1/XLPO	400 MCM	3	0.055	9881.30	2668.0	Power & Lighting; IEEE 383
31	S1/XLPO, Metal Armor	400 MCM	3	0.055	9743.60	2533.30	Power & Lighting; IEEE 383
32	PP, Polyester/PVC	18 AWG	44	0.020			Special Purpose; IEEE 383
33	XLPE/PVC	12 AWG	3	0.011			Power & Control; 600V; Tray Cable, Type TC, IEEE 383
34	EP/PE-C1-S	14 AWG	1	0.0043	39.10	20.0	Control & Lighting; 600V; 125C
35	EP/PE-C1-S	12 AWG	3	0.011	219.50	125.0	Power 600V; IEEE 383
36	EP/PE-C1-S	2/0 AWG	1	0.016	810.0	178.50	Power 600V
37	EP/PE-C1-S	4/0 AWG	1	0.019	1212.0	236.0	Power 600V
38	EP-FR/None	14 AWG	1	0.0035			Control
39	EP-FR/None	2/0 AWG	1	0.015			Power
40	EP-FR/None	4/0 AWG	1	0.018			Power
41	EP-FR/None	14 AWG	37	0.028	1347.60	607.60	Signal
42	PE-C1/None	1/0 AWG	1	0.015	665.20	134.70	Control
43	ETFE/EA	-	10	0.010			Control
44	PVC/PVF	24 AWG	8	0.0050			Signal; C-Plenum Cable; Type CMP, UL910
45	FEP/FEP	-	50	0.0079			Signal
46	FEP/FEP	22 AWG	12	0.0097	138.0	80.40	Power Limited; Class 2-75C; NEC 725-2(b) Circuit

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II

BACKGROUND

Numerous studies have been performed on cable fires [6-27]. Several standards exist for the testing of cables. The oldest standard is the IEEE-383 test for power cables in the nuclear industry [5], while the latest one is for telecommunication cables [28]. Although the IEEE-383 test is one of most widely used tests in the power industry, it is considered to be inappropriate in describing the fire resistance of cables under all conditions in the telecommunication industry [28], which is in agreement with the conclusion of the FM Ad Hoc Cable Flammability Committee.

2.1 STANDARD TESTS SPECIFIED IN CODES

2.1.1 IEEE-383/ANSI N41.10-1975 Test

The IEEE-383-1974/ANSI N41.10-1975 test [5] is a flame test for grouped power and instrument cables to determine the relative ability of cables to resist fire. The fire test is performed to demonstrate that the cable does not propagate fire even if its outer covering and insulation have been destroyed in the area of flame impingement, i.e., there is no self-sustained fire propagation.

In the test, a 2.44 m (8 ft) long, 0.30 m (12 in.) wide and 0.076 m (3 in.) deep vertical ladder type metal tray is used. Multiple lengths of cable are attached to the metal tray in a single layer, filling at least the center 0.15 m (6 in.) portion of the tray with a separation of about 1/2 the cable diameter between each cable. A 0.25 m (10 in.) wide, 11-55 drilling, propane-air premixed ribbon gas burner is used for igniting the cable. The burner is placed 0.61 m (2 ft) from the bottom of the tray and 0.076 m (3 in.) away from the cable surface. The burner is kept parallel to the cable surface so that the propane flame impinges the cable surface at right angles. The propane and air flows (1 to 6 ratio) to the burner are adjusted to give a chemical heat release rate of 21 kW (70,000 Btu/hr) (flame temperature of about 1500°F, measured by a thermocouple located in the flame close to but not touching the cable surface). The propane flame, which covers the entire width and lengths of about 0.23 to 0.30 m (9 to 12 in.) of the cables arranged on the tray, is applied for 20 minutes and then turned off. The cable is allowed to burn itself out. The tests are performed in naturally ventilated rooms or

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enclosures free from excessive drafts and spurious air currents. Cables for which fire propagates to the top of the tray fail the test; those that burn out short of the top pass the test.

