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Clean Agent Suppression of Energized Electrical Equipment Fires

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Abstract. The NFPA 2001 standard on the use of clean agents for the suppression of fires arose from the phase-out of Halon 1301. Standard methods exists for specifying the amount of clean agent required for Class A and Class B fires, but the recommendation for Class C fires (those involving energized electrical equipment) defaults to the Class A values. While this may be appropriate for some Class C fires, there is concern that higher agent concentration may be necessary if energy is added to the fire by the electrical source. A number of test methods have been proposed to determine the amount of agent required to suppress fires in energized electrical equipment; however, there has been no broad agreement on a test method to include in NFPA 2001 for Class C fires. Further, some of the test methods suggest that the current recommended total flooding concentration is sufficient, while others suggest that higher concentrations may be necessary for some fires. This report reviews the role of energy augmentation in the suppression of fires over condensed phase materials. A test protocol is suggested which can quantify the effects of added energy on the suppression process.

Keywords: Class C fires, Halon replacements, Fire suppression, Clean agents

Abbreviations

NFPA	National Fire Protection Association
EHF	The external heat flux
DPC	Data processing center
TCO	Telecom central office
NEBS	Network Equipment Buildings Standard
PC	Polycarbonate
PVC	Polyvinylchloride
LOI	Limiting Oxygen Index
MEC	Minimum extinguishing concentration
ANSI	American National Standards Institute
UL	Underwriters Laboratories
NIST	National Institute of Standards and Technology
FTIR	Fourier transform infrared
EAC	Energy-augmented combustion
PWB	Printed wiring board
REED	Radiantly Enhanced Extinguishing Device
EVA	Extra-terrestrial Vehicle Activity

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WSTF White Sands Test Facility
NASA National Aeronautics and Space Administration

1. Introduction

The suppression of fires by clean agents (those that leave no residue and are not electrically conductive) is covered by the National Fire Protection Association (NFPA) Standard on Clean Agent Fire Suppression Systems, NFPA 2001 [1]. This standard was developed in response to the phase-out of the effective and widely used agent Halon 1301. Fires are typically classified as Class A, B, C, D, or K, and NFPA 2001 describes test procedures to be used in determining the design extinguishing concentration of the agents based on the fire class. For Class A fires, a testing procedure is required which meets, at the minimum, the procedures in UL 2127[1] (for inert agents) or UL 2166 (for clean agents, typically hydrofluorocarbon, HFC; or hydrochlorofluorocarbon, HCFC agents). The minimum design concentration of the agent is that determined in the UL test times a safety factor of 1.2 for automatically actuated systems and 1.3 for systems that are actuated by manual means only. For Class B fires, the cup burner test is specified, and the minimum design concentration is the cup burner value times a safety factor of 1.3 (Class D fires are not covered, and Class K is a subset of Class B). Fires involving energized electrical equipment (Class C) are covered in Section 5.4.2.5 of NFPA 2001, which states:

> Minimum design concentration for Class C hazards shall be at least that for Class A surface fire.

While it is desired to remove the power from the electrical equipment prior to fire suppression, that decision can be at the discretion of the equipment owner, taking into consideration (1) ancillary loss of life due to the shutdown, (2) fire threat to occupants or property, (3) economic loss due to loss of function, and (4) economic loss due to facility damage. Hence, there are cases where fire suppression systems will be designed under the assumption that energized electrical equipment will be present. Unfortunately, there exists no standard test method for the amount of agent necessary to suppress fires in cases where the combustion may be augmented due the addition of energy from an electrical source.

The problem of fire protection in electrically energized environments has been discussed in review articles [2, 3], and several test methods have been used to simulate the effects of energized electrical equipment. These include tests which strive to suppress a flame over a realistic electrical failure event, with representative polymeric materials [4–7], and those that attempt to control the salient parameter

[1]A portion of this work was carried out by the National Institute of Standards and Technology (NIST), an agency of the U. S. government and by statute is not subject to copyright in the United States. Certain commercial equipment, instruments, materials or companies are identified in this paper in order to adequately specify the experimental procedure. This in no way implies endorsement or recommendation by NIST. The policy of NIST is to use metric units of measurement in all its publications, and to provide statements of uncertainty for all original measurements. In this document, however, data from organizations outside NIST are shown, which may include measurements in non-metric units or measurements without uncertainty statements.

(the external heat flux, EHF) [8–11]. In general, the test results have shown that higher agent concentration is required to extinguish flames in the presence of energy input from the different sources [8–13], while the results in refs. [4–7] indicated that a typical design concentration of 7% (by volume) for HFC-227 in Class A fires was sufficient to extinguish their test cases (although modification of one of the tests and the extinguishment criterion in Ref. [5] implied a higher agent concentration for suppression [14, 15]). Despite the extensive work, no generally accepted test procedure has emerged, and no consensus exists as to the relationship between any of the test methods and the actual fire threats.

The two objectives of the present work are: (1) to define typical fire hazards for applications involving energized electrical equipment (Class C fires) that normally are protected by clean agent fire extinguishing systems, and (2) to develop and suggest a test protocol that can provide scientifically justified minimum extinguishing concentrations of clean agents required to protect typical energized electrical equipment.

The first step in this work was to assemble information and input from the technical panel members and corporate sponsor representatives of the NFPA Fire Protection Research Foundation Project on Clean Agent Suppression of Energized Electrical Equipment. Following that, the literature dealing with suppression of burning polymers was reviewed. Topics included fire suppression, material flammability, suppression of flames over condensed-phase materials, and finally, the effect of energy addition on the suppression of flames over materials. The focus of the reviews was information essential to interpretation of both the actual suppression of fires in energized electrical equipment and any test designed to mimic the fire suppression. Based on the information provided by the technical panel (and the sources which they recommended) we attempted to define the threat to be controlled by the clean agent systems. With those threats in mind, the existing tests and data were reviewed extensively. Many of the tests proposed were based on the principle of replicating, in the laboratory, the actual threats expected in the field. Hence, they could serve as useful test cases for which more detailed analysis could be performed. From the interpretation of the phenomena occurring in the test methods, more insight could be gained concerning the phenomena as well as the tests. Using the analyses of the test methods and their results, we generate a list of desirable properties in a standard test, and then recommend a test method based on that list. Finally, we recommend further research which would help to better define the threat, which would allow a better specification of the test method.

2. Results

2.1. Input from Industry Technical Experts

To define the threat to be suppressed by clean agents in electrically energized equipment fires, we gathered input from experts who comprise the technical panel and the sponsors for the Fire Protection Research Foundation project on Clean Agent Suppression of Energized Electrical Equipment. The goal was to elicit from them critical applications, equipment types, fire threats, potential clean agent applications, agent discharges, and reported incidences, or names of contacts who may have such information. Phone interviews were conducted with all but one of the technical panel, and experts from all but two from the sponsor organizations, as well as several individuals who are world-renowned experts in the fields of materials flammability and ignition. The conversations were very informative and notes from the phone conversations (nineteen in all) are listed in the final report for that project (Ref. [16]).

2.1.1. Results of Phone Survey of Project Technical Panel and Sponsors. The phone interviews provided excellent background to the problem. The responders represented national or international experts on the topic, with a wealth of practical information. Several of the respondents gave detailed accounts of some fires, and FM Global provided written descriptions of three case histories, which are outlined below and provided in full in Ref. [16]. Their responses are organized below with regard to specific topics.

<u>Need for Addressing Effects of Energy Augmentation on Fire Suppression.</u> Some of the respondents felt that there is no problem, and that the topic was really a non-issue, while others felt that a major fire in a data processing center (DPC) or telecom central office (TCO) is a disaster waiting to happen—that it's inevitable. The former respondents cited the small number of fires in telecom and data processing which have occurred so far, and the highly successful fire prevention rate. The latter felt that the good record so far was due largely to the success of the Network Equipment Buildings Systems (NEBS) used in telecom. They believed that the new buildings housing telecommunications and data processing equipment are much more varied, do not follow a single standard as stringent as NEBS, and hence are more vulnerable than such buildings have been in the past.

Most of the respondents in between these two extreme views felt that there probably are differences in behavior when suppressing electrically energized equipment fires, and that it's best to do the right thing and try to understand them, and incorporate that understanding into a test. That is, there probably are some types of electrically energized equipment fires that will not be extinguished by minimum extinguishing concentrations determined by the current NFPA 2001 tests, and it would be good to understand what those fire types are.

Three of the respondents had a similar view: that the problem was ill-defined. Electrical ignition sources are just that: ignition sources. After the ignition occurs, there is little energy addition from the ignition source, and the fire moves on to another location. Two of these three, however, felt that the nature of some electrical ignitions is such that they create a much larger initial ignition site. Since the fire is much larger from the outset, the usual arguments about radiant heating from adjacent flames applies, and one has to test for the material burning and suppression with added radiant heat loads typical of larger fires.

Everyone who mentioned it agreed that in electrically energized equipment fires, if the power is left on, there is a likely possibility of re-light after the suppressant concentration decays. There was always a general acceptance that if energy is added to the system, the quantity of agent required is higher. Several respondents noted that there was no situation in their facilities in which a clean agent would be released into an electrically energized equipment fire.

<u>Need for Better Information on Actual Fire Threats to be Suppressed by Clean Agents.</u> Nearly everyone, except some of those who felt that it was a non-issue, felt that there was a need for better information on what the fire threats actually are.

<u>Likelihood of Power-Down with a Fire.</u> Of the respondents who discussed it, there was almost unanimous feeling that in telecommunications central offices or data processing centers, everyone is trained to avoid shutdown, and it was very unlikely that employees would shut down the facility in the event of a fire. The sentiment was that intentional shut down would only occur if there were no other choice—or perhaps even never at all. On the other hand, some said that while shut down was very unlikely, their *policy* was to shut down before releasing agent.

<u>Value of Central Power-Down Switch or Procedure.</u> Many felt that in the event of a localized fire, the problem of de-powering would be much easier if there were a single-point shutdown switch, or at least a well-specified shutdown procedure. But many also felt that a single-point shutdown was either not practical (the systems were too complicated), or that such a switch made system failure more likely (due to mistakes, single-point failure, or sabotage). The need for better procedures and training for shut down were generally agreed upon by those discussing it.

<u>Relevant Size of Electrical Sources of Energy, Power Levels to Consider.</u> Nearly everyone felt that the problem was very broad, with a very large range of electrical energy input possible. Nearly everyone also felt that the problem could be limited to telecommunications central offices and data processing centers, since those represented 80% to 95% of the clean agent system installations in the field. There was a general agreement from most that, even in these situations, power cables should be treated differently from data cables. Several respondents noted that power cables are sometimes un-fused, and the over-current devices can fail, so in some systems the power can be limited only by the cable size (typically oversized to limit voltage drop), and the current capacity of the battery back-up system. Hence, power levels of up to 4000 kW are possible. On the other hand, for data lines, power will be limited to a few hundred watts. A few respondents felt that the power going into a cabinet (typically 1500 W) was the limiting power, and this should be one category (separate from power cables). One respondent suggested that the power level of the ignition fire in the NEBS rack-level test (average value of 2.5 kW, peak 5 kW) was an appropriate level of power to consider. Many respondents felt that for energy input above a certain amount, clean agents (at the levels at which they are typically added) won't put out the fire, so that feature should be brought out and made clear in the literature.

<u>Risks in New Datacenters as Compared to Telecom Central Offices Following NEBS.</u> Everyone agreed that NEBS has been a great success, and that facilities

following NEBS are safe with respect to fire risk. Most felt that there was a need for a replacement for NEBS for the new applications (i.e., data centers), and that currently the standards being followed are not as good, and certainly not as uniformly followed as were NEBS. Respondents felt that movement towards a new standard was a good thing. Several felt that the success of NEBS has created some complacency: that the low level of fires is due to the success of NEBS, but with changes due to rapid innovation in Information Technology systems, things are not as safe as NEBS, but there needs to be the same level of commitment to stringent standard to insure continued success. One respondent felt that there are good standards for data processing centers that can be followed, and that some owners are following them.

Risks from Contracted Work. Several of the respondents felt that the more common use of sub-contractors to do work in DPC and TCO sites leads to more variability and greater risk of mistakes and accidents. They felt that the contractors often use lower standards for their training, procedures, workmanship, and materials, and that these are not as tightly controlled as had been the case with the old Bell system. One respondent disagreed, and felt that some of the larger data processing centers are very careful with regard to fire safety procedures in their data processing centers.

Approaches for Specifying a Test Method. Most of the respondents felt that the problem had to be broken down into different categories of fire threats, based on energy input. A few felt that it was still difficult to make it tractable (because of the wide range of conditions), and so picking a few specific examples (or even just one example) to start with, and studying that, would be the best way to move forward. Others contended that the problem is still too widely defined, so it's best to just design a test for which the externally input energy to the burning material is an independent variable, find the sensitivity of the suppression process for a given material to the energy input, and then let the system designers (or Fire Protection Engineers) decide on what electrical systems they can protect with what amounts of suppressant.

Clean Agent Effectiveness in High-Energy Electrically-Energized Fires. Four respondents felt that energized high-energy cable fires should not be suppressed with clean agents, and one more thought the same for "large enough fires."

2.1.2. Case Studies Supplied by Factory Mutual. FM Global graciously supplied three detailed case studies of fire incidents from their experiences. In the first case study (2006), workers from a sub-contractor were installing a sixth static switch (adding to the five already present). As they were pulling cables under a raised floor, they heard a series of loud noises (described as "three explosions in sequence") coming from one of the five existing static switches in the data processing room. Apparently, wiring inside one of the five existing static power switches overheated and caught fire in an electrical cabinet, setting off smoke alarms. The automatic Halon 1301 system had been turned to manual operation mode prior to the start of work (to prevent a false-alarm release). The system design was for automatic emergency power off in the event of halon release, which did not happen here. Heavy smoke was developing from within the switch's metal enclosure, so employees proceeded to the Medium Voltage room below, and manually tripped the breaker feeding power to the affected room. Employees then opened the cabinet and manually discharged CO_2 extinguishers into the cabinet. Later, the public fire department arrived and fully extinguished the fire, and started ventilating the room. Upon inspection, the fire's thermal damage was found to have occurred in a 10 cm length of a group of plastic-insulated cables inside the metal cabinet's enclosure. The source or cause of ignition was not determined.

The second case history (1997) involved an electrical equipment cabinet (3 m long, 3 m high, and 1 m deep) with three bays. The central bay has AC-DC power conditioning equipment, with 208 V 3-phase power input, and 12 V, 290 A, 5 V, 500 A output. End bays are data storage bays, and power is delivered around the perimeter of each bay on four buses. Each of the end bays contains eight rows of four disk drives per row. Each hard drive is connected to a mid-plane, extending the width of the bay. The hard drives are encased in plastic, and the data storage bays contain polycarbonate (PC), fire retarded PC, and polyvinylchloride (PVC). The three bays are separated by metal sheet, and each bay is ventilated by exhaust fans in the top. The room smoke alarm activated, and the fire department arrived but could not find the fire because of thick black smoke. At about 22 min elapsed time, the emergency power off switch was activated, and at 24 min, the fire department found and extinguished the fire using several 4 kg portable Halon 1211 extinguishers. Inspection revealed that an area 15 cm $\times$ 15 cm on the bay mid-plane (presumably plastic) was consumed, and the plastic casing on ten of the hard drives was partially or totally consumed. Copper wiring was found intact, and no melted copper wiring was found. The failure leading to ignition was not reported.

The third case history (1993) involved an automatic voltage regulator in a data processing center. The involved area, the 170 m^2 (1800 ft^2) VAX room, contained four VAX 8000 series computers, and 35 RA series disk drive units, other CPUs and modem units. A fire alarm activated three of the four present automatic Halon 1301 systems, and twelve 64.5 kg (142 lb) halon cylinders were released, one in the VAX room ambient, one in the VAX room under-floor, and one in the larger electronic data processing center space, 400 m^2 (4300 ft^2) surrounding the VAX room. Firemen saw that the halon system had activated and saw no flames, so they entered the VAX room. They noted that the fire had occurred in the automatic voltage regulator on a perimetral wall of the VAX room, that the room had been completely electrically de-energized (part of the system design), and that the halon had completely extinguished the fire. According to the FM Global investigators, the voltage regulator (45 kV and 380 V) could have caught fire because of an overheating automatic regulation rheostat. The fire could have propagated from the voltage regulator, through the under-floor cables to the other VAX equipment, as evidenced by the partially burned cables which fortunately were extinguished by the halon.

Table 1
Summary of FM Global Case Studies

Case	Voltage	Material burned	Power-down prior to agent release	Agent (manual/ auto release)	Fire extinguished
1	380 V AC	10 cm of plastic cable insulation "10 cm of grouped low-current, plastic-insulated cables inside the metal cabinet's enclosure"	Yes	CO_2 (Manual)	Yes
2	12 V/ 5 V DC	10 plastic hard drive cases, 225 cm^2 area of PC, FR-PC, or PVC in the cabinet bay (unclear which material)	Yes	Halon 1211 (Manual)	Yes
3	45 kV/ 380 V AC	Voltage regulator, cables	Yes	Halon 1301 (Auto)	Yes

Table 1 summarizes the FM Global case studies. Voltage supplied to the involved equipment varied from 5 kV to 45 kV. In all of these cases, the power was shut down before release of the agent. The agent (CO_2, Halon 1211, or Halon 1301), successfully extinguished the fire. In the third case, the specific component which failed is clearly implicated, in others, the cause is unknown.

One cannot extract any information about the effect of electrically energized equipment in the fires (there was not any), but we can look at the effects of flame interaction. In both Case Studies 1 and 2, it does seem that there was interaction between multiple burning surfaces. Hence, in these examples the suggestion of Respondent 18 is validated: in electrical fires, the initial area of involvement can be bigger initially, so one must consider the classic arguments about including radiant augmentation when assessing material flammability (or suppression of flames on materials).

These case studies provide probably about as much detail as one might hope to get about a fire incident, unless one is involved in an actual forensic investigation, or has unique access to the documents or people involved. Yet it is difficult to use any of the information here to come up with a test method which considers the effect of keeping the system electrically energized while suppressing the fire. For all of these fires, the electrical service was shut off before suppression. In two of the three, there are no details of the failure mechanism itself, let alone estimation of the power levels involved in the failure and the duration of their involvement (which is the information need to design a test procedure which includes the effects of energy-augmented combustion). This is not a criticism of the case studies; we are very fortunate and indebted to FM Global for providing these materials. Rather, to provide the level of detail of information which we need for our task, the investigators at the site probably have to go into their investigation intending to extract information specifically about the topics listed in Table 2.

Given the difficulty in even determining the source of the fire, one would be very lucky to get this detailed information from an incident report. Nonetheless,

Table 2
Useful Questions for Forensic Fire Investigators to Keep in Mind to When Gathering Information Useful for Understanding Suppression of Electrically Energized Equipment Fires

1. What power level was involved?
2. For what time period was it involved?
3. Was there any electrical involvement just an ignition source, or did it add energy to the burning material, before, during or after the ignition?
4. Did the energy-augmentation continue during suppression?
5. What was the configuration of the electrical energy release?

with material and configuration data, it might be possible to estimate the amount of heat feedback from the electrical source to the area of burning material.

One approach to getting more detailed information in future studies would be to identify someone who has done a lot of forensic studies of electrically-induced ignitions in data processing or telecommunications equipment. If asked to keep in mind the questions of Table 2, they would probably be a good source of information in the future.

2.2. Literature Review

The areas of material flammability and flame suppression are too big to review here, but some background is provided in areas which are important for the suppression of electrically energized equipment fires.

2.2.1. Materials Flammability. The burning of solid materials in a fire is a complex and well-studied phenomena, yet simple descriptions are available in the literature [17–19]. A description based on heat balance at the surface is illustrated in Figure 1. Heat input comes from convection and radiation from the hot flame over the polymer, as well as from any external source. These external sources include radiation from adjacent flames, hot upper layers, arc discharges, or radiant heaters, as well as conduction from hot surfaces (e.g., overheated wires, resistive heaters) or from adjacent hot gases. Heat losses from the system include reflection of incoming radiation, re-radiation of the hot polymer surface, and conductive losses into the interior of the polymer. The heat conducted into the interior of the polymer is a loss (for short times) since the energy may not yet be contributing substantially to the mass loss; at larger times, that energy comes back out, as the material burning at later times is essentially preheated.

