EFFECTIVENESS OF CLEAN AGENTS ON BURNING POLYMERIC MATERIALS SUBJECTED TO AN EXTERNAL ENERGY SOURCE

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INTRODUCTION

Testing over the past few years has shown that liquid and solid fuel fires burning in the presence of an uninterrupted electrical energy source can be more difficult to extinguish than those fires burning without such a source [1,2,3]. This situation can pose problems to a system designer during selection of a proper extinguishing design concentration. Critical applications exist where electrical energy passing through the equipment cannot be immediately and automatically powered down or turned off. In a Class C fire event, an uninterrupted power supply can continue to reignite the Class A or B fuels within close proximity. If sufficient electrical energy remains on during and after a system discharge, tests have also shown that, with inadequate agent concentration, surrounding materials may readily reignite.

The NFPA 2001 Standard on Clean Agent Fire Extinguishing Systems [4] provides guidance for selection of design concentrations for clean extinguishing agents. The design concentration is found by adding a safety factor to the minimum extinguishing concentration for a given fuel, determined by the cup-burner method [5] or by full-scale testing. Section A-1-4.2.3 of NFPA 2001 suggests that clean agents are suitable for use around electrical equipment. This same section continues to describe that the electrical equipment could be the source of ignition and should be powered down prior to or during the agent discharge. Section A-3-7 provides the following additional guidance:

> Energized electrical equipment that might provide a prolonged ignition source should be de-energized prior to and during agent discharge. If electrical equipment cannot be de-energized, consideration should be given to the use of extended discharge, the use of higher initial concentration, and the possibility of the formation of combustion and decomposition products [4].

No criteria for identifying the appropriate agent concentration in the event that electrical equipment cannot be immediately and automatically de-energized are provided. Therefore, for facilities where immediate power-down is not desirable or not an option. information needs to be provided outlining appropriate extended discharge times or appropriate higher level of initial concentrations. This research continues the ongoing effort to quantify those criteria.

PURPOSE AND OBJECTIVES

During the past two years, testing at the National Institute of Standards and Technology (NIST) has shown that current minimum design concentrations may be inadequate to extinguish fires of polymeric materials when subjected to an electrical energy source [6]. Additionally, as levels of radiant energy are increased, there is a need for higher extinguishing concentrations to achieve flame extinction and maintain fire control.

This paper documents part of a continuing Cooperative Research and Development Agreement (CRADA) between NIST and 3M Company. Six clean extinguishing agents are being evaluated in a continuous energy fire scenario, the purpose of which is to create a testing apparatus that provides an indication of the effectiveness of clean agents when subjected to electrically heated surfaces as might be present in Class C fire hazards.

It is hoped that this may lead into a standardized test method similar to the cup burner. The test apparatus, called the Radiant Enhanced Extinguishment Device (REED), will be able to provide a minimum extinguishing concentration for agents for a specified radiation level and. if appropriate. list the practical limits of the agent. This will generate recommendations for future studies for determining how the test data from the REED should be correlated with actual energized fire events.

APPARATUS DESCRIPTION

The REED was first developed in early 1997 at NIST. Initial testing included a characterization period, which provided necessary information for identifying the range of test conditions. including fuel sample size, gas flow rates, and operating procedure for determining the inertion concentration. The main components of the REED are the circular brass base. two concentric Pyrex tubes, a brass shield, glass bead mixing chamber, fuel platform, conical heater, and three calibrated rotameters for monitoring gas flow (Figure 1).

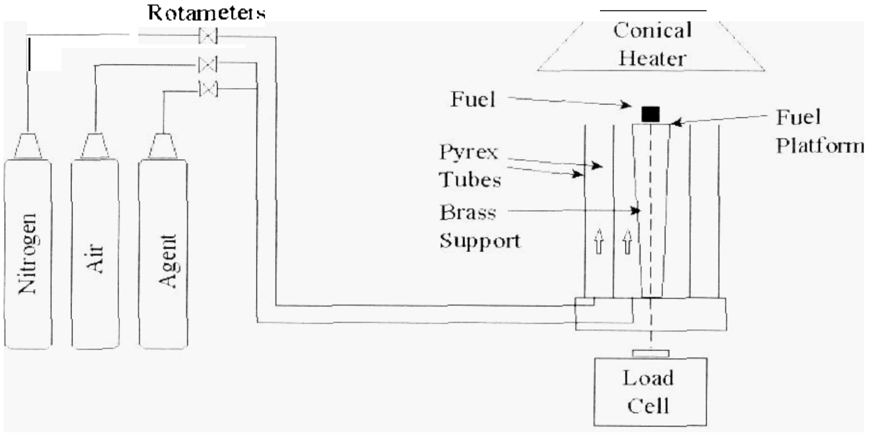

Figure 1. REED apparatus schematic.