Variations on the standard test in terms of using higher intensity propane flames and locating the tray in a corner have been used by several groups. Tests have been performed with propane chemical heat release rates of 61 kW (210,000 Btu/hr) and 118 kW (400,000 Btu/hr). It is, however, not clear from the results that such modifications improve the test significantly.

2.1.2 Tests for Communication Cables

The 1987 National Electrical Code requires that communications cables meet one of the four levels of fire-resistance and are marked as being one of the four types of cables [28]: Type CM are general purpose communications cables; Type CMP are plenum communications cables; Type CMR are riser communications cables and Type CMX are ordinary communications cables restricted to a few applications. Type CMX cables must pass the Underwriters' (UL) VW-1 (Vertical-Wire) Flame Test; Type CM cables must pass the UL Vertical-Tray Flame Test, which is identical to IEEE-383 Test; Type CMR must pass the UL-1666 Riser Cable Fire Test and Type CMP must pass the UL-910 Plenum Cable Fire Test [28]. The UL-910 Plenum Cable Fire Test is performed in the ASTM E-84 Tunnel and is the most severe test for cables. The severity of the tests decreases from the UL-910 Plenum Cable Fire Test to UL-1666 Riser Cable Fire Test to UL Vertical-Tray Flame Test (IEEE-383) to UL-VW-1 Vertical Wire Flame Test. The severity of the tests is judged on the basis of the ignition sources used [28].

The UL-910 Test is performed in a 7.62 m (25 ft) long, 0.30 m (1 ft) high and 0.30 m (1 ft) wide tunnel made of fire bricks [28]. The tunnel is extended at the inlet to 1.37 m (4.5 ft) for introducing air. At the outlet end of the tunnel, a 12.2 m (40 ft) long and 0.41 m (16 in.) diameter duct is attached for exhausting the fire products. A 88 kW (300,000 Btu/hr) methane burner located 1.37 m (4.5 ft) from the tunnel inlet is used as an ignition source. The burner flame extends to a length of about 1.37 m (4.5 ft) in the tunnel. A single layer of 7.3 m (24 ft) long cables, touching each other, is placed on a 0.30 m (1 ft) wide horizontal cable tray, located 1.37 m (54 in.) from the tunnel inlet, in the center and 0.21 m (8.25 in.) from the floor. The air flow is set at 1.22 m/s (240 ft/min). In order to pass the test, in

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20 minutes, the fire propagation on the cable surface should be limited to less than 2.9 m (9.5 ft) or 39.7% of the length of the cables of which 18.8% is in the ignition zone. The maximum optical density should not exceed 0.5 or 1/3 light transmission across a path length of 0.41 m (16 in.) in the exhaust duct and a maximum average optical density of 0.15 or 70% light transmission.

The UL-1666 Riser Cable Fire Test simulates cable installation in a building's riser shaft [28]. A vertical bundle of cables about 5.18 m (17 ft) in length and 0.30 m (1 ft) in width is used. The bundle is located between two 0.61 m x 0.30 m (2 ft x 1 ft) holes, one at the floor and the other at the ceiling of a 3.66 m (12 ft) high and 2.44 m (8 ft) wide enclosure. The bottom 0.60 m (2 ft) of bundle is outside the floor and the top 0.91 m (3 ft) of the bundle extends into the second floor. A 0.30 m x 0.30 m (1 ft x 1 ft), 145 kW (495,000 Btu/hr) propane burner is used as an ignition source and is located below the hole on the floor at a height of 0.60 m (2 ft). In order to pass the test, the fire should not propagate to the top of the bundle in the first floor (3.66 m or 12 ft) in 30 minutes.

The UL Vertical-Tray Flame Test is identical to the IEEE-383 Test [28].

The UL Vertical Wire-1 Flame Test is performed using a 0.25 m (10 in.) long single vertical cable [28]. In the test, a 1 kW Tirrill burner (similar to a Bunsen burner) is used as an ignition source. The cable is exposed to the ignition source for 75 seconds in intervals of 15 seconds. A Kraft paper indicator is located 0.25 m (10 in.) above the burner and a surgical cotton is located at the base of the burner. The cable passes the test if flames do not propagate to the paper indicator, if cotton does not ignite or the cable does not burn for more than 1 minute after the five ignition flame exposures of 15 seconds duration.