If the heat gains and losses are summed into a net heat input to the polymer q_{net}'', the mass loss rate at the surface can be described by:

$$\dot{m}'' = \frac{q''_{net}}{L_v}, \tag{1}$$

in which $\dot{m}''$is the mass loss rate per unit area, q_{net}'' is the heat input per unit area, and L_v is the latent heat of phase change/decomposition. The net heat input q_{net}'' is defined by:

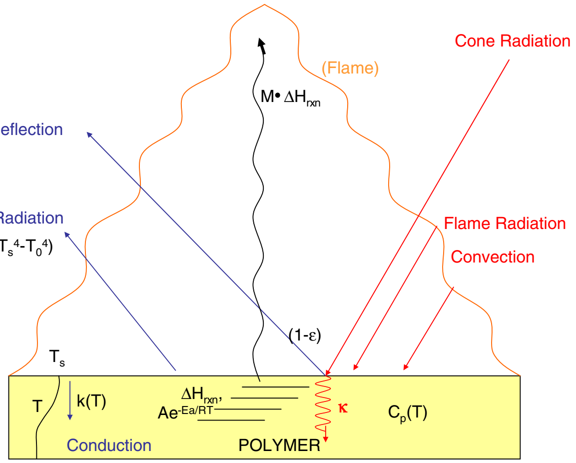

Figure 1. Heat flows at the surface of a burning thermoplastic polymer, with some of the processes in the condensed phase illustrated also.

$$q''_{\text{net}} = q''_{\text{f,,rad}} + q''_{\text{f,conv}} + q''_{\text{external}} - q''_{\text{re-rad}} - q''_{\text{poly,conv}} - q''_{\text{poly,cond}},$$

in which $q_{\text{f,,rad}}$'' and $q_{\text{f,conv}}$'' are the radiation and convection heat transfer from the flame to the polymer, and q_{external}'' is the externally applied radiation. The re-radiation heat losses from the polymer to the ambient is given by $q_{\text{re-rad}}$'' which is equal to $\varepsilon\sigma(T^4_{\text{pol,surf}} - T^4_{\text{amb}})$; $q_{\text{poly,conv}}$'' is the convective heat losses from the polymer surface to the ambient, and $q_{\text{poly,cond}}$'' is the heat loss into the polymer by conduction.

An illustration of the effects of different heat input rates on the burning of a polymer [20] is shown in Figure 2, where a 25.4 mm thick slab (1-D) of polymethylmethacrylate (PMMA) is subjected to external heat fluxes of 10 kW/m^2 to 70 kW/m^2; Figure 3 shows the same data for earlier times. As Figure 2 shows, samples subjected to higher fluxes have a higher average mass loss rate, and a shorter burning time. The shape of the curves is also different. At 20 kW/m^2, the mass loss rate barely reaches a steady state, and at 70 kW/m^2, the peak mass loss rate at the end of the burning period is very high. These effects are caused by conduction into the polymer. The transient in the beginning is caused by conductive *losses* into the polymer, while the peak at the end results from heat *gains* as the heat previously conducted into the polymer has raised its temperature (effectively preheating the polymer), so that it has a higher burning rate.

The differences in the mass loss rates at early times as shown in Figure 3 result from two causes. The conductive heat losses (around 4 kW/m^2) are a bigger fraction of the total heat input for the low flux cases, so the energy left to cause mass loss is much smaller. Also, the mass loss itself causes regression of the polymer surface, which affects development of the temperature profile. That is, there is a thermal wave propagating into the polymer, as well as a surface regression rate, which are

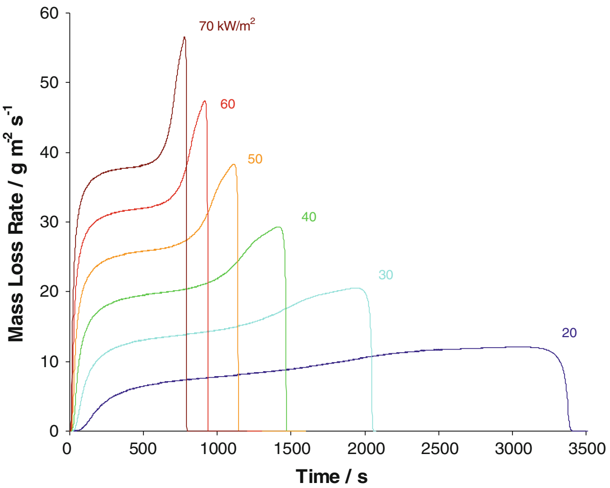

Figure 2. Calculated mass loss rate of 25.4 mm thick PMMA as a function of time for incident external flux rates of (10, 20, 30, 40, 50, 60, and 70) kW/m^2.

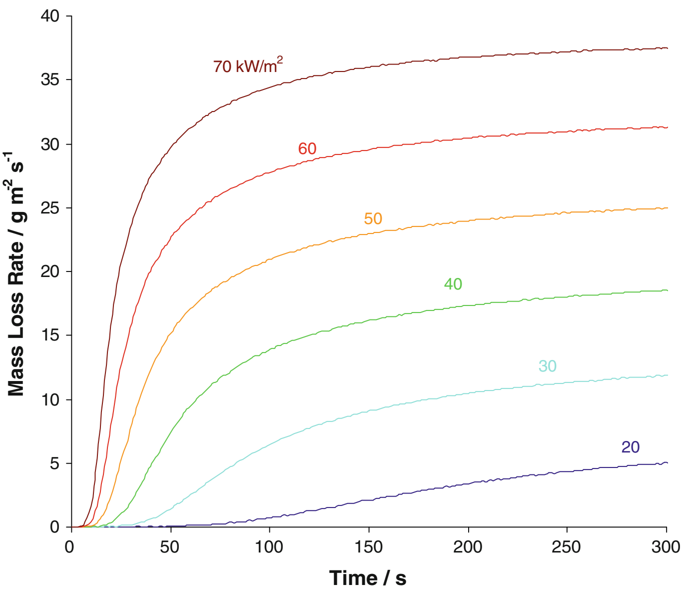

Figure 3. Same data in Figure 2 but at shorter times.

inter-related. The temperature profiles as a function of time are shown in Figures 4 and 5, for 20 kW/m^2 and 70 kW/m^2 external heat input. In Figure 5, the cluster of overlapping temperature profiles near $t = 400$ s corresponds to the steady burning

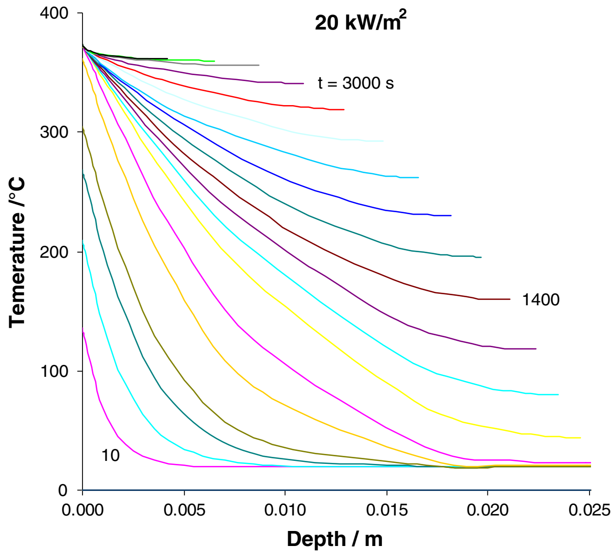

Figure 4. 1-D temperature profile through PMMA slab (initially 25.4 mm thick) as a function of time (indicated on curves), at incident flux or 20 kW/m^2.

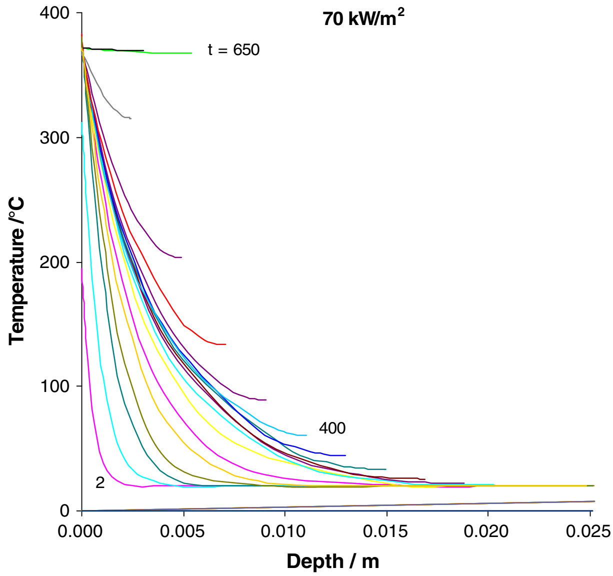

Figure 5. 1-D temperature profile through PMMA slab (initially 25.4 mm thick) as a function of time (indicated on curves), at incident flux or 70 kW/m^2.

period (200 s to 500 s in the 70 kW/m^2 curve of Figure 2). As Figures 4 and 5 show, the temperature profiles reach a steady state much faster in the high flux case. This is not because the energy is conducted in faster (the surface temperature is about the same in both cases and the thermal diffusivity is about the same); but, rather, the surface is swept away more rapidly in the high-flux case, allowing a steady-state temperature profile to develop, which is present until the thermal wave reaches the back side of the sample and the entire remainder of the sample heats to the decomposition temperature. The significance of these results for the case of energy-augmented combustion is two-fold. First, at low flux (i.e., at early stages of burning when the heat feedback from the flame is small), the mass loss rate is very sensitive to any additional heat input since the conduction losses (as well as re-radiation losses) are a large fraction of the net heat (which may not even be greater than zero). Hence, additional heat from a radiative source or an electrical short will have a big effect. Second, if suppression tests are performed on a solid sample, the net energy flow into the polymer is affected by the heat losses, and these in turn are influenced by: preheating from the flame, preheating from any external energy source, thickness of the sample, and time for initiation of the suppressant flow. Hence, these influences must be carefully considered in the test procedure. Of course, these effects are magnified geometrically since a burning solid sample is a positive feedback system: heat feedback increases the mass flow of fuel, which makes the flame bigger, which increases the heat feedback.

2.2.2. *Fire Suppression.*

Unified View of Fire Suppression. Simple models of flammability (and hence suppression of fires) were based on the fire triangle: fuel, oxidizer, and heat are needed to maintain a flame [21]. Upon development of the brominated fire suppressants, this was extended to be the fire tetrahedron, in which chain reaction (i.e., robust concentrations of chain-branching radicals) was also a requirement for fire. A more comprehensive description of fire suppression was described by Williams [22], in terms of the characteristic chemical reaction time, τ_c, and transport (i.e., flow or diffusion) time, τ_r. In general, the chemistry must be fast enough to keep up with the flow field effect, or the flame will extinguish. This process is described in terms of the Damköhler number, $D \equiv \tau_r/\tau_c$, which is the ratio of the characteristic flow residence time to chemical reaction time, or alternatively, the ratio of the chemical rate to the transport rate. The chemical rate is given by an Arrenhius-type expression:

$$w = c_F^n c_O^m A \exp(-E/RT), \tag{2}$$

in which w is the reaction rate, c_F and c_O are the concentrations of fuel and oxidizer, A and E are the Arrenhius collisional term and activation energy, and T is the temperature. The chemical reaction time τ_c is the density divided by the volumetric reaction rate

$$\tau_c \equiv \rho/w = \rho c_F^{-n} c_O^{-m} A^{-1} \exp(E/RT). \tag{3}$$

The characteristic flow residence time is either

$$\tau_r = l/v \tag{4}$$

or

$$\tau_r = l^2/D, \tag{5}$$

depending upon whether convection or diffusion is the major process of transport into the reaction zone during the extinction. Here, l is a characteristic length, and v a representative velocity, and D is an appropriate diffusion coefficient. Using asymptotic theory, approximate results with general applicability have been developed [23], and a condition for flame extinction is available [22] as:

$$\left(l^2/\rho \mathrm{D}\right) c_{\mathrm{F\,b}}^{n} c_{\mathrm{O\,b}}^{m} A \exp(-E/RT_{\mathrm{AF}}) < k\left[\left(RC_{\mathrm{P}}T_{\mathrm{AF}}^{2}\right)/(EQ_{\mathrm{F}})\right]^{3} \tag{6}$$

where T_{AF} is (approximately) the adiabatic flame temperature, k is a constant (usually around 10^{-3}), C_{p} is the average specific heat at constant pressure for the gas phase, Q_{F} is the heat released per unit volume in the gas phase, and b denotes conditions at the system boundary (i.e., inlet). The significance of this framework is that all of the approaches for fire extinguishment:

1. cooling the gas phase,
2. cooling the solid phase,
3. isolating the fuel,
4. isolating the oxidizer,
5. inhibiting the chemical reactions, or
6. blowing away the flame,

can all be described analytically by the above equation. Anything which lowers the left side of Equation 6 enhances extinction, for example, reducing the temperature (lowering T_{AF}), lowering the concentration of fuel C_{F} or oxidizer C_{O}, or cooling the condensed phase (also lowers C_{F}). The form of Equation 6 relevant for convective flow control (rather than diffusion) replaces l^2/d by l/v, so that increasing the convective flow (i.e., blowing on the stabilization region), increases v, and again lowers the left-hand side of Equation 6 and enhances extinction.

Flow-Field Effects. As an illustration of these effects, the results for Halon 1301 and halon replacements added to the air stream over opposed-flow heptane-air diffusion flames is shown below [24]. In the experiment, the oxidizer is directed down (stagnation flow) against a 50 mm diameter pool of heptane. The oxidizer flow velocity is set, and agent is added to the air stream until extinction occurs. If the velocity of the oxidizer flow is increased (i.e., the flow residence time decreases), the amount of agent required for extinction also decreases. Figure 6 shows the extinction mass fraction of the suppressant in air as a function of strain rate,

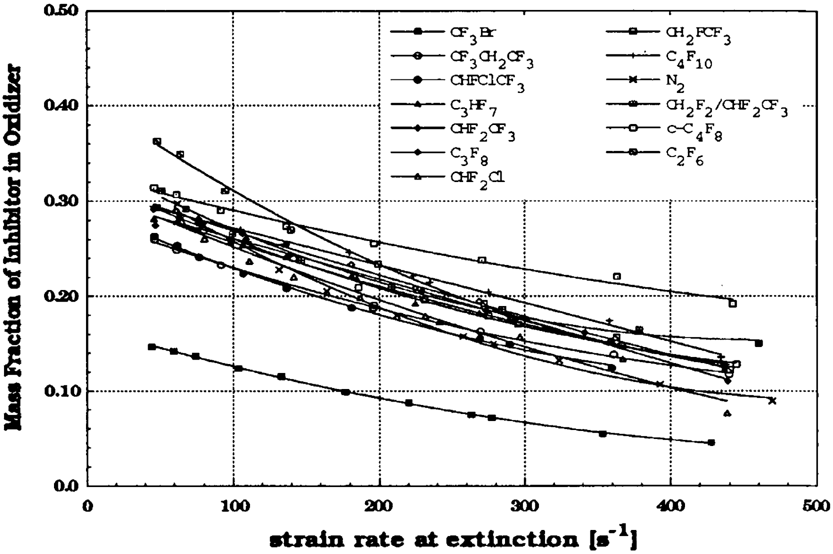

Figure 6. Mass fraction of inhibitor in the oxidizer flow (air) necessary to extinguish a counterflow diffusion flame over heptane, as a function of strain rate ($T_{air,\ inlet}$ = 25°C).

a, for gas inlet temperature of 25°C. The strain rate (s^{-1}) is the normalized velocity gradient along the streamline dv/dy; where $v = -ay$ for a stagnation flow, so a is proportional to v. Curves are shown for a large number of agents. As indicated, higher gas velocities (strain rates) require a lower agent mass fraction for extinction. Figure 7 shows the comparable data for gas inlet temperature of 150°C. As indicated, higher gas temperatures require more agent (at all flow velocities). This is because, as described by Equation 6, as the inlet temperature goes up and the left hand side of the equation goes up, making the flame harder to extinguish.

One might ask what amount of agent would be required if there were no limiting characteristic flow time (i.e., at zero strain rate). This would represent a condition for which all flames of the given mixture would be extinguished. One can arrive at this value by extrapolating the above curves to zero strain rate at extinction. Alternatively, these have been obtained in premixed systems as the inerting concentration of agent for all values of the fuel/air mixture (stoichiometry) for a particular fuel [25]. As the inlet temperature of the mixture increases, the flammability limits widen, and the amount of agent required for inertion increases.

For many flames, a suppressant is added at concentrations much lower than the inerting concentrations, and the flame extinguishes because of local flame destabilization and blow off. That is, there is a crucial location in the flow-field, the stabilization point, where addition of a suppressant causes the characteristic chemical time to become larger than the characteristic flow time; the chemistry cannot keep up with the flow, and the flame extinguishes at the point (blows off). An example of this is the cup burner flame, for which the blow-off extinguishment has been

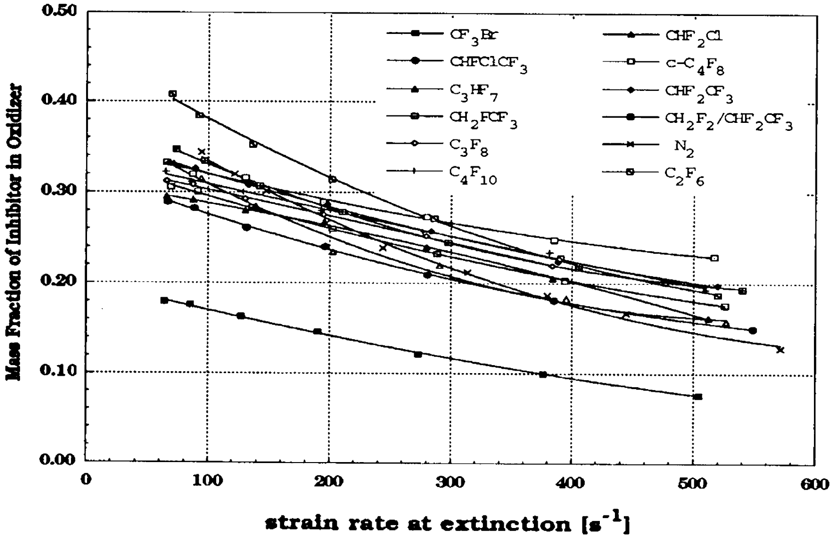

Figure 7. Mass fraction of inhibitor in the oxidizer flow (air) necessary to extinguish a counterflow diffusion flame over heptane, as a function of strain rate ($T_{air,\ inlet}$ = 150°C).

found to occur due to destabilization of the flame at the base region [26]. As can be seen in Figure 8 below (from Ref. [27]), the cup burner flame blow-off concentrations (lower set of symbols and line in the figure, for CO_2, N_2, Ar, and He) are significantly lower than the inertion concentrations (upper set of symbols and line). For flames in microgravity, however, where the strain rate is very low (due to a lack of buoyancy-induced flow), the flames are much more robust and require more agent for extinguishment (i.e., the stabilization is not upset by the buoyancy-induced flow near the base). In microgravity, the flame tip extinguishes before the flame blows off, and the amount of agent required for extinguishment in microgravity is essentially equal to the premixed flame flammability limits measured elsewhere [25]. That is, in microgravity, without flame base oscillation caused by the buoyancy-induced vortices [28], the flame stabilization is much better, the flame requires about 43% more agent for suppression, and the suppression concentration is essentially the inerting concentration. Hence, for a particular flame configuration, it is very important to consider the flow field and flame stabilization when considering the apparent extinguishing concentration.

Effects of Heat Addition on Suppression. Within the framework described above, the effects of energy-augmented combustion on clean-agent suppression of flames over condensed-phase fuels can be understood clearly. Adding energy to the condensed phase increases C_F, and adding it to the gas phase increases T_{AF}, in these cases reducing the likelihood of extinction. Adding a halogenated clean agent which decomposes in the flame (CF_3Br or CF_3H) [29], lowers the overall reaction

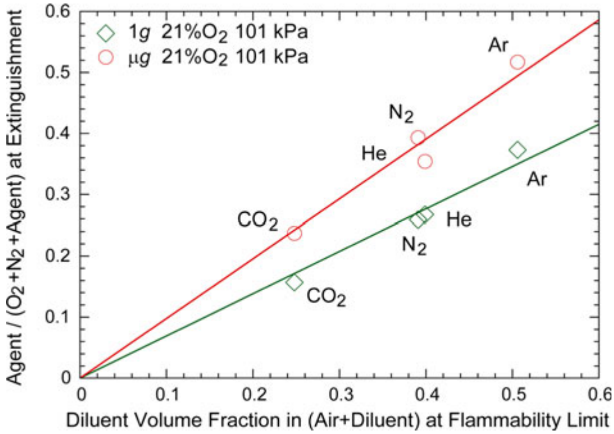

Figure 8. Correlations between the cup burner extinguishment limits and the critical flammability limits expressed in terms of the agent volume fractions in oxidizer, from [27] for a methane-air flame.

rate [30, 31] (lowers A or raises E), lowering the left-hand side of Equation 6 and enhancing extinction. Increasing the flow velocity (i.e., blowing on the stabilization region) decreases the flow residence time (decreasing the left-hand side), again enhancing extinction.

