

ABSTRACT

Title of Document: EFFECTS OF RADIANT HEAT FLUX ON
CLEAN AGENT PERFORMANCE FOR
CLASS-C STANDARDS

Romil Patel, M.S. Fire Protection Engineering,
2012

Directed By: Professor and Chair, Dr. James A. Milke,
Department of Fire Protection Engineering

This thesis investigates the effects of radiant heat flux on clean agent extinguishing concentrations. This data is sought to support standards that address Class C hazards. Using the REED apparatus, performance of clean agents IG-100, IG-55, IG-541, HFC-125, HFC-227ea and FK-5-1-12 at heat flux levels of 0-40 kW/m² was examined. It was found that clean agent extinguishing concentrations increased with an added heat flux.

An alternate method of testing with the REED apparatus was also examined. Clean agents examined in the test were IG-100, IG-55, IG-541, HFC-125 and HFC-227ea at heat flux levels from 0-5 kW/m². It was found that clean agent extinguishing concentrations increased by 33 to 45 percent from the original testing method. The new testing method was also found to be more repeatable and less time consuming.

EFFECTS OF RADIANT HEAT FLUX ON CLEAN AGENT PERFORMANCE
FOR CLASS-C STANDARDS

By

Romil J. Patel

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Masters of Science
2012

Advisory Committee:
Dr. James A. Milke
Dr. Andre Marshall
Dr. Stanislav Stoliarov

© Copyright by
Romil J. Patel
2012

Acknowledgements

I would like to thank the following people for giving me the opportunity to make this study possible:

- Dr. Milke, I would like to thank you for giving me the opportunity to join the Fire Protection Engineering program. Without your support none of this would be possible. You gave me an opportunity when I needed it most and for that I am very grateful. You are an exceptional professor and mentor, UMD is lucky to have a faculty member like you.
- Paul Rivers, thank you for giving me the wonderful opportunity to join 3M Company. Without the opportunity, I would have not had the ability to be exposed to so many great studies and experiments. In particular, the REED apparatus project has been of great importance to me and has given me the opportunity to use it for my thesis. You are a great mentor and a friend.
- Olga Zeller, thank you for helping me get the lab experiment set up and providing equipment necessary to perform testing.
- Faculty and Staff of Fire Protection Department, thanks for your continual support and help with everyday needs.
- Thesis Committee, thank you for taking the time out of your busy schedule to be part of this thesis.

Table of Contents

Acknowledgements	iv
Table of Contents	v
List of Tables	vi
List of Figures	vii
Chapter 1: Introduction	1
1.1: Problem Statement	1
Chapter 2: Review of Literature	6
2.1: Previous Testing on Clean Agent Extinguishing Concentrations	6
2.1.1: Radiantly Enhanced Extinguishing Device	12
2.1.2: FM Global Fire Propagation Apparatus	18
2.1.3: Vertical Polymer Slabs Ignited by a Loop of Nichrome Wire	20
2.1.4: Wire Cable Bundles with Heated Nichrome Wire	21
2.1.5: Resistively Heated Polymer Sample	22
2.1.6: Heated Metal Surface Ignition of Premixed Gases	23
2.1.7: NASA WSTF Tests of EVA Suit Wire-Failure Ignition	23
2.1.8: NASA-GRC Test for Suppression of Flames Over PMMA	24
2.1.9: Summary	25
2.2: Role of Radiant Heat Flux on Blade Servers	26
Chapter 3: Current REED Apparatus Testing	32
3.1: Apparatus and Testing	32
3.2: Protocol	41
Chapter 4: Results and Discussion	44
4.1: Graphical Results	44
4.2: Visual Observations	51
Chapter 5: Alternative Method for Testing	53
5.1: Proposal of IAR Testing Method	53
5.2: Results and Discussion	56
Chapter 6: Summary	60
Appendix	62
References	66

List of Tables

Table 1: Cost per Minute for Downtimes for Various Business Applications

Table 2: Thermal Onset of Damage in IT Equipment

Table 3: Mass Loss Rates of 2.54 cm Long PMMA Rods of Various Diameters

Table 4: Radiant Heat Flux Emitted by Blade Servers in respect to Surface Area and Power Density

Table 5: Clean Agent Used in this Study by Classification and Composition

Table 6: NFPA 2001 Class C Design Concentration versus REED Apparatus Extinguishing Concentration

List of Figures

Figure 1: Thermal heat transfer of burning polymer with induced external radiant heat flux

Figure 2: Mass Loss Rates as a Function of Time for 25.4 mm Thick PMMA Sample with Incident Radiant Heat Flux, kW/m^2 .

Figure 3: Mass Loss Rates as a Function of Shorter Time Span for 25.4 mm Thick PMMA Sample with Incident Radiant Heat Flux, kW/m^2

Figure 4: Radiant Enhanced Extinguishing Device

Figure 5: Preliminary REED Apparatus Data: Extinguishing Concentrations as a Function of Radiant Heat Flux

Figure 6: FM Global Flammability Apparatus

Figure 7: Results of Extinguishing Concentrations versus Agent Volume Fraction Compiled from FMRC, NIST and 3M Company

Figure 8: Power Consumption of Components within a Blade Server by Load Conditions.

Figure 9: CPU Power Consumption Trends

Figure 10: Horizontally Stacked Blade Servers Emitting Thermal Radiation on Cable

Figure 11: BIOS Met Lab[®] 800 Series Flow Meter

Figure 12: Hukseflux Model SBG01 Heat Flux Sensor

Figure 13: Heat Flux Sensors: Gardon (top) and Schmidt-Boelter (bottom)

Figure 14: Heat Flux Measurements versus Temperature of Cone Heater

Figure 15: MLR of PMMA sample with respect to time with 0 kW/m^2 radiant heat flux.

Figure 16: Mass of PMMA sample with respect to time with 40 kW/m² radiant heat flux.

Figure 17: Configuration of Air Supply and Clean Agent using Swagelok Tee Union for Pre-Mix Supply Prior to Entry in REED Apparatus.

Figure 18: PMMA Sample Before (Left) and After (Right) Wrapped in Foil

Figure 19: FK-5-1-12 Testing Equipment Set-Up

Figure 20: FK-5-1-12, HFC-125 and IG-55 Clean Agent Extinguishing Concentration for 0-40 kW/m²

Figure 21: IG-541, IG-100 and HFC-227ea Clean Agent Extinguishing Concentrations for 0-5 kW/m²

Figure 22: IG-541, IG-100 and HFC-227ea Clean Agent Extinguishing Concentrations for 0-40 kW/m²

Figure 23: IG-100 Extinguishing Concentrations from REED Testing Compared to NFPA 2001 Extinguishing Concentrations for Class C Hazards

Figure 24: HFC-227ea Extinguishing Concentrations from REED Testing Compared to NFPA 2001 Extinguishing Concentrations for Class C Hazards

Figure 25: HFC-125 Extinguishing Concentrations from REED Testing Compared to NFPA 2001 Extinguishing Concentrations for Class C Hazards

Figure 26: IG-541 Extinguishing Concentrations from REED Testing Compared to NFPA 2001 Extinguishing Concentrations for Class C Hazards

Figure 27: FK-5-1-12 Extinguishing Concentrations from REED Testing Compared to NFPA 2001 Extinguishing Concentrations for Class C Hazards

Figure 28: IG-55 Extinguishing Concentrations from REED Testing Compared to NFPA 2001 Extinguishing Concentrations for Class C Hazards

Figure 29: PMMA Fuel Flame Size Before (Left) and After (Right) Exposure to Clean Agent

Figure 30: IAR Testing Method Configuration

Figure 31: Clean Agent Extinguishing Concentrations using Modified IAR Method for REED Apparatus, 0-5 kW/m²

Figure 32: Original versus IAR Testing Method Extinguishing Concentrations using REED Apparatus, 0-5 kW/m²

Chapter 1: Introduction

1.1 Problem Statement

This thesis addresses the need for clean agent performance data for use in standards and guidelines for Class C hazards, in particular, server room fires. The associated down times, although uncommon, associated with server room fires can be financially expensive for corporations. Clean agents, which are fire suppression chemicals that leave no residue and are not electrically conductive, have been used in electrical cabinets and computer rooms since the early 1960's. Due to the unique properties of clean agents, "telecommunication and data processing facilities account for approximately 80 percent of clean agent applications" [3]. Since the introduction of Halon 1301 (clean agent) the National Fire Protection Association (NFPA) standard was developed to provide guidance to fires classified as Class A, B, C, D or K.

Where:

Class A hazard is a fire which involves materials such as wood, trash, plastics and cloth.

Class B hazard is a fire which involves flammable liquids.

Class C is a fire which involves energized electrical equipment and wirings.

Class D is a fire which involves combustible metals such as magnesium and sodium.

Class K is a fire which involves cooking oil or fats.

For agents to be available in the NFPA Standard 2001 Standard on Clean Agent Fire Extinguishing Systems section 5.4.2.5 standard, they must be tested based

on Underwriters Laboratory *UL 2127 and UL 2166 for Class A* hazard standards [10,11]. For example, all clean agents recognized for applications involving Class A fires are required to comply with UL 2166 and inert agents are required to comply with UL2127. NFPA 2001 Section 5.4.2.1 requires Class B clean agent concentrations to be based in accordance with Annex B, the cup burner method with an additional 20 percent safety factor [12]. Section 5.4.2.5 of the NFPA 2001 standard provides guidance for Class C fires as followed:

“The minimum design concentration for a Class C hazard shall be the extinguishing concentration, as determined in 5.4.2.2, times a safety factor of 1.35”

Section 5.4.2.2 of the standard refers to Class A extinguishing concentrations.

Similarly, ISO 14520 standard stipulates clean agent requirements for Class C hazards as:

“Use the higher of the Class A design or 95% of the design value determined using the heptane Class B extinguishing test used under certain conditions”.

In both NFPA 2001 and ISO 14520, concentrations of extinguishing agents for Class C fires are based on concentrations for other classes of fires [12,13]. The rationale for the use of the Class A concentrations for the protection of Class C fuels is there is a lack of test data to provide the technical basis for minimum extinguishing concentrations necessary to suppress energy augmented electrical fires. However, applying a multiple of Class A and B extinguishing concentrations for Class C fires is questioned as there is no data to support the relationship between either of these two fire hazards with Class C fires.

Data server room and telecommunication facility fires can have significant financial impact [1,2]. Interruption of service can erase permanent and temporary memory due to the physical loss of memory storage devices costing companies millions. Average downtime costs for computing infrastructures are estimated at \$42,000 per hour [3]. Significantly greater losses are experienced in telecommunications and e-commerce facilities, where costs can be as much as \$1 million per hour outage [3]. The estimated downtimes per minute from various business applications are shown in Table 1.

Table 1: Cost per Minute for Downtimes for Various Business Applications [2,3]

Business Application	Estimated Outage Cost per Minute
Supply Chain Management	\$11,000
Electronic Commerce	\$10,000
Customer Service Center	\$3,700
ATM	\$3,500
Financial Management	\$1,500
Messaging	\$1,000
Infrastructure	\$700

Research has been conducted to determine the cause of typical Information Technology (IT) equipment fires. According to M.L. Robin, fires in data centers typically occur in “wiring, power distribution components and various types of IT

equipment” [5]. Materials found in IT equipment rooms are usually Class A items such as power cables, circuit boards, paper and data storage devices [5].

In the research, Robin and Craig demonstrate that IT equipment is particularly susceptible to thermal damage as well as electrical circuit shortage [5]. Table 2 shows the temperature of thermal damage onset on equipment for various components.

Table 2: Thermal Onset of Damage in IT Equipment [5]

Component	Onset of Damage
Storage Media (magnetic tape, floppies, etc.)	125°F (52°C)
Hard Drives	150°F (66°C)
Electronic Components	174°F (79°C)
Paper	350°F (177°C)
Polystyrene cases, reefs	650°F (310°C)
Microfilm	225°F (107°C)

Thermal damage is not the only issue of concern for fires and IT equipment. Products released from fires such as soot and gaseous products of combustion have particularly devastating effects. As soot deposits onto the equipment, the conductive and non-conductive particles can cause shorts in the circuit. Malfunctions in hard drives from soot particles “as small as 0.5 microns” have been shown to occur [5].

Early detection and suppression systems are suggested as mitigation strategies of fire related damage. Particularly in IT rooms, smoke detectors and alarms should be used in accordance with NFPA 72 [13]. “In reported U.S. electronic equipment room fires in structures other than houses, three of five fires show smoke alarm

equipment present, with an associated two-thirds reduction in average loss per fire”[6]. Commonly used fire suppression systems used are water based sprinkler systems or clean agent system. Water suppression systems are used to control the fire and confine it to a given space. Water suppression systems are activated when the thermally activated bulb near the sprinkler head reaches a designed temperature; usually 135° F. By the time temperatures at this level are reached in the enclosure, substantial damage to equipment by heat and soot may have already occurred.

Clean agent systems in contrast are designed to quickly extinguish fires. With early detection and discharge of agents, damage to IT equipment can be reduced. Clean agent use in IT equipment storage rooms can reduce, perhaps eliminate down times as well as simplify clean up. Currently the most widely used clean agents are inert gases, hydrofluorocarbons (HFC’s) and perflourocarbons (PFC’s). Inert gases extinguish fires by depletion of oxygen to 15 percent from 21 percent. Inert gases are also environmentally safe and have low toxicity. In contrast, HFC’s and PFC’s extinguish fires by reducing the temperature of the flame. The high specific heat of the HFC’s and PFC’s absorb heat away from the flame until the temperature is below that which pyrolysis can be sustained [7].

Chapter 2: Review of Literature

2.1 Previous Testing on Clean Agent Extinguishing Concentrations

Studies demonstrating the effects of radiant heat flux on clean agent performance have been conducted by several organizations. In the late 1990's, Linteris at the National Institute of Standards (NIST) and 3M Company in collaboration sought to determine a testing protocol and provide data for clean agent extinguishing concentrations of fuel samples subjected to external radiant heat flux [7]. Linteris' scope of the research was:

- 1.) Define the problem associated with Class C electrical equipment hazards.
- 2.) Develop and suggest a test protocol that will provide a minimum extinguishing concentration of clean agents required for a selected fuel.
- 3.) Discussion of results from the proposed testing protocol.

First, Linteris received input from a group of technical panel members and corporate sponsors to define the problem [7]. Linteris also conducted a literature search to review the "suppression of flames over a condensed-phase materials and the effects of energy addition on the suppression of flames over materials"[7].

Next, Linteris developed a model to describe the complex phenomena of the solid materials. The model, depicted in Figure 1, involved burning flat polymer samples with an added external radiant heat flux. The model was developed to define the problem associated with fires over condensed-phase materials.

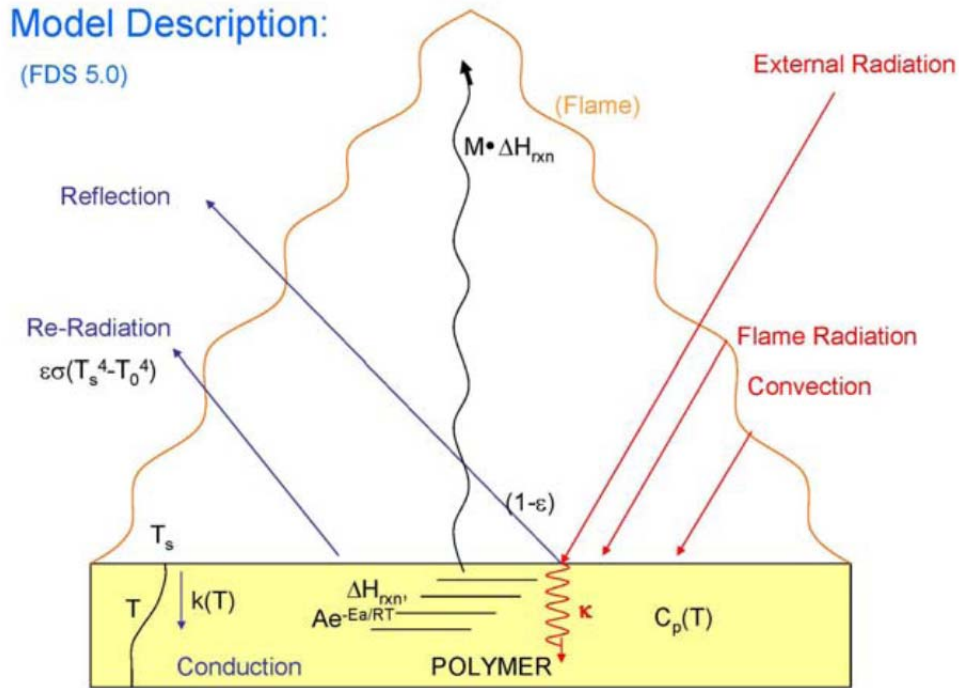


Figure 1: Thermal heat transfer of burning polymer with induced external radiant heat flux. [7]

From the model, the net heat gains into the polymer q_{net}'' (kW/m²) were calculated to determine the mass loss rate \dot{m}'' .

$$\dot{m}'' = \frac{q_{net}''}{L_V} \quad \text{Eq. 1}$$

Where:

\dot{m}'' = mass loss rate per unit area.

q_{net}'' = net radiant heat flux.

