COMPARING CLASS A COMPRESSED AIR FOAM SYSTEMS (CAFS) AGAINST PLAIN
WATER SUPPRESSION IN LIVE FIRE GAS COOLING EXPERIMENTS FOR INTERIOR
STRUCTURAL FIREFIGHTING

A Thesis
presented to
the Faculty of California Polytechnic State University,
San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Fire Protection Engineering

by
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June 2013

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TITLE: Comparing Class A Compressed Air Foam Systems (CAFS) Against Plain Water Suppression in Live Fire Gas Cooling Experiments for Interior Structural Firefighting

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ABSTRACT

Comparing Class A Compressed Air Foam Systems (CAFS) Against Plain Water Suppression in Live Fire Gas Cooling Experiments for Interior Structural Firefighting

Sean Carter Mitchell

Wildland fire services have successfully integrated compressed air foam systems (CAFS) into their fire suppression arsenal over the last few decades to effectively increase the firefighting ability of water. Many urban fire departments have done the same, but far more still rely on plain water to extinguish Class A fires. Many claims have been made about the advantages and disadvantages of firefighting foams, but only limited research has been conducted on the subject to date. Fire departments need more information, beyond that provided by foam suppliers and CAFS equipment manufacturers, to make an independent decision on whether or not to adopt the technology. This thesis is part of a larger project sponsored by the United States Department of Homeland Security Assistance to Firefighter Grant Program (grant ID: EMW-2010-FP-01369) to evaluate the capabilities and limitations of compressed air foam systems (CAFS) for use in structural firefighting applications. Large-scale tests comparing water and foam suppression, which includes aspirated foam and CAFS, in a variety of scenarios were performed to measure the ability of the hose streams to reduce the temperature of a hot gas layer within a structure. These temperature reductions were recorded with thermocouples and are analyzed to determine which suppression agent has a superior gas cooling ability.

Keywords: Compressed air foam systems, CAFS, aspirated foam, water, suppression, structural firefighting, gas cooling, temperature, thermocouple, Class A, foam.

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1 INTRODUCTION

1.1 Background

The United States Department of Homeland Security Assistance to Firefighter Grant Program, under grant ID: EMW-2010-FP-01369, sponsored this nationwide research project. A partnership between the California Polytechnic State University San Luis Obispo (Cal Poly), the National Institute of Standards and Technology (NIST), and the National Fire Protection Association's Fire Protection Research Foundation (FPRP), was formed to evaluate the capabilities and limitations of compressed air foam systems (CAFS) for use in interior structural firefighting applications. The overall goal of the project is to enhance the scientific knowledge base regarding its effectiveness and safety implications in fireground operations. CAFS have been widely used by wildland fire services since the 1970s, and many urban fire departments have adopted their use in the last few decades. Those that have had a positive experience with CAFS claim it can knockdown fires much faster, using less water, and reduce the possibility of rekindle. Many others, however, have become skeptical of the new technology. For example, Montgomery County Fire & Rescue Service (MCFRS) purchased thirty-six (36) CAFS, but in 2010 the fire chief issued a general order prohibiting their use after an incident occurred where firefighters were burned while performing interior structure suppression operations, citing that the technology lacked comprehensive research.

Prior to this grant much of the research conducted has been performed by CAFS manufacturers. The fire service needs independent research to decide whether or not the use of CAFS for interior structural firefighting is effective, safe, and a justifiable investment. Pilot programs and testing have been performed by independent fire departments that examine implementation and effectiveness of CAFS; however, minimally instrumented tests were also performed by foam solution suppliers and CAFS equipment manufacturers. Other studies have been conducted by laboratories and universities, but still a lack of knowledge exists.

There is a demand for enhanced firefighting agents and systems within the fire service community. During the 2005 National Fire Service Research Agenda Symposium, one of the issues raised was to “improve extinguishing agents and delivery systems.” The purpose of this research is said to “reduce the exposure of firefighters to the risks of interior fire suppression by developing more effective extinguishing agents and systems. These advances should also result in reductions in civilian deaths and injuries as well as property damage (National Fire Service Research Agenda Symposium, 2005).”

The use of CAFS in wildland firefighting and structural firefighting is very different. In the wildland environment CAFS is used directly on the burning fuel in open air. In an interior structural fire, firefighters must be able to navigate an unfamiliar environment, and are often exposed to hot combustion products. En route to the source of the fire, hot gas layers within the structure may present a serious hazard, which must be cooled before personnel can safely proceed. These conditions differ from wildland firefighting considerably and need to be better understood when using CAFS as the primary means of suppression.