In both experiments and detailed numerical modeling, a higher temperature flame requires more agent for extinguishment, with either chemically reacting or inert agents. For example, extinguishing heptane cup burners by addition of Halon 1301 can require 2.5 times as much agent when the oxygen volume fraction in the air goes from 0.21 to 0.286 [32], and CF_3H can require 1.75 times as much when the oxygen volume fraction goes from 0.21 to 0.264 [33]. Likewise, for extinguishing methane-air cup burner flames with CO_2, about 2.1 times as much agent is required when the oxygen volume fraction goes from 0.21 to 0.30 [34]. For the inert agents with higher O_2 concentrations, the larger agent concentration is required to reduce the flame temperature to the same equivalent value at which extinguishment occurs [34]. For the chemically-active agents at higher oxygen concentration, the flame temperature is higher, causing higher radical concentrations, which then require more agent to bring them down to the levels at which extinguishment occurs. Figure 9 shows the variation in the final flame temperature and volume fraction of H atom due to changes in the oxygen content of the oxidizer stream, for a premixed $CH_4/O_2/N_2$ flame. For oxygen volume fractions increasing from 0.2 to 0.3, the adiabatic flame temperature rises 354 K, from 2181 K to 2535 K, while the final [H] goes from 260 μL/L to 3200 μL/L. The significance of these findings, to the present problem of energy-augmented combustion in electrically-energized equipment, is that for premixed or diffusion flames, higher gas-phase temperatures will require higher agent concentrations for extinguishment. Alternatively, if the energy is added to the condensed phase, a larger flame results,

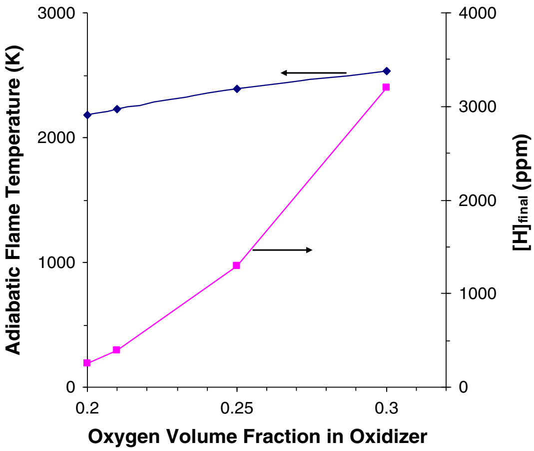

Figure 9. Adiabatic flame temperature and final H-atom volume fraction as a function of oxygen volume fraction in the oxidizer in a $CH_4/O_2/N_2$ premixed flame.

and the heat losses represent a smaller fraction of the total, so that the gas-phase temperature will again rise.

2.2.3. Suppression of Flames Over Condensed-Phase Materials. Existing standard (or nearly standard) tests for fire suppression include the Limiting Oxygen Index (LOI), cup burner, NFPA 2001, the UL tests referenced in NFPA 2001, and the pan tests for fire extinguishers. In the LOI test [35–37], a polymer sample is held vertically in an oxidizer flow, and the oxygen volume fraction necessary to just maintain combustion is noted. This is equivalent to a suppression test, since the volume fraction of added nitrogen (to air) needed to extinguish the flame is calculated directly from the LOI (oxygen volume fraction in the oxidizer) as $X_{N_2} = 1 - 4.76$ (LOI). In the cup burner test [1, 38, 39], the fuel is a liquid in a fuel cup, or a gas issuing from straightening screens in the cup (31 mm outer diameter), located concentrically in an 85 mm inner diameter chimney, through which air and agent flow at a specified mixture and velocity. The minimum extinguishing concentration (MEC) of suppressant required to extinguish (i.e., blow off [40]) the flame is determined. As mentioned above, the NFPA 2001 design concentration for Class B fires is specified by the cup burner MEC values times a safety factor of 1.3. For Class A fires the minimum extinguishing concentration of an agent is determined by test procedures in UL 2127 (inert gases) and UL 2166 (clean agents). The minimum agent design concentration is determined by multiplying the MEC value from those tests by a safety factor or 1.2. In the UL tests, a large (100 m^3) enclosure is used, with the fuel centered in the enclosure and located approximately 20 cm from the floor. Fuel arrays consist of either four vertical plastic sheets (20.3 cm × 40.6 cm × 0.953 cm; PMMA, PP, and ABS) spaced 1.27 cm to 3.18 cm apart; or a wood crib, composed of four layers of six kiln-dried spruce or fir blocks (3.8 cm × 3.8 cm × 46 cm). Ignition is by a pan of heptane burning for 6 min (for the wood crib) or 90 s (for the polymer sheets). In the pan tests for fire extinguishers (ANSI/UL 711), large heptane pan fires of various sizes (0.2 m^2 to 4.65 m^2 for indoor tests), or (7 m^2 to 18.6 m^2 for outdoor tests), or large wood cribs (72–400 block, increasing sizes), are extinguished manually. There are no agreed-upon tests for Class C fires, but a number of tests have been proposed, as discussed below in Sect. 2.4.2.

Several features of the suppression of flames over condensed-phase materials are noteworthy in comparison to the similar suppression of flames over gaseous fuels. First, necessary heat lost to the surface (to provide the fuel) weakens the flame (due to a lower flame temperature). With agent addition, the flame lifts off (to allow more mixing time, better premixing, and a stronger flame [28]), but also leads to less fuel supply—which further weakens the flame, and makes the heat losses more important. This is illustrated in Figures 10 and 11, which show the cup burner heptane or methanol consumption rate as a function of CO_2, CF_3Br, or R-125 volume fraction [41, 42]. As indicated, the fuel consumption rate drops very rapidly as the agent concentration nears the extinguishing value. Although agent addition affects the flame temperature somewhat (at near-extinguishment concentrations CO_2 lowers the peak flame temperature of methane-air flames by about 200 K, and CF_3Br raises it by 30 K [43]), the main cause of the reduced liquid fuel consumption rate is likely to be flame stand-off. As indicated in Figure 12, for methane-air cup burner flames, the flame base distance from the burner is seven (or three) times higher with CF_3Br [43] (or CO_2 [28]) added at

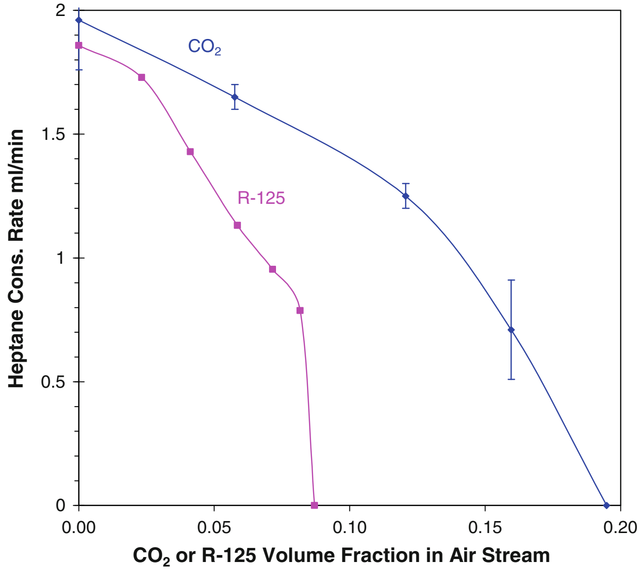

Figure 10. Cup burner heptane consumption rate as a function of CO_2 or R-125 volume fraction in air.

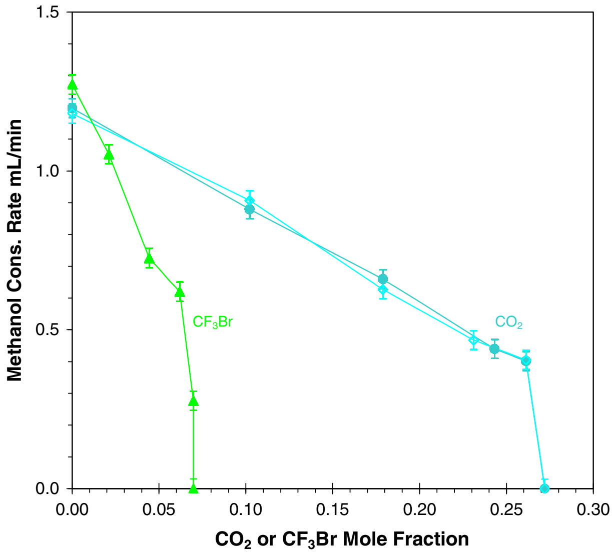

Figure 11. Cup burner methanol consumption rate as a function of CO_2 and CF_3Br volume fraction in air.

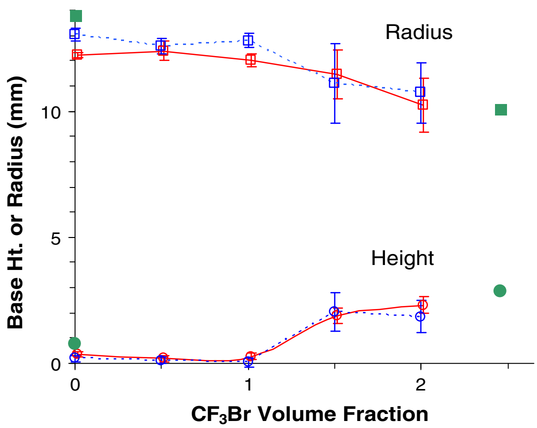

Figure 12. Flame height and radius for methane-air cup-burner flames with CF_3Br added to the air stream at increasing volume fraction [44].

near-extinguishment concentrations. This lower heat release rate near extinguishment has also been shown in flames over condensed-phase materials in a cup burner like configuration [44].

Another difference in suppression of flames over condensed-phase materials is that the flame stabilization process is intimately connected to the material configuration. Since the flame must exist near the surface of the burning material (to supply the heat feedback necessary to supply the fuel), the configuration of the material affects the flame stabilization, and hence, the amount of agent necessary to extinguish the flame. For example, in recent experiments, Takahashi et al. studied cylindrical burners with methane issuing from porous surfaces [44]. The cylindrical porous burner was oriented for either radial fuel supply (from a continuous rod), end up, or end down, as shown in the left, middle, and right images of Figure 13. The first configuration, radial fuel supply, was the most stable, and required 23% more CO_2 for suppression that the end-up fuel supply (which were very close to the methane-air cup burner values).

Other effects are also important for the suppression of flames over condensed-phase fuels. Because the fuel supply rate is dependent upon material temperature (which drives the decomposition), preheating of the material has a large effect on the fuel supply rate, and the amount of agent necessary for suppression. This has been shown by Goldmeer and Urban [45] and Ruff et al. [46] for flames over cylindrical PMMA.

Also, melting and dripping also occur for solid fuels, and these effects can both change the shape of the burning surface (affecting stabilization and heat transfer from the flame and any auxiliary source), as well as draw energy from the reaction zone [44, 47, 48].

Because of the intricate balance of heat flows as described in Sect. 2.2.1 above, any changes in the net heat flux near the critical values for ignition have a large effect on the burning behavior. This is illustrated in Figure 14, which is a flammability diagram from PMMA [49]. The figure shows the following, as a function of the imposed heat flux from a radiant heater: the flame spread rate, upward or downward (left two curves); the steady mass loss rate (upper right curve); and the time to ignition (lower right curve). As indicated, changes in the net heat flux near 8 kW/m^2 have a huge effect on the flame spread rate and the time to ignition; of course, these

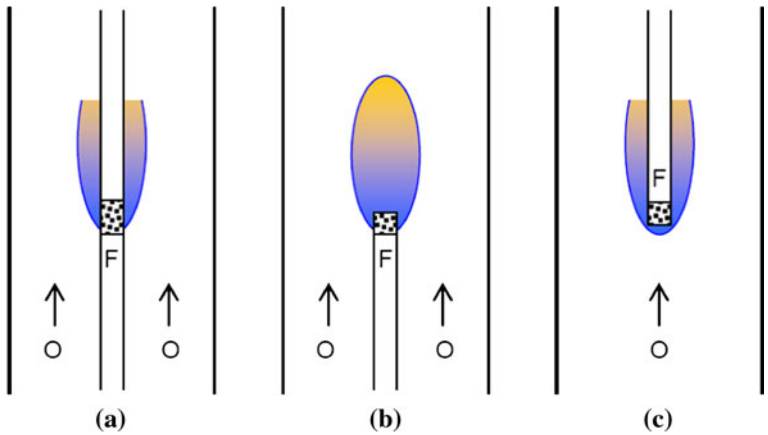

Figure 13. Cylindrical fuel configurations methane-air porous burners (from Ref. [44]; used with permission of the author).

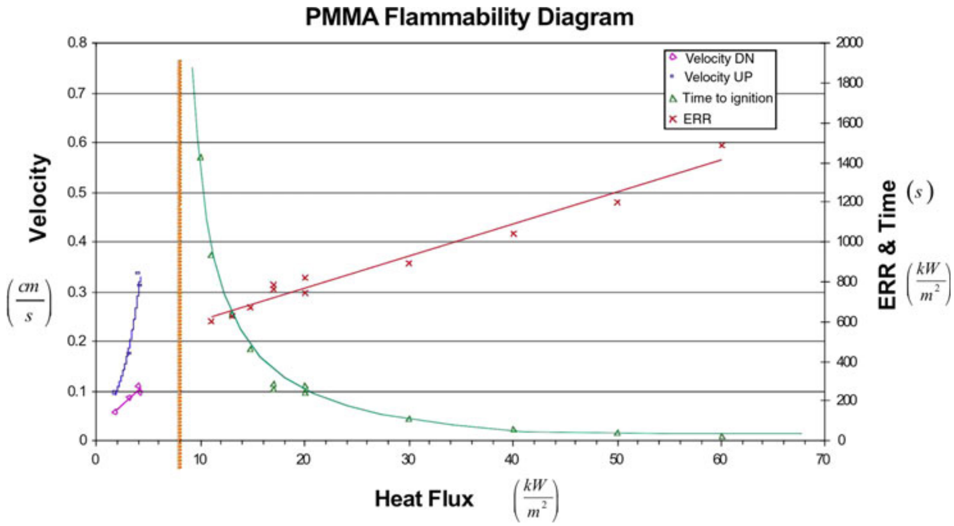

Figure 14. Flammability diagram for PMMA (from Ref. [49]; used with permission of the author).

results will vary with polymer type. It would be immensely valuable in the context of the current work to have such diagrams in the presence of increasing amounts of gas-phase suppressants for materials used in electrically energized equipment.

2.3. Threat Definition

One of the goals of the present research was to define the Class C fire threats which are typically protected by the clean agents. Given the diversity of the equipments types in the field, however, this was far beyond the resources of the present project. A survey of industry would be useful, to characterize the critical applications, equipment types, fire threats, potential clean agent applications, agent discharges, and reported incidences. This, together with statistical data on fire incidents from databases, would be a useful first step to define the fire threats typically protected by clean agents. Nonetheless, surveys and statistical data are unlikely to be sufficient to define the role of energy augmentation on the suppressant needs. In general, databases on fire incidents in electrical equipment have few data points and few details, such that, often, even the cause of ignition is not available in a fire incident database. Hence, for the purpose of defining the threat, surveys are useful but not sufficient.

As an example of fire event data used for understanding energy augmentation and fire suppression, all of the fires related in the technical expert phone interviews (and the FM case studies) are listed in Table 3. Most of the fires described occurred in power equipment (batteries, cables, power switches, etc.). In none of the fires was suppression attempted with electrical power still on. With more time, the energy fluxes in all of the fires reported by Respondent 05 might have been discernable (and they were mostly huge, intense events). In none of the other

Table 3
Summary of Fire Events Described by Respondents

#	Description	Source	Voltage	Power kW	Material burned	During servicing	De-powered?	Extin. method
Batteries								
1	Cracked battery, leaked, shorted, burned	2	DC	High	Battery jar	?	Self	SE
2	Cracked battery, leaked, shorted, burned	5	540 V DC	400	PP battery jar, conductor failure	Y	Self	SE
3	Attached reverse polarity, shorted	5	48 V DC	High	Battery jar, conductor failure	Y	Self	M, H_2O
Rectifiers, varistor, power electronics								
4	Rectifiers, varistor, power electronics	2	?	?	?	?	?	A, 1301
5	Power-shutdown induced failure of varistor	5	? DC	High	Varistor	Y	na	SE
6	Fire in automatic voltage regulator	F3	45 kV AC 380 V AC	High	Cable insulation	N	Y	A, 1301
Cable fire								
7	Overheating of a group of plastic insulated low-current wires in a static power switch	F1	380 VAC	?	10 cm of plastic cable jacket	Y	Y, M	M, CO_2
8	Cable connector failure in cable tray	5	DC	High	?	?	?	?
9	Power conductor shorted to fire stop material	5	?	High	Composite fire stop material	?	?	?
AC/DC power supply								
10	DC power plant	5	48 V DC	2400	?	Y	Y,M	
11	Bus-bar accident	5	13.8 kV, 600, 347 VAC	4000	Little	Y	na	SE
12	Interlock device failure	5	240 V 3ϕ	400	?	?	?	?
Data processing equipment								
13	Fire in hard drive bay	F2	5 V, 12 V	?	Plastic encl. + hard drive cases	N	Y, M	M, 1211
14	Power supply failure	10	?	?	Smoke, no flames.	N	Y,A	A
15	Power receptacle wiring error	10	120 V	?	Smoke, no flames	N	N	?
Other								
14	Transformer fire	5	High AC	100	6” of windings	?	?	?
15	Return air fan motor (7.5 kW) burnout	5	AC	?	?	?	?	?
16	Overheated Diesel Exhaust (several)	5	na	na	?	?	?	?

2: respondent 02; 5: respondent 05; 10: respondent 10; F1: FM case study 1; F2: FM case study 2; F3: FM case study 3
A: automatic; M: manual; 1301: Halon 1301; 1211: Halon 1211
Y: yes; N: no; na: not applicable; Self: self de-powered; SE: self-extinguished

reported events was there enough information available to quantify the energy flux to the burning material. These conversations are probably at the higher end of information typically available. As described later, threat definition will probably require access to individuals performing forensic analysis, or laboratory re-creations and modeling of failure events based on statistical data and expert input.

2.4. Test Method Evaluation and Development

2.4.1. Performance versus Prescriptive-Based Approach. To specify a test method, there are two basic approaches. The first is scenario-based, and the other is performance-based. In the scenario based approach, one seeks to characterize individual fire threats, as in the work of Keski-Rahkonen [50]. In that work, they studied ignition phenomena in electrical equipment through statistical data on failures followed by laboratory and modeling studies of the failure mechanism. In the present work, however, rather than studying ignition, the goal would be to understand the role of energy-augmented combustion in the *fire suppression*. Based on statistical data or surveys, one would identify a likely failure mode, and then through laboratory experiments and modeling, study the fire characteristics with regard to the relevant parameters which control the suppressant concentrations (Table 4 questions). Following these steps, a test method would be designed to reproduce the appropriate values of the relevant parameters in Table 4, and the suppressant levels could be determined for each agent. Since equipment types and the failure modes are quite different, this approach would have to be applied on a case-by-case basis. After enough understanding was developed, the cases could be grouped, and the suppressant requirements for each group of expected failure types could be specified. Of course, a single worst-case scenario could be identified and used as the test method to specify suppressant requirements for all electrically

Table 4
Questions Which are Necessary to Answer About a Fire in Electrical Equipment Useful in Developing a Relevant Test Method

1. Is there energy addition from an external (i.e., electrical) source or not?
   a. If there is energy addition, how much, and for what duration?
   b. Is there pre-heating of the material prior to ignition? If so, how much?
2. How does the ignition occur?
   a. Is autoignition required, or is there a separate ignition source?
   b. If separate ignition source, what is its assumed duration?
   c. What are the characteristics of the initial ignition event with regard to size of initial flame?
3. What is the material burning?
4. What is the configuration of the burning material
   a. Adjacent materials,
   b. Orientation,
   c. Temperatures,
   d. Confinement of melting and dripping materials
5. Is there involvement (i.e., heat feedback) from adjacent flames?
6. What is the ventilation condition in the burning area?
   a. Velocities,
   b. Stabilization condition of the flames?

energized fires (but as with all prescriptive-based codes, this could lead to an inefficient use of suppression resources).

