Clean Extinguishing Agents and Continuously Energized Circuits: Recent Findings

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Abstract

Recent testing by Niemann, et al[1] indicates that even low energy, **48** W and 192 W Class C energized fire scenarios require elevated clean agent concentrations for proper mitigation of the hazard (flame extinguishment and inertion). Agents included for that study are recognized by the NFPA 2001 standard as follows: FC-3-1-10 (CEA-410), HFC-227ea (FM-200), HFC-23 (FE-13) and IG-541 (Inergen).

This study, of which this paper reports in part, involves several phases. Phase I of the study' encompasses a modification of the cup burner apparatus included in NFPA 2001 "Standard on Clean Agent Fire Extinguishing Systems - 1996 ed.". Two terminals from **a** 1.2 kW DC power supply were fixed to the top of the burner and **a** length of nichrome resistance wire between them was employed to complete the circuit. The purpose of this experiment was to demonstrate the effect of a continuously energized circuit on extinguishing concentration for **a** steady fuelienergy scenario.

Phase II of that study extended the investigation to increased energy levels for the halocarbon agents. It is suspected that **a** point of diminished performance will be reached **at** which time the agent concentration may become excessive(above cardiotoxic limits). The magnitude of thermal decomposition was documented to illustrate whether adverse effects to sensitive equipment located within the protected enclosure should be expected. The purpose of Phase II testing was to demonstrate the performance capabilities of various clean agents on continuously energized fuellenergy sample on an intermediate scale scenario. Energy levels to 1500 W are expected to be tested in this test series.

Phase III testing (an extension of previous tests) involves analysis of similar continuously energized fuel samples and an initial quantification of the production of thermal decomposition products measured via advanced data analysis techniques. **A** number of items were discovered. **A** minimum agent concentration exists below which extinguishment or prevention *of* reignition does not occur for a given fuelienergy scenario. In fact, insufficient agent concentration resulted in continuous or intermittent flaming of the sample causing continuous agent breakdown at a decomposition rate **as** high **as** 8-10 ppmv/sec. The HF to COF, ratio of total thermal decomposition products levels reported was found to be in the range of 1.5-5:1 depending upon agent concentration with HFC-23 having the lowest ratio(most COF, in the mix) and FC-2-1-8 having the highest ratio. Degradation of agent concentration in the volume does not occur in quantities sufficient to cause reignition of the test sample after initial extinguishment. In other words, the sample is reigniting for reasons other than **a** reduction in agent concentration or agent loss. Increases in agent concentration seemed to show an improvement in performance in terms of extinguishment, prevention of reignition and reduction of TDP. Performance leveled off, particularly with regard to thermal decomposition at the higher concentrations for this fuel energy scenario.

Results indicate **a** need for elevated design concentrations to effect faster extinguishment, minimize thermal decomposition and to assure sufficient time to respond to **a** real energized fire event. This **is** in agreement with previous studies of energized systems, electrical or otherwise. Finally, the limited data quantifying the characteristics of this type of fire illustrates the lack of guidance to the fire professional in designing active fire suppression for energized electrical hazards and the need for quantitative performance-based design criteria.

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[1] R. Neimann, H. Bayless, and C. Craft, Modular Protection Group, "Evaluation of Selected NFPA 2001 Agents for Suppressing Class 'C' Energized Fires", Halon Options Technical Working Conference Proceedings, May 7-9, 1996, pp. 399-412.

[2] M. Driscoll, P. Rivers, "Clean Extinguishing Agents and Continuously Energized Circuits". presented at the NIST Annual Conference of Fire Research, Gaithersburg, MD, October 28-31, 1996.

Introduction

The telecommunications industry has had an exemplary fire incident record over the past 100 years. In more than 52,000 telephone exchange facilities in the U.S. there have occurred roughly 189 tires for the period from 1988 to 1992. Their success in maintaining a low incident ratio is due primarily to their proactive stance when coping with fue related issues. Although a relatively small incident ratio, the effects incurred to local communities have been substantial'. Almost twenty percent of the 189 incidents resulted in service disturbance to the telecommunications community and in several cases significant disruption'. Due to the high severity of such incidents the telecommunications industry invests millions of dollars annually in fue protection measures.

The telecommunications industry has some unique attributes to consider when planning the fue protection details of a given facility. Unlike data processing equipment, which typically operate in the 5 to 10 volt dc range, telecommunications equipment is supplied with 12, 24, 48. or 130 volts dc depending on system requirements. The ability of energized equipment to malfunction via short circuit and/or electric arc resulting in a Class C fue does exist and has been well documented. The NFPA defines Class C fires as "fires that involve energized electrical equipment where the electrical non-conductivity of the extinguishing media is of importance."* A more apt definition may be "fires that involve energized electrical equipment where an uninterrupted power supply will continue to re-ignite the surrounding Class A or Class B fuels and where the electrical nonconductivity of the extinguishing media is of importance."

Due to the high volume of energized equipment in a typical telecommunications facility there is a relatively high potential for Class C fire events. Data compiled by the National Fire Incident Reporting System(NFIRS) for the period of 1976 to 1979 illustrated that of the reported 189 individual telephone exchange fires, 35 percent of the fires occurred in electrical or electronic related facilities. Of these, 42 percent involved some sort of electrical short or circuit overload and 31 percent involved electrical wire failure[6].

Like the nuclear power industry and certain chemical processes circuit integrity in a telecommunications facility must be maintained through the duration of a fire event. De-energizing a typical facility once a fue incident has been detected and verified is a involved process that is not trivial. The procedures for manual power down require time. Time requirements may range from a few minutes to half of an hour or more. Similarly, fire incidents occurring in intermittently occupied facilities require a time interval for detection and emergency personnel response. Depending on location of the facility response times may range to thirty minutes or more.

Before or during these time delays, a clean agent system may detect a fire event and automatically actuate. If properly designed the system should; completely extinguish the initial fire event, prevent subsequent re-ignition, and minimize products of decomposition. However, little guidance is available to the fire protection engineer designing suppression systems in continuously energized facilities where the threat of re-ignition from an overloaded circuit or electrical arc is imminent.

Previous intermediate scale work' involving HFC-23, HFC-227ea, FC-3-1-10, and FC-2-1-8, has illustrated, that continuously energized Class B fuels require elevated extinguishing concentrations(greater than 160% of the minimum cup burner extinguishing concentration) to properly mitigate the initial fire event and prevent fuel re-ignition. As more heat energy (via energized resistance wire) was added to the fuel/energy system higher extinguishing concentrations were required to completely extinguish the flame. Similarly, trends illustrate that more demanding Class A fuel/energy scenarios (higher energy inputs to the fuel) required elevated agent levels to attain extinguishment of the initial flame front. Further increases in the agent concentration were required to attain a sample *inertion period.* The time period between initial sample flame extinguishment, via clean agent application, to subsequent sample reignition was defined as the ***inertion period.*** The achievement of extended inertion periods also required higher agent design concentrations.