A circular brass base serves as the foundation of the REED and rests on an aluminum platform. In the center of the base is a threaded hole allowing attachment of a hollow brass support. This brass support is tapered and similar in shape to the cup found in a cup-burner apparatus. The shape of the support limits the amount of turbulence in the gas flow at the top of the Pyrex tubes. An aluminum rod extends from a load cell beneath the platform and base up through the center hole in the brass support where a recessed fuel platform is attached. The load cell allows collection of mass loss data. Recessing the fuel platform beneath the top level of the support and the contour of the support prevents lifting of the sample platform. thus allowing accurate mass loss data to be recorded.

The base has a diameter of 152.4 mm (6 in) and is 31.8 mm (1.25 in) tall. Two machined annular rings allow Pyrex tubes to rest easily in the brass base and prevent them from tipping over. The Pyrex tubes create two passageways for gas travel. The innermost tube has an inner diameter of 76 mm (3 in) and outer tube has an inner diameter of 124 mm (4.88 in). This inner tube diameter is slightly smaller in comparison with the new ISO/NFPA cup-bumer internal diameter of 85 mm [4]. Two holes have been drilled from the top and side of the brass base, which allows passage of gas through the base and into the two chambers created by the concentric Pyrex tubes. The innermost chamber carries air mixed with extinguishing agent while the outermost annulus carries a flow of nitrogen. The nitrogen serves as a protective shield and funnels the flow of decomposition products away from the cone heater. Pyrex glass beads, nominally 5 mm in diameter, fill the bottom of both chambers to a height of 75 mm (2.95 in) and provide a mechanism for mixing the air and agent mixture.

The conical heater used in the REED prototype at NIST has an 80 mm (3.15 in) opening at the top and a 190 mm (7.48 in) opening across the bottom. The cone heater was selected to provide the continuous energy because it offers a repeatable, measurable, uniform, and constant energy source. The cone is controlled with a variable voltage source, and the heat flux levels are measured using a Schmidt-Boelter type heat flux gauge.

An aluminum box, 244.5 mm (9.6 in) wide and 311.2 mm (12.3 in) deep, which was constructed out of 3.2 mm (0.13 in) thick aluminum, encloses the brass base and Pyrex tubes. The front section of the box is removable for specimen placement and a Pyrex glass window is provided for viewing. The purpose of the box is to minimize the effect of cross drafts from affecting the gas flow at the fuel specimen level.

A second REED constructed at 3M has been in use since July 1998. The main components of this REED (brass base and support, Pyrex rubes, glass beads and gas piping) were all constructed to the same tolerances of the original prototype built at NIST. However the cone heater, its supporting hardware and a temperature controller were components of a commercially available cone calorimeter, purchased as a packaged unit. This conical heater has an 80 mm (3.2 in) opening at the top and 160 mm (6.3 in) opening at the bottom.

The temperature of the cone heater is monitored by three symmetrically disposed thermocouples wired in parallel to a temperature controller. The controller maintained the heaters at a constant radiant heat output. A metal bracket, installed on the side frame of the cone, was used to hold a Schmidt-Boelter type heat flux gauge with an operating range of 0-100 kW/m^2. Also included on the cone heater is a 10 kV electric sparker. This is used at elevated heat flux levels to ignite the off gases from the sample.

A box was constructed out of 3.2 mm (0.13 in) aluminum, which encloses the brass base and Pyrex tube portion of the apparatus. A small cutout was made in the top center portion of the front wall to allow insertion and removal of fuel specimens. The front wall of the box is left in place and the cut out remains open during testing. The top of the box rests 12.7 mm (0.5 in) below the bottom of the cone heater and prevents cross drafts from affecting the gas flow. The 12.7 mm (0.5 in) space allows protective shutters to be opened and closed during testing.

Methods for exhausting the products of decomposition differ between the two laboratories, The original REED at NIST was placed on a laboratory bench top underneath a large exhaust hood. A flexible tube, approximately 15 mm in diameter, was attached to the hood at one end while the other end was held in place over the top of the cone heater. The 3M REED is placed entirely in a fume hood while the rotameters and necessary controls are mounted outside of the hood in a nearby cabinet.