In a performance-based approach, one would specify a test procedure which includes the important parameters that control the suppressant concentrations (Table 2 questions: energy addition, ignition duration, materials, configuration, ventilation, etc.), and then determine the amount of agent needed, based on values of each important parameter. It would then be up to the system designer to (or a Fire Protection Engineer) to determine, for a given application, the value of each parameter for the range of possible failure modes, and hence the amount of clean agent they would need to protect the equipment in the event of failure.

In either case, the goal is to first understand the actual values of the relevant parameters. The only difference is when the values of the relevant parameters are specified: (1) prior to the *test method* use, or (2) later when the system is designed and installed. One value of the latter approach is that it will emphasize, to the system designer, that the fire safety can be achieved either through initial design of the equipment, or by post-development suppression of fires. In either approach, the prescriptive or the performance based, it is most useful if the test procedure provides fundamental fire performance data which can then be used to predict the agent performance for a range of conditions. This is desirable in the prescriptive-based approach, since for electrically energized equipment fires, there is such a wide range of values of the possible energy fluxes that could occur, and these will affect the suppressant requirements. Hence, one would not want to have a separate test for each possible failure mode; it would be much more efficient if one test could apply to many scenarios, based on the value of one test parameter (e.g., the imposed external heat flux).

2.4.2. Analysis of Previous Test Methods for Suppression of Energized Electrical Fires.

Overview. Previous work to develop a test procedure to simulate the suppression of electrically-energized fires can be grouped into three categories. The first is based on the failure mechanisms deduced from the fire incident reports available in the statistical databases. The advantage of this technique is that from the start, it attempts to use conditions which are representative of the actual fire threats to be extinguished by the clean agents. The tests are essentially attempting to simulate a failure mechanism believed to be representative. The second category is based on creating conditions which control the most important parameter (for example, the external energy added to the burning polymer, or the autoignition temperature in the presence of suppressant), and quantifying the response of the suppression process to changes in that parameter. While little attempt is made a priori to correlate this parameter with its relevant value in suppressed Class C fires in the field, the advantage of this technique is that the most important parameter, the external heat flux, is carefully controlled and quantified in the experiments. For example, the tests are conducted over a range of external heat fluxes, so presumably the results can be used to understand the effects of this external heat flux on a wide range of conditions which may be present in actual suppression of electrically-energized fires. The tests allow better ranking of agents than does a pass/fail test, and since the measurements provide fundamental parameters, the results might eventually be used in performance based design calculations. Finally, a third category is a miscellaneous assembly of other test methods. Many of these can be placed in one of the first two categories, but in some cases they studied ignition (instead of suppression), or they did not add energy per se (although the results are informative for the present discussions). The relevance of these tests is better highlighted by keeping them in a separate category.

The first category, Tests Simulating the Failure Mechanism, includes work in the early 1990s at FM Global to simulate an arc discharge with copper-coated carbon rods with Halon 1301 added to suppress attached flames. Others developed a series of tests which aimed to simulate actual failing components in telecom and data processing equipment. These included work in the late 1990s by McKenna et al. [4, 5] which simulated ohmic heating of wire bundles, and conductive heating of an isolated wire, and printed wiring board arcing failure. Soon thereafter, Niemann et al. [14, 15, 51] suggested a modification to the conductive heating test to include a continuous ignition source. Work in the late 2000s by Stilwell et al., simulated an overheated hot wire in the vicinity of a flammable polymer [6], or embedded in a wire bundle [7]. Since most of these approaches are scenario based, they would lead to a standard test method that is prescriptive.

The second category, Test Methods Based on Controlling the External Heat Flux, includes work in the 1970s by Tewarson et al. using the Fire Propagation Apparatus [17], where PMMA samples were exposed to radiant fluxes up to 10 kW/m^2, and the oxygen volume fraction for extinction (i.e., the amount of nitrogen added to air) for extinction was determined. Using a similar apparatus, Tewarson and Khan [52, 53] determined the amount of Halon 1301 required to suppress a PMMA sample exposed to an external radiant flux of 50 kW/m^2. Taking a different approach, but again adding controlled amounts of energy to a polymer, Niemann et al. [9, 54–56], and Driscoll and Rivers [57], describe tests in which a polymer sample is wrapped with Nichrome wire, which adds energy while the polymer burns. The extinguishing concentration with the added energy was determined for various suppressants. In a test procedure similar to the FM Global Fire Propagation Apparatus work, but with smaller samples, National Institute of Standards and Technology (NIST) workers [10, 11], and Smith and Rivers [58] studied the effect of externally applied radiant heat on the suppression of PMMA. Since these tests (especially radiant heating) vary an important parameter, they could be used in a standard test method that is prescriptive. Alternatively, by specifying a particular energy input level, they could also be used for a prescriptive code.

Other tests which are of interest but which don't fit the above categories well are described below in the section: Other Miscellaneous Test Approaches. The hot-metal-surface autoignition tests of premixed fuel-air-suppressant mixtures, conducted by Hamins and Borthwick [12] and Braun et al. [13] describe the effects of the suppressant on the autoignition temperature. They also present the concentration of various agents necessary to inert a propane-air mixture to the hot surface ignition. Since these hot-surface tests study autoignition rather than suppression (which has different chemistry), as well as premixed flames (instead of flames over decomposing polymers) the results are not directly applicable, but are still of value to the present analysis (For example, they study the re-ignition propensity of the gas-phase decomposition products in the presence of a hot surface, which may be relevant, but only for special situations.).

Recent National Aeronautics and Space Administration (NASA) tests, using three different models of damaged-wire ignition, evaluated the current necessary for hot-wire ignition of space suit materials [59]. Test data were presented for a range of wire sizes, polymeric materials, and surface conditions. Other tests at NASA studied the suppression of fires over resistively-heated PMMA cylinders [45, 46].

Researchers at the Technical Research Centre of Finland (VTT) studied mechanisms of electrical ignition in data and power cables in nuclear power plants [50]. Starting with statistical data on fire events, they categorized the ignition mechanisms. They then developed analytical models of the phenomena, and conducted supporting experiments to validate the calculations. While the VTT work might be considered to fall into the first category of test method (Tests Simulating the Failure Mechanism), the work studied ignition rather than suppression, so their results are not directly usable in the present work (although they are still of interest).

The above research is described in more detail below. The strengths and weaknesses of each test are outlined, and the experiments are analyzed to estimate the order-of-magnitude of the relevant parameters in each scenario (for example, the imposed heat flux), so that the results can be inter-compared.

<u>Tests Simulating the Failure Mechanism with Suppression.</u> The first test outlined in this section is the FM Global Electrical Arc Apparatus, since it was developed the earliest. Most of the other tests are based on work conducted or coordinated by Robin, and extended by Niemann et al.

FM Global Electrical Arc Apparatus: In some of the first work to look at the suppression of simulated electrically-energized fires, Tewarson and Khan [52, 53] describe an experiment with suppression of a fire sustained by simulated electrical arcing. The FM Global Electrical Arc Apparatus exposed burning copper-coated carbon rods, which were undergoing high-energy electrical discharge, to an atmosphere of air and Halon 1301. Power dissipated in the arc varied from 0.6 kW to 1.4 kW, depending upon the halon concentration and time (i.e., arc separation). The test chamber was a cube, 30.5 cm on edge, and the halon was introduced into the sealed chamber where a small fan mixed the agent (and remained running during the tests). The power to the arc was supplied by DC arc welder. It was found that an agent volume fraction of between 0.075 and 0.09 was required to extinguish the gas-phase flame of the carbon (from the copper-coated rods) with air.

In related work using the same apparatus, Khan [60] described tests in which the copper-coated carbon rods were covered with PVC cable insulation, and the concentration of Halon 1301 required to extinguish the flames over the PVC were determined. To establish the arc, the voltage was initially set to 50 V with a current setting of 40 A; however, these dropped off as the experiment continued, such that power levels to the arc were generally between 0.5 kW and 1.4 kW. A Halon 1301 volume fraction of 0.03 was found sufficient for extinguishment, although lower concentrations were not tested. As reported by Khan [60], the oxygen volume fraction in the chamber was measured, and dropped from 0.209 at the start to 0.19 after Halon 1301 was added to a volume fraction of 0.09. This drop represents the dilution of the chamber air by the halon and, hence, oxygen depletion due to combustion did not contribute to the extinguishment. As noted by Khan, this generally needs to be considered in sealed chambers.

The test method has the advantages of relatively well defined suppressant concentrations and flow fields and a simple configuration, and the test can be operated with a wide range of materials. The air currents in the chamber from the mixing fan could affect the stabilization conditions of the flame attached to the burning PVC on the electrode; however, the heating-induced flow from the arc near the PVC is probably much greater, dominating the stabilization conditions. The energy input to the arc is well defined, but that reaching the burning polymer is less well defined (since the polymer regresses away from the arc as it burns). Nonetheless, the test can serve as an upper limit of the effect of energy addition, since flames extinguished near the arc discharge are probably well-stabilized, exposed to a high radiant (and conductive) heat flux, and have a continuous ignition source; i.e., a worst-case scenario.

Failure Mechanism-Based Approach of Robin et al.: McKenna et al. [4, 5] reported a series of tests which aimed to simulate suppression of electrically-energized fires in central office equipment. Three test configurations were conceived, built, and tested, and a range of materials were used. The goal was to replicate both the electrical involvement in the fire (with regard to both ignition sources and energy addition), as well as the materials and suppressants used in practice.

Three configurations were devised: (1) the Ohmic Heating Test; (2) the Over-Heated Connector Test; and (3) the Printed Wiring Board Test. The first simulates an over-heated cable fire, while the second simulates an overheated connection, each of which could occur from a shorted connection in energized electrical equipment. The third test simulates the development of an arc-track leading to a continuous arc between parallel power circuits on a printed wiring board. These three tests are very useful for understanding the general behavior of the burning polymers when the electrical power in the circuit adds energy to the system, and represent some of the few quantitative tests of suppression of burning polymers heated by simulated electrical shorts. Nonetheless, there are some physical parameters in the tests which are crucial for understanding both the burning rate and the suppression characteristics, but that are either not controlled in the work, or not reported. The same physical enclosure and system for agent addition were used for all of the tests.

The common test enclosure has some properties which affect all three of the tests listed above, and hence is discussed first. For example, the agent addition is impulsive, which leads to a few complications: (1) turbulent fluctuations in the local concentration of agent where the extinguishment is actually occurring, (2) a rapidly changing average concentration in the time during which the extinguishment occurs, and (3) non-uniform mixing of the agent with the ambient air, so that there can be spatial and temporal concentration gradients in the enclosure. These three effects make it difficult to know the actual concentration of agent at the burning polymer when extinguishment occurs. For example, in a test, the mass of agent in the bottle was set to provide a final concentration of agent in the enclosure corresponding to complete mixing of the agent with the air in the enclosure. When the agent is released, however, it forms a jet of agent with a concentration that is locally much higher than the final design concentration. The concentration of agent delivered to the fire is the fundamental parameter desired, but it is poorly characterized in this test. Note for example, Figure 6 in the McKenna 1998 report. As indicated in the figure, the average volume fraction (from a line-of-sight Fourier Transform Infrared (FTIR) spectrometer measurement) changes very rapidly at short times, going from 0% to about 7% (at the measurement location) in about 6.3 s. For comparison, the average fire out times are 9 s to 20 s for the conductive heating tests, 3 s to 16 s for the ohmic heating tests, and 2 s to 9 s for the printed wire board tests. Hence, the agent concentration is changing very rapidly in the same time scale of the extinguishment process, so that it is difficult to know what the concentration actually was when the fire went out. The situation is even more uncertain since the line-of-sight FTIR measurement spatially averages the values of the concentration, so that local fluctuations are likely to be greater. Also, the location of the burning polymer is even further along the flow streamlines than the FTIR measurement, so the time to reach peak concentration at the polymer will be even larger than the 6.3 s in the figure (which is the concentration at the FTIR-beam location). Since the agent release is impulsive and turbulent, the concentration at the burning polymer is probably also stochastic, further complicating data interpretation.

Another general concern has to do with airflow. The burning rate and stabilization (and hence, extinguishment conditions) of polymers can be sensitive to the air flow over the surface. Since most electronic equipment will have substantial cooling air flows, these must be considered in the test procedure. The airflow at the burning surface in the present test enclosure is uncharacterized, and that situation is made even more tenuous with the impulsive release of the agent, which could have small effects on the local flow field, that could affect the stabilization of the flame.

The stochastic nature of the concentration fluctuations and the oxidizer flow near the fire means that either a lower precision in the measurement must be accepted, or a much larger number of tests must be performed to provide an average value. While the test is perfectly reasonable for investigating the general behavior of a burning polymer in a configuration similar to that in telecom central office equipment, it is not as good for characterizing the behavior in terms of two of the most relevant parameters (e.g., extinguishment concentration and flame stabilization condition).

Finally, since the test chamber is sealed, with the polymer still burning, prior to the release of the agent, the possibility of suppression under vitiated conditions (i.e., depleted oxygen) exists. Some care must be exercised to insure that oxygen levels at suppression are still at ambient conditions. Besides these generic properties associated with the test enclosure, the individual tests are discussed below.

Ohmic Heating Test: In the Ohmic Heating Test, bundles of cables ranging in diameter from 3.26 mm to 0.403 mm (8 AWG to 18 AWG), with jacket materials typically used in telecom (see Table 5), were arranged in bundles, and some fraction of them was heated with a high current/low voltage resistive source. The goal was to auto-ignite the jackets with the ohmic heating; however, this is found to be difficult to accomplish due to melting, dripping, or smoldering of the jackets, and failure of the conductor. Since the delicate balance necessary for self-ignition was difficult to achieve, a butane pilot flame (of 25 s to 170 s duration) was ultimately used for the initial ignition of the polymers (except for the non-FR polyethylene which self-ignited).

These types of tests are very useful to start to get in the ballpark of how energy-augmented combustion (EAC) affects the minimum extinguishing value for suppressant agents, $X_{a,ext}$. As a research tool, they provide excellent insight into the behavior of the tested materials when subjected to simulated failure modes expected in the field. Nonetheless, the tests performed and the results provided did not give all of the relevant parameters necessary to characterize the behavior; i.e., the fundamentally controlling parameters were sometimes not provided. For example, the net power into the test material is what controls the polymer temperature (and hence the mass loss rate), but it was not provided in the reports. As described above, because of the delicate balance between heat feedback to the polymer, heat losses, and the fuel decomposition rate (which creates the fuel), the net power into the polymer has a big effect on the suppressant requirements. Also, near extinguishment, the burning rate (and hence the required suppressant concentration for extinguishment) can be highly non-linear with the input power, so it is important to report the extinction concentration of agent as a function of the input power level. A second concern has to do with the pilot flame used for ignition. Since the resistive heat source creates a polymer temperature field that is time-dependent, the burning behavior (and hence suppressant requirement) can vary widely with the time history of the heating. That is, the polymer can be much easier to put out early in its heating history, but more difficult later when the heat release will have grown geometrically. It may be more appropriate, if an external ignition source is used, to keep it on for the duration of the test. (Alternatively, one must make arguments about *when* in the heating history to light the polymer, and for how long to let it burn, before suppression.)

Also, it is important *where* in the polymer the energy addition is made. In some cases, the energy from the heated cable is added to the center of a bundle of cables, which is probably not where the cable is burning. If the sample is thermally thick,

Table 5
Jacket Materials Use in Work of McKenna et al. [4]

1. Cross-linked polyethylene (XLPE)
2. SJTW-A: Thermoplastic jacket over thermoplastic insulation
3. Polyvinylchloride (PVC)
4. Chrome PVC jacket over polyethylene
5. Neoprene jacket over rubber insulation

and the energy is added to the sample at the back side (or the center), the energy addition will have a smaller effect on the burning rate (and the MEC) than if it is added at the surface. Further, the burning rate depends not just on the total energy added, but also on the energy density. That is, adding 20 kW/m^2 to a single area has a much different effect than adding 10 kW/m^2 to twice the area. While failing, burning cables could conceivably be in any configuration, the most conservative case would be for the energy to be added at the burning surface. This is not always the case in the present study.

Many of the tests here picked a particular configuration and power level, and then determined the agent concentration required for suppression. Since the relevant parameters in an actual electrically-energized fire scenario are not that well known, it would be very informative to run the present tests for a range of power levels, air flow conditions, polymer containment conditions, and flame heat feedback conditions, to see the effect of these parameters on the MEC.

Overheated Connection Test (Conductive Heating Test): In the overheated connection test, a cylindrically-shaped heater (a "ring heater") clamped onto and heated one end of a relatively large diameter power conductor (350 MCM, or about 17.3 mm diameter). The clamped end of the wire (about 10 cm long) was stripped of the polymer insulation, while about 15 cm of insulated cable extended vertically above the heater. The heater temperature was set to 900°C, and it heated the cable until the far end of the cable reached 310°C, when a pilot flame was applied to the base of the exposed insulation for 15 s. The agent was injected, and the time to flame extinguishment was recorded.

As with the ohmic heating test described above, this test is a very reasonable approach for starting to understand the behavior (and suppression) of burning insulation on real power conductors exposed to heat loads when they are arranged vertically in isolation. As with the other test, additional information concerning the test conditions could make the test more broadly useful (For example, the temperature of the polymer surface, the wire temperature along the length, and the power going into the wire itself would be of value.). Concerns with this test are listed below.

Since the same enclosure is used for this test as in the ohmic heating test, all of the issues discussed above with regard to the agent addition and mixing apply here as well. As with the other test, it would be nice to include measurements or estimates of the power addition to the burning material, and to have performed the tests at varying power levels. The airflow velocity and configuration could have been better characterized, since these affect the flame stabilization and hence, the blow-off condition.

It is of value to know the energy flux to the polymer so that it can be compared with other test methods. The external heat flux can be roughly estimated as follows. The power level to the ring heater was 1 kW. For a copper rod (assumed solid core, and a thermal conductivity of 0.36 kW/m/K) with a linear temperature distribution and 900°C at one end and 310°C at the other, and 15 cm in length, in steady-state, heat is conducted into the rod at 0.33 kW. This value is about 1/3 of the total heat to the ring heater, which seems reasonable. The wire has an external surface area of about 80 cm^2, so the average heat flux into the polymer insulation estimated here is 45 kW/m^2. The heat loss through the polymer jacket along the wire varies significantly, because of the temperature gradient in the cable. Nonetheless, the temperature gradient along the length of the wire is likely steeper near the ring heater than at the far end (because the higher temperature at the ring end leads to larger heat losses than at the cooler end). This would make the power dissipated in the wire larger than the estimate here (by assuming a linear temperature distribution); the *variation* in the energy flux would remain the same, however, since the variation is maximum between the end points of the wire, and these are the same regardless of the temperature profile between them.

The variation in the heat losses along the cable are estimated as follows. The insulation must be considered, but there are two limiting cases which can bound the problem: no insulation, and insulation with a constant temperature (corresponding to a constant decomposition temperature of the polymer). For the first case, neglecting the polymer insulation, the heat losses by convection are linear with the temperature, so they vary by a factor of three along the cable, while the radiative losses (which are proportional to T^4) vary by about a factor of 18. Assuming an emissivity of 0.95 for the wire (dirty, carbon coated), and a convective heat transfer coefficient of 10 W/m^2/K, the estimated heat loss from the wire (which is equal to the heat flux into the wire insulation at that location) is shown in Figure 15, and varies from 8.1 kW/m^2 to 107 kW/m^2. The average heat loss in the wire is 45 kW/m^2, (which is the same as the value above calculated from the heat conduction input through the wire cross-section). For the second case, constant polymer temperature, the heat losses are only by conduction to the polymer and depend only upon the polymer temperature and the cable temperature (for

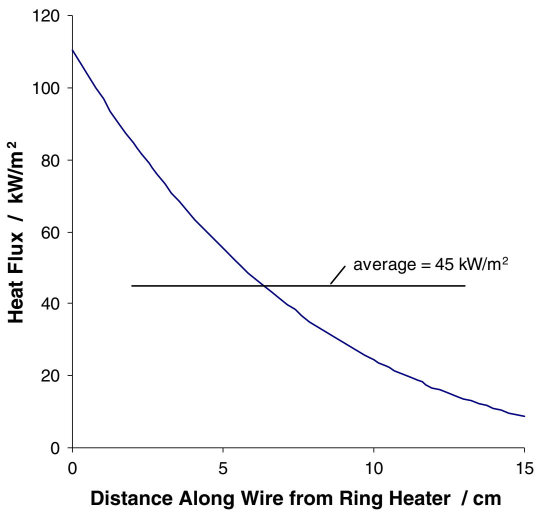

Figure 15. Estimated heat flux along wire in heated conductor test [5].

the limiting cases, we assume here that there is complete absorption of the thermal radiation from the wire by the polymer).