L_V = latent heat of vaporization.

q_{net}'' is defined by:

$$q_{net}'' = q_{f,rad}'' + q_{f,conv}'' + q_{external}'' - q_{re-rad}'' - q_{poly,conv}'' - q_{poly,cond}'' \quad \text{Eq. 2}$$

Where:

$q_{f,rad}''$ = radiant heat flux from the flame to the polymer

$q_{f,conv}$ '' = convective heat flux from the flame to the polymer.

$q_{external}$ '' = radiant heat flux applied from an external heat source.

$q_{poly,conv}$ '' = convective heat flux from the polymer surface to the ambient

$q_{poly,cond}$ '' = heat flux into the polymer by conduction [7].

The re-radiation heat losses from the polymer to the ambient is given by

q_{re-rad} ''

Where:

$$q_{re-rad}'' = \varepsilon\sigma(T_{pol,surf}^4 - T_{amb}^4) \quad \text{Eq. 3}$$

Where:

q_{re-rad} '' = re-radiation heat losses from polymer to the ambient

ε = emissivity of polymer surface

σ = Stefan-Boltzmann constant

$T_{pol,surf}$ = surface temperature of fuel polymer

T_{amb} = ambient temperature

To observe the effects of all the parameters in the model, Linteris conducted a series of experiments. Linteris first determined the effects of external radiant heat flux from 20 kW/m² to 70 kW/m² on mass loss rate (MLR) on 25.4 mm thick slab (1-D) polymethylmethacrylate (PMMA) samples. The resulting data is shown in Figures 2 and 3. The data shows higher mass loss rates with an increase in the external radiant heat flux [7]. From Figure 2 it can be seen at lower heat fluxes, the MLR takes longer to reach maximum levels than at greater heat fluxes. Also, an increase in MLR near

the end of the test is observed for greater heat fluxes. In the study, Linteris describes the effects “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”[7]. Results of the test indicated the sensitivity that external radiant heat flux has on mass loss rate, especially “at early stages of burning when the heat feedback from the flame is small” [7]. The effect of external radiant heat flux on the MLR is illustrated in Figure 3. Also, to establish a proper testing procedure, results from the experiment helped Linteris determine the influences of “preheating from the flame, preheating from any external energy source, thickness of the sample, and time for initiation of the suppressant flow” [7].

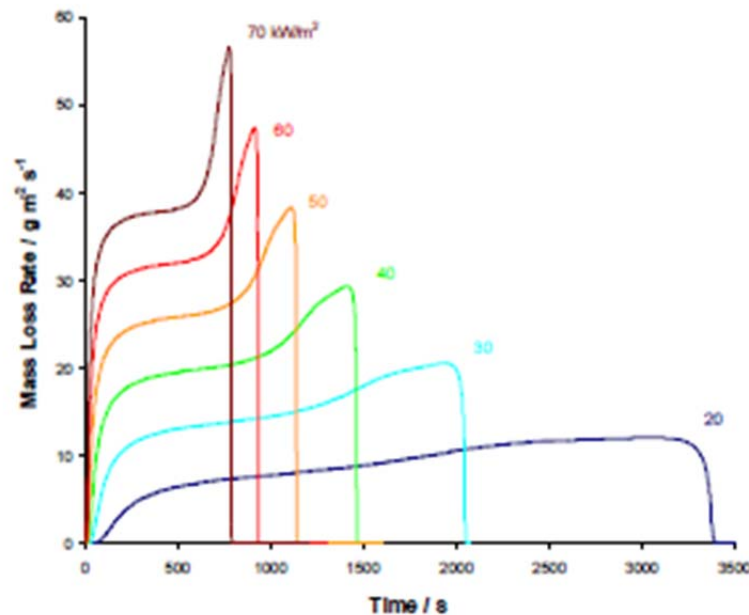


Figure 2: Mass Loss Rates as a Function of Time for 25.4 mm Thick PMMA Sample with Incident Radiant Heat Flux, kW/m² [7]

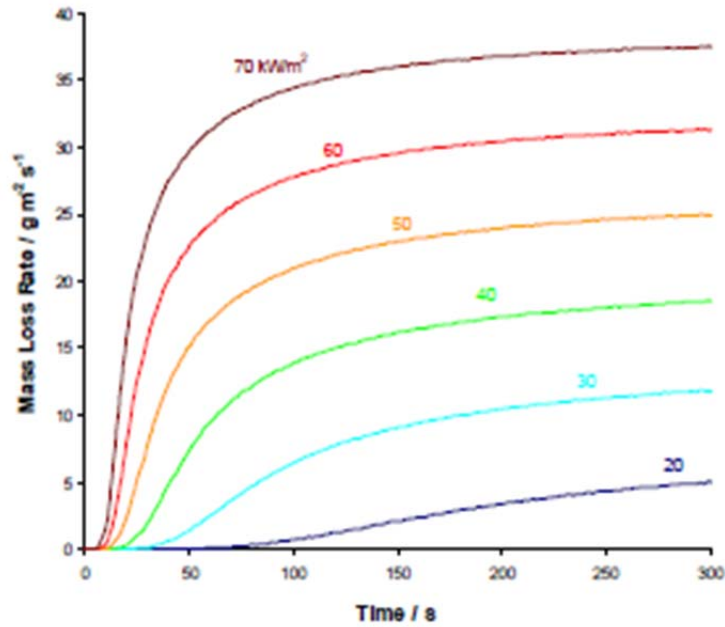


Figure 3: Mass Loss Rates as a Function of Shorter Time Span for 25.4 mm Thick PMMA Sample with Incident Radiant Heat Flux, kW/m² [7]

The next phase of the study was to characterize the suppression mechanism involved in clean agent extinguishment. Linteris developed the model expressed as equation 4 [7].

$$\left(\frac{l^2}{\rho D}\right) C_{Fb}^n C_{Ob}^m A \exp\left(-\frac{E}{RT_{AF}}\right) < k \left[\frac{R C_p T_{AF}^2}{E Q_F}\right]^3 \quad \text{Equation 4}$$

Where:

A= Arrhenius collisional term

C_{Fb}= Concentration of fuel

C_{Ob}= Concentration of oxidizer

c_p = Average specific heat at a constant pressure for the gas-phase

D = Domköhler number

E = Activation energy term

k = A constant.

l = Characteristic length

Q_F = Heat released per unit volume in the gas phase

R = Universal gas constant

T_{AF} = Adiabatic flame temperature.

ρ = Density of fuel

The model analytically describes all aspects of flame extinction; 1.) cooling the gas phase, 2.) cooling the solid phase, 3.) isolating the fuel, 4.) isolating the oxidizer, 5.) inhibiting the chemical reaction or 6.) blowing away the flame. When the left side of the Equation 4 is reduced, extinction is enhanced, for example by reducing the temperature (reducing T_{AF}), reducing the concentration of fuel C_F or oxidizer C_O . The form of Equation 4 can be modified to describe convective extinction by replacing $(\frac{l^2}{D})$ by $(\frac{l}{v})$. When convective flow is increased (velocity v is increased), the left side of the equation is reduced which enhances extinguishment [7]. Blowing away of the flame is addressed by the convective velocity term. With large enough velocity flow of the clean agent, blowing away of the flame could be the major mechanism for extinguishment. When larger extinguishing concentrations are

being tested, the subsequent larger flow rates of the clean agent should be considered as possible causes of flame extinguishment by blowing away.

Several testing apparatuses were considered by Linteris:

1. *Radiantly Enhanced Extinguishing Device (REED)*
2. *FM Global Fire Propagation Apparatus*
3. *Vertical Polymer Slabs Ignited by a Loop of Nichrome Wire*
4. *Wire Cable Bundles with Heated Nichrome Wire*
5. *Resistively Heated Polymer Samples*
6. *Heated Metal Surface Ignition of Premixed Gases*
7. *NASA WSTF Tests for EVA Suit Wire-Failure Ignition*
8. *NASA-GRC Test for Suppression of Flames Over PMMA*

2.1.1 Radiantly Enhanced Extinguishing Device

The first apparatus, REED, is a combination of the cup burner test and a cone calorimeter developed by Steckler, Donnelly and Grosshandler [14]. The general design of the apparatus is illustrated in Figure 4.

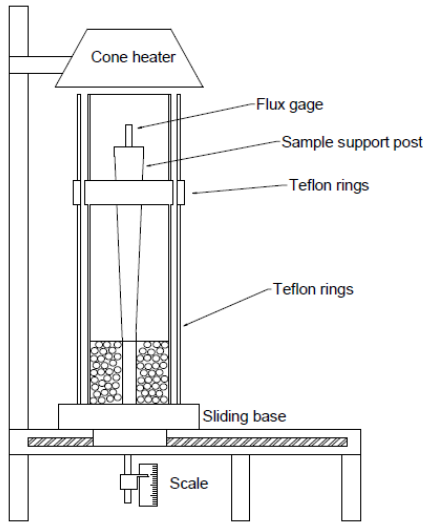


Figure 4: Radiant Enhanced Extinguishing Device [7]

The apparatus uses a 2.54 cm diameter, 2.54 cm thick cylindrical PMMA sample placed below a cone heater. The sample is ignited with a propane torch and pre-burned for 200 seconds. Agent is then introduced from below into the chimney until the sample extinguishes.

The apparatus design has the ability to determine the amount of agent applied. A principal benefit of the design is that a specific radiant heat flux can be applied in a test. Also, fuels of interest can easily be shaped and tested in accordance with the protocol.

The apparatus has several drawbacks. One of the shortcomings described by Linteris is the inability to determine the “actual heat addition rate from the electrical source in a typical energy augmented combustion (EAC) fire in a telecom or data processing fire scenario, so that the appropriate heat flux can be used for comparison in the REED test” [7]. Also, the heat flux delivered to the sample is dependent on the

absorptivity of the sample. Charring of materials can also create a thin layer of char acting as an insulator.

Smith, Kelly, Rivers, Braun and Grosshandler, described the development of the REED apparatus and the testing protocol [8]. The support platform for the apparatus is made of a 6 mm thick aluminum plate. A 152 mm by 31.8 mm tall brass base is fitted on top of the support. In the brass base there are two holes, one to introduce the clean agent and air mixture and the other for nitrogen. On top of the brass base are two PyrexTM tubes. The outer chimney is used to discharge nitrogen into the apparatus as a shield to protect the “heater from any corrosive products of decomposition as they pass through the cone to be vented” [8].

To make sure the nitrogen shield didn't provide any cooling effects, a preliminary test was conducted. In the test, the cone heater was adjusted to 30 kW/m². The nitrogen shield was set at 20 liters per minute (lpm) for 20 minutes. The heat flux was measured at the surface of the fuel sample after running a test with the nitrogen shield for the 20 minute duration. It was discovered that the heat flux level remained constant at 30 kW/m².

The inner chimney is used to introduce clean agent and air mixture into the apparatus and travel upward towards the fuel sample. The fuel sample is placed on top of a brass holder that is contoured, similar in shape to the cup burner test. Having a contour shaped holder reduces the turbulent flow of the agent and air mixture from the bottom to the top where the fuel sample is located. The cone heater is placed above the fuel to supply the external radiant heat flux. The cone heater is connected by three thermocouples to a control-box which is used to adjust the temperature of the

heater (and thus the radiant heat flux). Smith et al. calibrated the temperature to obtain the desired heat flux by a certified MEDTHERM™ heat flux meter.

Smith et al [8], also conducted testing cylindrical PMMA samples to determine the most suitable way to get a constant burning rate and prevent charring. Testing was conducted on samples wrapped on all sides except the top burning side and samples not wrapped. “Wrapping the rods in aluminum proved to be an effective method for controlling the burning rate and eliminated charring concerns on the sides of the samples” [8]. Consistency in the burning rate was important as it reduced “test to test variability” [8]. The results of the test presented in Table 3 show consistent mass loss flux for 2.54 cm long PMMA samples with varying diameters of 2.54 cm, 3.81 cm, 5.08 cm and 6.35 cm.

Table 3: Mass Loss Rates of 2.54 cm Long PMMA Rods of Various Diameters[8]

Diameter (in)	Surface Area (in²)	Mass Loss Rate (mg/s)	Mass Loss Flux (mg/s-in²)
2.54	0.79	2.4	3.1
3.81	1.77	5.5	3.1
5.08	3.14	11.1	3.5
6.35	4.91	17.2	3.5

With the mass loss flux being relatively constant for all diameter samples, it was established by Smith et al. to use 2.54 cm diameter by 2.54 cm thick cylindrical PMMA samples in all tests.

Smith et al. [8] used the following procedures to determine the extinguishing concentrations of clean agents using the REED apparatus:

1. "The heat flux meter is set in the position the fuel will occupy during testing. The input from the power supply is varied until the desired heat output from the cone is reached."
2. "The heat flux meter is removed and the fuel is placed, flat side up, on the load cell extension platform."
3. "The fuel is ignited using a propane torch."
4. "The front panel of the protective box is put in place."
5. "The air and nitrogen shield are set to flow rates of 10 and 20 lpm, respectively."
6. "The timer, data acquisition system and video camera are started."
7. "After a 200 second pre-burn period, the extinguishing agent is introduced. For the first test at zero flux exposure the initial agent concentration is set at 50% of the published cup burner value. As the flux level is increased the initial concentration is approximately 1% below the concentration that extinguished the flame at the previous flux level. The first test is primarily used to get a rough estimate of the extinguishing concentration."
8. "If the flame is not extinguished within 100 seconds then the agent concentration is increased one tick mark on the rotameter. (For the first run the increments are between 2 to 5 tick marks). Note: An increase of 1 tick mark can be anything between 0.3 and 1.0% increase, depending on the agent being used."
9. "Step 8. is repeated until the flame is extinguished."
10. "The extinguishing concentration is noted. The gas flows, data acquisition system and camera are stopped."
11. "Each heat flux level is tested 3 to 5 times to show repeatability."

12. “After the series of tests at each heat flux level the fluxmeter is used to measure the cone heater output to check the cone reliability.”

Smith et al. [8] also conducted tests to determine if re-ignition (inertion) of the fuel sample was possible. Procedures for the test were as follows:

Inertion Procedure

1. “After the flame is extinguished, the extinguishing concentration is maintained for 5 minutes to check for inertion of the fuel.”
2. “If re-ignition occurs the concentration is increased one tick mark on the rotameter and the 5 minutes timer is reset. This is repeated until re-ignition is not observed for 5 minutes or the fuel burns out.”
3. “Once inertion is observed for 5 minutes the agent flow is discontinued (the air and nitrogen shield are kept flowing) and the sample is again observed for re-ignition. Re-ignition at this point verifies that the inertion was a result of the agent concentration.”

Resulting data from the test conducted using the procedure listed above can be seen in Figure 5. Smith et al. concluded “that elevated concentrations of clean agents are needed to extinguish fires when the fuel is continuously subjected to an external energy source” [8].

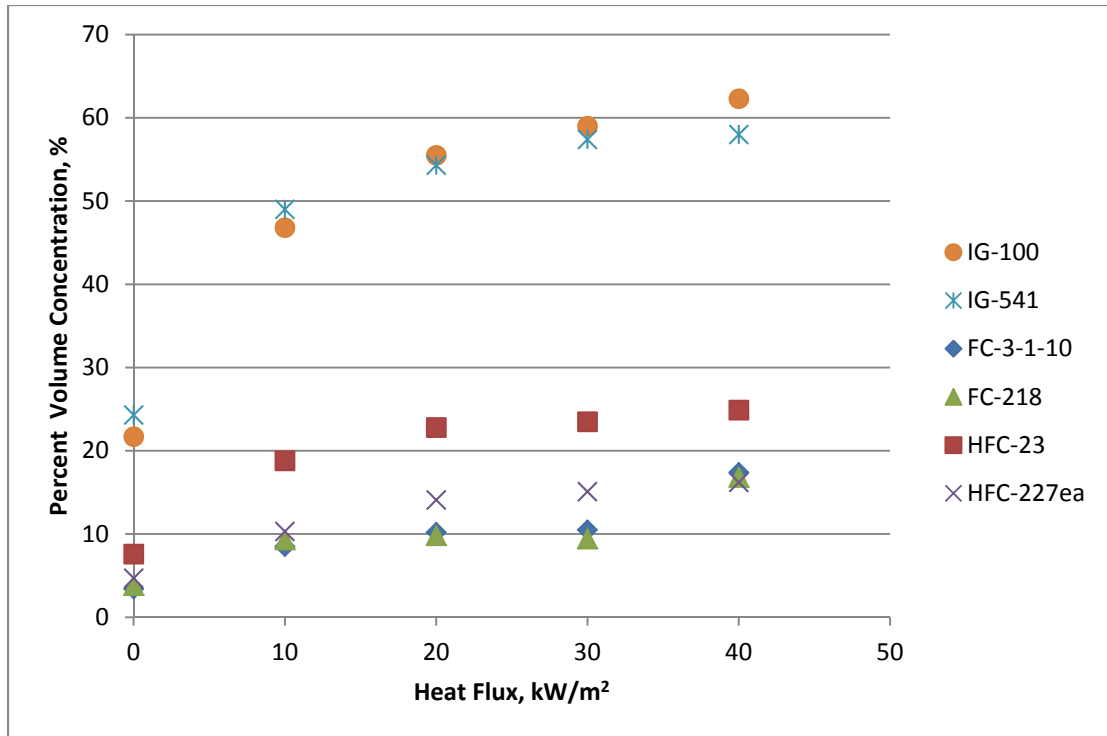


Figure 5: Preliminary REED Apparatus Data: Extinguishing Concentrations as a Function of Radiant Heat Flux [8]

Test results were replicated for nitrogen (N₂) and CF₃H (HFC-23) clean agents by an identical REED apparatus at NIST by Braun and Grosshandler [8].