1.2 Research Questions

In order to evaluate the effectiveness of CAFS for interior structural firefighting, both large-scale enclosure fire tests and fireground evolutions were performed. The large-scale tests involved comparing water and foam suppression, which includes aspirated foam and CAFS, in a variety of scenarios. They included:

1. What are the differences in hose stream spray distribution patterns?
2. Is CAFS able to reduce the temperature of a hot gas layer and improve the impact on ventilation and movement of fire gases within the structure as good as or better than plain water?
3. What effect does CAFS have on the thermal conditions, temperature and heat fluxes, that a firefighter would be exposed to while advancing a hoseline down the corridor toward a fire room and during the gas cooling and fire suppression phases?

The fireground evolutions involved developing test apparatuses and test procedures for measuring safety-related parameters. They included:

1. Does CAFS have an increased nozzle reaction force?
2. Is there a greater force required to kink CAFS hoses under both static and flowing conditions?
3. What are the hose stream throw and distribution characteristics of CAFS?
4. Does CAFS decrease the friction on a variety of wetted surfaces?

The focus of this thesis is on the second research question of the large-scale enclosure fire tests, the gas cooling experiments.

1.3 Thesis Statement

Does the temperature data from the large-scale gas cooling experiments support or refute the claimed advantages of using compressed air foam systems over plain water for interior structural firefighting?

1.4 Brief History of CAFS

Fire suppression foams have a long history beginning 100 years ago. The first use of foam additives to enhance the firefighting ability of water was documented in an 1877 chemical patent to create foam (Taylor, 1997). The concept of compressed air foam was developed much later. In the 1930s, the United Kingdom Royal Navy and the United States Navy both experimented with the technology (Darley, 1995). The US Navy continued to use CAFS for flammable Class B liquid fires in the 1940s. In the 1970s, the Texas Forest Service was the first to employ CAFS to use in wildland firefighting (McKenzie, 1992). Their suppression system, known as the “Texas Snow Job” for its snow like appearance on discharge, pioneered the Class A CAFS, using a pine soap derivative acquired from paper mills to produce the foam (Fornell, 1991; Taylor, 1997). The next big technological breakthroughs for CAFS were developed in the mid-1980s. A new type synthetic hydrocarbon surfactant foaming agent was manufactured in Canada (Madrzykowski, 1988). Research conducted by the US Bureau of Land Management lead to innovations in the

design of rotary air compressors, centrifugal pumps, and direct-injection foam-proportioning systems to better distribute the agent (Taylor, 1997). In 1988, CAFS received national attention when it was used to pretreat Old Faithful Lodge at Yellowstone National Park, preventing its destruction from a wildfire (Darley, 1995). In the 1990s, forestry officials hypothesized that, based on their experience with CAFS, it could be successful in interior structural firefighting, which interested many urban fire departments (Tinsley, 2002). To this date many fire departments have adopted CAFS, but far more are still using plain water on Class A fires.

1.5 Hypothesis of How CAFS Works

CAFS produces foam that is generated by mixing water, compressed air, and by injecting a foam concentrate. Each component is thought to contribute to the ability to fight the fire. Water is the most critical part of the mixture for Class A fires, as foam cannot extinguish a fire on its own (Steppan and Pabich, 2008), nor can air (unless it is rapidly cooling a small fuel source, such as a lit candle). Water dismantles the fire tetrahedron by absorbing the heat of the fuel, cooling it below its critical flame temperature. The fire tetrahedron is a convenient way to imagine the requirements to support flaming combustion (refer to Figure 1-1). If one piece in the tetrahedron is removed, the fire will be extinguished. Water is desirable as an extinguishing agent for a number of reasons. It has a high thermal inertia and high latent heat of vaporization. It can absorb more heat for its mass better than any other known element excluding mercury. Its latent heat of vaporization is four (4) times that of any other non-flammable liquid, allowing it to expand up to 1,700 times its original size when vaporizing. Water also has a higher specific heat than most other substances, which is the physical property that makes it an efficient extinguishing agent. It is easily transported by pumps, because it remains constant over a wide range of temperatures, and is generally available wherever humans live. Water's high surface tension allows it to be applied as small droplets or solid streams, but limits its extinguishing ability (Taylor, 1997; Lohr, 2002).

Figure 1-1 Fire Tetrahedron

The surface tension of water can be thought of as an elastic force on the liquids surface that is caused by the attractive forces between its molecules. This minimizes the surface area of water, making it bead up, or form droplets. When water reaches the seat of a fire, it cools the fuel, but much of the liquid is lost due to runoff. The surface tension in plain water also limits its penetrability on materials, such as fibers, cloths, and upholstery. In addition, water is very poor at coating most substances, and will not suppress vapor production unless the fuel is fully submersed (Darley, 1995; Taylor, 1997).