The polymer likely decomposes between 300°C and 500°C, and in either case, the heat losses out of the cable vary along its length by even more than they do in the case of no insulation (This is because, at either polymer temperature, the heat flow near the colder end of the cable is near zero, but is a larger, finite value new the hotter end.). Using the first case (no insulation, which predicts less variation in the heat flux along the wire), the heat flux into to polymer is likely is in the range of 8 kW/m^2 to 110 kW/m^2. The absolute power levels are probably greater than this since the heat losses are not constant along the rod so that the temperature gradient in the rod is not constant, but rather, steeper at the hot end.

Modified Conductive Heating Test: Niemann et al. [14, 15, 51] describe a modified version of the conductive heating test of McKenna et al. described above. In it, they add a spark ignition source to the top (i.e., coolest part) of the heated cable, and find that higher concentrations of agent are required to suppress all forms of flaming combustion. Since the conductive heating test of McKenna et al. [4] also uses a separate ignition source, there is some logic to keeping the ignition source in place for the duration of the test. In an actual fire scenario, if the ignition source—independent of the continuous cable heating—existed at some early time in the fire development, it can also exist at later times, so inclusion of a continuous ignition source, as suggested by Niemann et al. seems reasonable. On the other hand, their criterion for flame extinguishment may be too stringent. Flames existing *only* near the arc igniter (of these tests) may be due to the localized energy release of the arc, which is a separate phenomenon from what is intended by the ring heater (the energy density near the plasma of the arc is very high). Finally, the most likely region to support a flame is at the hot end of the rod, where the external heat flux is greatest (see Figure 15), and where the flame stabilization is strongest, due to the downstream boundary layer [44]. Hence, while their criterion for flame extinguishment may be too stringent, the location of their spark igniter may not be the most conservative.

Printed Wiring Board (PWB) Failure: In a series of tests with printed wiring boards (PWB), McKenna et al. [4, 5] simulated an arcing fault across power tracks. Varying the track width (0.304 mm, 0.63 mm, and 1.27 mm) and track spacing (0.304 mm, 0.63 mm, and 1.27 mm), solder mask type (LP1 or Vacra 1), and substrate material (FR-4 or FR-2), they attempted to obtain the most stable propagating arc faults for track voltages of 5 V to 9 V, with a current of 11.5 A. After the optimal conditions for a stable arc were established (8.5 V and 8.75 V), they attempted to extinguish flames on the board which were self-ignited by the arc. Quantities of HFC-227ea necessary to extinguish the flames (but not the arc itself) were established.

The experiments are very useful to start to understand the flames produced by such failures, as well as the amount of agent necessary to extinguish these flames. Using the descriptions in the reports, the energy flux to the substrate are estimated below. Following that, additional measurements, tests, and analyses are suggested which would increase the value of the experiments, and make their interpretation more universal.

The energy flux to the substrate material can be estimated as follows. With the given current (11.5 A) and voltage (5 V to 9 V), the power level released in the arc is 58 W to 104 W. The fraction of this power making it to the surface (and the area involved) is unclear, but can be estimated. If the electrically conducting (i.e., shorting) material is the pyrolyzed polymer, then all of the energy will be delivered to the polymer; whereas if the arc is in the gas phase, only part of the energy will be delivered. Assuming the second case, a lower limit of the energy delivered to the polymer would be about 50% (radiation and conduction are about equal towards and away from the surface). As for the area involved, the flame is described as about 2.54 cm in width, and assuming the depth is the same, we get an involved surface area of 6.5 cm^2. This estimate of the area is reasonable since the flame has a large effect on the polymer surface, promoting carbonization (and hence shorting), as well as on the gas-phase arcing (where ions and carbon in the flame again promote shorting through the flame region). If anything, the arc-heated area may be smaller than the flame area, since conduction within the substrate from the high-temperature arc-heated area will cause mass loss and flaming from a larger area than that of the arc heating. Assuming half of the energy into the wires makes it into the polymer, and an area of 6.5 cm^2 gives fluxes of 45 kW/m^2 to 80 kW/m^2, for 5 V and 9 V, respectively (Note, the other publication of this same work [4] describes the power input as 74 W, which with the above assumptions, gives about 57 kW/m^2.).

In order to extend the value of the PWB tests, several additional actions could be taken. For these tests, the effect of a second board in close proximity to the first would be very interesting to examine. While the authors did describe tests in which the arc was initiated on one board, with a second board close to and parallel to the first, they only noted whether the flame initiated on the first board then propagated to the second board. This is a useful result, but more interesting would be whether the flame on the second board affected the extinguishment of the flame on the first board—since heat feedback from adjacent flames is known to affect the heat flux to and burning rate of flames over condensed-phase materials [61]. Further, PWB in racks have ventilation air from cooling fans, and the average flow velocity over an individual board likely varies significantly. Since the burning rate (and the flame stabilization properties) vary with the airflow [44], it would be useful to see how the extinguishing concentrations vary with airflow velocity (and direction). The effects of ventilation are particularly important for parallel boards in close proximity, since under those conditions, the burning in the central region is likely to be ventilation limited. The effects of board orientation are a step in the direction of understanding some of the ventilation effects; however, orientation effects were mentioned in the reports, presumably only for single boards, and no results were given.

Vertical Polymer Slabs Ignited by a Loop of Nichrome Wire: Robin et al. [6] devised a test for assessing the effects of energy-augmented combustion on the clean-agent suppression of burning polymer samples. The configuration, shown in Figure 16, uses a U-shaped length of Nichrome wire which passes through rectangular slots in a vertical polymer slab. The Nichrome wire is resistively heated to provide a desired wire temperature. In these tests, the temperature is initially set

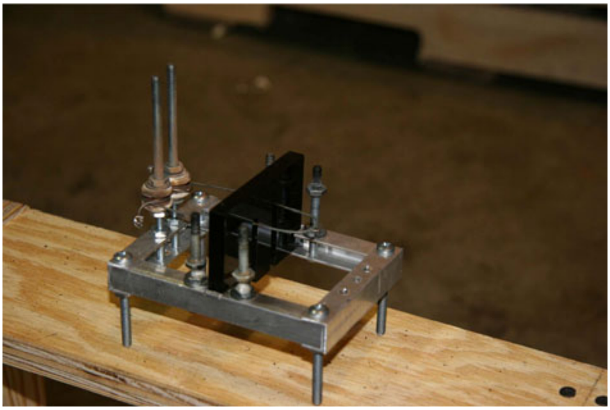

Figure 16. Test method employing U-shaped Nichrome wire in proximity to a vertical polymer sample (from Ref. [6], used with permission of author).

to 1256 K (1800°F) for the first 30 s (to establish ignition and burning of the polymer), followed by a setting of 922 K (1200°F) for the next 30 s. The apparatus in Figure 16 is placed in a large (1 m × 2.3 m × 2.4 m) enclosure, with a single nozzle for impulsive release of the suppressant agent, and baffling similar to the UL2166 test. The suppressant is introduced to the enclosure at 60 s.

The test configuration has similarities to hot wires in contact with polymers, which might occur in electrically-energized telecom or data processing equipment. It has the advantage of variable wire temperature and polymer type, allowing examination the sensitivity of the suppression process to these variables (although only data for variation in the polymer type was reported in Ref. [6]). The tests would be more broadly useful if the power input to the Nichrome wire were given, and if the fraction of the total power which goes into the polymer were provided as well. The minimum concentration of agent for extinguishment for a given power level would be very useful (as opposed to a pass/fail result for one agent at an unspecified power level). Also, the distance from the wire to the polymer sample when the suppressant is added would be helpful for characterizing the heat flux to the polymer. To some extent, the test procedure is like other polymer burning tests with radiant heat addition, with a difference here being that the radiant source is a small wire at higher temperature (rather than a cone heater [11] or quartz heaters at lower temperature [17, 53]), with a radiation intensity which has not been characterized. In addition to the radiant and convective heating of the polymer, the wire also provides an ignition source. Rather than attempting to obtain a simplified 1-d burning configuration as in the other tests, the present test has a complicated 3-d configuration with regions of electrical heating different from the regions of flame heating (since the flames extend up the sides of the vertical polymer, and are probably not present in the small, flame-quenched area in the slot where the wire passes through).

This test is part way between a simulation of some failure mode in the field, and a model, well-controlled experiment controlling a single parameter. While the test method has some positive attributes and potential, it also has some shortcomings. The discussion above with regard to the unsteady, impulsive flow of the suppressant agent (with a mixing time constant of the same order as the extinction time) is valid here. It would be more tractable to place the sample holder in Figure 16 into a flow tunnel with steady, well characterized flow (and pseudo-steady agent concentration, slowly increased), so that both the actual agent concentration (and the flow field) were better known at the extinguishment condition. A major shortcoming of the method is that the actual heat flux from the wire to the polymer is both unknown and changing with time as the polymer surface regresses from the wire. Also, the heat flux from the flame is difficult to estimate since it is not clear what part of the flame (if any) provides heat feedback to the region with the electrical heating. Estimates of the time-varying heat flux are described below. Finally, it is the net heat flux to the pyrolyzing region of the polymer which leads to mass loss. As described above in Sect. 2.2, a major difference between the net and gross heat flux into the pyrolyzing region is due to conductive losses (into the polymer), and this changes with time, particularly at short times, and for three-dimensional configurations.

To compare the present test to other tests with added energy, it is of interest to estimate the heat flux from the hot wire to the polymer. Modeling the wire as a horizontal cylinder, it is possible to estimate the radiative, conductive, and convective heat losses from the wire [62, 63]. Assumptions in the calculations are as follows. For radiation, the calculation is straightforward, with the only variables the wire temperature (known), the surface emissivity, and the distance of the wire to the polymer surface. The emissivity of the Nichrome wire was assumed to be unity (values range from 0.79 for bright wire, to 0.98 for oxidized wire [64], while if the wire were dirty due to polymer residual, the number would be near 0.95). For simplicity, the emissivity and absorptivity of the PMMA to IR radiation was also assumed to be unity [19]. The flux on the PMMA was calculated from the net energy radiated from the wire to a PMMA cylinder of radius equal to the separation distance plus the wire radius. This radiative heat flux to the polymer as a function of separation distance between the wire and the polymer is shown in Figure 17 (dot-dashed line).

The conductive/convective heat flux from the wire is more difficult to estimate since the flow configuration is not simple. Two limits can be obtained by assuming: (1) free, natural convection from a horizontal wire, (2) conductive heat loss from concentric cylinders (i.e., the wire with a concentric polymer surrounding it, separated by an annular region of air). Since the wire is initially very close to the polymer, free convective flow is not possible, and domain-limited conduction is more realistic. Nonetheless, the actual conductive layer will be complicated by blowing (mass loss from the polymer), which will tend to reduce the conductive heat flow to the polymer. As the separation becomes larger than the boundary layer, natural convection can develop; the separation distance of the polymer from the wire at 60 s is of interest, but was not provided in the report. For the conductive heat flux, the standard concentric cylinder estimate for heat flow was used

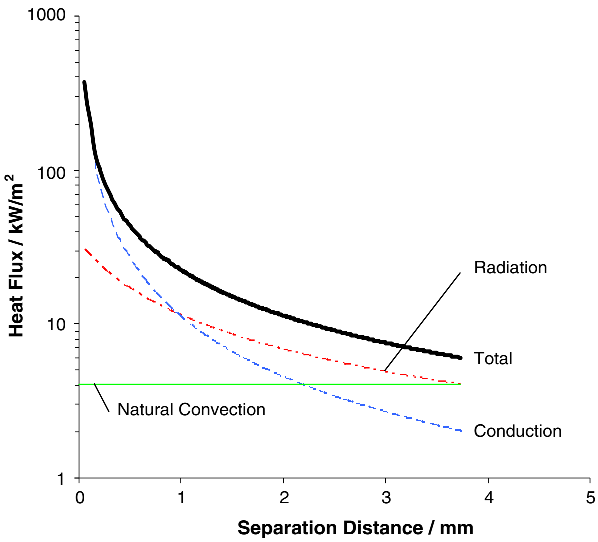

Figure 17. Estimated heat flux from a wire at 922 K (1200°F) to a polymer (at 330°C), as a function of their separation distance.

[63], with air properties at the mean of the surface temperatures. For the free convection, the standard correlations for a cylinder in cross flow (ambient air at 298 K) provided the heat losses [63], and all of the heat was assumed to impinge on the top of the slot in the PMMA (which has an area of 0.51 cm^2).

Estimates of the heat transfer from the wire to the top surface of the polymer slot from pure conduction and free convection are also shown (dashed and thin solid lines), as is the total heat flux (black line). The total includes the radiation and pure conduction, since the latter is more likely than free convection for the small separation distances expected. As indicted in the figure, there is large variation in the total heat flux with separation distance, from about 40 kW/m^2 at 0.5 mm separation, to about 10 kW/m^2 at 2 mm separation. The average heat flux will vary with polymer type since their regression rates (and hence, separation distances), will vary. Note that in general, very large variations in the heat flux can occur as the polymer regress, from about 100 kW/m^2 at 0.33 mm separation, to 6 kW/m^2 at 4 mm).

Using the heat flux predictions in Figure 17, together with the heat of gasification (1600 kJ/kg) and density (1200 kg/m^3) for PMMA [65], it is possible to estimate the regression rate of the PMMA (neglecting flame heat feedback), and then plot the separation distance (and heat fluxes) as a function of time, for the PMMA in the test as conducted. This is done in Figure 18; note that at $t = 30$ s, the wire temperature changes from 1256 K to 922 K, so the heat fluxes also change at $t = 30$ s. The local heat fluxes are very high at low times, but decrease rapidly as the surface regresses. The estimates here may also be higher than in practice due to neglect of the conductive losses into polymer. These losses create

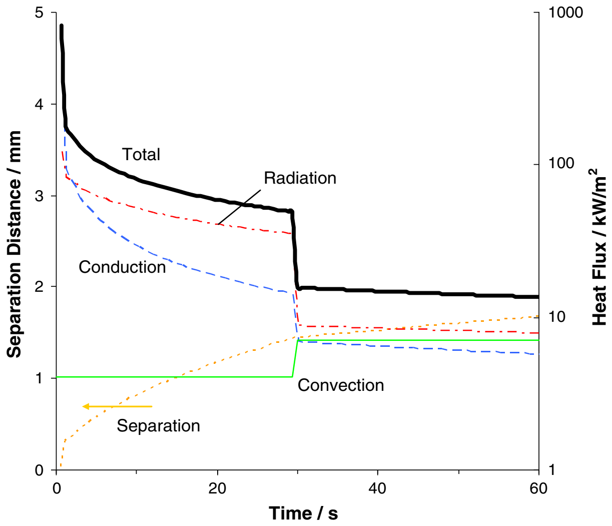

Figure 18. Estimated separation distance and heat fluxes (radiation, conduction, and free convection) as a function of time for a wire close to a horizontal PMMA surface.

lower net heat flux into the polymer, lowering the mass loss rates at early times—before a steady-state temperature distribution in the polymer has been established. Nonetheless, the three-dimensional, irregular, shape of the sample and non-uniform heat flux make estimates of the conductive heat losses into the sample difficult.

Despite the challenges in completely quantifying the conditions of the test which would be useful for its use as a test method, the experiments have tremendous value. As the calculations above indicate, in this experiment designed to simulate a failing, yet still energized electrical component, the estimated heat fluxes to the surface are in the range of 6 kW/m^2 to 100 kW/m^2. Hence, for experiments which more carefully specify the external heat flux, values in this range could conceivably be relevant.

As indicated in Figure 18, the estimated separation distance at 60 s is about 2 mm. The actual separation distance in the experiment, however, can vary due to: experimental positioning errors, sagging of the Nichrome wire when heated, flame-induced heat transfer, and buoyancy- and capillary-induced flow in the polymer melt [47]. The purpose of the heat flux calculation above is not to predict, a prior, the separation distance as a function of time, but rather, to show the *variation* in the heat transfer with separation distance, so that the difficulty of accurately controlling this parameter in the test is illustrated.

Finally, the area for heat addition from the electrical source is not the same as the area for flame heat feedback. This is because the flame extends up the side of the PMMA sample, rather than being attached to the underside of the slot where the wire is adding its heat. The result is that the total heat input into the polymer is distributed to a larger area, so that the conductive heat losses—which are very important at short times—become very large, leading to a lower burning rate and weaker flame than if the electrical energy and the flame heat flux were added at the same surface. Also, because of the complex configuration, the heat feedback from the flame to the surface is poorly characterized and hard to estimate.

It would be valuable to compare the extinguishing concentration of HFC-227 in this test to that in other configurations which involve energy-augmented combustion. To do this we need to know the heat feedback from the flame to the polymer, the conductive heat losses to the interior of the polymer sample at the time of extinguishment, the heat flux from the wire to the polymer. These can be estimated, but would require significant work. The mass loss rate data as well as the MEC as a function of wire temperature and preheating time would be very informative.

Wire Cable Bundles with Heated Nichrome Wire: In a follow-up conference paper, Robin et al. [7] describe a test to simulate suppression of energy-augmented combustion fires. In the test, an assembly of seven wire cables, each 15.2 cm long, is grouped together. The jacket of each cable contains a number (perhaps five) of individual insulated wires (unspecified size). An 18 AWG (1.024 mm diameter) Nichrome wire is inserted into the jacket of the central-most cable, and the Nichrome wire is heated to 1800°F (983°C). The wire ignites and burns for 60 s, when the suppressant is added. The same agent injection system and enclosure is used as in the Vertical Polymer Slab test described above. While the test does assess the suppressant requirement for HFC-227 for this particular configuration, it is not a very challenging test, and few details are provided which would help to make the results more universally useful (for example, the power input to the wires is not supplied, so the energy flux cannot be estimated).

The main difficulties have to do with the short time scale of the test, the area where heat is applied, and the flame stabilization. The heat is applied deep within the cable bundle, whereas burning occurs from jets of fuel gases from the pyrolyzed polymer insulation emanating from the ends of the cable bundle where the Nichrome wire enters and exist. Hence, the flames likely extend several inches up past the burning cable bundle, where they provide little heat feedback to the polymer, and even less (or no) heat to the area where the resistive heat is applied. Because the heated wire is buried deep in the cable bundle, most of the energy is spread out to metal and polymer mass which is not participating in the combustion process. That is, the cable bundle act as a large heat sink, so that most of the energy being put into the system preheats the insulation and wire, but does not cause more mass of polymer to be pyrolyzed. If the sample were allowed to burn longer, the burning rates (and likely, required suppressant concentrations) would be higher. In the present test, most of the energy conducted into the sample from the hot wire preheats the mass (which has not yet had a chance to burn). Placing the Nichrome wires on the outside of the wire bundle (and set to some reasonable power level) would be a more challenging test configuration for the suppressant, yet is still a plausible scenario.

<u>Test Methods Based on Controlling the External Heat Flux.</u> Other researchers have taken a different approach, and have devised experiments in which the heat

flux to the burning polymer is more accurately specified and controlled. These include tests in which the polymer is heated (externally or internally) by resistive Nichrome heating wires [9, 54–57], and others which impose a radiant flux on the sample [10, 11, 17, 52, 53, 58]. These researchers, while demonstrating the effect of the added energy on the suppressant requirements, have not reported estimates of the appropriate external flux level to simulate suppression of actual failure modes in electrically-energized fires.

Resistively Heated Polymer Samples: Niemann et al. [9] report a test method for the suppression of resistively-heated polymer samples. In it, the test sample (in this case, PMMA) is heated with Nichrome wire, which is either wrapped on the exterior surface, or sandwiched (with spacers) between two slabs of the polymer. The polymer sample is placed in a V-shaped holder, which is centrally located and raised about 20 cm above the floor in a test chamber (measuring $\sim$1 m on each side). The suppressant agent is added to the enclosure with a single nozzle located near the top, and injection velocity, together with buoyancy-induced natural convection currents (from the burning material) in the enclosure, provide mixing of the agent with the air. Two power levels were tested: 48 W and 192 W, and the test concentration necessary for extinguishment was determined.