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[3] NFPA Fire Protection Handbook, Seventeenth Edition, 1991, pp. 8-200-209.

[4] Karydas, Dimitrios, "Performance Based Standards as the Basis for Risk Management Decisions: A Case Study in the Telecommunications Industry Addressing Fire and Smoke Hazards", Factory Mutual Research Corporation, Norwood, Massachusetts.

[5] NFPA 2001, "Standard on Clean Agent Fire Extinguishing Systems", 1996 edition.

[6] E. Braun, "Review of Literature, Applicable Test Methods, and Incident Data for the Evaluation of the Fire Performance of Central Telephone Office Equipment", U.S. Dept. of Commerce, Washington DC, May 1981.

[7] ibid. reference *2.*

Objective

The following objectives were set for this investigation to extend the examination of agent performance for a representative fuellenergy configuration:

        a.) Determine the minimum volume fraction necessary to extinguish and provide a thirty minute inertion period for an electrically energized fire with the following clean agents: FC-2-1-8, FC3-1-10, HFC-227ea, HFC-23.

        h.) Quantify the levels of products of thermal decomposition.

Equipment

Test Enclosure

        Testing was performed in a 0.91m x 0.91m x 1.52m(3ft x 3ft **x** 5ft) enclosure with a $1.28m^3(45ft^3)$ internal volume. The "box" was constructed of 12.7mm(0.5in) polycarbonate walls reinforced with an angel iron frame and instrumented with pressure transducers to monitor nozzle, cylinder, and enclosure pressures. Data acquisition was performed via Lahtech Notebook version 7.3.0W software for DOS. The ventilation system was controlled manually with solenoid valves through a control panel. Two clear polycarbonate access ports 0.25m(10in) **x** 0.25m(10in) were mounted on the front and rear panels. A 30.4cm(12in) x 30.4cm(12in) x 20.3cm(8in) high rectangular baffle set on the floor of the enclosure surrounding the test sample reduced turbulence to the energized circuits during testing.

Piping Scheme and Discharge Time

        The discharge of agent into the enclosure was accomplished through a simple pipe network constructed from 0.64cm(0.25") NPT schedule 40 pipe and fittings(150 Ih. class black malleable iron, steel, and stainless steel). A $1000cc(0.035ft^3)$ cylinder was utilized to extend the range of achievable agent concentrations for HFC-227ea, FC-3-1-10, and FC-2-1-8. However, due to the high agent concentrations tested, an additional 1000cc cylinder was incorporated to the piping scheme to achieve the desired enclosure concentrations for the HFC-23 agent. Each cylinder assembly was equipped with a quarter turn ball valve for cylinder filling. The initiation of agent discharge was controlled manually through a Worcester Controls Model K-411NSE quarter turn ball valve.

        Nozzles were selected to gain a discharge time near ten seconds. For each test the data acquisition software yielded a pressure trace at the nozzle which was then used to determine of the discharge time.

Instrumentation

        Three Omega Engineering Model **PX-I**76 sealed gauge pressure transducers monitored the cylinder, nozzle. and enclosure pressure during agent discharge. A video camera was used to record the results of each test and to confirm observations (extinguishment, re-ignition, and discharge times) made during a given test. A 1.2kW Harrison(Model 6260A) DC power supply was utilized to energize the circuit. An OMEGA digital amperage meter (Model #005512) and a SOAR digital volt meter(Model #ME-550) were used to monitor amperage and voltage levels. A fan, located at one comer of the enclosure base, was pointed upwards to ensure a homogenous gas volume during sampling. Agent concentrations and acid gas levels were monitored with extractive Fourier Transform infrared FTIR testing. Infrared spectra were collected using two extractive FTIR systems incorporating MIDAC (Irvine. CA) FTlR spectrometers (G5000 and 12000 series). Each spectrometer was configured with a ZnSe beam splitter. A Icm (single pass) stainless steel gas cell was used to acquire clean agent concentration data. A 10cm (single pass) stainless steel gas cell was used to collect thermal decomposition data. A I mm mercury cadmium telluride (MCT) detector was used in both systems. All gas cell windows are uncoated ZnSe. All spectrometers have an ultimate wavelength resolution of 0.5 cm^{-1} unapodized. The software used to acquire all data was Lab Calc® Galactic Industries (Salem, NH) and Autoquant® MIDAC (Irvine, CA). All extractive FTlR systems included 110V gas sampling pumps and portable computers for data acquisition.

Calculations

Agent Concentration

Agent weight requirements were calculated as:

$$W = \frac{V}{s}\left(\frac{c}{100-c}\right)$$
Equation 1[8]

where V is the enclosure volume in m^3, s is the specific vapor volume in m^3/kg, c is the desired enclosure agent concentration, and W is the required agent weight in kg.

Experimental

Selection of Fuel/Energy Configuration

In order that agent performance was compared fairly, considerable effort was given to utilize a fuel/energy configuration and fuel material that burned in a consistent and reproducible manner. Particular effort was given to a scenario that resulted in a uniform heat release rate following a designated sample pre-burn interval. This test scheme also evaluated the potential for re-ignition of the sample and therefore needed to ensure adequate fuel/wire contact following pre-burn.

Loss history has identified low energy fires as a major problem in the telecommunications industry. Bell Atlantic, for example, requires the detection of a 0.10 kW fire in their facilities'. This criteria was used as a benchmark in determining a test fire size that would be representative of actual telecommunications equipment fires.

The decision to **use** polymethylmethacrylate (PMMA) as a test material was based on its **use** in fire testing historically and it's favorable burning characteristics(consistent, repeatable burning, moderate heat of combustion of 25.3kJ/g; low soot yield of 0.02g soot/g fuel. Sixteen(16) and eighteen(18) **gauge** nichrome resistance wire represented the sample ignition and energy input source. The heavier wire gauges prevented circuit interruption for the extended pre-burns and sample re-ignitions periods associated with this study.

Five fuel energy configurations were tested in a cone calorimeter to quantify the rates of heat release. The configurations are illustrated in Table 1 below.