2.1.2 FM Global Fire Propagation Apparatus

Testing results from the FM Global Flammability Apparatus were also used to compare extinguishing concentrations. The design of the FM Global “is conceptually the same” as the REED apparatus [7]. The apparatus is shown in Figure 6 and was designed by Tewarson and Pion 20 years prior to the REED apparatus. The FM Global Fire Propagation Apparatus uses a “horizontal polymer sample 60 cm² to 100

cm² in a chimney, with controlled atmosphere, and exposed to an external radiant heat flux”[7]. Radiation is provided by infrared panels on all sides of the chimney. Agent is introduced into a chimney; similar to REED apparatus, until the fuel extinguishes.

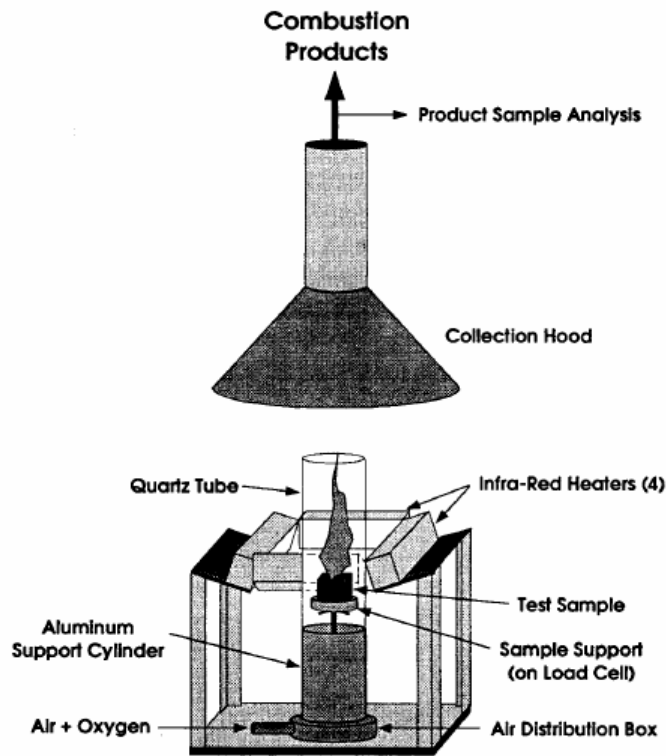


Figure 6: FM Global Flammability Apparatus [7]

Testing results compiled from studies conducted by Smith et al. [8] and Tewarson, Pion [15] are shown in Figure 7. The independent tests conducted by 3M Company and NIST resulted in similar extinguishing concentrations. Similarly, test conducted by FMRC using the FM Global Flammability Apparatus show extinguishing concentrations for nitrogen that correlate with the results from the REED apparatus.

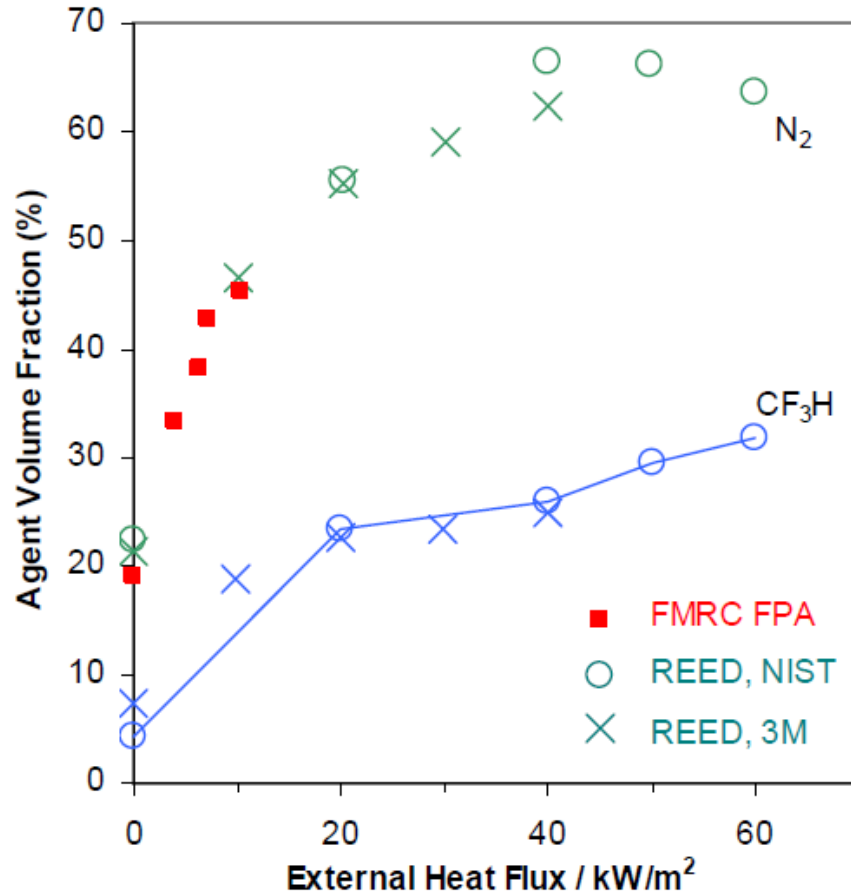


Figure 7: Results of Extinguishing Concentrations versus Agent Volume Fraction Compiled from FMRC, NIST and 3M Company [7]

2.1.3 Vertical Polymer Slabs Ignited by a Loop of Nichrome Wire

Robin, Shaw and Stilwell [16] developed a test method to determine the effects of radiant heat flux on clean agent suppression concentrations of burning polymer samples. The test uses a “U-shaped length of nichrome wire which passes through rectangular slots in a vertical polymer slab” as shown in Figure 7. In the test, the nichrome wire is “resistively heated to 1256 K (1800 °F) for the first 30 seconds

(to establish ignition and burning of the polymer), followed by a setting of 922 K (1200 °F) for the next 30 seconds” [7]. The apparatus is placed inside a 1 m x 2.3 m x 2.4 m enclosure and baffle similar to the apparatus described in UL2166 [11]. Clean agent is impulsively introduced into the enclosure via a single nozzle at 60 seconds. This test method is designed to simulate “hot wires in contact with polymers, which might occur in electrically-energized telecom or data processing equipment” [7]. The test method has some shortcomings. “The minimum concentration of agent for extinguishment for a given power level would be helpful (as opposed to pass/fail result for one at an unspecified power level)” [7]. Also, the test is difficult to obtain a simplified 1-D burning configuration. The test has a 3-D burning configuration with regions of electrical heating different from the regions of flame heating.

2.1.4 Wire Cable Bundles with Heated Nichrome Wire

Robin et al. [17] provides a testing method to “simulate suppression of energy-augmented combustion fires” [7]. In this test, “an assembly of seven wire cables, each 15.2 cm long is grouped together. The cable jacket contains insulated wires. Inserted inside the jacket is an 18 AWG (1.024 mm diameter) nichrome wire. The nichrome wire is heated to 1800 °F. The wire is pre-burned for 60 seconds until clean agent suppressant is introduced. The whole assembly is placed in the same agent injection system and enclosure used in the *Vertical Polymer Slabs Ignited by a Loop of Nichrome Wire* test [7,17]. The test lacks few critical details which are needed for the study. First, the power supplied to the wires is not provided, therefore the heat flux cannot be estimated. [7]. Second, Linteris postulated that the flames

from the fire likely extend away from the cable bundle. Because the flames extend further out, most of the heat feedback to the polymer, necessary to feed the flame, is not reaching the polymer. “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” [7].

2.1.5 Resistively Heated Polymer Sample

Niemann, Bayless and Craft [18] provide a method for determining clean agent suppression concentrations of a resistively-heated polymer. In the test, PMMA is “heated with nichrome wire, which is either wrapped on the exterior surface, or sandwiched (with spaces) between two slabs of the polymer” [7]. “The polymer sample is placed in a V-shaped holder, which is centrally located and raised 20 cm above the floor in a test chamber. 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 in the enclosure, provide mixing of the agent with the air” [7]. The tests were conducted at 48 W and 192 W being supplied to the nichrome wire. For the 48 W test, the heat flux incident on the polymer is 6.8 kW/m² assuming 100 percent transfer. For the 192 W test, heat flux levels of 110 kW/m² and 220 kW/m² are incident on the polymer based on 50 percent or 100 percent energy transfer.

This test has several advantages. First, the extinguishing concentration can be determined as a function of power. Also, the method allows for “any material or agent” [7] to be tested.

However, there are some shortcomings to this test. First, it is “difficult to know the concentration of agent actually reaching the burning polymer when it does extinguish” [7]. Second, the impulsive release of the agent may de-stabilize the flame which could give false suppression concentration results.

2.1.6 Heated Metal Surface Ignition of Premixed Gases

In two studies [19,20], researchers from NIST examined the auto-ignition temperature of ethylene on a nickel foil surface in the presence fire suppressing agents. The agents tested were N₂, 1G-542, HFC-23, HFC227ea, FC-218 and FC-3-1-10. The nickel foil surface was heated from 760 °C to 1100 °C until the onset of auto-ignition. Concentration of the fire suppressing agent required to suppress the fire was determined. Although the test “demonstrated the tendency of both chemically reacting and inert fire suppressant to become less effective at higher temperature” [7], it was found not useful in determining clean agent extinguishing concentrations. The test configuration may be unrealistic as the temperatures of the metal plates are high; it does not seem likely these temperatures could exist for components of electronic devices.

2.1.7 NASA WSTF Tests for EVA Suit Wire-Failure Ignition

Linteris [7] also examined an assortment of other tests. The first test was developed by NASA [21] after technicians examined an Extra-Terrestrial Vehicle Activity (EVA) suit that had returned from space with frayed wires. Researchers at the NASA White Sands Test Facility (WSTF) developed three tests to test the failure

of suits. The first two tests, known as the Multiple Locations Intermittent Arcing Method and the Single Location Intermittent Arcing Method, “used a needle-like anode electrode to scratch or poke through a test material against the cathode” [7]. On the third test, a “thin wire (34 AWG to 54 AWG) was pressed against the fabric, and the current (regulated) was increased until wire failure” [7].

Linteris found the results from the test to have significance. Results from the test showed all three tests ignited the suit. However, the third method of testing ignited the suit with the lowest amount of power. “Wire heating test preheated the surface of the polymer, making fuel species available in the gas phase for ignition” [7].

Significance of the results considered by Linteris was that “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” [7].

2.1.8 NASA-GRC Test for Suppression of Flames Over PMMA

In this test, Goldmeer et al. [22] examined the sensitivity of cross-flow on suppression of a flame over horizontal cylinders of PMMA. Results from the test showed “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.

Similarly, Ruff et al. [23] studied the effects of cross-flow on extinguishment of cylindrical PMMA samples. In this test, a resistive cartridge heater was used to pre-heat the center of the PMMA sample. CO₂ was added to the airstream until the flame extinguished. Results of the study indicated extinguishment was “sensitive to degree of resistive preheating” [7].

2.1.9 Summary

After reviewing all the methods and approaches which would be effective in simulating the effects of energy augment combustion fires, Linteris determined the REED [14] apparatus was the most desirable [7]. In the test, concentrations of the clean agent were known, as was the radiant heat flux. Therefore, for this thesis, test methods and approaches developed by Smith et al. [8] for the REED apparatus will be used.

In Linteris’s study, information regarding approaches for specifying a test method was sought out from technical panel members and corporate sponsor representatives of the NFPA Fire Protections Foundation Project on Clean Agent Suppression of Energized Electrical Equipment [7]. Respondents of the survey “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 that amount of suppressant” [7].

2.2 Role of Radiant Heat Flux on Blade Servers

Since determining radiant heat flux dissipated by various equipment in data processing centers can be difficult, a model needs to be developed. In this thesis, blade servers in particular will be analyzed. Blade server, equipment found in data processing facilities, are made of units (CPU), chipsets, storage device, memory, voltage regulators and power suppliers. Currently, planners and designers of data center facilities use a metric system called *power density* to define the hazard. Power density “refers to the average watts per square foot of available data com equipment power over the technical area of the datacom (data processing) facility” [9]. However, recently there has been a push to measure power density “for the more precise kilowatts per rack metric” [9]. For this thesis the more recent definition of power rack density will be used.

Power rack densities are increasing due to the need for higher performing, more efficient processors. Components within a blade server require varying amounts power for processing. Figure 8 shows power consumption ratios within a blade server for components under heavy and idle load conditions.

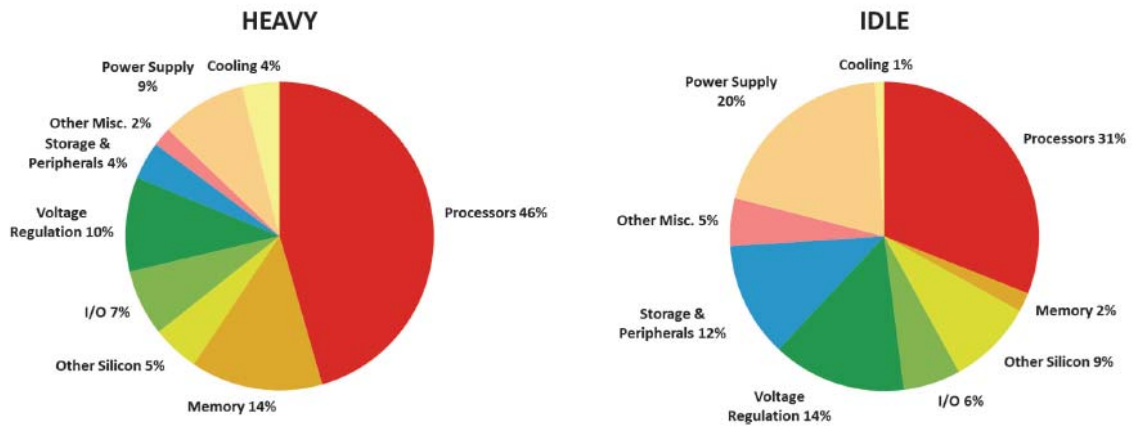


Figure 8: Power Consumption of Components within a Blade Server by Load Conditions. [9]

Since CPU's (processors) consume majority all power supplied, ASHRAE sought out to determine the trends in power consumption by CPU's in blade servers. Figure 9 shows the trends in CPU power consumption by year 2020 for four processor types; high power and low power high-performance computing (HPC) and two-socket and four-socket servers.

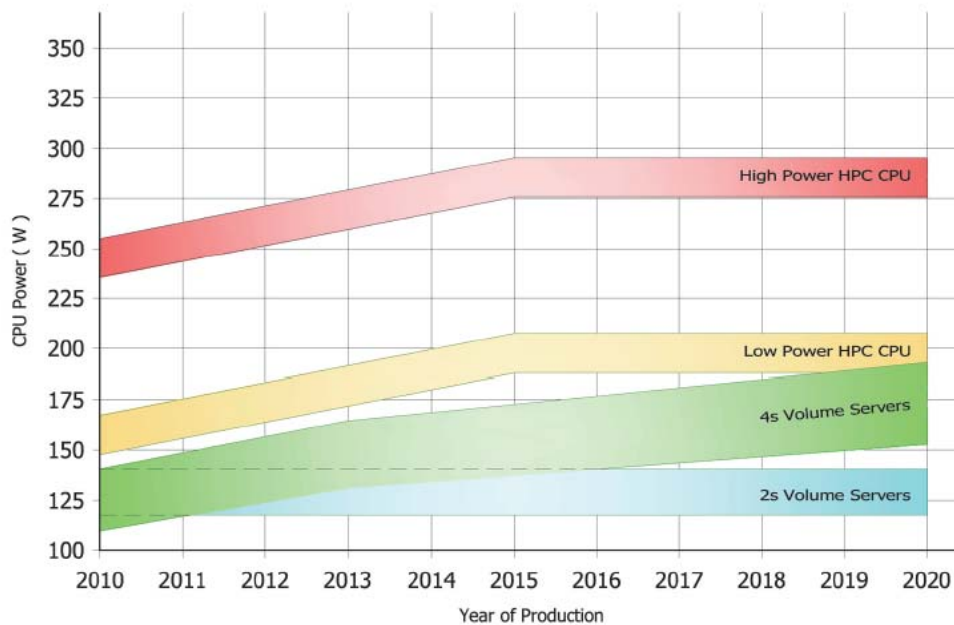


Figure 9: CPU Power Consumption Trends [9]

Similarly, in 2010 Ponemon Institute conducted a survey of 453 individuals in U.S organizations who have responsibility for data center operations [15]. One of the questions asked for power density (in kW) per rack in data centers in two years. Poll results from the respondents showed an average value of 11.4 kW per rack power density [10]. Increase in power consumption is directly related to total heat dissipated by the equipment. Focus on blade server power densities has been a concern in the fire protection industry because it is known radiant heating can enhance energized equipment fires, as demonstrated from studies conducted by Linteris [7] and Smith et al. [8].