Table II shows a comparison of the standard cable fire tests. In all the standard tests, the important factors that are considered include: 1) ignition source strength; 2) cable arrangement; 3) resistance to ignition; 4) extent of fire propagation and 5) air flow rate in closed systems such as the tunnel.

TECHNICAL REPORT

ELECTRICAL CABLES – EVALUATION OF FIRE PROPAGATION BEHAVIOR AND DEVELOPMENT OF SMALL-SCALE TEST PROTOCOL

By
Archibald Tewarson
and
Mohammed M. Khan

Prepared for:
Factory Mutual Research Corporation
1151 Boston Providence Turnpike
Norwood, Massachusetts 02062

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FMRC J.I. OM2E1.RC
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ABSTRACT

This report presents the results of a three year study for the development of test criteria for the classification of cables based on fire propagation for use in non-combustible constructions and occupancies, i.e., combustibles other than cables are present in negligibly small amounts.

In the study, 46 cables of various types were used. Most of the cables used in the study, passed the IEEE-383 cable tray test and the fire resistance tests specified in the 1987 National Electrical Code for communication cables. The cables were tested in the Factory Mutual Small-, Intermediate- and Large-Scale Flammability Apparatuses. Measurements were made for ignition and fire propagation (in terms of heat release rate, generation rates of smoke and other products and light obscuration). For describing the fire propagation behavior of the cables, a Fire Propagation Index (FPI) was determined from the ignition and heat generation characteristics of the cables.

Based on the FPI values and actual fire propagation behavior of cables in the small-, intermediate- and large-scale cable fire tests, cables were classified into three groups: 1) Group 1 cables (FPI values less than 10): self sustained fire propagation is not expected; 2) Group 2 cables (FPI values equal to or greater than 10 but less than 20): fire is expected to be self sustained with linear increase in the fire propagation rate and 3) Group 3 cables (FPI values equal to or greater than 20): fire is expected to be self sustained with very rapid increase in the fire propagation rate.

Of the 46 cables tested in the study, 56% were Group 1 cables, 29% were Group 2 cables and 15% were Group 3 cables. Group 1 cables were larger cables with diameters greater than 0.01 m (0.40 in.), except the highly halogenated cables.

Electrical overloading test results suggested that in the presence of electrical faults leading to cable overheating, fire propagation is expected irrespective of cable classification. Thus for all cables, irrespective of their classification, electrical protection is very important.

Factory Mutual has used the test apparatuses and procedures from this study and a specification testing standard has been proposed [41].

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SUMMARY

This report describes the results of a three year study program, undertaken by the Factory Mutual Research Corporation, based on the recommendations of the Factory Mutual Ad Hoc Committee on Cable Flammability [4]. The objective of the study was to develop test criteria for the classification of cables based on fire propagation for use in non-combustible constructions and occupancies, i.e., combustibles other than cables are present in negligibly small amounts. In the study, the Factory Mutual Flammability Apparatuses were used.

In the tests, 46 cables of various types were used; 36 of them were donated by the cable industry. Most of the cables used in the study passed the IEEE-383 cable tray test and the fire resistance tests specified in the 1987 National Electrical Code for the communication cables (Section 2.1). Of the 46 cables, 52% were power cables; 31% were control cables and 17% were communication, signal and special and general purpose cables. Twenty-seven percent of the cables were small cables (diameters in the range of 0.0035 to 0.0099 m (0.14 to 0.39 in.)), and 73% of the cables were larger cables (diameters in the range of 0.010 to 0.055 m (0.40 to 2.2 in.)) (Table I). The majority of the cable samples consisted of crosslinked polyethylene as insulation and jacketing material.