Config. No.	Fuel Dimensions (cm)	Sample/Wire Configuration	Sample Material	Wire Gauge Length	Energy Level (Ampere)	Peak Heat Release Rate (kW)
1	2.5 x 7.6 x 1.6 H x L x W	Vertical Sandwich (SL)	PMMA	18 (10.1 cm)	25	2.2
2	1.6 x 7.6 x 2.5 H x L x W	Horizontal Sandwich (SL)	PMMA	16 (10.1cm)	30	2.4
3	2.5 x 7.6 D x L	Horizontal Cylinder (W)	PMMA	18 (35.5 cm)	19	3.4
4	2.5 x 2.5 D x L	Vertical Cylinder (SL)	PMMA	16 (5.7 cm)	30	1.1
5	2.5 x 2.5 D x L	Vertical Cylinder (SL)	PMMA	16 (5.7 cm)	35	1.2
H = Height, L = Length, W = Width, D = Diameter SL = Straight length of wire through sample, W = Wrap wire around sample						

Table 1: Results of Fuel/Energy Configuration

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[8] NFPA 2001, Standard on Clean Agent Fire Extinguishing Systems, National Fire Protection Association, 2nd Edition, Quincy, MA (1996).
[9] Private conversation with Chuck Yaunches, Risk Manager, Bell Atlantic.

Based on calorimetry testing, Configuration No. 3, from Table 1 was chosen for further testing. Figure I below is a illustration of Configuration No. 3. Figure *2* presents three separate tests conducted with Configuration No 3 in the cone calorimeter and illustrates the reproducibility of the heat release rate for this scheme. Using these results, a fire size(kW) was extrapolated for a given pre-bum interval. **A** 300 second pre-burn, following sample ignition, resulted in approximately a 2.5 kW tire. Depending on the pre-bum duration, this fuellenergy configuration can achieve fire sizes ranging to a heat release rate of **3.4** kW. Longer pre-burn intervals(> **630** seconds) were not used with this configuration due to expected significant sample mass loss which would result in fuel migration from the heat source(energized wire) and potentially inadequate fuel/wire contact. This could affect the consistent re-ignition potential of the fuel material. **A** pre-burn interval of 300 seconds(2.5 kW initial heat release rate) was employed for this study.
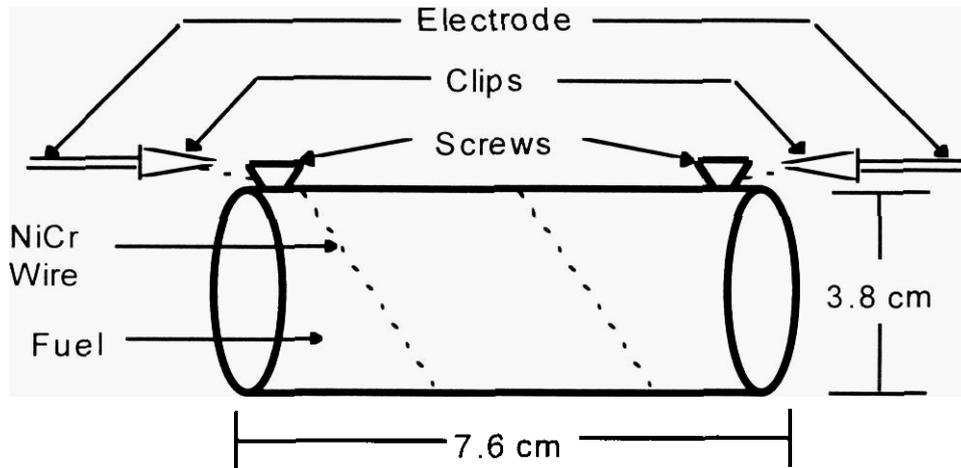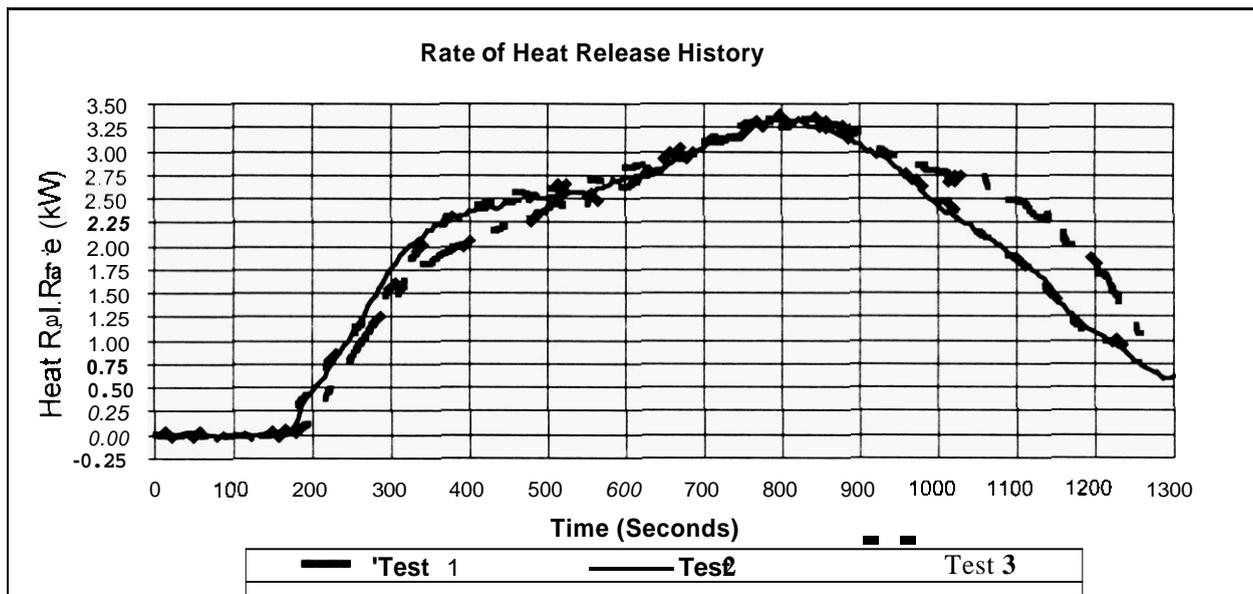

Figure 1: Configuration No. 3 - Fuel/energy scheme

Figure 2 : Rate of heat release history for fuellenergy Configuration No. 3

Procedures

The agent cylinder was disconnected, filled with the desired weight of selected agent, and super-pressurized with dry nitrogen to 25 bar (360 psig). In the case of HFC-23 no nitrogen pressurization was required. The PMMA wire wrapped sample was then connected to the DC power supply.

The data acquisition equipment is started and the ventilation system opened for the pre-bum of the sample. The video recorder was turned "ON" and the sample energized.