As discussed in the section above, the unsteady agent addition and poorly characterized agent mixing with the air lead to two problems in data interpretation. First, it is difficult to know the concentration of agent (or it's time variation) actually reaching the burning polymer when it does (or does not) extinguish. Second, the stochastic nature of the mixing and release process will lead to natural variability in the test results, requiring a larger number of tests to accurately define the concentration boundaries for extinguishment, or non-extinguishment. Also, when the agent is released impulsively, it is hard to interpret the effect of flow field changes due to the impulsive agent release on the flame stabilization. That is, the flame stabilization may be modified by subtle changes in the flow field near the stabilization point of the attached flame on the polymer when the agent is impulsively added to the test volume.

Despite the shortcomings in the method, it has some advantages. It does provide a general overview of the effects of heat addition to a burning polymer on the MEC. As with other tests with Nichrome wire described above, the amount of added energy *could* be continuously varied, so that suppressant requirements could be determined as a function of added power (although only two power levels were used in the present work). The heat is added to the polymer surface (in the 192 W case), which is where it can have the largest effect on the suppressant concentration for extinguishment. Also, the heat feedback from the flame overlaps to some extent (but not completely) with the area for heat addition from the wire. As with most of the other tests described above, any material or agent can be tested.

A challenge in interpreting the test results concerns the amount of energy added to the polymer. From the physical arrangement of the polymer sample with heating wires, it is difficult to know what fraction of the energy added to the wires actually makes it into the polymer. This is especially true for the configuration of the 192 W heat input case, but also true to some extent for the 48 W case (i.e., what fraction of the wires is in the polymer vs. outside). Assuming that 100% of the energy in the 48 W case makes it into the polymer (which sandwiches the Nichrome wire), this power corresponds to an energy flux of 6.8 kW/m^2. For the 192 W case, the energy flux is 110 kW/m^2 to 220 kW/m^2, based on 50% or 100% of the energy making it into the polymer.

Driscoll and Rivers [57] report further results using the same apparatus as in Niemann et al. In Driscoll and River's work, several shapes of PMMA are tested, and a cylinder (7.6 cm length $\times$ 2.54 cm) diameter was chosen for further testing. This cylinder was wrapped with Nichrome wire, and 225 W was added from a 12 V source. The energy flux to the PMMA was 32 kW/m^2, based on the total energy to the wire, or 16 kW/m^2 based on half of this energy making it inward). The concentration of FC-218, FC-3-1-10, HFC-23, and HFC-227 necessary for extinguishment (and to prevent re-ignition) was measured (along with acid gas production). Niemann et al. [55, 56] continued the work in Ref. [57] to provide data for extinguishment by HFC-125, HFC-218, and FK-5-1-12.

It would be useful in tests such as these for the researchers to always include data on the suppressant concentrations with no heat addition (or better, as a function of power levels). Then, the quantitative effects of the heat addition on the suppressant concentrations would be clearly demonstrated. Nonetheless, the results for the resistive wire heating of polymer samples can be compared with other tests with added energy, and this is done in the section "Comparison of Suppressant Requirements in REED and Wire-Wrapped PMMA Tests" below.

FM Global Fire Propagation Apparatus: In early work describing test methods for assessing the flammability of plastics, Tewarson and Pion [17] describe the equivalence of increased oxygen mole fraction in the air with externally added radiant heat. Using their method, they estimate the heat flux from the flame to the polymer, heat losses from the polymer surface, heat of gasification/pyrolysis/depolymerization, and the "ideal" burning rate (which is defined as the ratio of the heat supplied by the flame to the heat required to gasify/de-polymerize/pyrolyze the polymer; i.e., the burning rate which would occur if any heat loss terms were matched by an external heat input). Their method uses a horizontal polymer sample 60 cm^2 to 100 cm^2 in a chimney, with controlled atmosphere, and exposed to an external radiant heat flux. As the authors suggest in the conclusions of the paper, suppressants could be added to the air stream. While the authors did not present the data in such a way, it is possible to extract the values of the volume fraction of nitrogen necessary for flame extinguishment of the PMMA samples, as a function of the external radiant flux. Figure 19 shows the effect of external radiation on the required nitrogen for extinction of flames over PMMA in air from their data. As indicated, an external heat input of around 7 kW/m^2 leads to a doubling in the MEC. These tests are conceptually the same as those in the Radiantly Enhanced Extinguishing Device (REED) described below, but the sample is larger, and the experiments in Ref. [17] predate those in the REED by 20 years. Although Tewarson and Pion allude to suppression tests in the device with other agents, they do not perform those tests in this work. In more recent work, Xin and Khan [66] use the same apparatus to explore the relationship between exposed heat flux and nitrogen volume fraction at extinction.

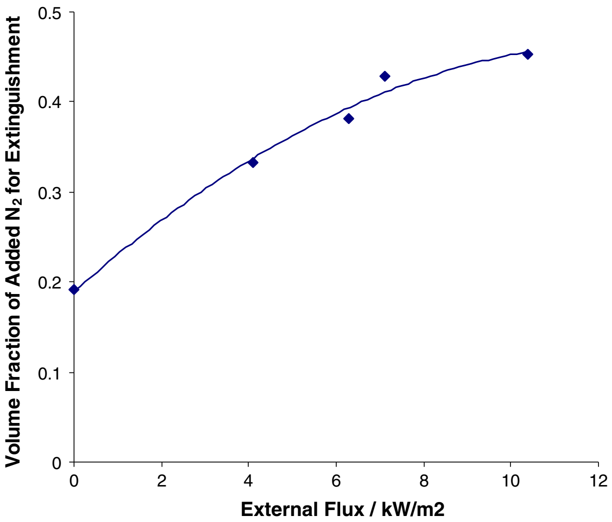

Figure 19. Required nitrogen added to air for extinction of flames over PMMA as a function of external radiant flux [17] (points: experimental data; line: curve fit).

FM Global 50 kW-Scale Apparatus: The FM Global 50 kW-Scale Apparatus of Tewarson and Khan [52, 53] is used to expose 10 cm × 10 cm × 2.54 cm PMMA slabs to radiant fluxes of 50 kW/m^2. A chimney permits addition of controlled atmospheres containing increasing amounts of suppressant (in these tests, CF_3Br), until extinguishment is achieved. The experiment measures mass loss rate, heat release rate, combustion efficiency, and production rates of CO, unburned hydrocarbons, and fluoride and bromide ions. At 50 kW/m^2, a volume fraction CF_3Br of about 0.06 is required to extinguish the PMMA, which is higher than the results of Bayless et al. [57] (0.03 and 0.048 ± 0.008), obtained at lower input energies (6.8 kW/m^2 and 16 kW/m^2 ± 5 kW/m^2).

Advantages of the test are a relatively well defined suppressant concentration and flow field, simple configuration, the possibility of testing a wide range of materials, and a relatively well defined energy input.

Radiantly Enhanced Extinguishing Device: Steckler et al. [10] and Donnelly and Grosshandler [11] describe a device for estimating the effects of external heat loads on the clean-agent extinguishing concentration for flames over burning polymers. The REED is a cross between a cup burner and the cone calorimeter. In it, a small, 2.54 cm diameter, 2.54 cm long polymer cylinder is placed at the location of the usual fuel cup in the cup burner, and air flows up a surrounding chimney, with co-flowing guard nitrogen in a second chimney around the first. A radiant heater identical to that used on the NIST cone calorimeter [67] sits above the polymer sample and provides a known radiant heat flux to the burning polymer sample. A propane torch lights the polymer sample, which is pre-burned for 200 s.

Agent is added to the air stream incrementally, with a 30 s waiting period between concentration increases. The procedure is repeated until extinguishment.

The technique has some desirable properties. The concentration of agent at extinguishment is well known, as is the radiant flux applied to the surface. The stabilization conditions of the attached flame are nearly constant and well-characterized. Any material which can be formed to the required sample shape can be tested, and the extinguishing concentration can be examined for a range of imposed external heat fluxes (from 0 kW/m^2 to about 150 kW/m^2).

The method also has some shortcomings related to the net energy transferred to the sample. The heat flux delivered to the sample depends upon the absorptivity of the sample to infrared radiation from the cone, and for some materials, this can change somewhat during the test. Also, for charring materials, a char layer will act as an insulator, and reduce the net energy conducted to the decomposition layer. While this isn't necessarily bad (the same polymer subjected to an electrical resistive heating load will act similarly), it requires that some care be exercised when designing the test protocol and data reduction, so that comparisons of required suppressant concentrations are made under consistent net heat flow conditions. Similarly, heat losses due to conduction into the interior of the polymer sample will reduce the net energy available for fuel-species generation, and these will be unsteady in time. The temperature profile in the solid polymer changes with time, especially at short times, and these are somewhat difficult to characterize because of three-dimensional effects for the small samples of the test. The effects of varying conductive losses play the same role as variable pre-heating of the sample, which has been shown to affect suppressant requirements for burning polymers [45, 46], as well as the electrical ignition of PVC cable [68]. Hence, it is important to determine the suppressant concentration for extinguishment at consistent conditions of conductive heat losses and sample preheating.

A significant challenge with applying the REED method is determining the actual heat addition rate from the electrical source in a typical energy augmented combustion fire in a telecom or data processing fire scenario, so that the appropriate heat flux can be used for comparison in the REED test. Heat addition from radiant heaters is equivalent to that from an electrical short; however, there has been little work done to characterize the heat flows to burning polymers from failing electrical components. Estimates of the heat fluxes in some of the other test methods proposed for Class C fire suppression by clean agents are discussed in Sects. 2.4.2 and 2.4.3, where a comparison is also made of the heat added through the radiant source, or through the wrapped Nichrome wire, and their effect on suppression concentrations.

Other Miscellaneous Test Approaches.

Heated Metal Surface Ignition of Premixed Gases: In a pair of papers [12, 13], NIST researchers examined the autoignition temperature of premixed hydrocarbon-air mixtures in the presence of various fire suppressants. For ethylene as the fuel, the agents tested were N_2, IG-542,[2] HFC-23, HFC-227ea, FC-218, and FC-3-1-10. In addition, methane, ethylene, and propane were tested with CF_3Br, CF_3I,

[2] composed of 0.52 N_2, 0.40 Ar, and 0.08 CO_2 volume fractions.

N_2, HFC-227ea, and C_2HF_5. The heated metal surface was nickel foil, which was heated to the range of 760°C to 1100°C until auto-ignition occurred. The effect of the suppressant on the autoignition temperature was determined. Also, the concentration of agent required to suppress all hot-surface ignition in the tests with ethylene was determined [13].

For all of the fuels, CF_3Br raised the autoignition temperature by 100°C to 200°C at a volume fraction of only 2%, and the effect for CF_3I was similar for CH_4 and C_2H_4 fuels. HFC-227ea and HFC-125 raised the autoignition temperature for ethylene, but lowered it for methane, and HFC-125 also lowered it for propane. To completely suppress hot-surface ignition of premixed, stoichiometric ethylene-air mixtures, agent concentrations near to the propane-air + 10% inerting concentrations were required for all agents (except in the case of FC-3-1-10, which required twice the inerting concentrations). The inerting concentrations are much higher than the suppression concentrations for flames.

These results demonstrate the tendency of both chemically reacting and inert fire suppressants to require more agent at higher temperatures. For example, the inert agents tested in ref [13] required 1.5 to 1.8 times as much agent to suppress the hot surface autoignition as to suppress heptane cup burner flames, whereas the HFCs required 1.9 to 2.3 times as much, and the FCs, 3.1 to 4.8 times as much. While it should be noted that autoignition chemistry is somewhat different from propagating flame chemistry, the lowered effectiveness at higher temperature has also been noted for *flame suppression* in cases of enriched oxygen combustion (as described above in Sect. 2.2.2).

The question naturally arises as to whether the configuration in the tests of Hamins [12] and Braun [13] is realistic with respect to suppression of electrically-energized fire suppression. While overheated metal components of that temperature are possible, as has been noted [7], it does not seem likely that such high temperatures (on the order of 1000°C) would exist for long. Copper (the likely conductor) melts at 1085°C; and to maintain the metal at a high temperature without overheating and failing, the power input rate (i.e., current and voltage) would have to be matched very closely with the heat loss rate to achieve a near steady-state. Flammable decomposition products could be present from pyrolyzing polymers, and they could premix with air, in stoichiometric proportions, and impinge on a hot surface; however, a more likely scenario is a diffusion flame.

The most significant results of the hot-surface tests are the quantities of agent required to completely suppress ignition. The primary role of hot metal surface in these tests, besides promoting the autoignition, is to preheat the reactants. As described above in Section "Effects of Heat Addition on Suppression", heated reactants require more suppressant for extinguishment. The results of Hamins [12] and Braun [13] illustrate that the same appears to be true for autoignition.

NASA WSTF Tests for EVA Suit Wire-Failure Ignition: Recently, NASA technicians examining an Extra-terrestrial Vehicle Activity (EVA) suit which had just been returned from space, found frayed wires [59]. The wires could have been an ignition source during an EVA, with severe consequences in the oxygen-enriched environment of the suit. In order to understand the shorted-wire ignition of materials on the interior of the EVA suits, researchers at the NASA White Sands Test

Facility (WSTF) developed three new tests and evaluated them. Two tests, the Multiple Locations Intermittent Arcing Method (Scratch Test) and the Single Location Intermittent Arcing Method (Poke Test) used a needle-like anode electrode to scratch or poke through a test material (fabric) against the cathode. The third method pressed a thin wire of diameter 0.16 mm to 0.0158 mm (34 AWG to 54 AWG) against the test fabric, and the current (regulated) was increased until wire failure. The power supply for the tests was designed to simulate the voltages and currents of the EVA battery pack, and delivered voltages between 2 V and 35 V, and currents, 0.6 A and 6 A. The third test was found to be the most challenging (and thus most conservative) and was used for the understanding the ignition risk in the EVA suits.

Several findings of the report are of particular value in the present work. Current was generally more important than voltage. Material configuration affected the ignitibility, and frayed materials ignited at much lower power. In the Scratch Test and Poke Test, it was difficult to insure that the arcing event was in intimate contact with the test material (if it were not, ignition did not occur). Similarly, in the wire-break test, if the wire were in direct contact with the material, the power required for ignition was much lower than if it were not in contact. A significant finding of the testing was that while all three tests methods could ignite the fabrics, the third test ignited them with the lowest power. The reason was that the wire heating test preheated the surface of the polymer, making fuel species available in the gas phase for ignition. Further, the energy added during the preheating of the wire up to the failure point was three orders of magnitude greater than the energy released during the wire-failure event.

The findings from the NASA WSTF tests are of significance to the electrically-energized fire suppression test desired in the present work. Preheating of the test material prior to its burning and suppression must be considered both in the analysis of the equipment failure mode, and in the development of the test method itself. This finding is further supported by the NASA Glenn Research Center results on suppression of flames over PMMA discussed below.

NASA-GRC Tests for Suppression of Flames Over PMMA: Goldmeer et al. [45] studied the suppression of flames over horizontal cylinders of PMMA in cross-flow, in normal and microgravity. The suppression was achieved through depressurization of the test volume, inducing a flow which blew-off the flames. The sensitivity of the flames to extinguishment was strongly dependent upon the degree of preheating of the PMMA, as well as on the forced convective air flow velocity in the test chamber.

Ruff et al. [46] also studied the extinguishment of PMMA cylinders in cross-flow. In their tests, the PMMA cylinder was preheated with a resistive cartridge heater in the center of the PMMA, and CO_2 was added to the air stream to extinguish the flame. The CO_2 extinguishment of PMMA was again found to be sensitive to degree of resistive preheating.

Takahashi and Katta [44] performed experiments and detailed numerical modeling on the suppression of cylindrical polymer samples (PMMA, high density polyethylene, and polyoxymethylene) and cylindrical porous surfaces fueled by methane. The configurations tested are shown in Figure 13 (note that the polymer flames were only tested in the end-up configuration, as in the standard cup burner). They noted that the requirement for heat feedback to the surface for fuel generation resulted in a much different stabilization behavior for the polymer flames, and that with CO_2 added at near extinguishment concentrations, the heat release (i.e., evaluated via the flame size [69]) was much lower. They also noted the importance of melting and dripping.

VTT Electrical Ignition Source Studies: Keski-Rahkonen and Mangs [50] described multi-faceted work to understand risks from electrical ignitions in Finnish nuclear power plants. They performed statistical analysis of fire event data from both nuclear and non-nuclear power plants. For the most common, simple mechanisms of ignition, they performed analytical modeling of the processes to understand the controlling parameters, and also performed experiments of the idealized systems which were modeled. The statistical database provided a useful overview of the problem; however, they found much uncertainty in the data. The fire incidents are reported by the fire officer in command at the fire, not through more comprehensive forensic analysis. Many of the causes are listed as "possible" or "supposed," and a significant fraction of the total are "unknown electrical." Using the statistical fire-event databases, the authors could tabulate the data in terms of the failure mechanism (e.g., overheating, short, ground fault, arcing, etc.) or the failed component (cable, switch, breaker, etc.); however, there was not enough detail to understand the sequence of events leading to the fire, or even the physics of the failure mechanism which finally occurred. This lack of detail necessary to provide the precursor events or to identify the true root causes has been pointed out by others (Madden reference in Ref. [50]) with regard to the Sandia and EPRI databases.

The physical modeling and supporting experiments of Mangs and Keski-Rahkonen are useful for understanding electrical ignitions. The authors identified a particular ignition scenario, did some literature review to understand the current state of understanding of the physics, and then made an analytical model of the phenomenon. Finally, they performed supporting experiments. One scenario approached in this way was a loose contact. It was modeled as a plane, cross-sectional source of energy in a wire, which transiently heated the wire (that was subject to convective and radiative cooling). They estimated that for a copper wire of cross-section 0.5 mm^2 to 4 mm^2, only 1 W to 12 W of electrical power was necessary to heat the wire to a temperature which would ignite combustibles nearby (200 K temperature rise), in a time of 5 s to 160 s. They also modeled, and performed experiments on, the heating of an overloaded cylindrical cable, and found that fairly high currents were required to produce 200 K of temperature rise. Based on their calculations, both of these tests, the loose contact and the overheated wire, were deemed to be plausible ignition paths. In some of their supporting experiments, they found as did others [5], that unrestrained PVC insulation on cables in a furnace quickly melted off the cables and dripped away, and hence could not be auto-ignited.

Experiments and modeling were performed for electrical arcs between metal rods. The authors, as did McKenna et al. [5] experimentally found that they had difficulty producing stable arcs, and that the copper quickly melted and failed. They also found that their arcs were so violent that they often blew-off any flames which were formed. They used batteries, however, rather than the DC arc-welding equipment which others have found to be more controllable [60]. Nonetheless, they investigated the physics of electrical arc, and estimated that for copper conductors, 36 V is the minimum for stable arcing, and that higher voltages (e.g., 50 V DC) would produce more stable arcs (This result is not consistent with the much lower voltages supporting a stable arc in the work of McKenna et al. [4, 5] and Khan [52, 53, 60]. In these latter cases, the presence of decomposing polymeric surfaces and the attendant impurities in the gas-phase arc likely affect the required voltages.).

Finally, the authors overloaded components on printed-circuit boards, and found that only power transistors were likely to lead to ignition of the boards, which could be modeled as piloted ignition.

The data collection, analyses, and experiments in the work of Mangs and Keski-Rahkonen were well thought out and executed. It seems that there is great potential in their approach, but as they also noted, they did not have the resources to pursue all of the fruitful avenues they uncovered. As pointed out by Babrauskas [68], given the importance of electrical ignition to fires in residential structures, relatively little research has been done to understand the basic physical mechanisms which lead from electrical wire faults to structure ignitions. The same is probably true for the physics of electrically-energized fire suppression: there is little fundamental understanding of what the fire scenarios are, making design of a realistic test method somewhat speculative.

2.4.3. Role of External Energy Flux in EAC Fires.

Comparison of External Energy Flux in Various Test Methods. In some of the above discussions of the individual tests, estimates were made of the external heat flux (from electrical, radiant, or adjacent flames). It is useful to gather those estimates here, and discuss them, and this is done in Table 6. For each test, the estimated energy flux to the polymer is provided in the Power Added column (and these estimations are described above in Sect. 2.4.2). This parameter is listed as the range of fluxes existing within one test (due to variation with position on the sample for the FMGlobal Electrical Arc Apparatus, or the Overheated Connection Test; or due to variation in time as the sample burns away from the hot wire in the Vertical Polymer Slabs Ignited by a Loop of Nichrome Wire test). For the Overheated Connection Test, the average heat flux on the surface of the rod (45 kW/m^2) is also estimated. For the Printed Wiring Board Test, the average range of 46 kW/m^2 to 80 kW/m^2 is estimated based on the range of voltages for which the stable arcs could be established. The last two columns describe whether the energy added from the external source was added at the burning surface, and whether the heat from the attached flame added heat where the mass loss was occurring. The tests are grouped using the same scheme as in Sect. 2.4.2 above, in the order previously presented.