In the study, three types of tests were performed: 1) ignition tests; 2) fire propagation tests using external heat flux and sustained electrical overloading of conductors to initiate fire propagation, and 3) large-scale validation tests. Ignition tests were performed in the Factory Mutual (FM) Small-Scale (10 kW-Scale) Flammability Apparatus (Figure 1A). Fire propagation tests were performed in the FM Intermediate (500 kW-Scale) Flammability Apparatus (Figure 1B). Validation tests were performed in the FM Large-Scale Flammability Apparatus, called the Fire Products Collector (Figure 1C).

For ignition tests, a single, 0.13 m (5 in.) long horizontal cable sample was selected (Figure 2). In the tests, 0.013 m (0.50 in.) of both ends of the cable sample were tightly covered with heavy duty aluminum foil. The surface of non-black cables was painted flat black. In the tests, time to piloted ignition of cable vapor air mixture was measured at various external heat flux values. Ignition data were used to calculate the critical heat flux and

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thermal response parameter of the cables (Table III). Critical heat flux is the minimum heat flux at or below which ignition is not expected to occur. Thermal response parameter is the property of the cable which governs the time delay for ignition when the cable is exposed to heat flux. Thermal response parameter is one of the important parameters which governs the fire propagation characteristics of the cable.

For the fire propagation tests in the 500 kW-scale apparatus, a single 0.61 m (2 ft) long vertical cable sample was selected. The sample was surrounded by an airtight, 0.25 m (10 in.) diameter and 0.61 m (2 ft) long glass tube attached to an aluminum tube of the same dimensions (Figure 13). The bottom 0.20 m (8 in.) of the cable was exposed to an external heat flux of 50 kW/m². A pilot flame was provided near the surface to ignite the cable vapors generated as a result of the heat flux exposure. For the simulation of large-scale flame radiation conditions, air with an oxygen concentration of 40%, flowing at a rate of 0.005 m³/s (11 cfm), was used. In the propagation tests, measurements were made for the generation rates of carbon dioxide (CO₂) and carbon monoxide (CO) to calculate the chemical heat release rate. Measurements were also made for the generation rates of total gaseous hydrocarbons and smoke, and depletion rate of oxygen and light obscuration.

The test data for thermal response parameter from the ignition tests and the chemical heat release rate determined from the fire propagation tests were used to describe the cable fire propagation characteristics in terms of a Fire Propagation Index (FPI):

$$FPI = \left(\frac{0.40 \times \text{Chemical Heat Release Rate}}{\pi \times \text{Number of Cables} \times \text{Cable Diameter}} \right)^{1/3} \times 1000 / \text{Thermal Response Parameter},$$

where chemical heat release rate is in kW; cable diameter is in meter and thermal response parameter is in kW^{1/2}/m².

Based on the FPI values, cables were classified into three groups:

1) Group 1: Cables with FPI values less than 10 belong to this group. The cables in Group 1 are not expected to have self-sustained fires. Thus in the absence of extended external heat sources and with adequate electrical protection to prevent sustained overloading and arcing, Group 1 cables are not expected to require protection (such as sprinklers) due to thermal damage

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threat (heat damage). Depending on the cable insulation and jacketing materials and additives, damage due to smoke, corrosive and toxic compounds (non-thermal damage) is possible. It may be possible to classify cables into two subgroups, i.e., 1) Group A cables: non-thermal damage (damage due to smoke, toxic and corrosive compounds) is expected to be negligibly small and 2) Group B cables: non-thermal damage (damage due to smoke, toxic and corrosive compounds) is expected.

Of the 46 cables tested in the study, 56% were Group 1 cables. These cables were larger cables (diameters greater than 0.01 m (0.40 in.), with the exception of highly halogenated cables).

Group 1 cables can be called "less flammable" cables; this classification thus satisfies the program objective.

2) Group 2: Cables with FPI values equal to or greater than 10 but less than 20 belong to this Group. Fires are expected to be self-sustained and fire growth rates are expected to increase linearly. For Group 2 cables, fire protection would be required.

Of the 46 cables tested in the study, 29% were Group 2 cables.