A 300 second pre-bum followed sample ignition. Ignition typically occurred 5 - 10 seconds after the system was initially energized. At 285 seconds into the pre-bum the access door to the enclosure was secured. Ten seconds later (295 seconds into pre-bum) the ventilation system was closed. At the 300 second mark the agent was discharged to the enclosure. Flame extinguishment of the sample was observed. The fan was employed at flame extinguishment to ensure a homogenous enclosure mixture for gas sampling.

Energy was maintained to the sample for a thirty minute hold period. During this time the enclosure gas volume was continuously sampled and analyzed for agent concentration and products of decomposition with extractive FTIR. However, tests conducted at agent concentrations too low to extinguish the sample were stopped prior to 30 minutes.

Following the thirty minute hold period the ventilation system and access port were opened. During this ventilation period, if the sample had not reignited, the sample remained energized to verify it would reignite once agent was vented. All tested samples reignited within 90 seconds of the start of ventilation. The data acquisition was stopped after the enclosure volume concentrations dropped to zero as measured by FTIR.

FTIR Sampling Techniques

The extractive gas sampling systems used for chamber testing consisted of ~2 meters of unheated Teflon® lines configured at the inlet of the unheated 10cm and Icm infrared gas cells. 110 volt vacuum pumps were configured at the outlet of the gas cells. Samples of the enclosure gas were continuously drawn through the Teflon sample line and the 10cm and Icm stainless steel gas cells used in the two independent infrared instruments. The sampling flow rate was ~1.0 l/min. for all chamber sampling and instrument calibration checks. Flows were set to constant rates with pre-calibrated rotameters at the regulators of the calibration gas cylinders used for instrument calibration checks and with electronic mass flow controllers at the exhaust of the infrared gas cells prior to the vacuum pumps for total sample flow control. Flow rates were verified on-site using a Dry Cal flow meter (Bios International/Pompton Plains, NJ).

Sampling of test chamber gas for the presence of HF and COF, was accomplished using undiluted sample gas with a 10cm infrared gas cell. Sampling of test chamber gas for the analyses of Halon and Halon replacement levels was accomplished using dynamic dilution of sample gas with ~20,000 ppmv CH, cylinder gas and a Icm infrared gas cell.

Quantitative error assessments are estimated at (+/-) 5-10% based on uncertainty calculations.

Summary

Extractive Fourier Transform Infrared (FTIR) testing was used to determine background levels of halon replacement agents and HF and COF, emission levels during controlled bums conducted in a $1.28m^3$ test chamber. Agent concentrations, HF, and COF, levels were recorded for the following sixteen tests(nominal agent concentrations arbitrarily chosen to show a range of performance: FC-2-1-8(9%, 11%, 13%, **15%** by vol.), FC-3-1-10(6%, 8%, 10%, 12% by vol.), HFC-227ea(7%, **9%,** 11%. 13% by vol.), and HFC-23 (14%, 16%, **18%,** 20% by vol.).

Results and Discussion

Figures 3 - 6, below, illustrate the relative "tightness" of the test enclosure. Fluctuations can be attributed to agent sampling techniques, "Nominal" values were calculated by averaging data points between the peak of the initial agent concentration spike, attained during the discharge phase of a test, and the onset of the enclosure ventilation period, characterized by the sharp decrease in agent concentration. Series 7(Figure **4)** and series 14(Figure 6) do not illustrate complete data sets do to malfunctions in the sampling equipment. However, enough data points were collected, prior to malfunction, to gain an adequate quantification of the enclosure agent concentration and were therefore included for analysis.

Figures 7 - 10, below, depicts the levels of thermal decomposition products(TDP) versus time for various agent concentration times. TDP levels were calculated by summing levels of enclosure hydrofluoric acid gas(ppmv HF) and carbonyl fluoride gas(ppmv COF_2) for any one time. enclosure levels were approximately three to five times higher than corresponding levels of carbonyl fluoride. This trend was consistent for all four agents tested.

Series 1, 5, and 9 of Figures 7, 8, and 9, respectively, illustrate the effects of intermittent sample flaming on enclosure TDP levels. Intermittent sample flaming was caused by enclosure agent concentrations inadequate for extinguishment. This resulted in continuous agent breakdown and excessive enclosure TDP generation rates, which in the case of HFC 227ea and FC-3-1-10 were approximately 8 and 10 ppmvisecond, respectively, All three of these tests were discontinued due to concerns over loss of TDP gases from the test enclosure. Series 13 of Figure 10 does not illustrate a continuous increase in TDP levels due to the absence of intermittent flaming at the tested enclosure agent concentration. However, it can be assumed that there is an agent concentration, below 16.5 volume percent HFC-23, at which point complete flame extinguishment does not occur for this energy/fuel configuration, resulting in a continuous increase in TDP levels with time.

Series 2 - 4(Figure 7), 6 - 8(Figure 8), 10 - 12(Figure 9), and 14 - 16(Figure 10) demonstrate the effects of increased agent concentration on TDP levels. The downward linear trend of many of these series can be attributed to the reactive nature of these chemical compounds(e.g. adsorption onto enclosure test surfaces and sampling lines). Table 2, below, summarizes all test results and includes extinguishment times and average enclosure TDP levels for the test period.

| Agent	Enclosure Agent Concentration (Volume Percentage)	Extinguishment Time* (Seconds)	Intermittent Sample Flaming (Present/Not Present)	Average Enclosure TDP (ppmv)
C_4F_{10}	5.4	No Extinguishment	Present	2086
	6.8	24.5	Present	1689
	8.9	21.0	Not Present	1299
	9.9	18.0	Not Present	1373
C_3F_7H	6.0	27.0	Present	3479
	7.1	22.7	Present	1566
	9.8	16.5	Not Present	1355
	11.0	16.0	Not Present	1413
C_3F_8	8.0	No Extinguishment	Present	1878
	9.2	13.5	Present	1130
	10.8	18.0	Not Present	1026
	11.8	15.0	Not Present	896
CF_3H	16.5	9.0	Not Present	1730
	19.6	14.0	Present	1035
	20.8	11.4	Not Present	791
	22.5	8.6	Not Present	700
* Extinguishment Time = elapsed time from beginning of agent discharge to complete flame extinction				