The tests in which the external heat flux was specified and controlled (middle rows of Table 6) are the most straightforward to discuss. The geometry for heat addition is more-or-less constant in time and over the burning sample for all of these tests. Hence, there is only a single value of the flux for each test. This is not completely true, since the shape of the burning sample does change in the REED

Table 6
Estimated (or measured) Heat Flux to the Burning Polymer in Various Test Methods

Test method	Power added (kW/m^2)		Heat added at burning surface	
	Range	Average	Auxiliary	Flame
Tests simulating the failure mechanism with suppression				
FM Global electrical arc apparatus	100–3000	na	Y	Y
Ohmic heating test		*, dnd	N	N
Overheated connection test	10–100	*, 45	Mostly	Y
Printed wiring board test	na	46–80	Y	Y
Vertical polymer slabs ignited by loop of nichrome wire	* 6–100	Na	Mostly	N, mod
Wire cable bundles with heated nichrome wire	*, dnd	*, dnd	N	N
Test methods based on controlling the external heat flux				
Resistively heated polymer samples, Case 1	na	*, 6.8	Y	Y
Resistively heated polymer samples, Case 2	na	*, 16 ± 6	Y	Y
Resistively heated polymer samples, Case 3	na	*, 24 ± 8	Y	Y
Radiantly enhanced extinguishing device (REED)	na	0 to 6	Y	Y
FM global 50 kW apparatus	na	*, 50	Y	Y
Miscellaneous test approaches				
Heated metal surface ignition of premixed gases	dnd	dnd	na	na
NASA WSTF tests for EVA Suit Wire-failure ignition	dnd	dnd	Y	na
UL-2127 and UL-2166	0–3.2	na	Y	Y
NEBS Fire-spread test, methane igniter burner	12–32	na	Y	Y

* Could be varied but was not, na: not applicable, mod:could be modified to do this, cnd: could not determine, dnd: did not determine (but could be done with more data from the test)

experiment and in the Nichrome wire-wrapped polymer experiments. This variation should ultimately be estimated, but this estimate is beyond the scope of the present project. Shape variations which affect the external heat flux to sample could be important, and ultimately would have to be accounted for or eliminated. Also, as discussed above, there is some uncertainty in the heat flux (due to varying absorptivity to IR and wire contact effectiveness), and these would have to be accounted for more accurately than done here. Nonetheless, the effects of shape variation are expected to be secondary, and can be controlled.

The wire-wrapped polymers had heat fluxes which varied from about 7 kW/m^2 to 24 kW/m^2; presumably, these could be varied from zero to higher values as well. The REED experiment had heat flux values of 0 kW/m^2 to 60 kW/m^2, and this range could be extended up to about 100 kW/m^2. The FM Global 50 kW Apparatus used 50 kW/m^2, which again could be extended. In all of these tests, the added energy from the external source was added to the surface, which was the same location where the attached flame added energy to the polymer.

External power input fluxes were also estimated for the Tests Simulating The Failure Mechanism with Suppression, and these are listed in the top set of rows in Table 6. Several of the tests (FM Global Electrical Arc, Overheated Connection, and Vertical Polymer with Wire) are estimated to produce fluxes which vary over the surface of the tested materials. To estimate the flux from the electrical arcs in the FM Global test, the power input to the arc (1 kW) is dissipated in the (reported) 6.35 mm diameter sphere, and this flux drops off as l/r^2 (assumed distances of the polymer to the arc are 2 mm to 25 mm, and these can occur in a single test). This yields a very high flux of 100 kW/m^2 to 3000 kW/m^2, depending upon where on the adjacent burning polymer surface one is considering. For all the other tests in this group, the details of the flux estimates are provided above in Sect. 2.4.2. The flux in the Overheated Connection Test is estimated to vary from about 10 kW/m^2 to 100 kW/m^2, depending upon the location on the wire, and the average value is about 45 kW/m^2. These values could have been varied by changing the ring heater temperature; however, a varying heat flux at different positions is a characteristic of the test method. In all cases, the external heat is added to the backside of the polymer; whereas the flame heat is added at the burning surface. Depending upon the time of the test, and the thickness of the insulation, the polymer may be behaving as a thermally thin material, in which case the back-side heat addition is fine. Otherwise, this could affect the influence of the added heat. For the Vertical Polymer Slabs Ignited by Nichrome Wire Test, the energy flux varies because the burning polymer regresses in time from the adjacent hot Nichrome wire. There is probably spatial variation as well (since all parts of the polymer are not equidistant from the wire, and the flame adds heat mostly to different locations than the wire). The external energy is added at the surface of the polymer, but this may not be the same surface at which the flame adds heat. The heat flux from the wire is estimated to range from 6 kW/m^2 to 100 kW/m^2, decreasing in time as the test proceeds. The average heat flux in the Printed Wiring Board Test is estimated to range from 40 kW/m^2 to 80 kW/m^2, varying only according to the voltage and current used to establish the arc. The flux is probably relatively constant during the test. It was not possible to estimate the external heat flux in the Wire Cable Bundle Tests since the power level dissipated in the wire bundle was not given.

In the Miscellaneous Test Approaches, the external heat flux for the Heated Metal Surface Ignition tests and the EVA Suit Ignition tests were not determined, but this could have been done. The heat flux in the UL-2127 and UL-2166 tests is estimated (below) through comparison of the MEC in that test with those in the REED. The values are 0 kW/m^2 (no adjacent flames on some surfaces) to 29 kW/m^2 $\pm$ 7 kW/m^2 (where the uncertainty represents the range of fluxes experienced by the single surface). The heat flux from a flame to a burning PMMA polymer surface has also been estimated based on the mass loss rate. The net heat flux on a single vertical piece of free-burning PMMA (10 cm $\times$ 10 cm) was found to range from 12 kW/m^2 to 32 kW/m^2, depending upon the location on the PMMA, with an average value of 18.2 kW/m^2 [70], while Tewarson and Pion [17] give an average value of 17.1 kW/m^2. The heat flux in the NEBS flame spread tests is also shown in Table 6, and the rational is described below.

Another existing test method which can serve as a basis for assessing the heat flux to polymers in electronic equipment is the NEBS Flame Spread Test. As described above, one technical expert suggested that the power level of the ignition fire in the NEBS rack-level test was an appropriate level of power to consider. The logic is as follows. In the NEBS tests, using this ignition source as the initiator, and insuring that the fire-retardant capability of the adjacent components is sufficient to stop propagation, NEBS equipment has demonstrated superior fire resistance. Hence, for the same energy input, if protection is to be obtained by clean agents (instead of by meeting a NEBS standard), then they should be able to suppress materials fires subjected to the same initiating heat flux. The design fire for the NEBS tests is shown in Figure 20. The average power input in the NEBS test is 2.5 kW, over a 330 s time period, with a peak value of 5 kW. The heat flux (power per area) is estimated through analogy with the vertical PMMA slab heat fluxes used above. Since methane-air flames and PMMA-air flames have similar temperature, and their scale and configuration is also similar, the heat flux from the two flame types to a surface is probably similar. Hence in Table 6, the NEBS test is estimated to provide external heat fluxes from the line burner methane flame of 12 kW/m^2 to 32 kW/m^2.

As Table 6 shows, in the tests for which it was possible to estimate the energy flux, most fall in the range of 0 kW/m^2 to 100 kW/m^2. This is also the range in which the test results can be compared to those done in the REED device [57]. Hence, it is possible not only to compare the fluxes to which the polymers are exposed, but also the concentration of agent which extinguished the fires for the different tests when subjected to equivalent levels of added heat. To do this, of course, requires test data for the same materials. Unfortunately, many of the tests simulating the failure mechanism of components used different materials from those used in the REED tests. Also, it was not possible to estimate the heat flux in several of the tests, or the extinguishing concentration was given only as a pass/fail results, rather than in terms of a minimum extinguishing concentration. Nonetheless, for the tests which can be compared, the results are given below.

<u>Comparison of Suppressant Requirements in REED and UL Tests of NFPA 2001.</u> Since the existing tests UL-2127 and UL-2166 are the basis of the current NFPA 2001 standard for clean agent concentration requirements for Class A fires (and, hence, Class C fires), it is of interest to determine the effective heat flux to

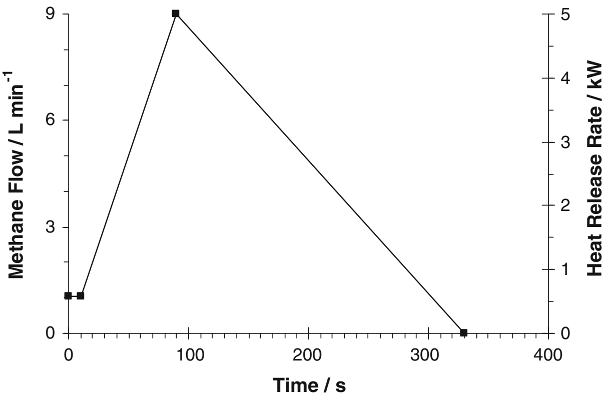

Figure 20. Input power versus time for NEBS fire test [71].

the surface of the PMMA in those tests. Since the UL tests have adjacent vertical PMMA (and other polymer) sheets, there is heat feedback from one burning surface to the other. This heat feedback will increase the suppressant requirement relative to that for sheets in isolation. Taking the suppressant concentrations in the UL tests for comparison, the REED experiments can be examined to determine the heat flux for which that concentration of agent was required. This was done, and the results are listed in Table 7. As indicated, the heat fluxes are in the range of 2.2 kW/m^2 to 3.6 kW/m^2. That is, the flame on the first sheet of PMMA appears to impose a heat flux of 2.2 kW/m^2 to 3.6 kW/m^2 on the second sheet. Hence, REED heat fluxes of the order of 2.2 kW/m^2 to 3.6 kW/m^2 replicate the amount of agent for suppression of the flames from the adjacent PMMA sheet in the UL-2127 and UL-2166 Class A test.

Comparison of Suppressant Requirements in REED and Wire-Wrapped PMMA Tests. The agent required to extinguish PMMA samples with heat added by wrapping with Nichrome wire [57] can be compared to that with heat added radiantly (i.e., the REED experiment [11]). As a rough estimate, we can assume for the wire-wrapped PMMA that 50% of the energy dissipated in the Nichrome wire goes into the polymer (i.e., half of the heat flow inward, half outward). This would be a lower limit, while an upper limit would be to assume that 100% of the energy to the wire makes it into the PMMA. These estimates provide the energy flux into the polymer, and the extinguishing concentration of agent is given [57] for these conditions. Using these values of the heat flux from the wire-wrapped PMMA experiments, the REED extinguishing conditions at those values of the heat flux are found from the data of reference [11]. The equivalent heat flux values are 6.8 kW/m^2 [9], 11 kW/m^2 to 22 kW/m^2 [9], and 16 kW/m^2 to 32 kW/m^2 [57], and the agents considered are HFC-23, HFC-227ea, FC-2-1-8, and FC-3-1-10. The extinguishing volume fractions of the agents at the equivalent values of the heat flux are shown in Figures 21; 22 shows the data of Figure 21 together with the data for the agent IG-541. In the figures, the average value of the NIST and 3 M data (when available) are given for the REED device [57], and the error bars for the Y-axis represent the limits of these two results. For the wire-wrapped PMMA, the values of the extinction concentration are given for flames with some re-flash, or complete inertion, and the error bars in the X-axis represent the limits

Table 7
NFPA2001 Class A PMMA Suppressant Requirement [72], and the REED Heat Flux [11] at that Concentration, for Several Agents

Agent	NFPA 2001 Class A X_{ext}	REED X_{ext}	REED Flux
HFC-227ea	0.058	0.058	2.2 kW/m^2
HFC-23	0.11	0.11	3.1
IG-541	0.326	0.326	3.6

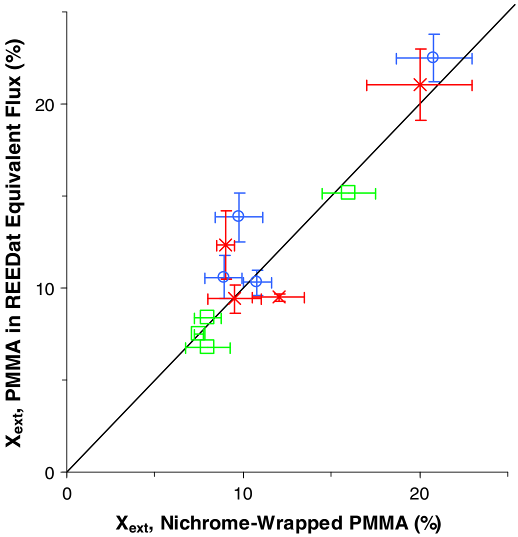

Figure 21. **Agent (HFC-23, HFC-227ea, FC-2-1-8, and FC-3-1-10) extinguishing volume fraction for PMMA with Nichrome wire heating, or at an equivalent heat flux achieved in the REED device (○: Ref. [57]; □ and +: 48 W and 192 W cases of Ref. [9].**

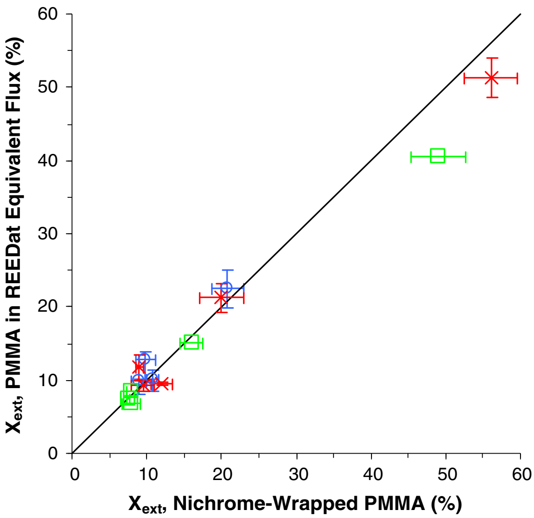

Figure 22. **Agent extinguishing volume fraction with the agents in Fig. 21 as well as with IG-541 for PMMA with Nichrome wire heating, or at an equivalent heat flux achieved in the REED device (○: Ref. [57]; □ and +: 48 W and 192 W cases of Ref. [9].**

of these values. As the figures show, the two measurements (with the error bars shown) agree with each other within about 15%.

Adding energy to the polymer surface with the REED device appears to be equivalent to adding by wrapping with Nichrome wire. That is, as shown above, the wire-wrapped PMMA extinguishment results give extinguishing concentrations in close agreement with the REED device. In addition, the NFPA 2001, UL-2166 and UL-2127 tests give results for multiple PMMA sheets which are also consistent with the REED test results (at equivalent levels of imposed heat flux).

The agreement in Figures 21 and 22, while quite good, could be improved even more if other factors were controlled. For example, the configurations and air flow (and hence flame stabilization) differ somewhat between the test methods, and these can affect the suppression process. Also, as described above in Sect. 2.2.1, the energy flux of interest is really the net flux to the polymer, not the imposed external flux. Nonetheless, these additional effects are expected to be of secondary importance for the tests compared here, but in other configurations, the additional effects may be more significant.

Fundamentally, if energy were added to the surface of a burning polymer, it will increase the suppressant requirement for extinguishment. It would not matter too much if the energy were added radiantly, with conducting hot surfaces, or from adjacent flames. The primary challenge is to understand the conditions of actual energy-augmented combustion electrical fires sufficiently well to determine the appropriate energy flux levels (in the REED or any other test method).

Comparison of Suppressant Requirements in Other Tests. Two additional tests can be compared with the REED results: the FM Global Fire Propagation Apparatus tests and the Vertical Polymer Slabs Ignited by a Loop of Nichrome wire test, both of which were performed with PMMA. The FM Global FPA tests and the REED tests are shown in the upper curves of Figure 23 (for N_2 extinguishment). As indicated, the results agree well. For the vertical PMMA with the hot wire, the extinguishing volume fraction of HFC-227ea was given as <0.058. It is difficult to estimate the heat flux for this condition, since the separation between the wire and the PMMA at the end of the test (when the suppression occurs) is not known. Nonetheless, using the REED results for this agent with PMMA [58] indicates that a volume fraction of HFC-227ea of <0.058 implies a heat flux of <7.8 kW/m^2. Using Figure 17, we see that this corresponds to a separation distance of >2.9 mm. While the exact details of the conditions is this test are hard to specify (as described in Sect. 2.4.2), the two tests give consistent results. It should also be kept in mind that the phenomena described above (stabilization and heat losses) are not completely controlled between the tests, so exact agreement is not expected.

Effect of External Added Energy on Suppression Concentration.

General Comments: It would have been very interesting to have results, from all of the test approaches described above, at variable amounts of external heat input. This would be useful because: (1) The amount of external heat added in real, failing electrical components is not well known, so understanding the sensitivity of the suppressant requirements to this parameter is important, and (2) Data from all the tests

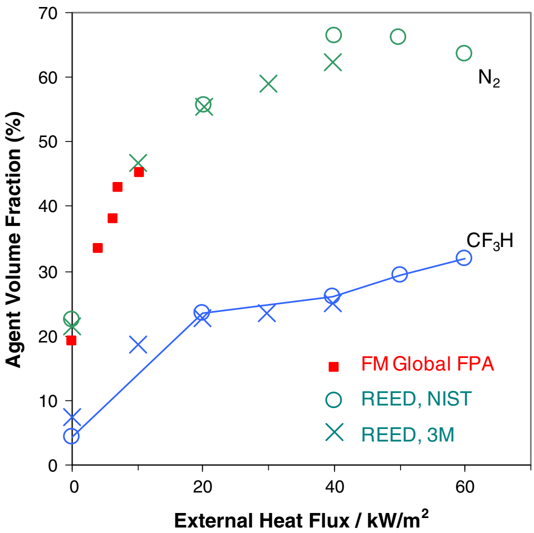

Figure 23. HFC-23 or N_2 volume fraction for extinguishment of PMMA in the REED device as a function of external heat flux (NIST and 3M results are given). Tests with N_2 extinguishing PMMA in the FM Global FPA [17] are also shown.

at the same values of the external heat flux would allow cross-comparison of the test results, which probably could be unified with the relevant fundamental parameters. Of course, these test results would be needed for the same materials (Preheating and stabilization conditions would have to be accounted from as well, but to first approximation, external heat flux and material type are probably most important.).

The influence of heat addition on the suppressant concentration is most clearly shown by the REED test results, since these were done for a range of external heat flux values. For all agents tested, the required agent volume fraction for suppression increased rapidly at low external heat flux. Such results are illustrated for N_2 and CF_3H in Figure 23. As the tests for other agents show [58], doubling the suppressant concentration in the REED device requires low heat fluxes, around 9 kW/m^2 for inert agents, and around 6.4 kW/m^2 to 8.1 kW/m^2 for HFCs. At higher external heat flux, the amount of agent tended to reach a maximum, beyond which the increase in agent requirement was little or none. This is consistent with the findings in the suppression tests of arc-heated PVC cables by CF_3Br [60], in which the flames were extinguished even at very high external heat fluxes.

Influence of Gas-Phase versus Solid-Phase Heating: As indicated above for PMMA (Figure 23), an external heat flux of 6.5 kW/m^2 is required to double the amount of CF_3H necessary for suppression in the REED device. It is of interest to estimate the external heat flux which would be required if the heat was added only to the gas-phase products rather than to the polymer surface. This can be done as follows. As a rough estimate, one can assume that the effect of the gas-phase temperature on the suppression of flames of PMMA combustion is similar to that of methane combustion. This is a reasonable assumption since it has been demonstrated that flame suppression behavior of hydrocarbon fuels is very similar because they are all dominated by the same chain-branching radical reactions, common to the hydrocarbon fragments created by breakdown of the initial fuel molecule [71]. Also, for PMMA in a cup burner like configuration [44], the MEC for CO_2 was found to be essentially the same as for cup burner flames with methane as the fuel [26]. Hence, using the experimental cup burner results described above (see "Effects of Heat Addition on Suppression" in Sect. 2.2.2 "Fire suppression"), a doubling of the CF_3H extinguishing requirement implies a change in the oxygen volume fraction in the oxidizer from about 0.21 to 0.27, which corresponds to a change in the final temperature from 2230 K to 2456 K, or 226 K. A free-burning PMMA sample 10 cm × 10 cm × 2.54 cm, horizontal or vertical, loses mass at about 8 g/m^2/s [74], and its complete combustion requires 2.5 mol air/m^2/s. To raise this amount of air by 226 K requires a heat flux of 17 kW/m^2. Hence, a local energy density of 17 kW/m^2, added to the gas phase, would likely raise the final temperature of the products by about 226 K and cause an increase in the amount of CF_3H for extinguishment by a factor of two. This is two or three times the external heat flux that was required in the REED device (which added the heat to the polymer surface). Hence, adding energy to the polymer surface appears to have a much larger effect (by about two or three times) than adding the energy to the gas phase. This is likely due to the positive feedback of the system: heat added to the polymer surface creates more fuel, which creates a larger flame, which increases the heat feedback, etc.