3) Group 3: Cables with FPI values equal to or greater than 20 belong to this group. Fires are expected to be self-sustained, and the fire propagation rates are expected to increase very rapidly. Fire protection would be required.

Of the 46 cables tested in the study, 15% were Group 3 cables.

The data from this study suggest that thermal response parameter and chemical heat release rate are the two most important factors governing the fire propagation behavior of cables. Figure S1 shows a plot of Fire Propagation Index versus cable thermal response for the three groups of cables. For Group 1 cables, thermal response parameter is greater than about $260 \text{ kW s}^{1/2}/\text{m}^2$, and above about $350 \text{ kW s}^{1/2}/\text{m}^2$, there is no overlap with Group 2 cables. In cases where there are overlaps between thermal response parameter values, the cable classification is governed by the differences in the chemical heat release rates. Cables with insulation and jacketing materials with additives with low heat release rates and high thermal response parameters are expected to belong to lower groups. For the same insulation and jacketing materials and additives, as the cable size is increased, thermal response parameter will increase, changing their classification towards lower groups.

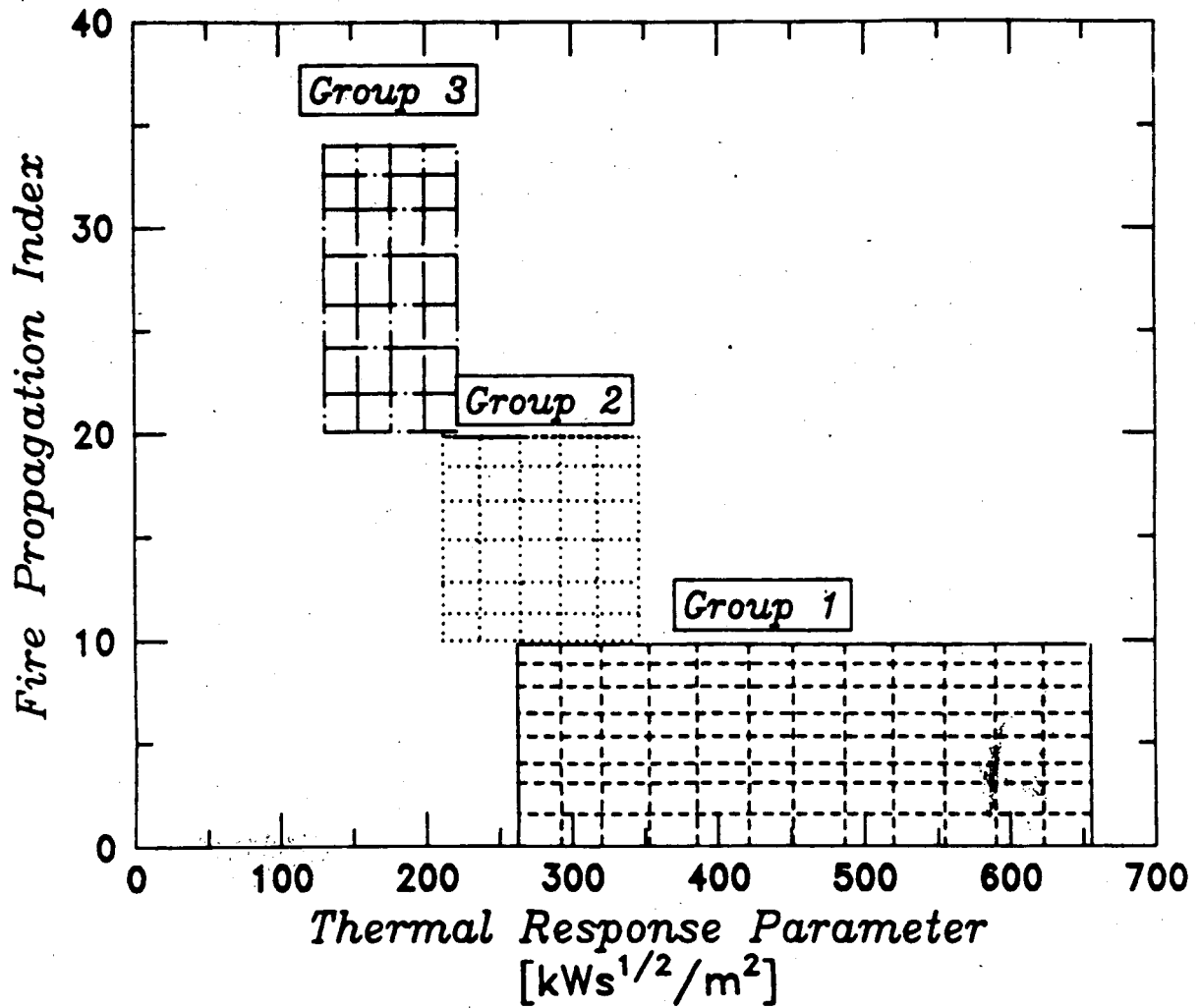


Figure S1. Fire Propagation Index Versus Thermal Response Parameter.

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For the large-scale validation tests in the FM Fire Products Collector, two 4.9 m (16 ft) long and 0.61 m (2 ft) wide vertical sheets of Marinite separated by about 0.30 m (1 ft) were used. A single layer of 5.2 m (17 ft) long cable samples touching each other was attached to both Marinite sheets with cable layers facing each other. For ignition, a 61 kW (210,000 Btu/hr) propane air sand burner with a flame height of about 0.60 m (2 ft) was used. The burner was placed at the bottom between the two sheets. Chemical heat release rate was determined from the generation rates of carbon monoxide and carbon dioxide, very similar to the procedures used in the fire propagation tests in the FM Intermediate-Scale (500 kW-Scale) Flammability Apparatus. FPI values were determined in the large-scale cable fires using chemical heat release rate from the tests and the thermal response parameter from the ignition tests (Table III).