In this study, it is assumed all power consumption by blade servers is being emitted from the blades via radiation. It is also assumed all racks hold 42, 1U blade servers. The “U” term refers to 1.75 in (44.45 mm) vertical height within a rack between blades. Since it is known most blade server fires originate to a single

component, the radiant heat flux that is energizing that fire are the surround two blade servers. Two horizontally stacked blade servers are shown in Figure 7 with a cable running between them.

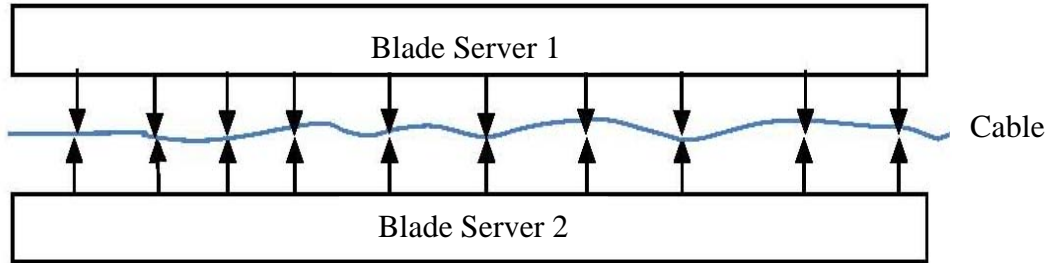


Figure 10: Horizontally Stacked Blade Servers Emitting Thermal Radiation on Cable.

Assuming the cable is on fire and the blade servers are still in operation, a radiant heat flux will be emitted towards the cable proportional to the power consumed by each blade server. With power consumption per rack of blade servers expected to be 11.4 kW by year 2012, power rack densities of 10 kW and 20 kW were used in calculating radiant heat flux emitted by each blade server. Radiant heat flux emitted by blade servers was calculated as shown below:

$$Q = \frac{P}{H} \quad \text{Equation 5}$$

$$q'' = \frac{Q}{A} \quad \text{Equation 6}$$

Where:

Q= heat output (kW) per blade server,

P= power density (kW) per blade server rack.

H=number of blade servers in a 42U rack (42 blade servers)

q''= radiant heat flux emitted by blade server.

A=surface area of blade server.

Table 4 shows radiant heat flux emitted by blade servers of various surface area and power density. From the table it is seen the largest radiant heat flux emitted is 4.76 kW/m² from a blade server with a 0.1 m² surface area on a 20 kW rack. It is important to keep in mind these radiant heat flux levels are for rack power densities which exceed expected power densities in the near future. Based on the results indicted in Table 4 which provide upper limits of the radiant heat flux for a particular power level, it is evident clean agent performance should be studied at lower radiant heat flux levels of 0-5 kW/m².

Table 4: Radiant Heat Flux Emitted by Blade Server in respect to Surface Area and Power Density

	Blade Server Area (m ²)	10 kW Rack	20 kW Rack
Radiant Heat Flux (kW/m ²)	0.1	2.38	4.76
	0.15	1.59	3.17
	0.2	1.19	2.38
	0.25	0.95	1.90
	0.3	0.79	1.59
	0.4	0.60	1.19

Clean agents tested in this study were IG-100, HFC-227ea, HFC-125, IG-541, FK-5-1-12 and IG-55. Table 5 shows the agents used based on classification (HFC, PFC or Inert Gas) and composition.

Table 5: Clean Agent Used in this Study by Classification and Composition

Agent	Classification	Composition
IG-100	Inert Gas	Nitrogen 100%
IG-541	Inert Gas	Argon 40%, Nitrogen 52%, CO ₂ 8%
IG-55	Inert Gas	Argon 50%, Nitrogen 50%
HFC-125	Hydrofluorocarbon	CHF ₂ CF ₃
HFC-227ea	Hydrofluorocarbon	CF ₃ CHFCF ₃
FK-5-1-12	<u>Perfluorocarbons</u>	C ₆ F ₁₂ O

Chapter 3: Current REED Apparatus Testing

3.1 Apparatus and Testing

The REED apparatus used in this study was adapted from that used by Smith et al. The apparatus was in storage for more than 10 years prior to this study so the first task was to make sure that all the components were still functional. After a thorough examination, the apparatus was assembled. For the purpose of this study, some parts of the REED apparatus were either removed or modified. First, the load cell was removed as measurement of mass loss rate (MLR) was unnecessary because the PMMA fuel samples tested in this thesis are similar in dimensions from the Smith et al. study [8]. Also, the purpose of measuring MLR by Smith et al. was to confirm the fuel was burning at a steady state. Studies from Smith et al. have already shown PMMA samples reach a steady burning rate after a 200 second pre-burn period so that time delay could be incorporated into the revised procedure used in this current study. Second, the measurement of clean agent concentrations was measured using a BIOS Met Lab[®] 800 Series flow meter as shown in Figure 11. Clean agent volumetric flow rate (lpm) is measured as the agent flows from the left and exits through the opening on the right. Originally, rotameters were used to measure clean agent volumetric flow rates. Use of the BIOS flow meter increases volumetric flow rate measurement accuracy from $\pm 2\%$ to $\pm 0.15\%$. Third, radiant heat flux emitted by the cone heater is measured by Hukseflux model SBG01 radiant heat flux sensor as shown in Figure 12. Signal is output with the cable shown in the middle and the two long aluminum ports on the side are used for circulating water to cool the sensor.



Figure 11: BIOS Met Lab[®] 800 Series Flow Meter

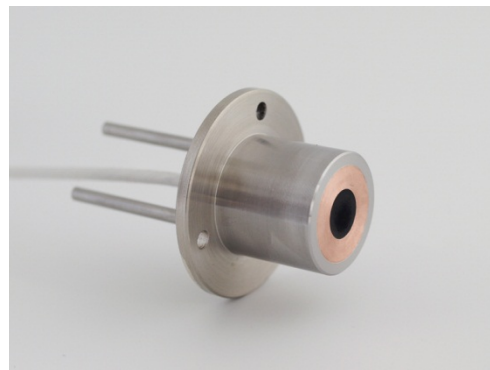


Figure 12: Hukseflux Model SBG01 Heat Flux Sensor

Method and Procedures:

The first task for testing is to calibrate the cone heater using the Hukseflux radiant heat flux sensor. Heat flux sensors are transducers which generate a voltage proportional to the applied heat flux. Figure 13 shows a similar Gardon (top) and Schmidt-Boelter (bottom) heat flux sensor. The Hukseflux heat flux sensor used is similar in design to the Schmidt-Boelter design. As heat flux is emitted onto the

sensor, it is absorbed by the black paint; “it measures the temperature difference across a thin, thermally insulating layer to determine the incident heat flux” [25]. The Hukseflux radiant heat flux sensor is positioned so that the top of the sensor is 3.5 cm below the bottom the cone heater. This position of the radiant heat flux sensor is so it is the same distance away from the cone heater as a fuel sample will be. With the heat flux sensor positioned the proper distance from the cone heater, radiant heat flux readings recorded will be similar to found on the surface of the fuel sample. Next, water is circulated through the housing of the sensor to prevent damage to the black paint on the sensor from high temperatures.

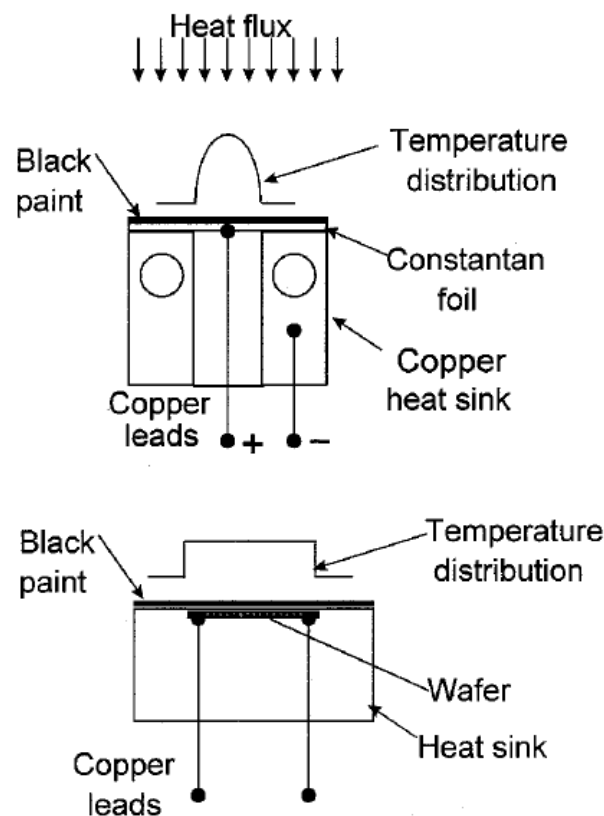


Figure 13: Heat Flux Sensors: Gardon (top) and Schmidt-Boelter (bottom)

Once the heat flux sensor was placed under the cone heater, a voltmeter was attached to it to measure voltage produced from the heat flux. Next, the cone heater was turned on by the control box. Temperature of the cone heater was adjusted using the control box. The voltage reading was converted to the corresponding radiant heat flux using the manufacturer provided sensitivity coefficient from equation 7.

$$q'' = \frac{V}{\varepsilon} \quad \text{Equation 7}$$

Where:

q'' = radiant heat flux (kW/m²)

V= output signal (mV)

ε = sensitivity coefficient ($0.323 \frac{mV \cdot m^2}{kW}$)

The first reading was taken with the cone heater off at ambient temperature. Next, voltage output was recorded with the cone heater temperature adjusted in 50 °C increments from 50 ° to 650 °C. The corresponding voltage readings were converted to heat flux using equation 7. Results of the calibration test are shown in Figure 14.

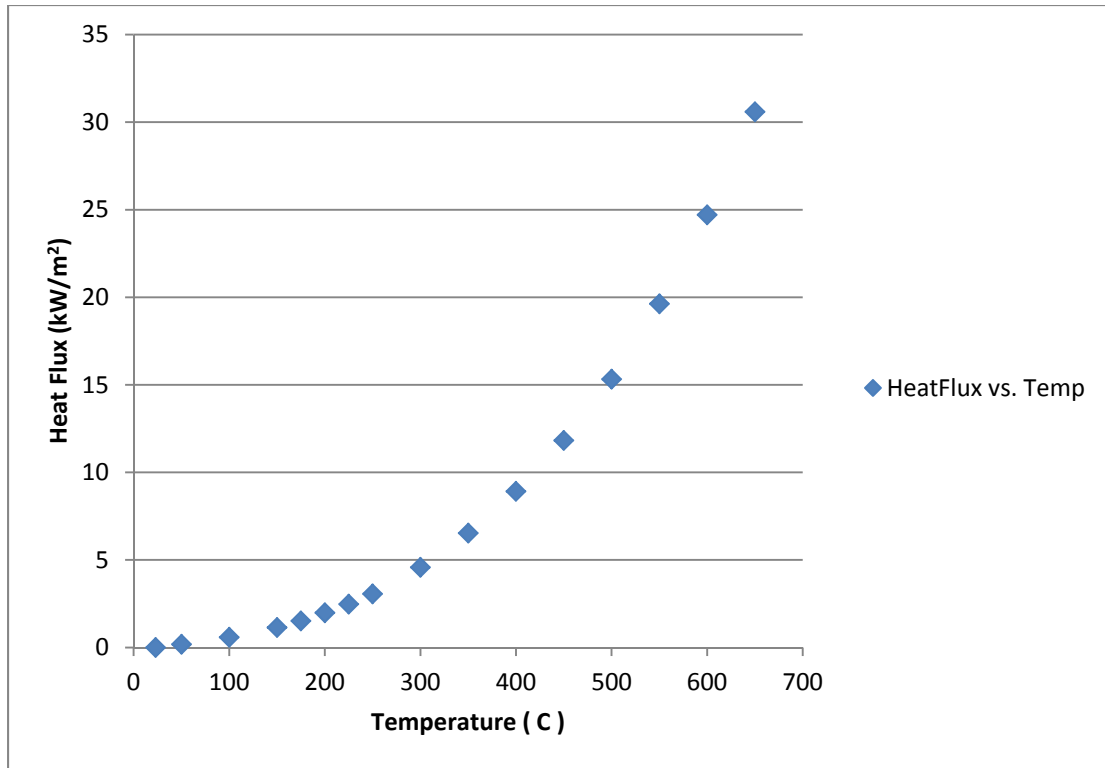


Figure 14: Heat Flux Measurements versus Temperature of Cone Heater

Results from the calibration were used to set cone heater temperatures for the desired heat flux. In this thesis, the experiment is conducted from 0-5 kW/m² for clean agents that were previously tested by Smith et al.[8] and 0-40 kW/m² for clean agents that have never been tested using the REED apparatus. Consequently, IG-100, HFC-227ea and IG-541 are tested with heat fluxes ranging from 0-5 kW/m² while FK-5-1-12, IG-55 and HFC-125 are tested with heat fluxes ranging from 0-40 kW/m².

PMMA fuel samples are prepared by wrapping all except the top burning side with aluminum foil as shown in Figure 13. This allows the burning rate to be simplified to a 1-D process, similar to Smith et al. [8]. Excess aluminum foil left at the bottom of the sample is consistent for all tests to maintain a constant distance of the fuel surface to the cone heater for all samples.

To ensure the PMMA samples used in this study will reach a steady state burning rate with the 200 second pre-burn period, mass loss rate measurements were taken at 0 kW/m² and 40 kW/m². PMMA samples are placed on load cell under the cone heater. External heat flux of cone heater is adjusted using heat flux gauge. Data acquisition system is initiated to read mass measurements of sample. PMMA sample is ignited using propane torch. The resulting MLR is shown in Figures 15 and 16.

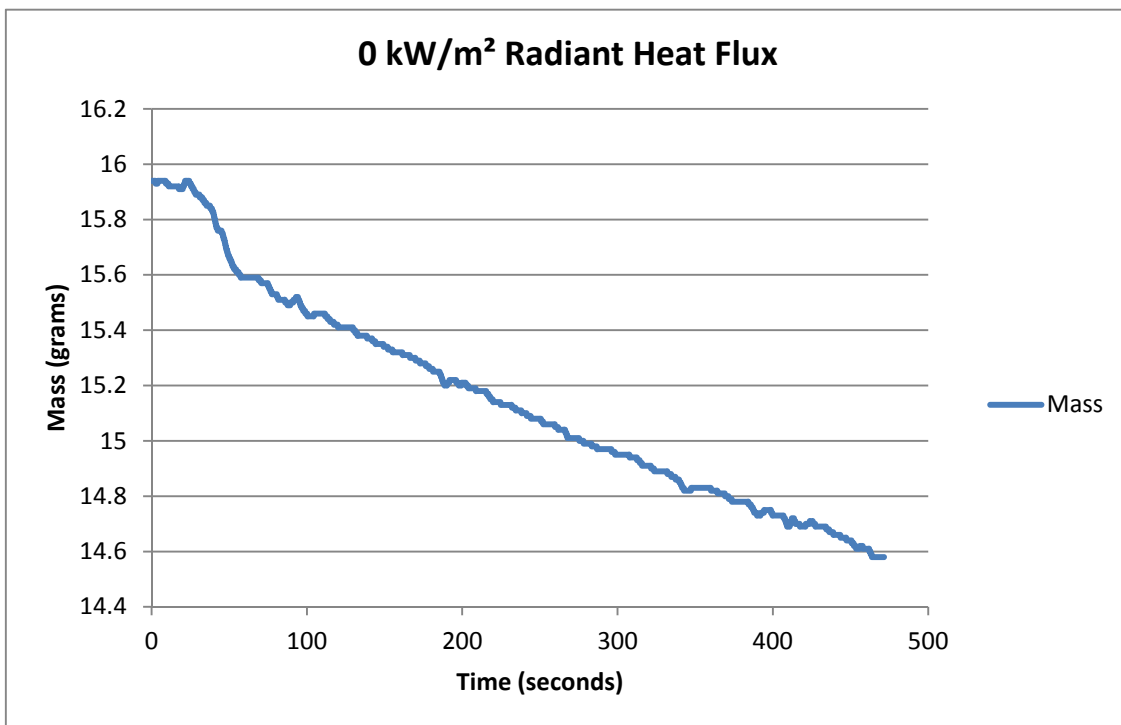


Figure 15: MLR of PMMA sample with respect to time with 0 kW/m² radiant heat flux.