TESTING MATERIALS

Six extinguishing agents (N_2; IG-541 (52% N_2, 40% Ar, 8% CO_2); FC-2-1-8; FC-3-1-10; HFC-227ea; and HFC-23) were chosen for this study because they are likely halon alternatives. Of these six agents, nitrogen and FC-2-1-8 are currently not listed in the 1996 Edition of NFPA 2001; however, data for both have been submitted for inclusion in the next edition. The remaining four gases are listed in the 1996 Edition of NFPA 2001. Two agents. N_2 and IG-541. are inert gases; FC-2-1-8 and FC-3- 1-10 are perfluorocarbons; and HFC-227ea and HFC-23 are hydrofluorocarbons. Selected properties for all six agents can be seen in Table 1.

TABLE 1. SELECTED PROPERTIES OF CLEAN AGENTS

Extinguishing Agent	N_2	Inergen	C_3F_8	C_4F_{10}	C_3HF_7	CHF,
NFPA 2001 designation	IG-100	IG-541	FC-2-I-X	FC-3-1-10	HFC-227ea	HFC-23
Molecular weight (g/mole)	28.0	34.0	188.0	238.0	170.0	70.0
Vapor pressure (Mpa) @ 25 "C	14.48	15.2	0.88	0.29	0.46	4.73
	(cylinder pressure)					
Boiling point (°C)	-195.8	-196.0	-37.0	-2.0	-16.4	-82.1
Heat capacity (vapor)(kJ/kg °C) @ 25 °C	1.041	0.574	0.794	0.804	0.808	0.737

Polymethylmethacrylate (PMMA) was chosen initially as a fuel because it has a consistent burning rate, undergoes no surface charring, and produces a low amount of soot. These properties and behavior make it an ideal fuel for scientific studies. Although PMMA serves as an ideal fuel source for testing purposes. it does not reflect many of the materials present in electrical equipment. The fuels chosen for the current study include gray PVC, natural ABS, and polypropylene. The specimens are 21.5 mm long cylinders cut from 22.5 mm diameter rods. These materials were selected because they are likely to he included in the construction of electrical equipment either as wiring insulation or as a plastic protective enclosure. Aluminum foil was wrapped around the bottom and curved surface of the specimens to minimize edge effects and contain dripping.

TEST PROCEDURE

A period of testing was sei aside in the early stages at NlST for device characterization. The distance from the top of the sample to the bottom of the cone heater was examined before 35 mm (I .38 in) was selected. This distance was chosen on the original REED because it allowed the cone to reach 40 kW/m^2 without reaching the maximum position on the power supply. The gas flows were determined by examining mass loss data for multiple PMMA sample sizes. The flows for air and nitrogen were chosen to remain constant at 10 L/min and 20 L/min, respectively. This resulted in the flows having approximately the same velocity from the channels based on the device geometry. Extinguishing volume fractions were then determined by slowly increasing the extinguishing media until flames from the samples were extinguished.

When testing began at 3M, the distance from the top of the sample to the bottom of the cone heater was reexamined. A distance of 25 mm (0.98 in) was investigated because that is the distance used for specimen clearance in a cone calorimeter. Difficulties were experienced in keeping the sample burning when the nitrogen shield was turned on during tests using this decreased distance. Extinguishing data for nitrogen and FC-2-1-8 at 0 and 20 kW/m^2 were lower than previous results compiled when the distance was 35 mm (1.38 in). The effect of placing the sample closer to the heating element was not studied in detail as it was believed to be more important to use the same testing conditions that were present in the first series of tests.

The procedure for determining the extinguishing concentration remained the same. The air supply was set to flow at a constant rate of 10 L/m. Extinguishing agent was added in small increments until flame extinction. At that time, the flow of the extinguishing agent was recorded and the extinguishing volume fraction determined from the following equation:

$$Ext.Conc. = \frac{F_{agent}}{F_{air} + F_{agent}} \bullet 100\% \qquad (1)$$

where:

F_{agent}= Flow rate of extinguishing agent [L/min]
F_{air}= Constant flow rate of air [L/min]

RESULTS

Prior to testing at higher energy levels or with new materials with the 3M REED, tests were conducted at energy levels of 0, 20 and 40 kW/m^2 using PMMA as the fuel. This allowed comparisons between the new data and previous data collected at NIST on the original REED. When this was completed, results were found to be consistent and energy levels were then increased to SO and 60 kW/m^2.