Table 2: Results Summary
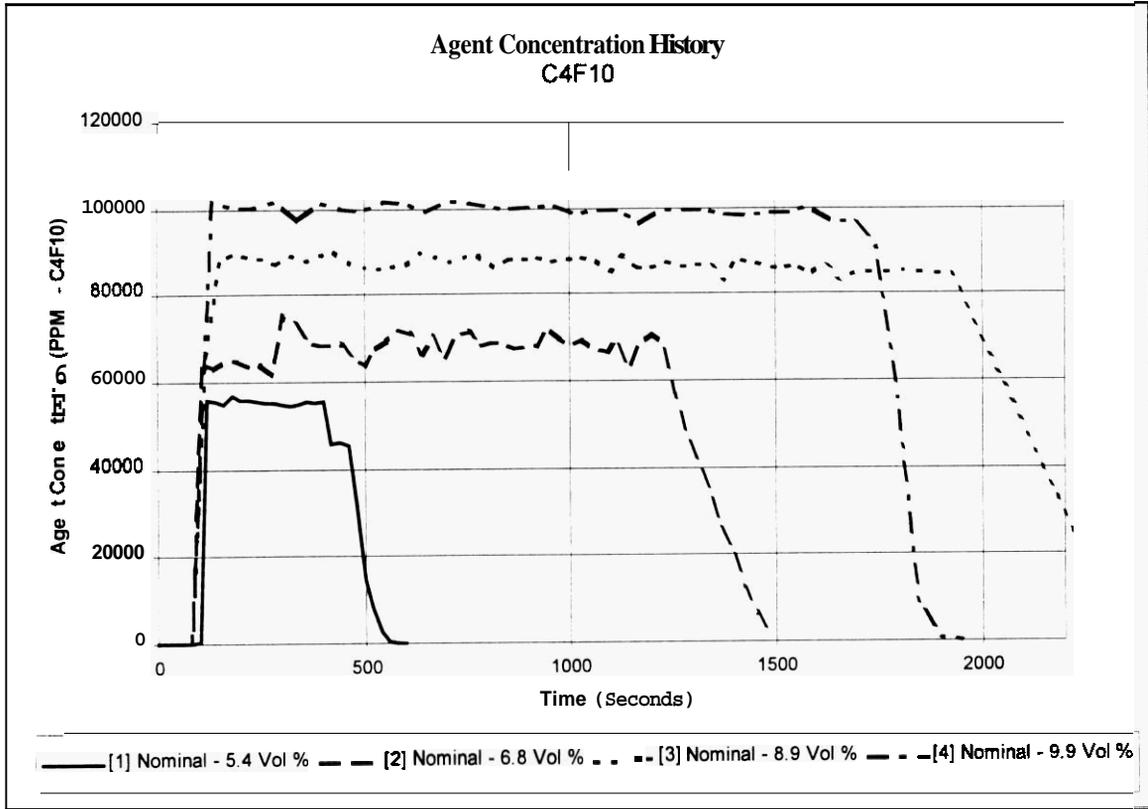
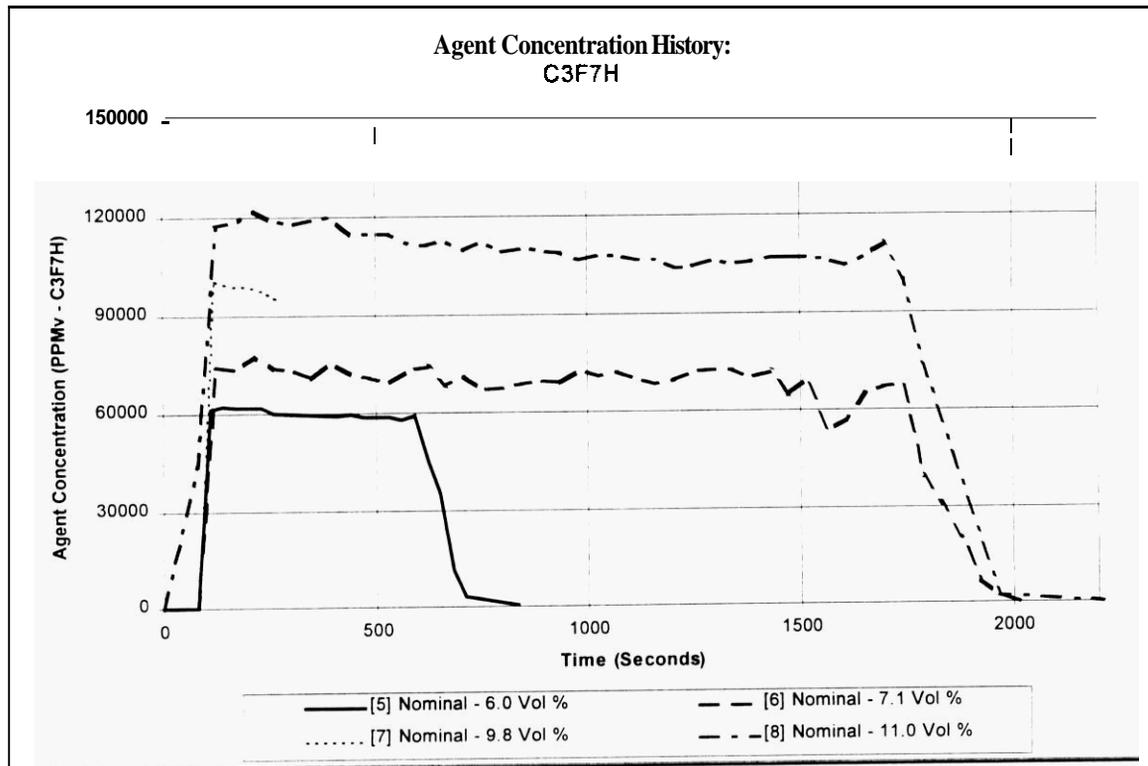**Figure 3: FC-3-1-10 Agent Concentration History**