The MLR reaches a steady-state level at 50.6 seconds. This is indicated by the steady negative slope of the curve.

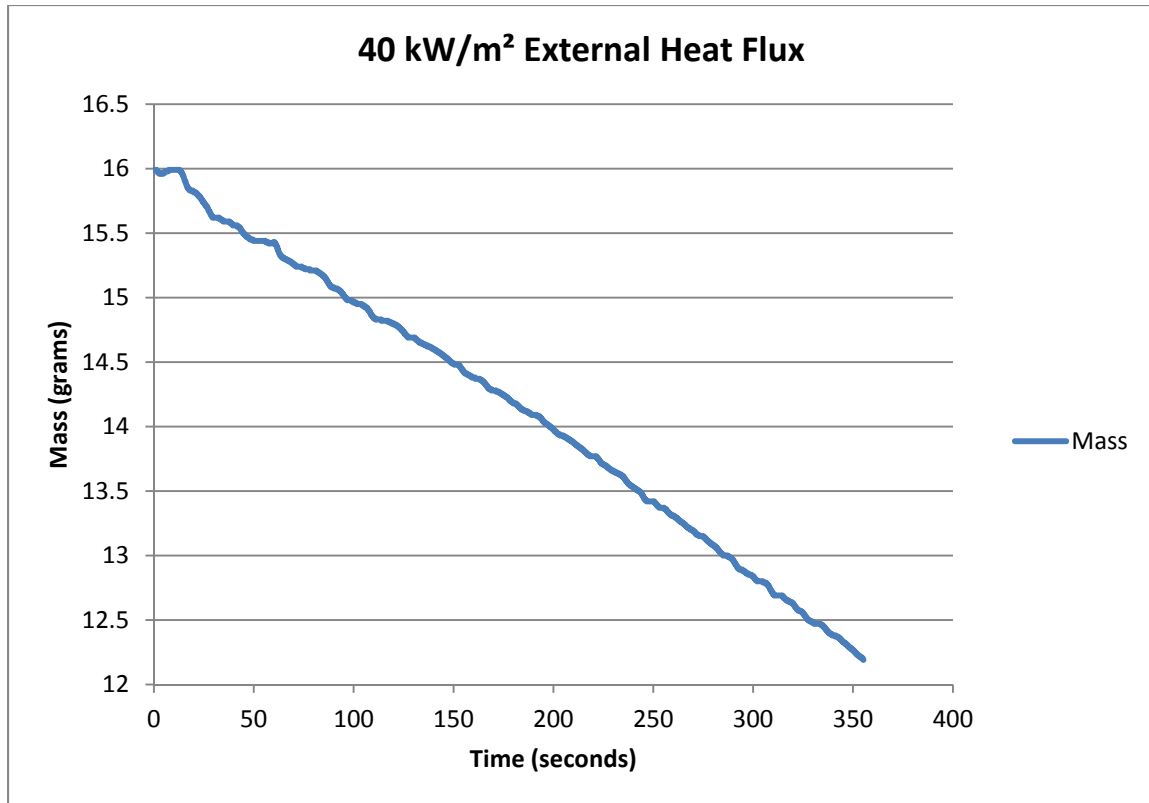


Figure 16: Mass of PMMA sample with respect to time with 40 kW/m² radiant heat flux.

The MLR reaches at steady-state at approximately 28.2 seconds after ignition. This is indicated by the steady negative-slope of the curve.

The next step is to ensure that a constant volumetric flow rate (20 lpm) of nitrogen is being supplied to the REED apparatus for shielding the cone heater. Needle valves are attached to the nitrogen supply hose to adjust the flow rate. The hose is initially run through the BIOS flow meter and adjusted until the flow rate was at a constant 20 lpm. After the flow rate has been achieved, the BIOS flow meter is removed and the nitrogen supply hose is attached directly into the REED apparatus.

Smith et al. [8] premixed the clean agent with a constant of 10 lpm supply of air. In order to get similar air flow rates, ambient air is run through the BIOS flow meter and adjusted with needle valve until it reached a constant 10 lpm. After the desired air flow rate is reached, the supply line is removed from the BIOS flow meter and attached directly to the Swagelok Tee union fitting. Configuration of the air supply and clean agent supply are shown in Figure 17. In the graphic, the clean agent is supplied from a pressurized cylinder to a flow meter with a supply hose. The supply hose has a needle valve to adjust volumetric flow rates. The clean agent exits from the right side of the flow meter which then connects to the number-one side of the Swagelok tee union. The number-two side of the tee union has a constant supply of air (10 lpm). Both agent and air premix and exit out the number-three side and into the REED apparatus.

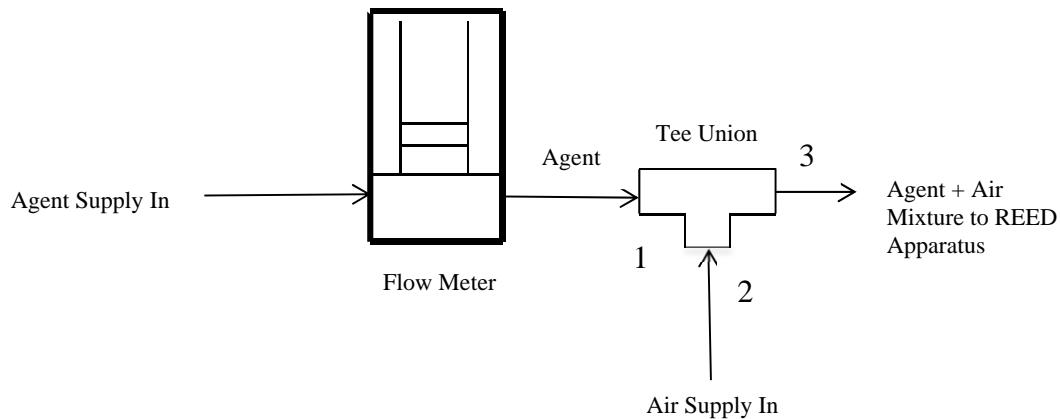


Figure 17: Configuration of Air Supply and Clean Agent using Swagelok Tee Union for Pre-Mix Supply Prior to Entry in REED Apparatus.

Since the BIOS flow meter displays agent volume in liters per minute, it must be converted to volumetric percent concentration. Concentration of clean agent used to suppress the fire was calculated using Equation 8.

$$\frac{X}{X+Y} * (100) = Z \quad \text{Equation 8}$$

Where:

X= Volume of Clean Agent (liters per minute)

Y= Volume of Air (10 liters per minute)

Z= Concentration of Clean Agent and Air Mixture (%)

Ignition of the PMMA fuel sample prevents the uneven burning of the surface which could affect results. Using a propane torch, the PMMA fuel sample should be ignited evenly throughout the entire surface. Aluminum foil should also be wrapped tightly onto the sample to ensure the flame doesn't move down the sides of the sample. Figure 18 shows a PMMA sample wrapped with aluminum foil. All sides except top surface (burning surface) are covered to isolate the burning surface.

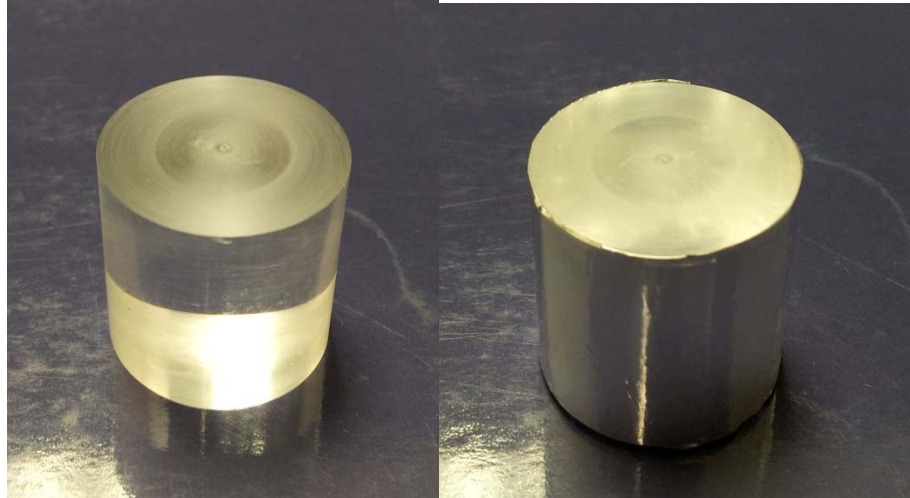


Figure 18: PMMA Sample Before (Left) and After (Right) Wrapped in Foil

The FK-5-1-12 clean agent required a different method for measuring percent volume concentration than the conventional method. FK-5-1-12 has a higher boiling point (49°C) than the other clean agents tested and remains a liquid at room temperature. Therefore, the natural reaction was to raise the temperature of the clean agent past the boiling point and then measure the clean agent concentration using the BIOS flow meter. However, the clean agent started to condense as soon as it entered the flow meter. To prevent a malfunction of the flow meter and acquire accurate data results, a different method was developed.

The new method used a Fourier Transform Infrared Spectrometer (FTIR) to determine FK-5-1-12 clean agent concentrations. FTIR Spectrometry is a method used for analysis in determining the amount of component, quality and also unknown impurities in a sample. This is achieved with an IR radiation source being passed through the sample. As the IR radiation passes through, some of the radiation is absorbed and some is transmitted proportional to the agent type and concentration.

The detector on the other side of the sample collects the infrared radiation signal that has passed through the sample. The data collected provides a unique fingerprint which can be converted to display a spectrum for the user to interpret. Based on the spectrum, an analysis can be conducted to determine the concentration of the agent. Figure 19 shows the set-up of the experiments for FK-5-1-12. The agent is submerged in a heat bath set at 90 °C to bring the agent to a gaseous form. All the piping that routes the agent to the REED apparatus is also wrapped in heated tape set at 90 °C. This prevents the agent from condensing. During testing, the valve for the cylinder that holds the clean agent is opened and the flow of the clean agent being supplied to the REED apparatus is controlled with a needle valve. After the agent and air mix in the Swagelok Tee union, it is run through a chimney with glass marbles on the bottom. Running the agent and air mixture through the glass marbles ensures the mixture is homogenous. At the top of the chimney, after the glass marbles, samples of the agent are taken from a sample port. A syringe is inserted into the sample port and four (5 mL) samples of the agent/air mixture are taken when the PMMA fuel extinguishes.

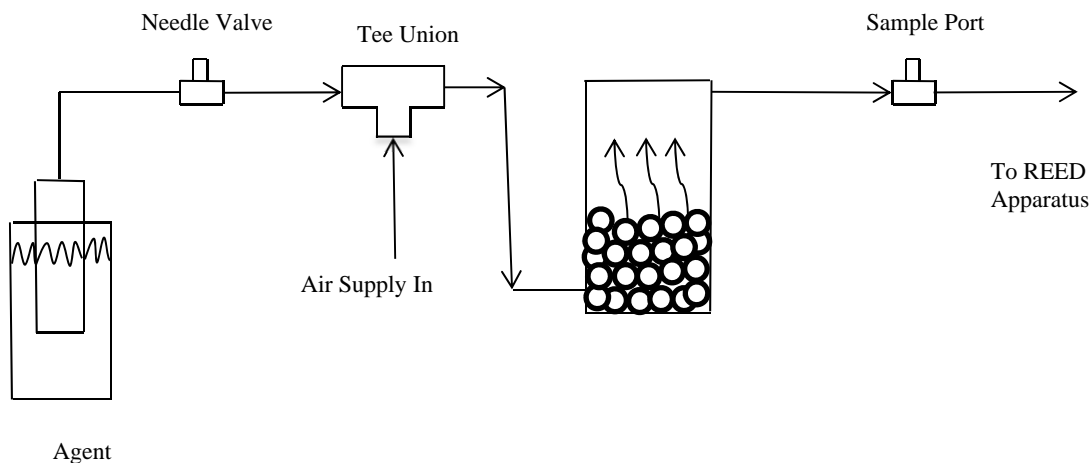


Figure 19: FK-5-1-12 Testing Equipment Set-Up

The samples taken are analyzed by the FTIR spectrometer to determine the concentration of agent that was supplied to the REED apparatus when it extinguished the fuel. Results of the analysis are given in terms of the concentration in percent-volume. Resulting concentrations from all four syringe tests are averaged for the overall concentration.

3.2 Protocol

Procedures used for testing all clean agents (except FK-5-1-12) were as follows:

1. The heat flux meter is set in the position the fuel will occupy during testing. The temperature of the cone heater is varied until the desired heat flux output from the cone is reached.
2. The heat flux meter is removed and the fuel is placed, flat side up, on the brass extension platform.
3. The air and nitrogen shield are set to flow rates of 10 and 20 lpm, respectively.
4. The fuel is ignited using a propane torch.

5. The front panel of the protective box is put in place.
6. The timer is started.
7. After a 200 second pre-burn period, the extinguishing agent is introduced. For the first test at zero heat flux exposure the initial agent concentration is set at 50% of the published cup burner value. As the heat flux level is increased the initial concentration is approximately 1% below the concentration that extinguished the flame at the previous heat flux level. The first test is primarily used to get a rough estimate of the extinguishing concentration.
8. If the flame is not extinguished within 100 seconds then the agent concentration is increased by 0.3 to 1.0 % using a needle valve.
9. Step 8. is repeated until the flame is extinguished.
10. The extinguishing concentration is noted. The gas flows is stopped.
11. Each heat flux level is tested 3 to 5 times to show repeatability.
12. After the series of tests at each heat flux level the heat flux sensor is used to measure the cone heater output to check the cone reliability.

The following procedures were used for testing FK-5-1-12:

1. The heat flux meter is set in the position the fuel will occupy during testing. The temperature of the cone heater is varied until the desired heat flux output from the cone is reached.
2. The heat flux meter is removed and the fuel is placed, flat side up, on the brass platform.
3. The air and nitrogen shield are set to flow rates of 10 and 20 lpm, respectively.
4. The fuel is ignited using a propane torch.

5. The front panel of the protective box is put in place.
6. The timer is started.
7. After a 200 second pre-burn period, the extinguishing agent is introduced. For the first test at zero heat flux exposure the initial agent concentration is set at 50% of the published cup burner value. As the heat flux level is increased the initial concentration is approximately 1% below the concentration that extinguished the flame at the previous heat flux level. The first test is primarily used to get a rough estimate of the extinguishing concentration.
8. If the flame is not extinguished within 100 seconds then the agent concentration is increased by 0.3 to 1.0 % using a needle valve.
9. Step 8. is repeated until the flame is extinguished.
10. After the fuel extinguishes, four syringes are used to sample (each 5mL) of the agent/air mixture.
11. The gas flows is stopped.
12. Syringe samples are analyzed using FTIR spectrometer.
13. Resulting concentrations are averaged and recorded

Chapter 4: Results and Discussion

4.1 Graphical Results

Experiments were conducted on clean agents , IG-100, IG-55, IG-541, HFC-125, HFC-227ea and FK-5-1-12. Testing results for all the agents are presented in Figures 20 and 21.

Figure 20 shows results for clean agents tested from the 0-40 kW/m² range. In the results, the agent concentration increased at a more rapid rate with increasing heat flux rates. Beginning at 10 kW/m², the curves start to plateau. This trend is similar to results seen from Smith et al. [8].