Determination of the inertion concentration was difficult using the procedure developed at NIST; samples would bum out on their own due to the length of time used in the procedure, or they would not reignite after the initial extinguishment. Gray PVC was not amenable to the procedure at all and was dropped from the test matrix due to its inability to maintain flaming combustion even when subjected to a radiant external flux level of 20 kW/m^2. The data obtained for the two inert gas agents are plotted versus the heat flux in Figure 2. The curve displays the general trend found for all six agents. As the heat flux level is increased, the extinguishing concentration needed also increased. However, at elevated levels of SO and 60 kW/m^2, the extinguishing concentrations increased or decreased depending upon the specific agent.

The resulting extinguishing concentrations determined for heat fluxes at SO and 60 kW/m^2 are considered accurate. However, the effect of the higher heat fluxes on the extinguishing concentration is being closely examined. While checking for inertion concentrations at these higher levels. flames reappeared at locations well above the top surface of the fuel specimen. At times, reignition took place in the upper portion of the conical heater and above the top of the heater.

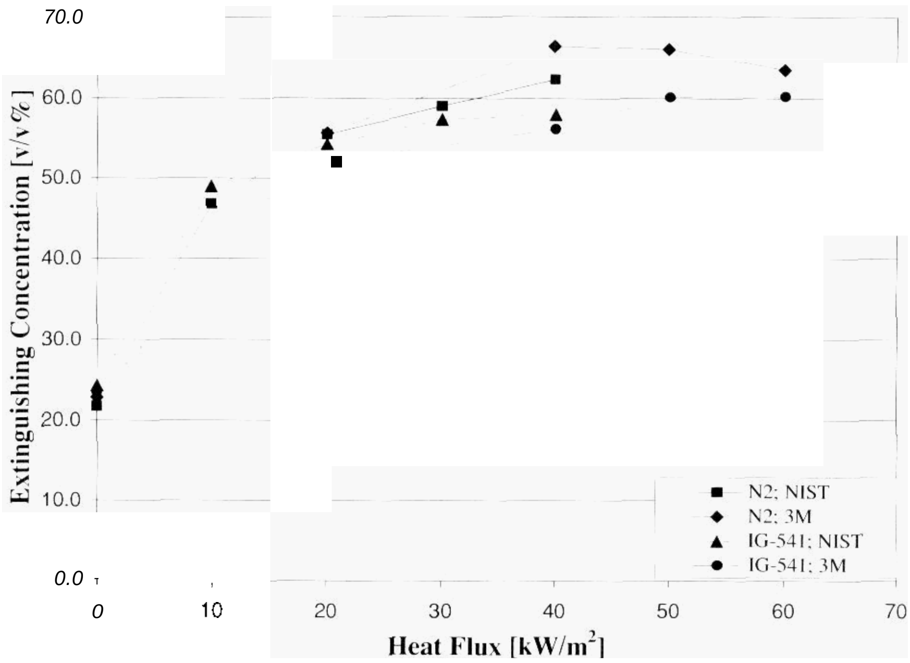

Figure 2. Heat flux vs. extinguishing concentration inert gases (PMMA fuel).

Problems similar to those observed at 40 kW/m^2 also were encountered during inertion periods at higher flux levels. In addition, high energy levels increased the burning rates to a point where the sample would burn out leaving an empty aluminum foil wrapper. Although further testing at 50 and 60 kW/m^2 was postponed, it will be reinitiated if it is found that these high flux levels can be related to events found in an actual electrical fire.

During tests at 3M and while using nitrogen as the diluent, extinguishing concentrations at 0, 20, and 40 kW/m^2 were as much as 6.5% higher than those determined at NIST. Results at 3M using IG-541 at 0, 20, and 40 kW/m^2 showed slightly lower extinguishing concentrations than the data obtained at NIST, with differences ranging from 3.1 to 4.4%.

A large difference in results between the two devices occurred with FC-2-1-8 and FC-3-1-10 at 40 kW/m^2, when the extinguishing concentrations measured **at 3M** were found to be 25 and 38% lower, respectively. The original extinguishing concentrations from the NIST data at 40 kW/m^2 were even higher than those determined at 3M for radiant external energy levels of 50 and 60 kW/m^2. This can be seen in Figure **3.** These more recent data indicate that the inertion volume fraction required for FC-2-1-8 and FC-3-1-10 may be lower than 3.2 times the cup-burner values as reported in Reference 6.

Comparisons between the earlier and current work for flux levels of 0 and 20 kW/m^2 were more consistent, with differences ranging from 2 to 8%. Extinguishing concentrations measured at 3M for both of the perfluorocarbons increased at 50 kW/m^2 and dropped at a higher level of 60 kW/m^2. This trend does not follow the pattern found in the inert gases where the extinguishing concentration dropped at both levels for nitrogen and increased slightly for IG-541.