Component Temperature or External Heat Flux as the Relevant Parameter: One question which has been raised is whether the relevant parameter to duplicate in a test method is the failed component temperature or the heat flux from the failed component. If the failed component is being considered as a possible ignition source, then temperature is important. However, in the context of the current project, it can be assumed that ignition has already occurred; i.e., a fire has been detected, a clean agent is about to be deployed, and the question is how much agent needs to be added; i.e., does the failed equipment add energy to the system and does this energy affect the quantity of agent required for suppression. Hence, considering the failed component not primarily as an ignition source, but as a source of additional energy, is more relevant.

From the discussions above in Sect. 2.2.1, the main effects of added heat are to raise the temperature of the burning polymer (or the gas phase). The final temperature of the polymer (or the gas phase) is determined by an energy balance, and that is controlled by the heat flows. Of course, *one* parameter affecting the heat flow is the temperature. In general [75], the amount of heat transferred is proportional to the temperature difference, the area, and the heat transfer coefficient $\dot{q} = hA(T - T_0)$; radiation transport is an exception in which the heat transfer is proportional to T^4. The only limitation on the temperature of the heat source is that it be higher than the object into which the heat is flowing. Since polymers typically decompose at relatively low temperatures (300°C to 500°C), and heat can be added to air at the air inlet temperature, or to the polymer at lower temperatures (preheating), the heat source temperatures need not be excessively high. Of course, high heat fluxes (power per unit area) typically require high temperature sources, but it is the heat flux which is the relevant parameter. To some extent, that is influenced by the power available in the equipment.

2.4.4. Recommended Test Method.

Overview. Based on the energy fluxes from the simulated equipment fires, and the thoughts of the technical experts, significant energy addition to the burning materials can occur for some configurations in the field (either from adjacent flames, large-area initial ignition, conductive heat transfer from a component, or radiant heat transfer from failed components). Hence, a test procedure must include this parameter as a variable. A review of the fundamental aspects of suppressed flames over burning polymers with energy addition indicates that the forms of the added heat, radiant or conductive (e.g., from a resistive source) are equivalent. It was not possible in the present project to gather enough information to understand the appropriate energy flux level from energy-augmented combustion for all electrically energized equipment fires (nor did the review of the literature indicate that anyone else has done this, although progress has been made). Nonetheless, the review suggests that a test procedure based on radiantly heated polymer samples with two limiting fluxes is appropriate, as discussed below.

Considering the background material outlined in the present report, it is possible to specify the desired qualities in a test procedure for determining the suppressant concentrations necessary for extinguishing a wide range of electrically energized equipment fires, and these are listed in Table 8.

If one wanted a relatively conservative test method, it would have:

1. *Constant (low-power) ignition source*. In the application to be protected, a recurring ignition source could exist, separate from the failed component adding the energy. These could include a small arc discharge from a shorting com-

Table 8
Desired Properties in Test Method to Determine Suppressant Quantities for Class C Fires

1. Not too expensive or time consuming
2. Accurate and repeatable
3. Applicable to a wide range of electrically energized equipment fires
4. Known concentration of agent at the flame stabilization point when extinguishment occurs
5. Well-characterized, and strong flame stabilization (i.e., consistent and tractable configuration, known and consistent flowfield and gas velocity)
6. Understood, consistent, and repeatable level of material preheating and conductive heat losses
7. Well-characterized and variable (down to zero) amount of added energy to the burning polymer surface
8. Desired level of radiant input from simulated adjacent flames can be incorporated
9. A range of materials can be used (especially realistic ones), that can be formed to the shape required by the test method, accounting for the desired level of melt-drip containment
10. Independent ignition source, which adds little additional energy to the combustion process, with controllable start and stop times

ponent, an attached flame, or an adjacent flame. Hence, a continuous ignition source should be included.

2. *Optimum ventilation and good flame stabilization*. Since both the ventilation condition and stabilization are very configuration dependent, and such a wide variation in shapes and configurations is possible in the field, one must consider that both good flame stabilization and adequate air flow could be present.
3. *Heat input from and adjacent flame*. The arguments in item 2 above apply here. Unless one is considering just a particular piece of equipment, the possibility exists for adjacent burning materials.
4. *Realistic materials, thicknesses, and configurations*. While test methods can be developed and run with any materials (for example PMMA, which is nearly a standard for materials flammability studies), the arguments about the volume fraction of agent required for suppression should be based the materials contained in the equipment to be protected.
5. *Variable external heat flux*. Since there are expected to be a wide range of possible failure modes in electrically energized equipment fires, it is important to determine the sensitivity of the suppressant requirements to the flux of added energy.

The properties in Table 8 constrain the test method. For example, items 4 and 5 imply that the device has a chimney, with controllable, quasi-steady agent concentrations and gas velocities. Items 6 and 9 imply that the sample might not be too small, or that special attention to transient heat losses will be required. Items 7 and 8 concern the energy addition, and require discussion. A radiant source (as in [11, 52, 53]) is possible, as is a Nichrome wire-wrapped sample. In the latter case, intimate contact could be insured with pre-loading of the wires against the polymer; however, if the material intumesces, or melts excessively, maintaining the proper location of the wires would be difficult. Also, as discussed above, the amount of energy which makes it into the polymer is not straightforward to estimate a priori, although measurements could be made (e.g., mass loss) to characterize this heat transfer. One could use a thermally-thin sample around a resistive cartridge heater, but sample preparation for a range of material types might become challenging. Of these possibilities, radiant energy input appears to be the easiest to apply since it can be used with a wide range of material types, and excessive custom sample preparation is not required. Item 10 on the list implies that a small pilot flame or low-energy spark igniter with programmable duration is available.

One can't completely specify the test method until the supporting characterization experiments have been done. For example, we do not yet know the appropriate input power levels. Nonetheless, based on the energy fluxes estimated for the test procedures proposed to date to describe electrically energized equipment fires (see Sects. 2.4.2 or 2.4.3), we can propose a test method, and provide two realistic energy fluxes as upper and lower limits.

Test Method Configuration. The basic configuration recommended is a horizontal sample, with insulated bottom and edges, in a chimney with a radiant heat source above. The chimney allows controllable oxidizer flow velocity and composition (set by the operator), and the agent concentration is increased slowly until extinguishment occurs. The radiant source allows direct examination of the effect of added energy on the extinguishment. To contain any melted sample, the test material is wrapped on the bottom and sides with aluminum foil. The foil provides the added benefit of maintaining the heat flux to the sample relatively constant as the sample surface regresses. A small methane-air pilot flame 1 cm above the surface and slightly in from the edge provides a continuous ignition source. The sample size and thickness is variable. The thickness of the materials should be that expected to be used in the equipment. The perimeter should be as small as possible to allow a smaller heater and chimney. A size of 10 cm × 10 cm is large enough, but it is worth considering a smaller sample.

A configuration like the FM Global Fire Propagation Apparatus [17] seems reasonable. A variation of that apparatus used for testing of Halon 1301 extinguishment of PMMA with added heat [52] is shown in Figure 24. It has a chimney, controllable agent/air concentration and flow, controllable energy input, and reasonable sample size (10 cm × 10 cm × variable thickness). All of the parts of the device typically used for measuring heat release rate would not be necessary

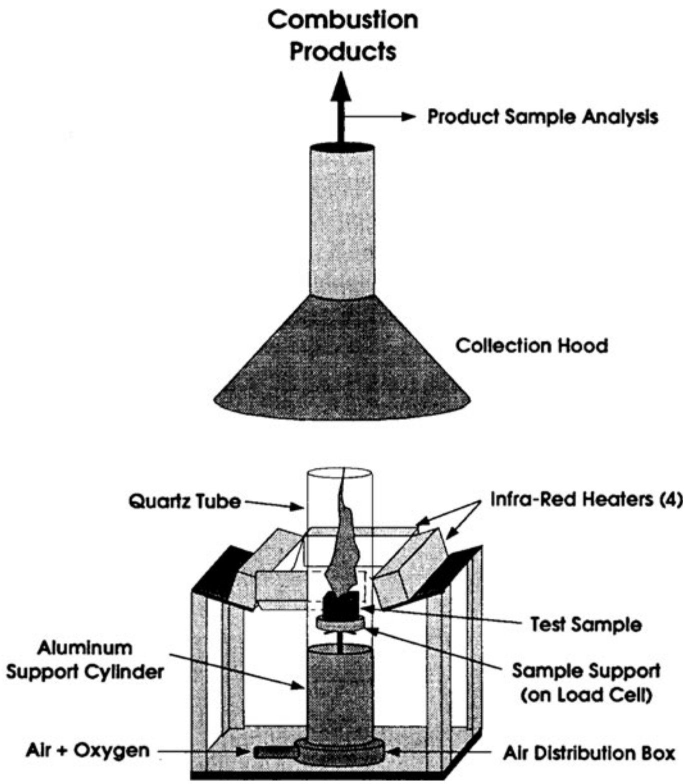

Figure 24. FM Global flammability apparatus (50 kW scale) [52].

(although in some situations they would be useful for research purposes). A disadvantage is that the heaters in the FM Global device use a relatively high-temperature source, so the absorptivity of the polymer surface, which could be coated with carbon black initially, might change during the test. Alternatively, a configuration like the controlled-atmosphere cone calorimeter [76] is a possibility; however, the halogens in the clean agents might attack the cone heater too rapidly, and the quantities of agent required might be too large (the nominal air flow is much larger through the cone). The REED device is a possibility if the sample size can be shown to be large enough (or if the sample holder can be modified to control heat losses), or if larger samples are used, and a continuous ignition source is added. The REED device is shown in Figure 25 (A guard flow of nitrogen from the outer chimney in the REED device is intended to reduce corrosion of the cone heater—and this could be done in the cone calorimeter as well. While no adverse effects of acid gases on the heater were reported in the REED tests, the possible need for further remedial action should be kept in mind.).

In this test method with a radiantly heated sample in a flow chimney, the power input would need—at some point in the agent specification process—to be connected to the power levels actually expected in the protected equipment. This con-

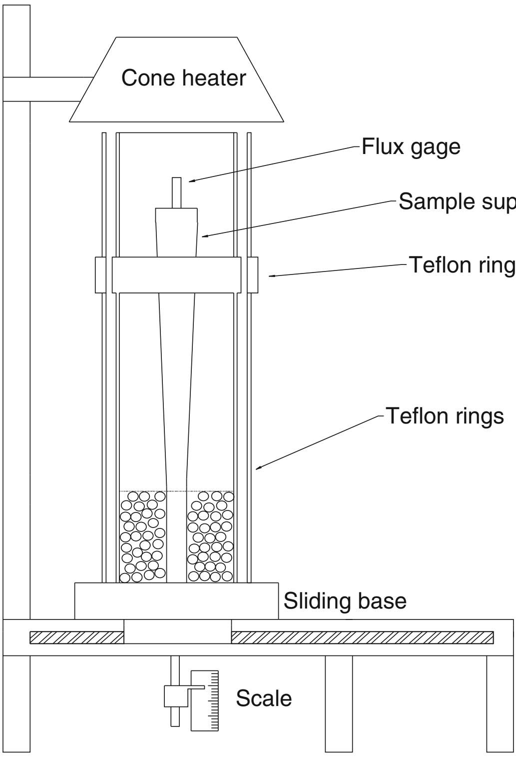

Figure 25. Radiantly Enhanced Extinguishing Device (REED) [11].

cern has been expressed in earlier work [6]. It is believed, however, that determining the appropriate (if any) power input level which occurs in applications in the field is required for any test method. For example, in the Tests Simulating the Failure Mechanism with Suppression described in Sect. 2.4.2 above, engineering judgment was required to determine the appropriate power level to assign in the test method to represent failures in the field. As described above, these tests can serve as a basis for specifying the radiant flux levels in the proposed test. A similar process will be required for applying the proposed test method to specific threats in energized electrical equipment for which laboratory simulations have not yet been performed. Nonetheless, two limiting cases can be specified already, as described below.

Added Power Levels. Two power levels are recommended initially. The first, 20 kW/m^2, represents a power input to the burning material only from an adjacent flame on similar burning material. No power input from an electrical source is simulated here, only the possible scenarios in which the burning material is in a configuration where the burning surfaces interact with each other. This is essentially a lower limit of plausible heat flux. The source for this number is the estimate of the heat flux from a flame on PMMA to the burning material (12 kW/m^2 to 32 kW/m^2) [17, 70], described above. This number is likely to be similar for other burning polymers (besides PMMA) since the adiabatic flame temperature of hydrocarbon flames is similar, and the heat transfer is dominated by the flame temperature.

The second recommended heat flux corresponds to well-heated, melted cables, with a continuous electrical energy source. To estimate the flux appropriate for this scenario, we can examine the REED results [58]. In those tests, the required agent for extinguishment increases roughly linearly at low flux, and then asymptotes to a constant concentration at higher flux. The heat flux at which the agent concentration asymptotes (generally around 50 kW/m^2) represents the heat flux at which the heat losses (transient heating, edge losses, re-radiation) are no longer affecting the marginal burning rate. That is, below about 50 kW/m^2, the flame temperature likely increases with flux, whereas above 50 kW/m^2 the flame temperature is probably a maximum, constant value. Some justification of this number also comes from the estimates of heat flux from simulated failed electronic components to the burning polymers in the section above: Tests Simulating the Failure Mechanism with Suppression. The heat flux values, listed in Table 6, are 10 kW/m^2 to 100 kW/m^2 in the overheated connection test, 4 kW/m^2 to 80 kW/m^2 in the printed wiring board test, and 6 kW/m^2 to 100 kW/m^2 in the Nichrome Wire Near PMMA test. The estimates are listed as ranges since the heat flux varies with position on the polymer. For the Overheated Connection Test, the average heat flux is at least 45 kW/m^2. Based on these estimates, heat flux values of 50 kW/m^2 can be representative.

A few additional details remain in applying the proposed test method to the problem of suppression of fires in energized electrical equipment. In the test procedure, the role of preheating will require attention. For example, at a given input flux, the amount of preheating prior to suppression will affect the MEC. When repeating the suppression tests, it should be possible to quickly identify the approximate MEC, so that consistent values of the preheating time (for example, 2 min), can be used when the flame over the sample is suppressed. In addition, tests must be conducted using realistic materials. Finally, as described above, for cases of added electrical energy between the limit cases, the amount of power possible for a failed component (and the associated energy flux) must be estimated and then specified for the radiant heating tests.

2.5. Recommended Research

The approach intended for the present project at the outset: literature review, survey of industry experience with suppression of electrically energized equipment fires and fire event databases, threat definition, and test method evaluation and development is sound. Nonetheless, the work to date suggests that a key additional component is needed. Because the statistical fire data as well as industry surveys are not expected to provide the level of detail necessary to understand the physical phenomena well enough to specify a realistic test method, expected failure modes must be identified, and then studied through laboratory experiments and analytic modeling. Since the range of equipment environments and failures is too wide to be handled together initially, this must be done on a case-by-case basis until general principles can be developed. The steps recommended to approach this problem are listed in Table 9 below.

This is basically a hybrid approach. It uses the statistical database examination of Keski-Rahkonen and Mangs, the survey or McKenna et al., the specific design

Table 9
Recommended Future Research to Specify a Test Procedure for Suppression of Electrically Energized Equipment Fires

1. Do a survey, as broad and as deep as possible, to understand the fire events which have occurred in the equipment of interest
2. Collect statistical data on fire events in electrically energized equipment fires. Using the statistical data and survey, categorize the failures in terms of equipment classes (e.g., energized DC power cable fire, energized AC power cable fire, power supply failure, PWB circuit short, battery room fire, etc.)
3. Consult with equipment experts (perhaps at organizations like the National Electrical Equipment Manufacturers, NEMA) who understand the equipment failures well, and can provide insight on what their typical failure mechanisms are.
4. Categorize the fire events in terms of the relevant parameters (using Table 4 as a guide), and develop as many Example Cases as necessary to cover the classes of fire events of interest.
5. For specific Example Cases, model the failure and do laboratory experiments in support of the modeling, to understand the importance and values of parameters in Table 4 for that particular Example Case
6. Conduct suppression studies in the experiments developed above which mimic the Example Cases
7. Select an appropriate power level for the radiant test procedure, and refine the standard test method procedure outlined in Sect. 2.4.3 above (or select a new one) to be appropriate for the Example Case examined in the modeling and experimental work
8. Categorize the Example Cases in terms of the relevant parameters, and group them together, if possible, in similar test procedures

failure approach of McKenna et al. and Keski-Rahkonen and Mangs, and modeling of Keski-Rahkonen and Mangs. Yet after the failure is understood, is seeks to put the relevant fundamental parameters into a test method in a controllable way, as in the work of Babrauskas, Grosshandler and Donnelly, Smith and Rivers, and Tewarson and Khan. The key feature is that it is approaching the problem initially in terms of specific equipment failures, seeking to understand the controlling parameters in that case, and using these specific example cases to determine the relevant values of the controlling parameter. Then, the appropriate test method—-which has the correct cut-off values of the controlling parameters, can be specified. Only after this has been done for a number of specific failure modes (example cases) will it be apparent whether some general principles or approaches to the test methods can be applied, and what the appropriate grouping of the recommended test procedures is for the range of threats expected in the field.

3. Conclusions

The problem of suppression of fires over condensed phase materials with heat addition from an electrical source has been reviewed. Discussions with industry technical experts in fire suppression have been outlined, and a number of cases studies have been presented. Suggested test methods for determining the suppressant requirements for fires in electrically energized equipment have been reviewed. Approximate estimates of the energy fluxes in those tests have been made and compared. The major conclusions of the present study are listed below.

1. The material burning rate (and suppressant concentration) is very sensitive to the heat feedback (especially near extinction); hence, changes to the net external heat flux (from any source) will affect the minimum extinguishing concentration of suppressant.
2. Based on analysis of the test procedures simulating electrical failures proposed to date, the magnitude of the external heat flux in most of the tests is similar in magnitude to that which can be obtained with radiant heating experiments.
3. In cases where the external heat flux could be estimated, the materials were the same, and the flame stabilization was similar, the suppressant concentration measured with the different tests agreed with each other reasonably well.
4. Many of the test methods previously proposed do not combine the relevant parameters in ways which produce the most conservative (yet plausible) test.
5. A test based on an external radiant heat flux source, a large sample (10 cm $\times$ 10 cm) in a chimney, and realistic materials is a good starting point for a test procedure.
6. Two radiant flux levels in the proposed test method are suggested:

   (a) an incident flux of 20 kW/m^2 as a lower limit, representing the heat input without any electrical augmentation, but with an adjacent flame on similar burning material (which enhances the burning);
   (b) an incident flux of 50 kW/m^2 for cases representing sufficient electrical energy to bring the polymer to its decomposition temperature and main-

tain it there (in the absence of the flame). An example of this would be an energized cable fire.

7. To assign appropriate energy flux levels for electrical power addition intermediate between these two limits, better understanding of specific electrical failure modes is required.
8. An approach to determine the realistic power levels for situations between the limiting cases is suggested. The first steps are to survey the fire suppression industry and to collate statistical data on electrical fire incidents. These must be followed, however, by three additional steps: obtaining input from electrical equipment hardware experts (or experts in forensic investigation of electrical failures), performing laboratory experiments, and modeling to simulate the likely failure events so that the values of the relevant controlling parameters can be estimated.
9. The appropriate value of the external heat flux can be determined with either a prescriptive- or performance-based approach. As in item 8.) above, example cases for specific failure modes in the field can be developed, and then used to specify the heat flux and materials for the test procedure (to protect that threat). Alternatively, the test can be performed for a material at a range of fluxes, and it will be up to the system designer to determine the flux to be experienced in a failure for a specific piece of equipment, and the agent design concentration would then be specified for that application.

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