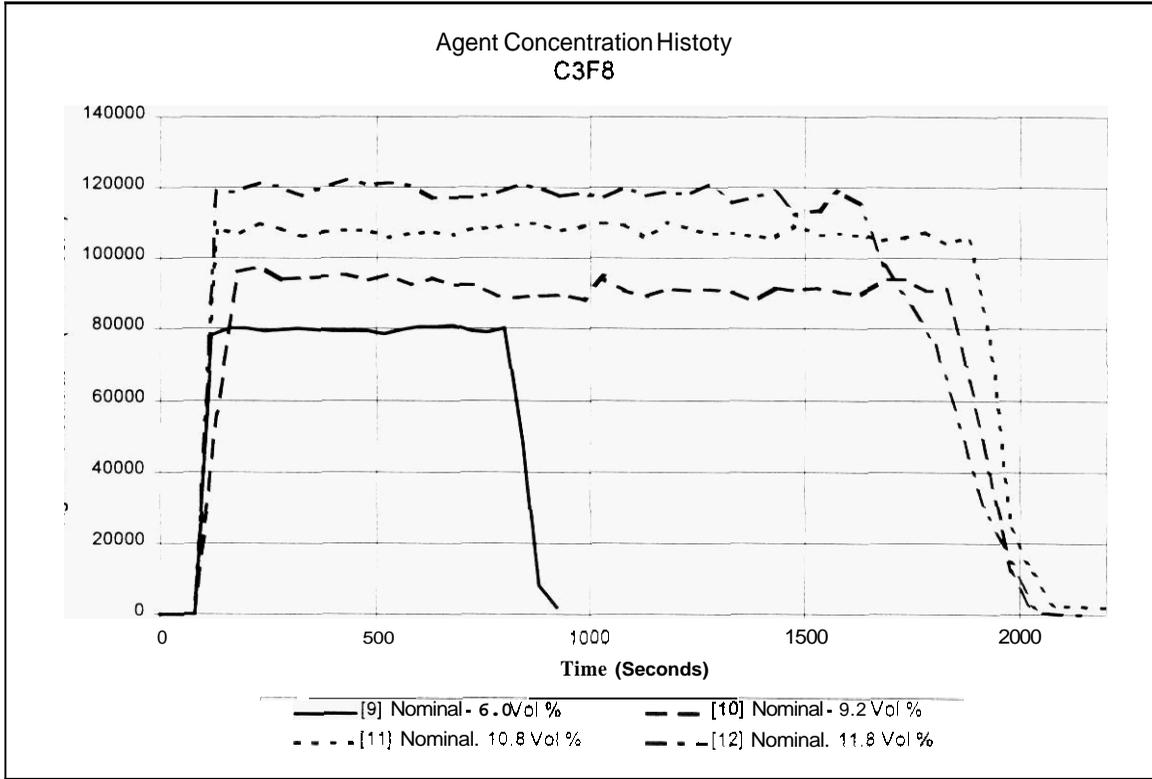**Figure 4: HFC-227ea Agent Concentration History**
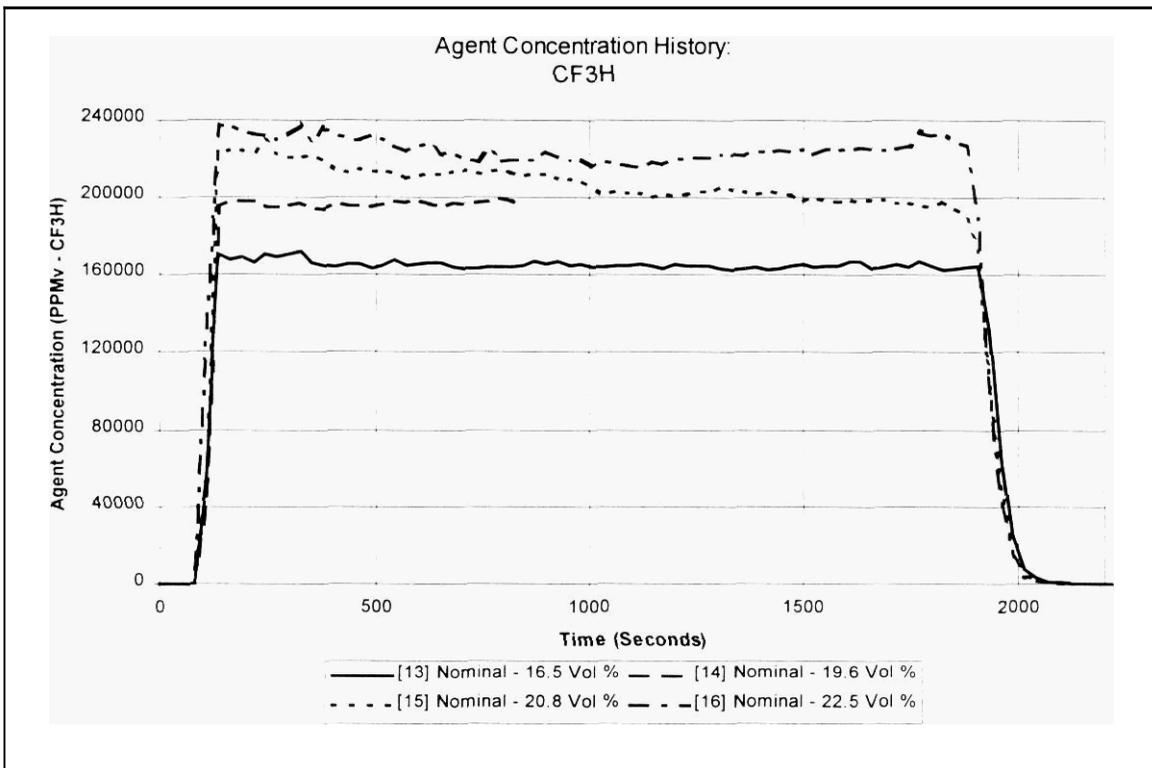
Figure 5: FC-2-1-8 Agent Concentration History

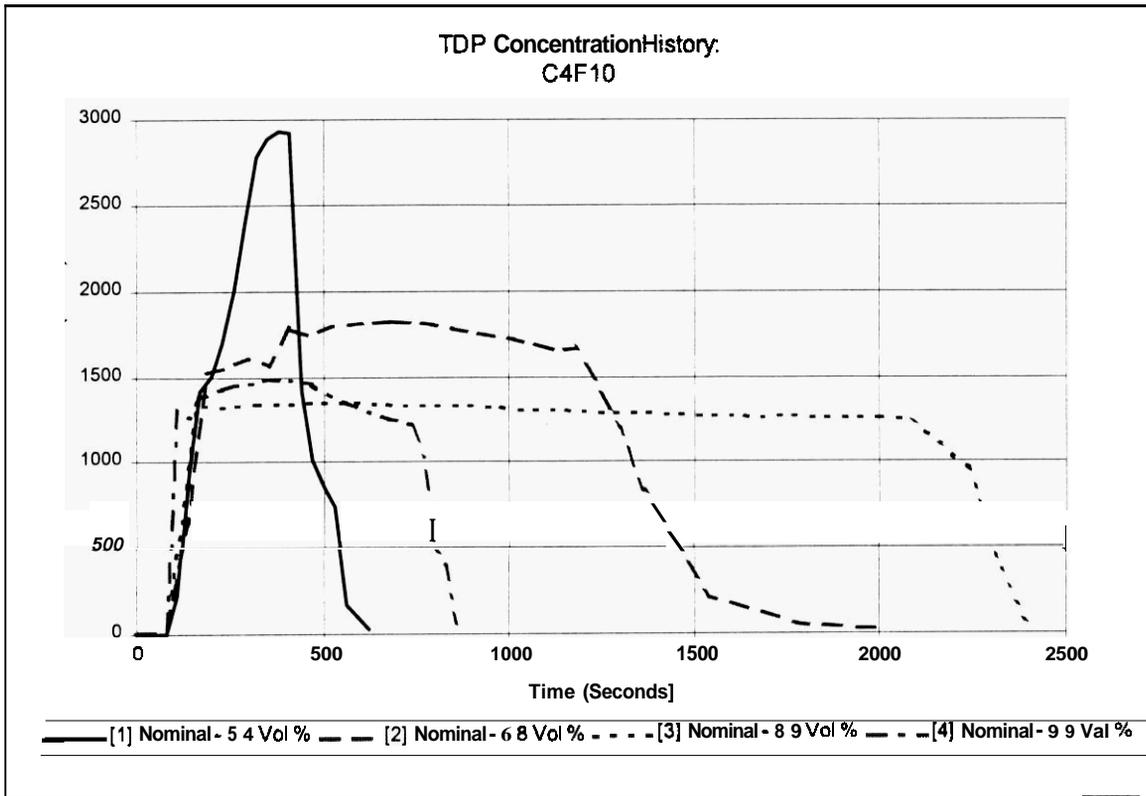
Figure 6: HFC-23 Agent Concentration History