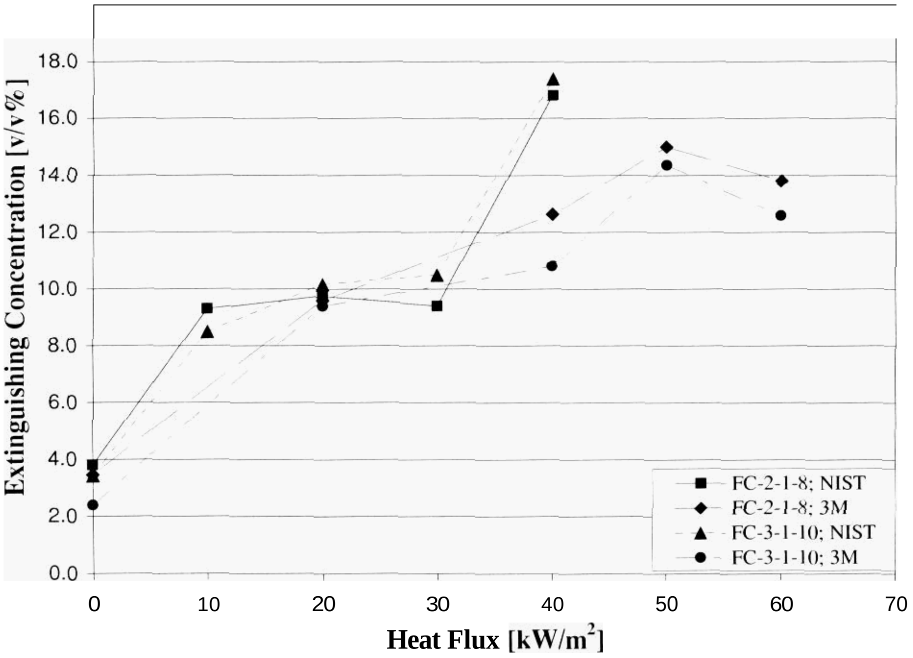

Figure 3. Heat flux vs. extinguishing concentration perfluorocarbon gases (PMMA fuel).

Results similar to the inert gases were found with the hydrofluorocarbons at levels of 50 and 60 kW/m^2; the required concentration of HFC-227ea decreased as the flux was increased from 50 to 60 kW/m^2, whereas the required concentration of HFC-23 increased at both flux levels. Data for these gases can be seen in Figure 4. The greatest deviation between the NIST and 3M PMMA data occurred with HFC-23 at 0 kW/m^2. NIST tests had established an extinguishing volume fraction of 7.6% while the result from testing at 3M was 4.4 %. Remaining values at 20 and 40 kW/m^2 were much closer, having a difference near 4%. HFC-227ea also produced similar results: however, the largest difference between the two sets of PMMA data (21%) occurred at 20 kW/m^2. Discrepancies in extinguishing volume fraction at energy levels of 0 and 40 kW/m^2 were 6.5 and 3%, respectively.

Tests with the new fuels are ongoing. To date, tests have **been** completed using Natural ABS and polypropylene at energy levels of 20 and 40 kW/m^2 using IG-541 and 20, 40, and 60 kW/m^2 using FC-3-1-10 and HFC-227ea as the diluents. Data obtained from these tests can be seen in Figures 5-7, which are plots of the average extinguishing volume fractions for each of the three previously listed agents for all tests conducted thus far. It is important to note that although the extinguishing volume fractions differ among the fuels, the effective extinguishing concentration continually rises, or is unchanged, **as** the radiant heat flux is increased.

The physical properties of the new fuels changed during the course of the tests. The polypropylene, when exposed to a radiant flux of 20 or 40 kW/m^2 melted and burned very easily. Noticeable levels of surface char were apparent on the ABS samples. At 40 kW/m^2, the top surface expanded above the top level of the aluminum foil wrap, and the small amount of exposed surface area soon became involved. To prevent spillage of polypropylene and increased surface area on the ABS samples, the side of the aluminum foil wrapper was increased upward