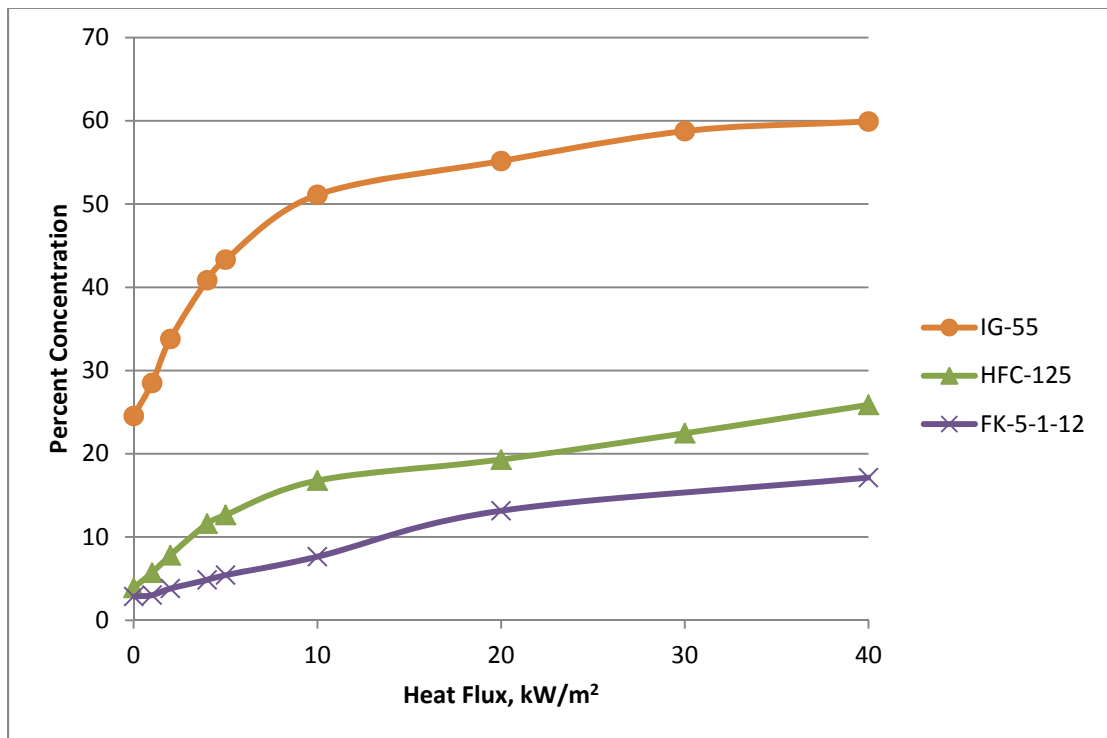


Figure 20: FK-5-1-12, HFC-125 and IG-55 Clean Agent Extinguishing Concentration for 0-40 kW/m²

Figure 21 shows results for clean agents, IG-100, IG-55 and IG-541. Results were conducted at the 0-5 kW/m² heat flux levels. At these lower heat flux levels, the plateau effect seen from higher heat flux levels as in figure 18 are not seen.

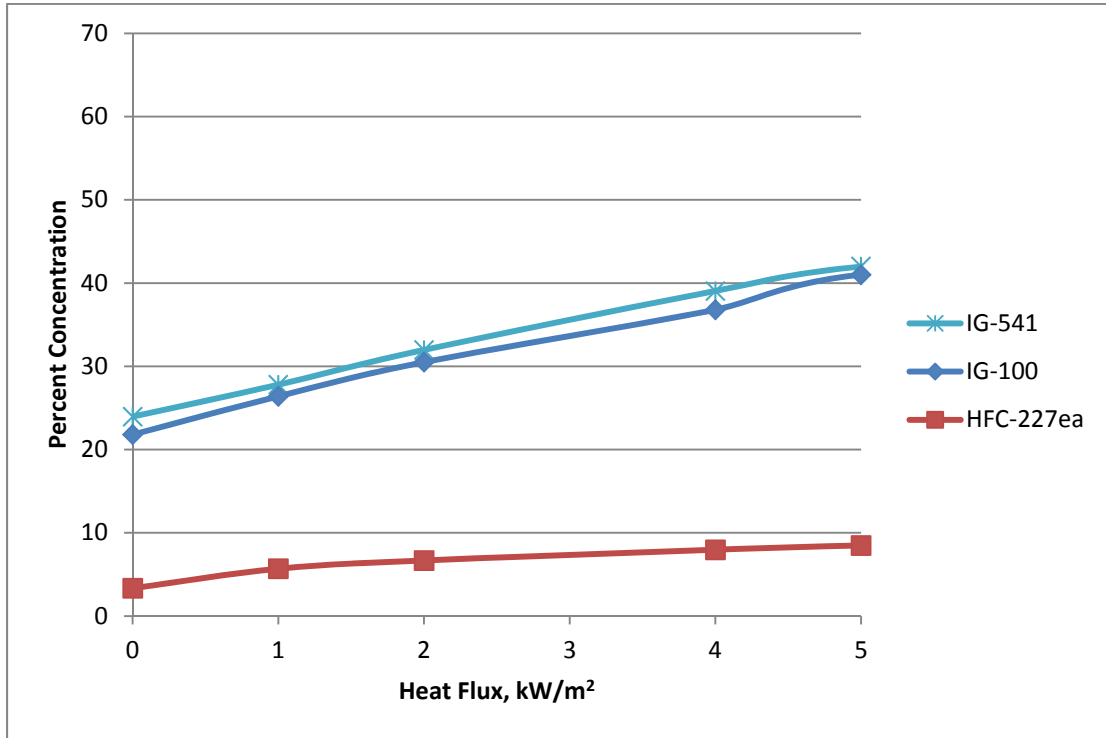


Figure 21: IG-541, IG-100 and HFC-227ea Clean Agent Extinguishing Concentrations for 0-5 kW/m²

Figure 22 gives results for clean agents IG-541, IG-100 and HFC-125 from the 0-40 kW/m². This helps to show how the results for these agents relate to results conducted previously by Smith et al. [8]. As can be seen, the data points from current tests follow a similar trend to results from prior tests (data points in red). This is important as it validates that procedures and methods used for current testing are reproduced accurately to those obtained by Smith et al. [8].

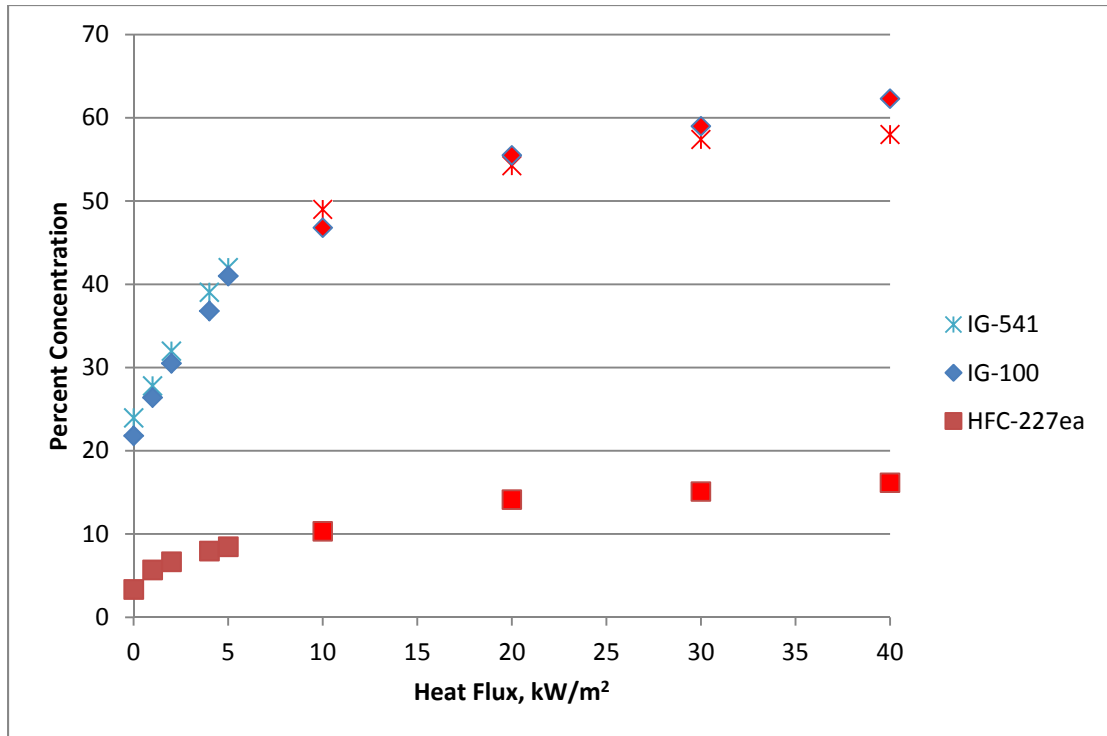


Figure 22: IG-541, IG-100 and HFC-227ea Clean Agent Extinguishing Concentrations for 0-40 kW/m²

A comparison of minimum extinguishing concentrations from the NFPA 2001 standard for Class C hazards versus extinguishing concentrations determined using the REED apparatus can be seen in Table 6. Significance of the results show that guidance for extinguishing concentrations of Class C hazards may be more beneficial if they were dependent based on emitted heat flux or power density; NFPA 2001's guidance based on Class A extinguishing concentrations with an added 35 percent safety factor may not be enough to suppress fires at the higher heat flux levels.

Table 6: NFPA 2001 Class C Design Concentrations versus REED Apparatus Extinguishing Concentrations.

Agent	NFPA 2001	0 kW/m ²	1 kW/m ²	2 kW/m ²	4 kW/m ²	5 kW/m ²	10 kW/m ²	20 kW/m ²	30 kW/m ²	40 kW/m ²
IG-100	40.5	21.8	26.4	30.5	36.8	41.0	46.8	55.5	59.0	62.3
HFC-227ea	7.0	4.7	5.7	6.7	8.0	8.5	10.3	14.4	15.1	16.2
HFC-125	9.0	3.9	5.7	7.8	11.6	12.7	16.8	19.3	22.5	25.9
IG-541	38.5	24.0	27.8	32.0	39.1	42.0	49.0	54.3	57.4	58.0
FK-5-1-12	4.7	2.9	3.0	3.8	4.8	5.4	7.6	13.2	N/A	17.1
IG-55	42.7	24.6	28.5	33.8	40.9	43.3	51.1	55.2	58.8	59.9

Graphical representation of Table 6 can be seen in Figures 23-28. The graphs show results for REED apparatus testing in comparison to extinguishing concentrations provided in NFPA 2001 for Class C hazards.

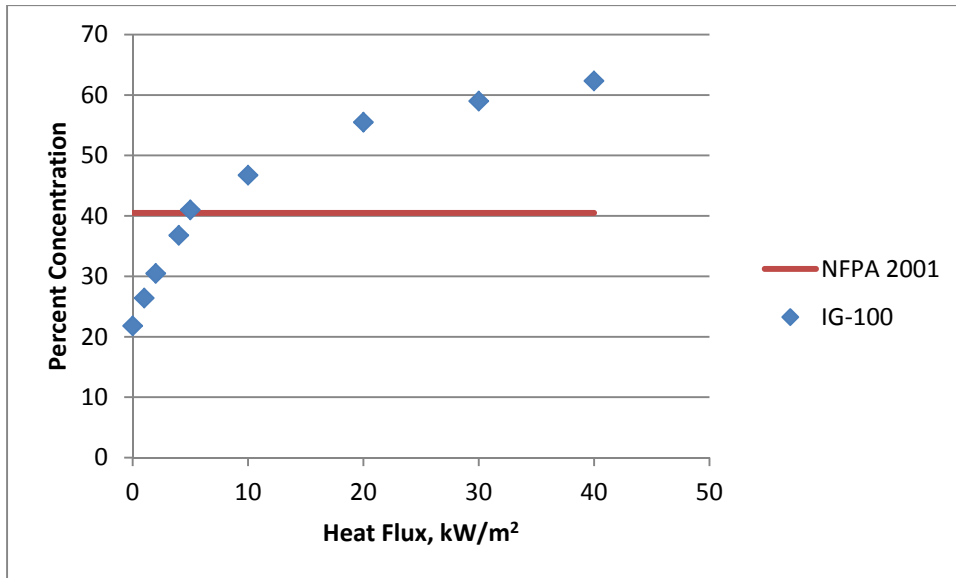


Figure 23: IG-100 Extinguishing Concentrations from REED Testing Compared to NFPA 2001 Extinguishing Concentrations for Class C Hazards

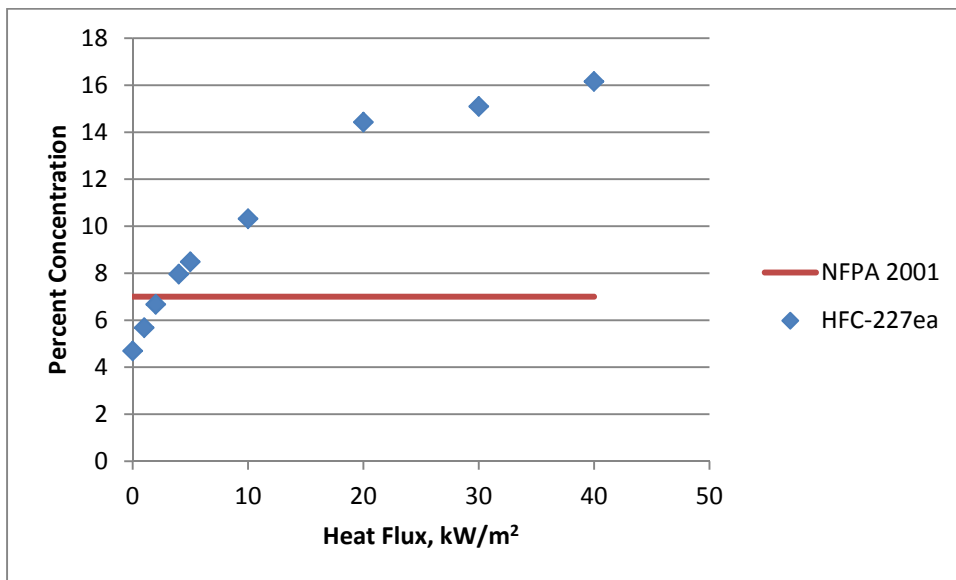


Figure 24: HFC-227ea Extinguishing Concentrations from REED Testing Compared to NFPA 2001 Extinguishing Concentrations for Class C Hazards

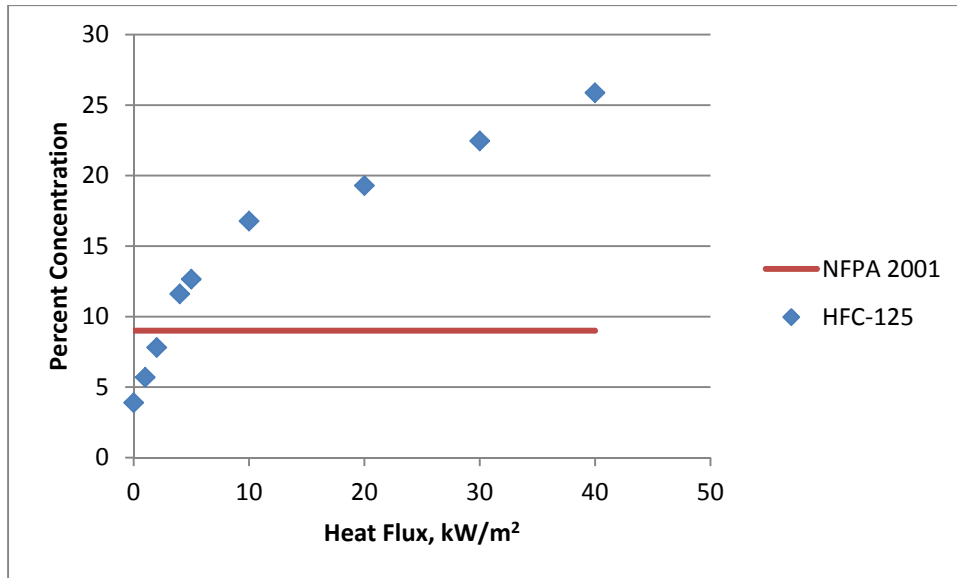


Figure 25: HFC-125 Extinguishing Concentrations from REED Testing Compared to NFPA 2001 Extinguishing Concentrations for Class C Hazards

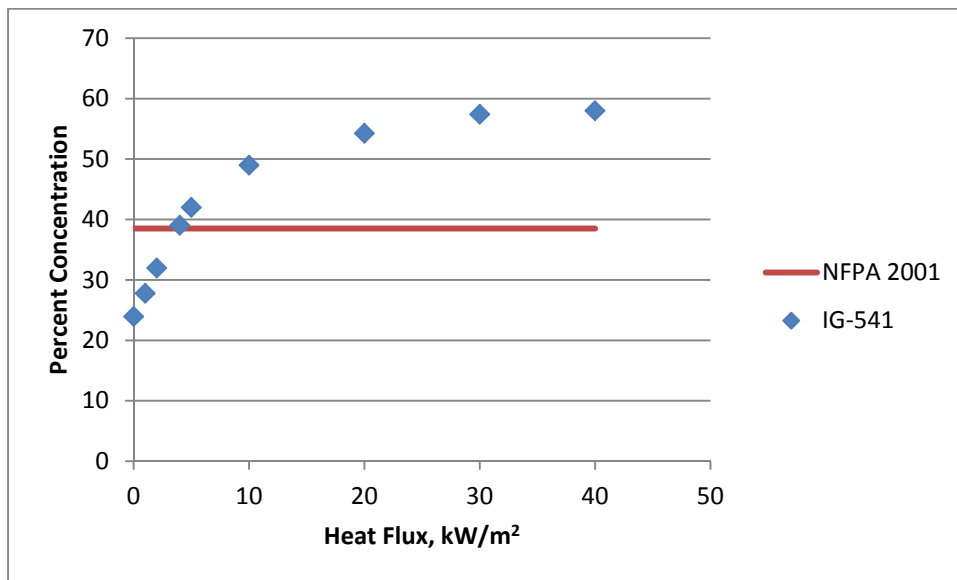


Figure 26: IG-541 Extinguishing Concentrations from REED Testing Compared to NFPA 2001 Extinguishing Concentrations for Class C Hazards