In the tests, one Group 3 cable and four Group 1 cables were used. The cable classification based on the Fire Propagation Index determined from the large-scale cable fire tests was in agreement with the classification based on the Fire Propagation Index determined from the fire propagation tests in the FM Intermediate-Scale (500 kW-Scale) Flammability Apparatus (Figures 27 to 31).

In the sustained electrical overloading tests, single vertical, 1.37 m (4.5 ft) long cable was used in the FM Intermediate-Scale (500 kW-Scale) Flammability Apparatus. Six power cables of various sizes were tested. Time to cable vapor formation, surface and conductor temperatures at various load currents were measured (Table V and Figure 32). Once the cable was heated to the critical heat flux conditions for ignition (Figure 35), the cable vapors could be ignited by a small butane flame, resulting in instantaneous fire propagation throughout the cable surface. The sustained electrical overloading test data suggested that in the presence of electrical faults leading to cable overheating, fire propagation is expected irrespective of cable classification. Thus the power cables, irrespective of their classification, should be provided with adequate electrical protection.

An examination of the cable classification based on the Fire Propagation Index and their performance in the IEEE-383 test (Section 2.1.1) showed numerous inconsistencies (Section 3.6) in cable classification based on the IEEE-383 test. Inconsistencies were also found (Section 3.6) in the cable classifications based on the standard tests for the communication cables specified in the National Electrical Code (Section 2.1.2). A highly

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halogenated cable, which passes the UL 910 test (CMP cable) is classified as Group 1 cable based on its Fire Propagation Index. Three other communication cables were also tested, all of which were classified as Group 3 cables based on their Fire Propagation Index; however, one of the cables was a CMR cable (passes the UL 1666 Riser Cable Fire Test), another was a CM cable (passes the UL Vertical Tray Flame Test, same as the IEEE-383 test), and the last one was a CMX cable (passes the UL VW-1 Flame Test).

The results of this study show that cables can be classified in the Factory Mutual Flammability Apparatuses. Factory Mutual has used the test apparatuses and procedures from this study, and a specification testing standard has been proposed [41].