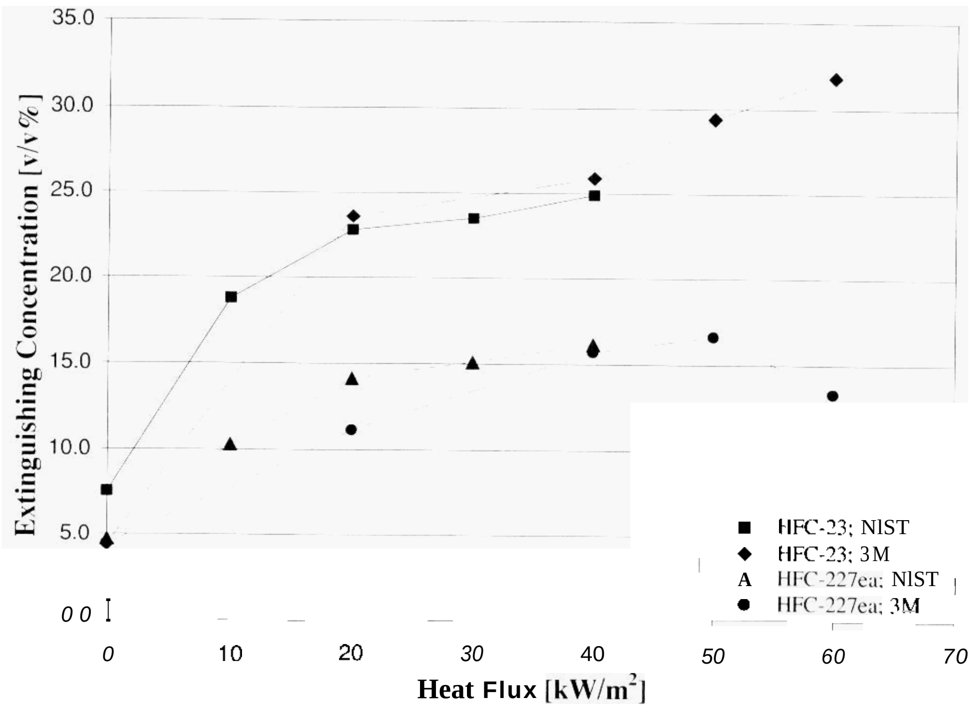

Figure 4. Heat flux vs. extinguishing concentration hydrofluorocarbon gases (PMMA fuel).

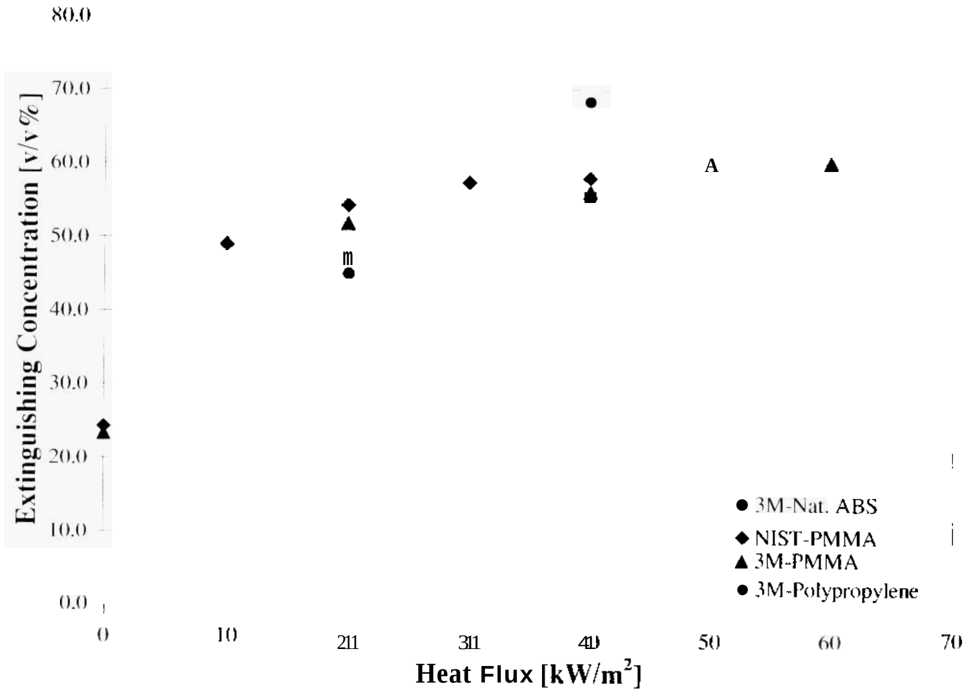

Figure 5. IG-541 diluent all fuel type comparison

approximately 3.2 mm (0.13 in). This contained the samples, but did not appear to affect the extinguishing concentrations.