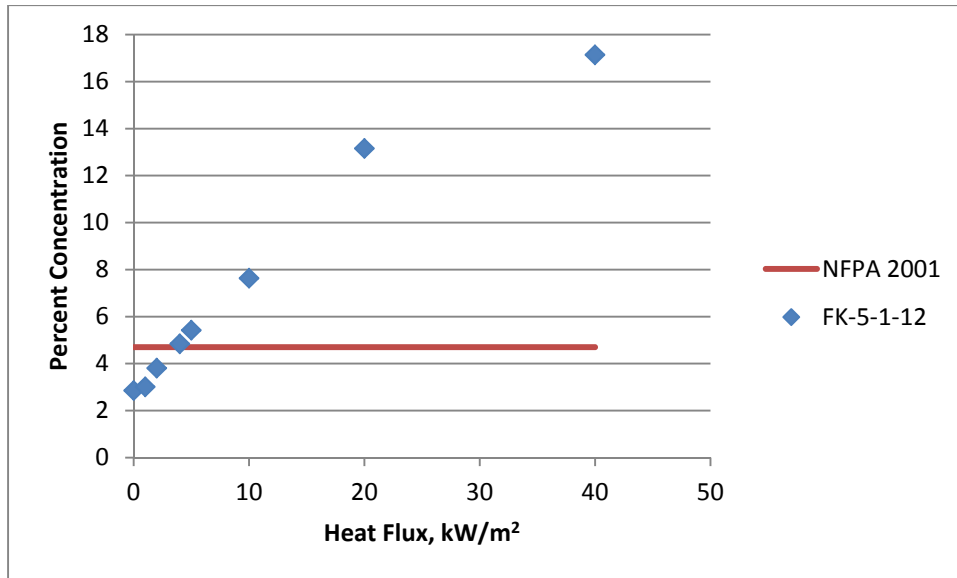


Figure 27: FK-5-1-12 Extinguishing Concentrations from REED Testing Compared to NFA 2001 Extinguishing Concentrations for Class C Hazards

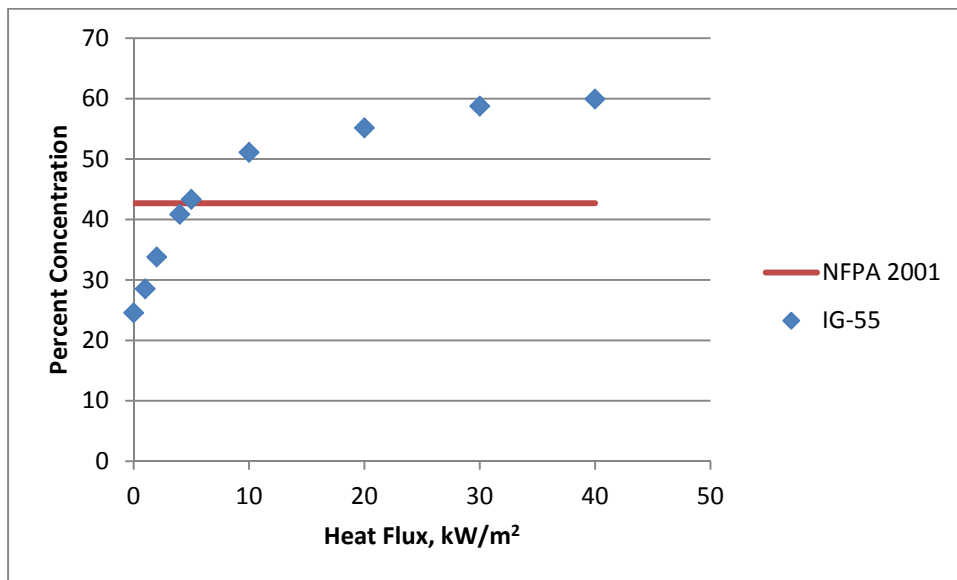


Figure 28: IG-55 Extinguishing Concentrations from REED Testing Compared to NFA 2001 Extinguishing Concentrations for Class C Hazards

4.2 Visual Observation

The behavior of the flame with agent addition was noted from visual observation during the test. As agent was introduced to the REED apparatus, the flame started to get smaller in volume as seen in Figure 29. Also, it was noticed the flame was lifting upwards between the fuel surface and ignition point. These findings are similar to the observations made by Linteris during his research [7]. In his test, it was theorized that as the flame weakens, the heat loss back to the surface is diminished. As the heat loss is diminished, so is the fuel supply, which further weakens the flame. To test the theory, Linteris recorded the fuel consumption rate of heptane and methanol in a cup burner test. It was found that the “fuel consumption rate drops very rapidly as the agent concentration nears the extinguishing value” [7].



Figure 29: PMMA Fuel Flame Size Before (Left) and After (Right) Exposure to Clean Agent

This phenomenon is of concern because it could mean the flame is being weakened by the long exposure to the clean agent. The weakened flame is more

sensitive to the added clean agent into the REED apparatus. A robust flame that is fully developed requires more agent concentration to extinguish than a weakened flame. This could be an indication that extinguishing concentrations may actually be lower than necessary for real world applications where flames may not be in a weakened state. The 100 second delay between agent concentration increases may be too long and may need to be revised to provide extinguishment without weakening the flame.

An alternative method for testing may be to lower the time between clean agent concentration increases dramatically to which the flame is not weakened and still provides enough heat feedback to the fuel surface. This alternative method was tested and results are discussed in the next chapter.

Chapter 5: Alternate Method for Testing

5.1 Proposal of IAR Testing Method

A new method for testing the REED apparatus was developed to alleviate weakening of the flame. The proposed method removes the 100 second time delay between agent concentration increases to 2 seconds. Two tests are conducted using the reduced time between agent increases at each specified heat flux level. The resulting extinguishing concentrations are averaged and recorded. The recorded extinguishing concentration would then be verified by running a test with Impulsive Agent Release (IAR). With the IAR method, clean agent is immediately supplied to the REED apparatus at the predefined flow rate based on extinguishing concentrations determined from the 2 second delay test. The idea is to introduce the clean agent to the flame at a known concentration. IAR method changes the 100 second time delay between the agent concentration increases to 2 seconds. This would prevent the flame from being weakened before it succumbs to extinguishment.

The IAR method is accomplished by using the same apparatus set up originally used in prior tests. During the 2 second time delay between agent concentration increases a needle valve is used to adjust the flow rate of the agent being supplied to the REED apparatus. After the two tests have been conducted to get an average of extinguishing concentrations, the needle valve is adjusted until the flow meter displays volumetric flow rates that equal extinguishing concentrations. Without further moving the needle valve, a ball valve prior to the needle valve is closed to stop all agent flow. When the third test is conducted to verify previous two tests, the ball valve is opened. Since the needle valve is positioned so the flow rate will produce

the specified concentrations, the agent will impulsively reach the REED apparatus without any concentration adjustments. If the fuel sample extinguishes within 15 seconds, the averaged extinguishing concentrations were determined to be validated. Apparatus configuration for the IAR method is shown in Figure 30.

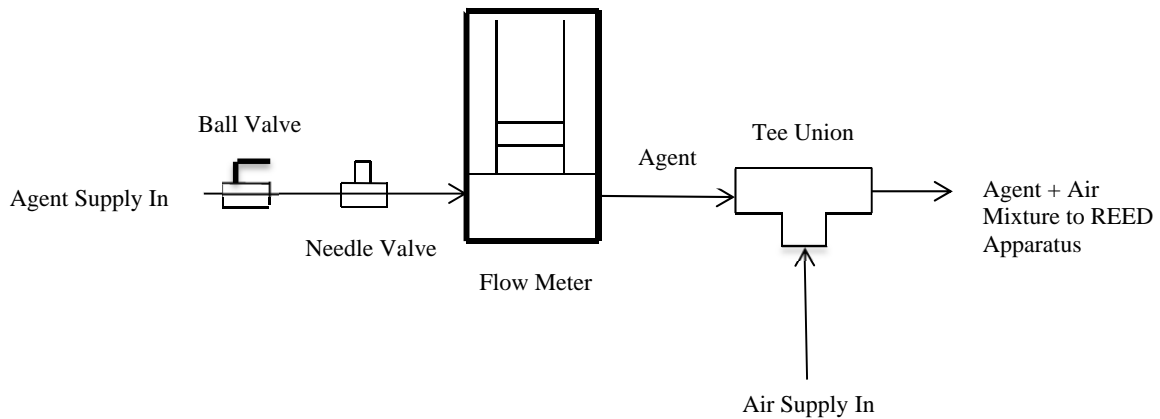


Figure 30: IAR Testing Method Configuration

Agents tested in the new method are IG-100, HFC-227ea, IG-55, HFC-125 and IG-541. These agents were tested from 0-5 kW/m². FK-5-1-12 could not be tested in this new method as the FTIR spectrometer was unavailable to measure extinguishing concentrations. In addition, materials such as the heat bath and heat tape were unavailable for testing.

Procedures for testing IAR method are as follows:

1. The heat flux meter is set in the position the fuel will occupy during testing. The temperature of the cone heater is varied until the desired heat flux output from the cone is reached.
2. The heat flux meter is removed and the fuel is placed, flat side up, on the brass extension platform.
3. The air and nitrogen shield are set to flow rates of 10 and 20 lpm, respectively.
4. The fuel is ignited using a propane torch.
5. The front panel of the protective box is put in place.
6. The timer is started.
7. After a 200 second pre-burn period, the extinguishing agent is introduced. For the first test at zero heat flux exposure the initial agent concentration is set at 50% of the published cup burner value. As the heat flux level is increased the initial concentration is approximately 1% below the concentration that extinguished the flame at the previous flux level. The first test is primarily used to get a rough estimate of the extinguishing concentration.
8. If the flame is not extinguished within 2 seconds then the agent concentration is increased by 0.3 to 1.0 % using a needle valve.
9. Step 8. is repeated until the flame is extinguished.
10. The extinguishing concentration is noted. The clean agent flow is stopped.
11. Steps 1-10 are repeated one more time.
12. Extinguishing concentrations of the two tests are averaged and recorded.

13. Needle valve is adjusted to get flow rate which would equal the averaged extinguishing concentrations.
14. Ball valve is closed.
15. Steps 1-7 are conducted
16. Ball valve is opened
17. If the fuel sample extinguishes within 15 seconds, averaged agent concentrations are considered valid.
18. After the series of tests at each heat flux level the heat flux sensor is used to measure the cone heater output to check the cone reliability.

5.2 Results and Discussion

Results of the newly proposed IAR testing method are shown in Figure 31. Results from the test show the trend where the extinguishing concentrations increase with increasing heat flux. This trend is similar to the results found from Chapter 3. Also, the curves for the inert gas clean agents have a more curved behavior which plateaus at 2 kW/m^2 . In the original testing method, the curves didn't start to plateau until roughly 10 kW/m^2 .

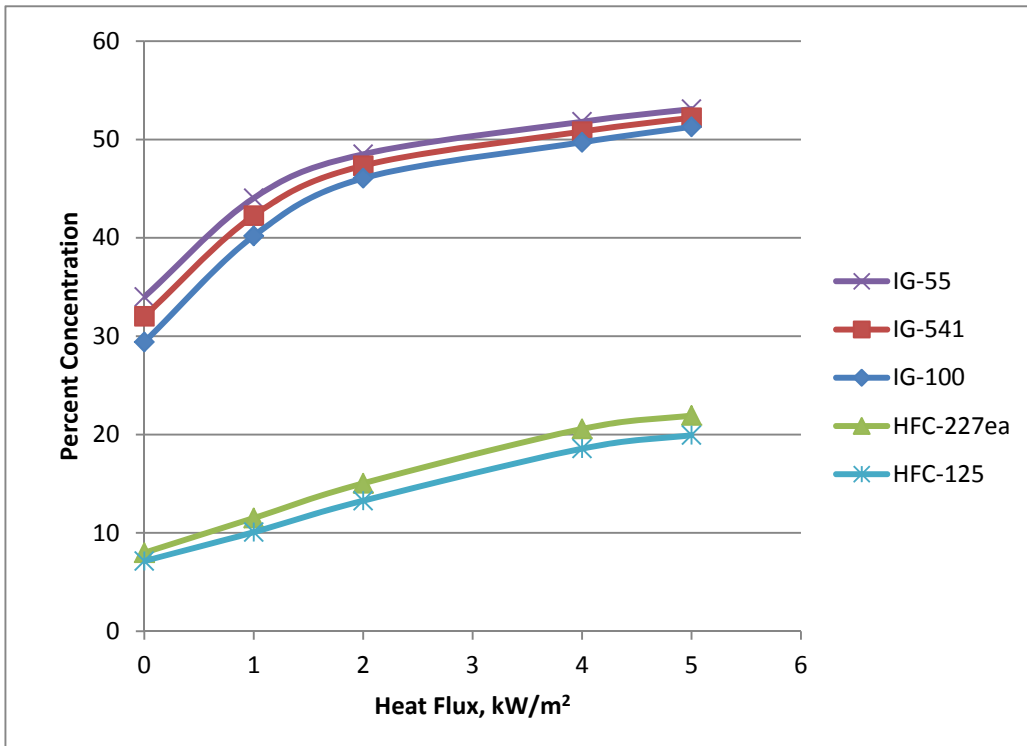


Figure 31: Clean Agent Extinguishing Concentrations using Modified IAR Method for REED Apparatus, 0-5 kW/m²

A comparison of the IAR testing results versus the original method from Chapter 3 are also shown in Figure 32. It is evident that extinguishing concentrations exceed the new IAR testing method by approximately 30 to 45 percent. Also, the curves for the inert gas clean agents have a more curved behavior which plateaus at 2 kW/m². In the original testing method, the curves didn't start to plateau until roughly 10 kW/m². It was also noticed that extinguishing concentrations of clean agent HFC-227ea were greater than HFC-125 in the IAR testing method. In contrast, the original testing method resulted in HFC-125 having greater extinguishing concentrations than HFC-227ea.

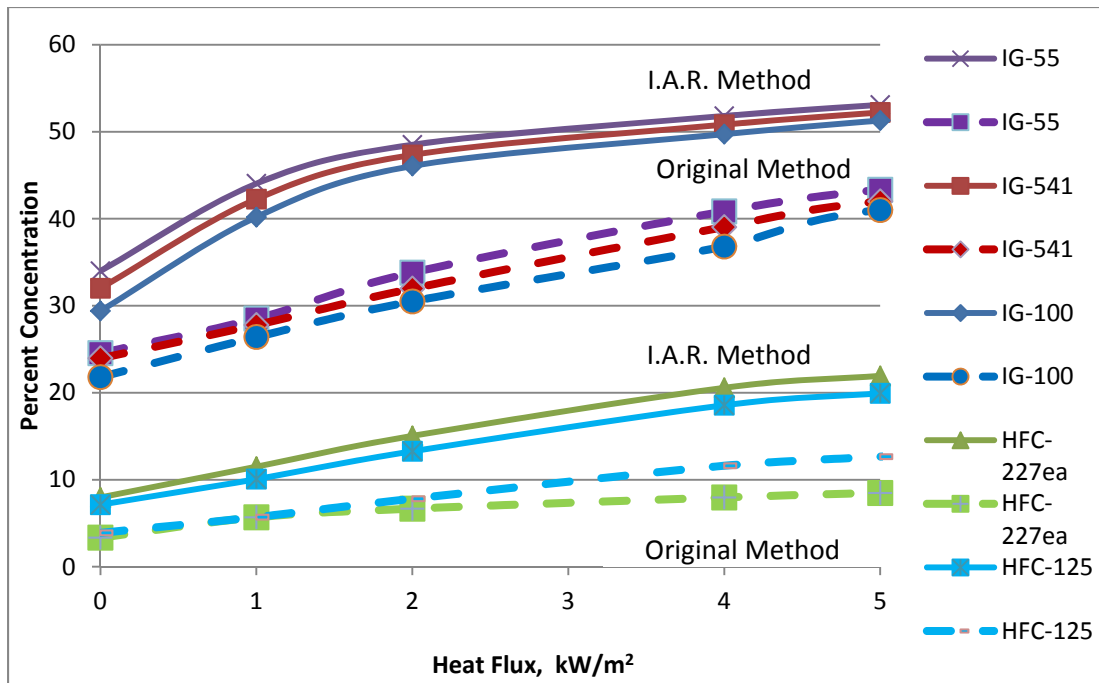


Figure 32: Original versus IAR Testing Method Extinguishing Concentrations using REED Apparatus, 0-5 kW/m²

The higher extinguishing concentrations from the IAR testing method could be larger than necessary. Since HFC clean agents extinguishes fires by reducing the critical temperature of the flame, the 2 second time between agent increases may not be sufficient to allow the agent to be fully effective. However, this cannot be explained for the inert gas clean agents.