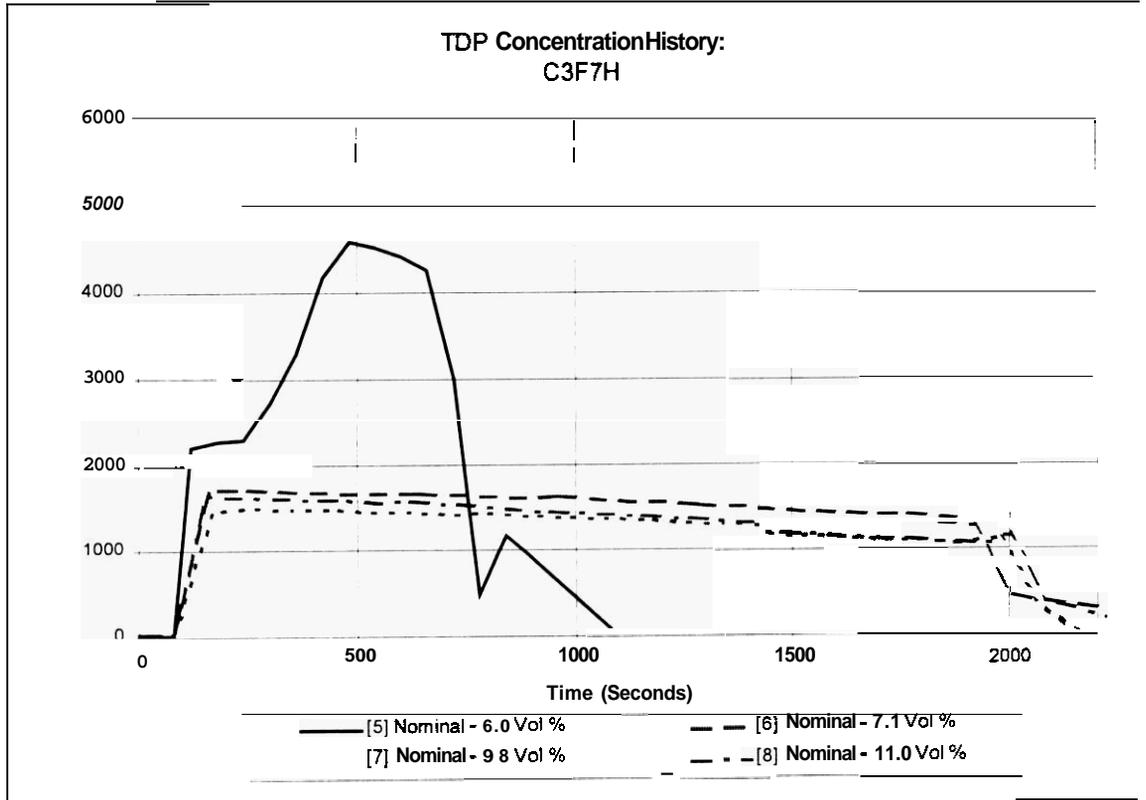**Figure 7: FC-3-1-10** TDP Concentration History