Similar difficulties were experienced with the ABS and polypropylene fuels at 40 kW/m^2 while checking for inertion concentrations. Either the samples would burn themselves out prior to determination or the samples would remain extinguished.

Comparing the results for IG-541 of ABS and polypropylene with those from previous PMMA test data, no specific trend is found that shows one fuel requires a higher extinguishing concentration than another. The results in Figure 5 show that a higher concentration was needed to extinguish the ABS sample in comparison to the polypropylene sample at 20 kW/m^2 but the opposite is true at 40 kW/m^2. The extinguishing concentration required at this level for polypropylene was also more than that required for PMMA.

In Figure 6. the extinguishing concentrations for FC-3-1-10 at 20 kW/m^2 were the same for both ABS and polypropylene, yet a higher concentration was needed at 40 kW/m^2 for ABS. Polypropylene, however, needed a higher concentration than ABS for extinguishment at 60 kW/m^2. A trend can be seen in the concentration data for FC-3-1-10 and HFC-227ea (Figure 7) when comparing the "new fuel" data with results obtained using PMMA as the fuel. Although the data are limited to only a few radiant heat flux levels, extinguishing concentrations for ABS and polypropylene were below those found for PMMA at either 3M or NIST at 20, 40, and 60 kW/m^2. At the radiant heat flux of 60 kW/m^2, the extinguishing concentration for PMMA dropped to a level comparable to that found using polypropylene. In addition to the extinguishing concentration dropping for PMMA at 60 kW/m^2, note that the extinguishing concentration for both ABS and polypropylene continued to increase. Results for HFC-227ea, using ABS as the fuel, showed a more significant increase from 40 to 60 kW/m^2 when compared to FC-3-1-10, whereas, FC-3-1-10 had a higher need for increased concentration at this same level when polypropylene was used as the fuel.

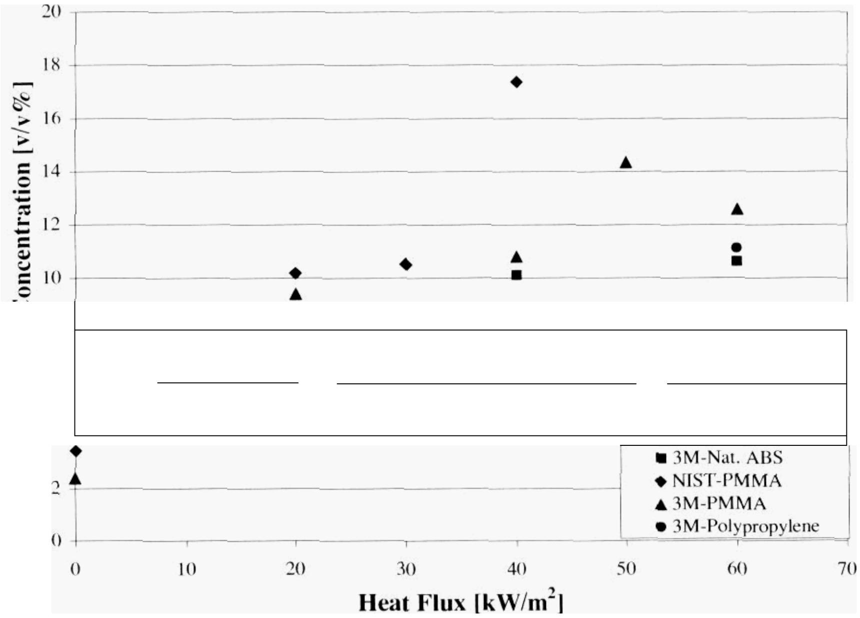

Figure 6. FC-3-1-10 diluent all fuel type comparison.