Another area of concern with IAR testing method could be blowing away of the flame. This phenomenon was discussed by Linteris in his research [7]. In summary, it was found that the “chemistry of the flame cannot keep up with the flow” [7] of the clean agent (blows off). The impulsive introduction of the agent on the flame could be destabilizing the flame to a point where it is being extinguished. However, if this were the case, the flame would extinguish immediately. This was not

the case; usually it took approximately 5 seconds after introduction of agent to extinguish the flame.

The IAR testing method was also noticeably more repeatable; extinguishing concentrations for a specified heat flux level were within one percent of each other.

Chapter 6: Summary

The current issues with Class C standards have been discussed. This study investigated current trends in blade server power densities. From the investigated surveys, levels of heat flux being emitted by blade servers were calculated. The calculated heat flux levels were then the focus of this study. Using the REED apparatus, extinguishing concentrations of clean agents were tested. Examination of the extinguishing concentrations confirmed that the REED apparatus followed a similar trend obtained from earlier tests at only large heat flux levels.

Also, an alternative method (IAR) of testing extinguishing concentrations was studied. The IAR method eliminated the 100 second time between agent increases. Resulting extinguishing concentrations were noticeably greater than the original method. This new method could be more conservative when used for server room fire hazards.

Further testing on alternative materials that are found in blade servers should also be considered. Resulting extinguishing concentrations can be compared with current results to see if there are any significant results. PMMA has been known to be to most difficult to extinguish due to its double bond molecular structure which breaks rapidly after reaching a critical temperature. Therefore it can be assumed current results are the most conservative.

A testing apparatus with actual blade servers emitting variable heat flux could be beneficial. In the REED apparatus, cone heater temperatures are associated with heat flux that is being emitted. Due to the different material properties of blade

servers, surface temperatures could likely be different to the same heat flux levels as from the cone heater of the REED apparatus.

A testing apparatus that also considers convective losses should be explored. Due to the cooling requirements of these servers rooms, many blade server racks are supplied with their own cooling systems. This cooling system could actually lower extinguishing concentrations necessary to extinguish the fire. Also, the cooling system may actually alter the concentration of clean agents being delivered to the fire due to turbulence.

Although there are many factors that still need to be considered for this data to be particularly useful in Class C standards, it does provide great data to support earlier testing data. In addition, the newly proposed IAR method could be utilized in testing to prevent the flame from weakening.

Appendix

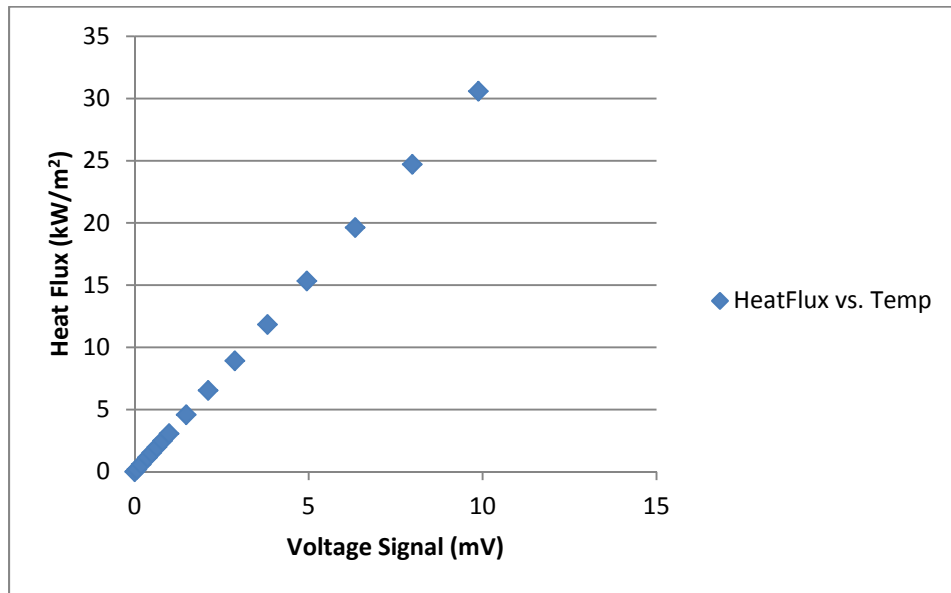


Figure A-1: Heat Flux vs. Voltage Signal (mV) Calibration Curve

Agent	Extinguishing Concentrations					
	0 kW/m ²	10 kW/m ²	20 kW/m ²	30 kW/m ²	40 kW/m ²	Inert @ 40 kW/m ²
Nitrogen C.B = 32.0%	22.0	44.0	54.0	59.0	63.0	n/a
	22.0	49.0	54.0	59.0	63.0	
	21.0	47.0	57.0	59.0	61.0	
		47.0	57.0	59.0		
Averages	21.7	46.8	55.5	59.0	62.3	
IG-541 C.B = 29.1%	27.0	50.0	53.0	59.0	57.0	
	25.0	48.0	56.0	57.0	59.0	
	23.6	48.0	53.0	58.0	57.0	
	23.0	50.0	55.0	55.0	59.0	> 61*
	23.0			58.0	58.0	> 61*
	Averages	24.3	49.0	54.3	57.4	58.0
FC-3-1-10 C.B = 5.3%	3.8	8.4	11.2	11.6	17.9	
	3.3	8.4	10.2	10.2	17.6	
	3.3	7.6	9.5	10.2	16.7	
	3.3	9.5	9.8	10.2	17.3	
				10.5		25*
Averages	3.4	8.5	10.2	10.5	17.4	
FC-218 C.B = 6.3%	3.8	9.4	10.3	9.4	17.0	
	3.8	9.4	9.9	9.0	17.0	
	3.8	9.4	9.4	10.3	16.3	34.1*
	3.8	9.0	9.4	9.0		
Averages	3.8	9.3	9.8	9.4	16.8	
HFC-23 C.B = 12.7%	7.8	19.4	22.8	23.7	25.0	25
	7.8	17.9	23.7	22.8	24.2	PMMA burnt out
	7.8	18.9	21.9	22.8	24.2	PMMA burnt out
	6.8	18.9	22.8	24.6	26.2	26.2
	7.1	18.6	23.9	22.7	25.5	25.5
			24.3	23.9	25.8	PMMA burnt out
Averages	7.6	18.8	22.8	23.5	24.9	
HFC-227ea C.B = 6.6%	5.0	9.8	13.2	13.2	14.0	14
	5.0	9.8	12.4	13.2	14.9	PMMA burnt out
	4.5	10.7	12.4	13.2	13.2	13.2
	4.5	10.7	12.4	17.2	16.8	PMMA burnt out
	4.6	10.1	16.8	17.1	18.5	18.5
		10.8	17.6	16.7	18.0	18
			16.2		17.7	PMMA burnt out
Averages	4.7	10.3	14.1	15.1	16.2	

* Preliminary unconfirmed data
Note: C.B is NIST cup burner value

Figure A-2: REED Testing Results from Smith et al. Study [7]

Agent	Extinguishing Concentrations									
	0 kW/m ²	1 kW/m ²	2 kW/m ²	4 kW/m ²	5 kW/m ²	10 kW/m ²	20 kW/m ²	30 kW/m ²	40 kW/m ²	
Nitrogen	21.82	26.20	30.15	36.46	40.83	44.0	54.0	59.0	63.0	
C.B = 32.0%	21.81	26.53	30.65	36.94	41.11	49.0	54.0	59.0	63.0	
	21.81	26.51	30.69	36.98	41.08	47.0	57.0	59.0	61.0	
						47.0	57.0	59.0		
Averages	21.8	26.4	30.5	36.8	41.0	46.8	55.5	59.0	62.3	
HFC-227ea	4.67	6.63	7.44	9.26	9.99	9.8	13.2	13.2	14.0	
C.B = 6.6%	4.71	6.74	7.47	9.17	10.31	9.8	12.4	13.2	14.9	
	4.70	6.69	7.48	9.34	10.23	10.7	12.4	13.2	13.2	
		5.71	6.66	7.96	8.46	10.7	12.4	17.2	16.8	
		5.67	6.71	7.99	8.51	10.1	16.8	17.1	18.5	
		5.68	6.67	7.94	8.49	10.8	17.6	16.7	18.0	
							16.2		17.7	
Averages	4.7	5.7	6.7	8.0	8.5	10.32	14.43	15.10	16.16	
HFC-125	3.97	5.76	7.78	11.54	12.56	16.12	19.4	22.18	25.7	
C.B = 8.7	3.89	5.64	7.73	11.61	12.73	16.73	19.2	22.43	25.9	
	3.82	5.72	7.90	11.68	12.67	17.49	19.3	22.78	26.0	
Averages	3.9	5.7	7.8	11.6	12.7	16.8	19.3	22.5	25.9	
IG-541	23.78	25.53	26.90	29.58	32.93	50.0	53.0	59.0	57.0	
C.B = 29.1%	24.13	25.65	26.84	29.58	32.88	48.0	56.0	57.0	59.0	
	23.97	27.90	31.93	39.10	42.03	48.0	53.0	58.0	57.0	
	23.94	27.80	32.02	38.99	41.96	50.0	55.0	55.0	59.0	
		27.69	31.97	39.06	42.00			58.0	58.0	
Averages	24.0	27.8	32.0	39.1	42.0	49.0	54.3	57.4	58.0	
FK-5-1-12	2.82	2.97	3.53	4.88	4.96	7.11	12.8		15.8	
C.B = 4.5%	2.97	3.06	3.93	4.81	6.04	7.56	13.5		18.4	
	2.78		3.98		5.28	8.21				
						7.66				
Averages	2.9	3.0	3.8	4.8	5.4	7.6	13.2		17.1	
IG-55	19.03	21.32	25.42	32.06	35.52					
C.B = 31.2	20.06	21.38	25.92	31.12	35.93					
*	20.80	21.19	26.36	31.74	35.93					
	24.21									
	23.98	28.32	33.86	41.02	42.87	51.23	54.89	58.79	59.98	
	24.89	28.48	33.57	40.87	43.34	51.12	55.23	58.95	60.02	
	24.78	28.75	33.98	40.67	43.79	50.98	55.38	58.55	59.77	
Averages	24.6	28.5	33.8	40.9	43.3	51.1	55.2	58.8	59.9	

Figure A-3: REED Testing using Original Method. Data in Yellow are Results from Testing at 3M, Data in Green are Results from Testing at UMD

Agent	Extinguishing Concentrations				
	0 kW/m ²	1 kW/m ²	2 kW/m ²	4 kW/m ²	5 kW/m ²
Nitrogen					
C.B = 32.0%	28.67	40.05	46.21	49.92	51.39
	30.12	40.33	45.90	49.52	51.20
Averages	29.4	40.2	46.1	49.7	51.3
HFC-227ea	7.91	11.57	15.07	20.63	21.98
C.B = 6.6%	8.01	11.43	15.01	20.51	21.88
Averages	8.0	11.5	15.0	20.6	21.9
IG-55	33.86	43.97	48.55	51.71	53.01
C.B = 35%	34.12	44.10	48.45	51.90	53.18
Averages	34.0	44.0	48.5	51.8	53.1
HFC-125	7.15	10.02	13.20	18.66	19.99
C.B = 8.7%	7.11	10.11	13.34	18.47	19.87
Averages	7.1	10.1	13.3	18.6	19.9
IG-541	32.06	42.31	47.29	50.76	52.15
C.B = 29.1%	31.95	42.21	47.39	50.86	52.29
Averages	32.0	42.3	47.3	50.8	52.2

Figure A-4: REED Testing Results using IAR Testing Method. Averaged Data is Concentration used by IAR Method.

References

- ¹ Robin, M.L. and McKenna, L., *Fire Protection Considerations for Telecommunication Central Offices*, International Fire Protection Magazine, Issue 22, May 2005.
- ² Alinenan ROI Report, January 2004; <http://www.alinean.com/Newsletters/2004-1-Jan.asp>
- ³ Robin, M.L. et al., *Development of a Standard Procedure for the Evaluation of the Performance of Clean Agents in the Suppression of Class C Fires*, DupontFluorproducts, Fike Corporation, June 2012; http://www.nfpa.org/assets/files/PDF/Proceedings/Development_of_a_Standard_Procedure...-M._Robin.pdf
- ⁴ Robin, M.L., *Fire Protection in Telecommunication Facilities*, Process Safety Progress, 19, 107 (2000).
- ⁵ Robin, M.L. et al., *Clean Agents Protect Data Centers from Fire*, Mission Critical, November (2011); <http://www.missioncriticalmagazine.com/articles/84557-clean-agents-protect-data-centers-from-fire>
- ⁶ Brian P. Rawson, “*Protection of Electronic Equipment*” NFPA Fire Protection Handbook, Cote et al, 20th Edition, Quincy MA.
- ⁷ Gregory T. Linteris, Ph.D. “*Clean Agent Suppression of Energized Electrical Equipment Fires*”, The Fire Protection Research Foundation, January 2009
- ⁸ David M. Smith, et al. “*Energized Fire Performance of Clean Agents: Recent Developments*”, 3M Specialty Chemicals Division, NIST Building and Fire Research Laboratory
- ⁹ Mark Owen et al. “*Datacom Equipment Power Trneds and Cooling Applications*”, ASHRAE Datacom Series, 2nd Edition.
- ¹⁰ *UL 2127, Standard for Safety for Inert Gas Clean Agent Extinguishing System Units*, Second Edition, March 22, 200, Underwriters Laboratories, Inc.
- ¹¹ *UL 2166, Standard for Safety for Halocarbon Clean Agent Extinguishing System Units*, Second Edition, March 22, 2001, Underwriters Laboratories, Inc.

- ¹² NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*, National Fire Protection Associations, Quincy, MA, 2012.
- ¹³ NFPA 72, *National Fire Alarm Code*, National Fire Protection Associations, Quincy, MA, 2010.
- ¹⁴ Donnelly, MK, Grosshandler, WL. Suppression of fires exposed to an external radiant flux. NIST IR 6827, Gaithersburg MD: National Institute of Standards and Technology; 2001.
- ¹⁵ Tewarson, A, Pion, RF. Flammability of Plastics .1. Burning Intensity. *Combustion and Flame* 1976; 26:85-103.
- ¹⁶ Robin, ML, Shaw, B, Stilwell, B, "*Development of a standard procedure for the evaluation of the performance of clean agents in the suppression of Class C fires*", NFPA Suppression and Detection (SUPDET), SUPDET-2007, National Fire Protection Association, Quincy, MA, 2007.
- ¹⁷ Robin, ML, Stilwell, B, Shaw, B, "*Summary of ongoing Class C fire research for the purpose of identifying and evaluating Class C fire risks and suppression needs in modern data centers, internet service providers and telecommunications facilities*", NFPA Suppression and Detection (SUPDET), SUPDET-2008, National Fire Protection Association, Quincy, MA, 2008.
- ¹⁸ Niemann, R, Bayless, H, Craft, C, "*Evaluation of selected NFPA 2001 agents for suppressing Class "C" energized fires*", In: Papers from 1991-2006 Halon Options Technical Working Conferences (HOTWC), CD-ROM, NIST SP 984-4, HOTWC-1996, National Institute of Standards and Technology, Gaithersburg, MD, 2006.
- ¹⁹ Hamins, A, Borthwick, P. "*Suppression of Ignition Over a Heated Metal Surface*", *Combustion and Flame* 1998; 112:161-170.
- ²⁰ Braun, E, Womeldorf, CA, Grosshandler, WL. "*Suppression Concentration of Clean Agents Exposed to a Continuously Energized Heated Metal Surface*". *Fire Safety Journal* 1999; 33:141-152.
- ²¹ Smith, S, Gallus, T, Tapia, S, Ball, E, Beeson, H. "*Electrical Arc Ignition Testing of Spacesuit Materials*". *Journal of ASTM International (JAI)* 2006; 3:229-246.
- ²² Goldmeer, JS, T'ien, JS, Urban, DL. "*Combustion and Extinction of PMMA Cylinders During Depressurization in Low-Gravity*". *Fire Safety Journal* 1999; 32:61-88.
- ²³ Ruff, GA, Hicks, M, Mell, WE, Pettegrew, R, Malcom, A, "*CO₂ Suppression of PMMA Flames in Low-Gravity*", In: NASA, Cleveland, OH, 2003.

²⁴Takahashi, F, Katta, V, "*Stabilization and Suppression of Axisymmetric Diffusion Flames*", In: 45th AIAA Aerospace Sciences Meeting and Exhibit, AIAA Paper: AIAA 2007-738, AIAA, 2007.

²⁵Benjamin K. Tsai, "Heat-Flux Sensor Calibration", NIST Measurement Services, NIST Special Publication, Bethesda, MD, 250-65