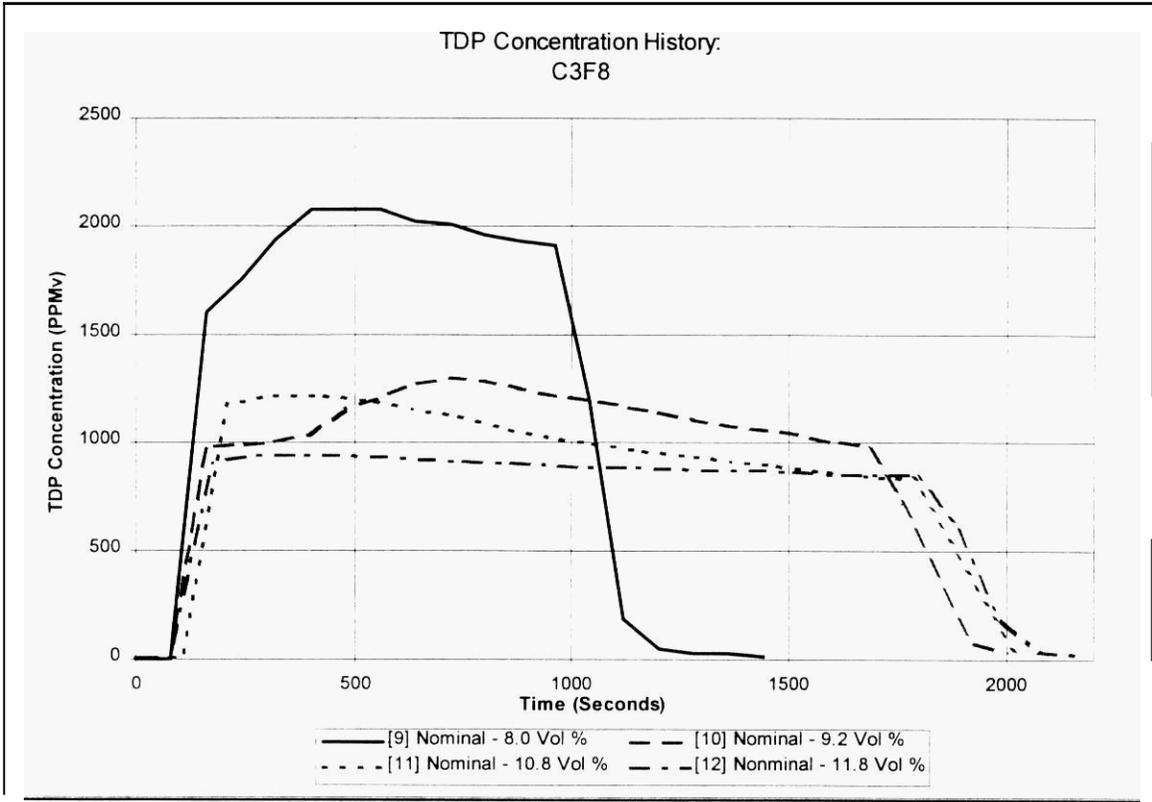Figure **8:** HFC-227ea TDP Concentration History
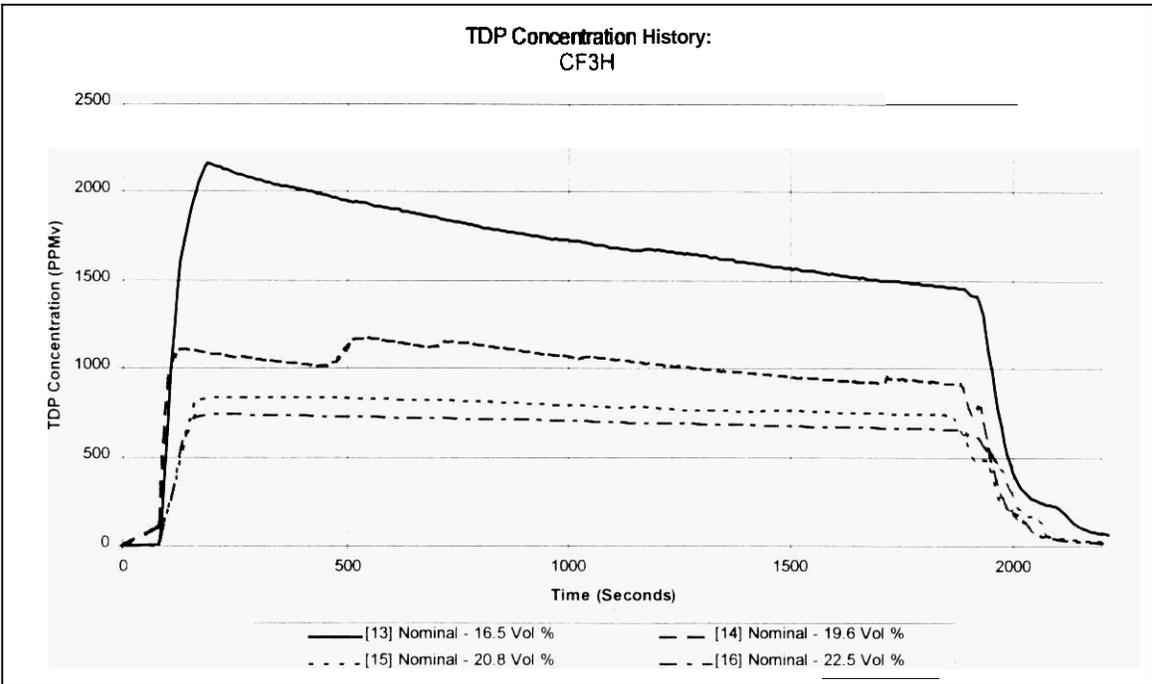
Figure 9: FC-2-1-8 TDP Agent Concentration History

Figure 10: HFC-23 TDP **Concentration** History

Table *2* illustrates a decrease in levels of **TDP** with an increase in agent concentration. Extinguishment times do not correlate (e.g. decrease in extinguishment time α decrease in levels of TDP) for all agents tested. This was due to the persistence of small flamelets which, in some cases, remained well after the onset of agent discharge. It is suspected that correlations exist between extinguishment times and levels of TDP provided a fundamental definition of extinguishment time be established **as** part of a future Class C test protocol (e.g. 90% flame extinguishment). Other correlations may exist as well, such **as** flame stability and temperature, wire temperature, hot surface vs. arcing and *so* forth.

Table 2 also demonstrates the existence of a minimum agent concentration which is required for complete flame extinguishment and an inertion period of 30 minutes. For this specific fuel/energy configuration the following ranges were established:

- FC-2-1-8   9.2 - 10.8 vol. %
- FC-3-1-10   6.8 - 8.9 vol. %
- HFC-227ea   7.1 - 9.8 vol. %
- HFC-23   16.5 - 20.8 vol. %

It is important to note that the above numbers are specific to the fuel/energy configuration implemented for this research. Modifications to the fuel type, ignition source, configuration, length of required inertion period, etc. will result in variations to the minimum agent concentration for flame extinguishment and flame inertion. Therefore, in considering Class C fire hazards and the appropriate protection of such hazards, it will be necessary to establish a fuel/energy configuration deemed "representative" to the specific occupancy.

Conclusions
This research resulted in the following conclusions:

1. For a given fuel/energy configuration there will exist a minimum agent concentration below which flame suppression will not be complete (e.g. no flame extinguishment or re-ignition following initial flame extinction).
2. Agent concentration traces verified that sample re-ignition, following initial sample flame extinguishment, was not the result of agent breakdown or **loss** from the test enclosure but more likely due to the presence of a continuous ignition source.
3. Levels of HF were approximately **1.5** to **5** times higher than corresponding levels of COF, depending on the agent.
4. Inadequate enclosure agent concentrations(no flame extinguishment or reignition following initial flame extinguishment) resulted in continuous agent breakdown, via intermittent sample flaming, and TDP generation rates **as** high as 8 - 10 ppmv/second.
5. Increases in agent concentration resulted in performance improvements (decreased flame extinguishment times, no sample re-ignition, and lower enclosure TDP levels). Due to the absence of an appropriate definition for flame extinguishment, as applied to Class C testing, there existed no consistent relationship between sample extinguishment time and TDP levels.
6. Future work needs to be directed at higher energy levels added to the system increasing from the **225** watt system used here up to **1.5** kW in energized power added. This may show heat release rates from the test samples up to **5** kW, the size of a typical circuit board in a switch bay, as an example. It may also indicate a practical circuit capacity limit for the use of clean agents in energized Class C fire scenarios above which they would they he inappropriate for use.
7. In addition to the test configuration included in this to date, an arcing configuration would be interesting to examine as a test series to quantify agent performance on that type of fire.