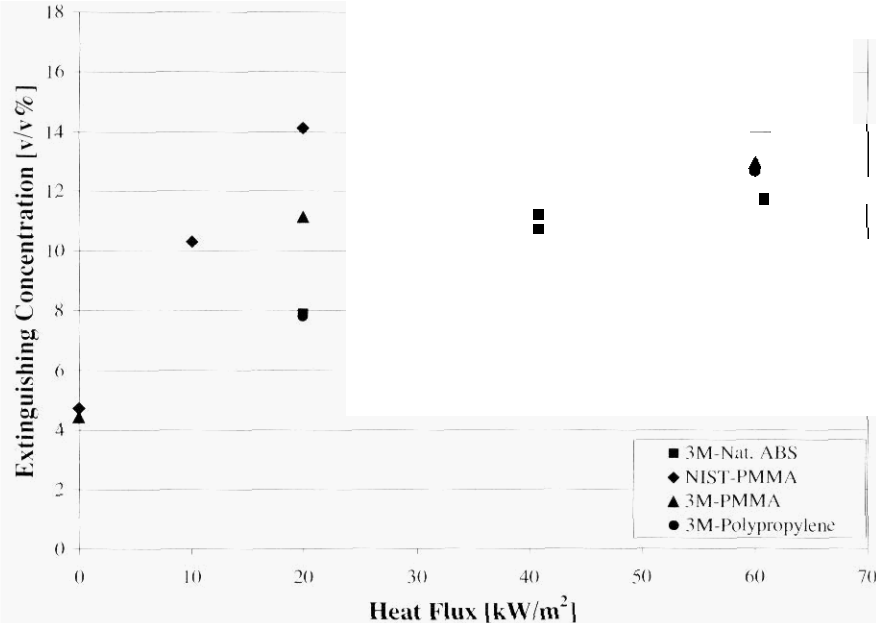

Figure 7. HFC-227ea diluent all fuel type comparison.

CONCLUSIONS

These tests have confirmed that more research is necessary to understand the effect of continuously energized equipment on extinguishing concentrations for halon alternatives. The need for higher concentrations for fuels subjected to continuously energized electrical sources was again proven through tests conducted in *a* separate facility using the same materials and an apparatus similar to that used previously at NIST [6]. These results are consistent with trends observed with different fuels and geometry by Braun [1], Driscoll and Rivers [2], and Niemann [3]. Initial indications that extinguishing concentrations as high as 3.2 times published cup-burner values are needed may need to be re-examined, although recent tests indicate values would remain near 2.5 times the cup-burner values published by NIST. This decrease should not affect the efforts being put forth, yet increase the need to determine a proper method of evaluation.

The results of these tests are preliminary and are being used to determine an appropriate method for evaluation. A direct correlation linking these test results to conditions in the field during an electrically energized fire does not yet exist. The REED does have advantages over previous work using hot metal surfaces, for the device closely resembles the cup-burner apparatus, an internationally recognized test method. In addition. the REED can provide comparison data with respect to the extinguishing concentration at a given energy level versus the No Observable Adverse Effect Levels (NOAEL) also listed in NFPA 2001. Using these criteria, design concentrations for N_2, IG-541, and HFC-227ea at energy levels above 20 kW/m² would then be above their respective NOAEL thresholds.

RECOMMENDATIONS FOR FUTURE RESEARCH

Reasons for the discrepancies between the NIST and 3M data when burning PMMA need to he elucidated. Additional testing with polypropylene and ABS is required to build up a larger statistical base for the expected variation in extinguishing volume fraction of clean agent as a function of the radiant heat flux. Alternative fuels (including PVC and polyethylene) and combinations (e.g., mixtures of PVC and PE powder, or a PMMA layer on top of a PP layer) should he examined to determine which conditions produce the most repeatable fire and consistent suppression results. Once enough data are compiled for the various **fuels** and clean agents, **a** theory should be developed for the relationship between radiant flux and extinguishing agent volume fraction. This would allow the results to be generalized in a manner similar to the way cup-burner results are generalized.

NIST is building an improved Radiation-Enhanced-Extinguishment-Device to perform the research needed. The repeatability of the REED will he determined and compared to data generated by 3M. Design specifications for the NIST facility will he made available and other laboratories are invited to participate in round-robin testing.

Although the REED can produce fundamental data that have general applicability, additional measurements in realistic energized fire scenarios are required in order to relate the results to actual field applications. What local heat flux levels can he generated in electrical equipment that is involved in a fire if the equipment is not de-energized? How do those heat fluxes correlate with the type of equipment or the rated power levels? Prior to conducting full-scale suppression tests (during which it is difficult to make the necessary concentration, temperature, and heat flux measurements), experiments should he planned to measure the local temperature, heat flux, and oxygen levels as a function of expected equipment parameters during a malfunction, including voltage input, equipment geometry, and power density. Discharge tests are then needed to determine the local concentration of clean agent at the positions where the fuel load and electrical input are likely to generate the most robust combustion (as predicted by the REED). The adequacy of the predictions can he checked at modest scale. Full-scale suppression tests should he designed so that the fuel, airflow, and the electrical power can be independently controlled, allowing full specification of the boundary conditions controlling the fire and suppression event.

ACKNOWLEDGMENT AND DISCLAIMER

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