CAFS can use Class A or Class B foam concentrates to produce foam. Class A foams are designed to extinguish ordinary combustibles, whereas Class B foams are designed to extinguish flammable and combustible liquids (NFPA 1145 Section 1.3). Class A and B foams should never be mixed, as they will congeal, gel, and clog system components (Taylor, 1997). Class A foam concentrate is made of a foaming agent and a wetting agent. The foaming agent creates the bubbles, and is often enhanced by a stabilizer to strengthen and maintain the bubble structure. The wetting agent, or surfactant, reduces the surface tension of the finished foam, allowing it to cover a larger surface area and penetrate deeper into organic fuels at an enhanced rate (National Wildfire Coordinating Group, 1993). The foam concentrate helps water to break the fire tetrahedron by blanketing and penetrating the fuel sources, which cools the fuel and blocks oxygen or flame from reaching the vapor barrier. The foam also insulates the fuel from convective and radiant heat with its empty space within the bubbles, reflects radiation with its opaque

surface, and interrupts the fire's chemical chain reactions (Taylor, 1997). These firefighting characteristics of foam would not be possible without the addition of air.

Air is necessary to create the bubbles in foam. There are two primary methods of adding air to the foam solution, to create the finished foam. The low energy method uses an aspirated nozzle at the end of a hoseline, and is known as aspirated foam. The high energy method uses a compressor or any compressed air source, and is known as compressed air foam. The base components of a compressed air foam system include a centrifugal water pump, a foam proportioning device, an air compressor, and a control valve. Foam concentrate is mixed with water to create a foam solution, which is then pumped to combine with the compressed air. As the solution and compressed air travel down the discharge line, scrubbing occurs between the inner hose walls to form the consistent, long-lasting bubble structure. A medium type foam is produced when one (1) gallon per minute flow of foam solution is matched for every cubic foot of compressed air (i.e. 120-gpm solution and 120-cfm air). A dry foam is created by using increased amounts of compressed air to reduce the amount of water in the foam (gpm solution < cfm air), and is typically used in exposure protection. A wet foam is made by using increased amounts of water to reduce the amount of compressed air in the foam (gpm solution > cfm air), and is effective for initial attacks (Darley, 1995). Not all CAF systems are identical, but they all use the basic mechanics outlined above to deliver an improved firefighting agent.

1.6 Claimed Advantages

Some of the claimed advantages that CAFS has over plain water, as reported by Taylor (1997), Stern, and Routley (1996), are summarized below:

1. Class A foam is faster than plain water in fire suppression and extinguishment
2. Class A foam uses water efficiently and conservatively
3. Class A foam concentrate is relatively inexpensive
4. Class A foam creates a protective blanket
5. The foam is clearly discernible during and after application

6. The foam adheres to most surfaces and is retained much longer than plain water
7. CAFS hoselines are much lighter than water hoselines
8. The foam may increase preservation of fire forensic evidence
9. Class A foam supports wildland/urban interface attack
10. Class A foam may provide long term financial savings and less severe property damage
11. The foam may help reduce stress and fatigue on firefighters
12. Class A foam enhances the cooling ability of water
13. CAFS has a much longer throw distance than plain water
14. CAFS has a lower impact on the environment and equipment

1.6.1 Class A foam is faster than plain water in fire suppression and extinguishment

Shorter knockdown times have been observed in fireground operations and experimentation when using Class A foam, or have been at least equally effective as plain water. In no written cases has a foam solution performed worse than plain water when using comparable equipment.

1.6.2 Class A foam uses water efficiently and conservatively

The foam enhanced water will knockdown a fire with much less gallons of agent due to the properties that enhance the effect of the water, especially when using CAFS. City of Boston in 1992 estimated that a fire engine using a 1,000-gpm pumper with a 700-gallon water tank, could operate a single CAFS 1 3/4-inch attack line for about ten (10) minutes before needing an additional water supply. Using plain water with the same configuration could only operate for approximately three (3) to four (4) minutes. Water conservation is particularly important when operating in rural areas with limited water supply. Using less water also translates to reduced water damage from overhaul.

1.6.3 Class A foam concentrate is relatively inexpensive

The foam is proportioned at rates between 0.1% and 1.0%. To produce 1,000 gallons of Class A foam solution at a concentration of 0.5%, five (5) gallons of foam concentrate would be required

with 995 gallons of water. At a rate of \$18/gallon (see cost calculations below) for concentrate this amounts to \$90 per 1,000 gallons of agent. This cost is estimated by one fire department to be offset by the savings in diesel fuel that result from shorter field operation durations. Reduced property damage could also justify the extra cost of foam concentrate.

The cost per gallon of foam concentrate is calculated from the expenses incurred by the Cambria Community Service District Fire Department during the fireground evolutions. A five (5) gallon pail of PHOS-CHeK Class A foam concentrate costs \$82.74 (from supplier ALLSTAR Fire Equipment, Inc.). Ten (10) pails cost \$827.40. With 7.5% Cambria, CA sales tax (\$62.06), the total comes to \$889.46. The after tax price per gallon of concentrate is:

$$(\$827.40 + \$62.06) / (5 \text{ gallons/pail} * 10 \text{ pails}) = \$17.79/\text{gallon} \approx \$18/\text{gallon}$$

1.6.4 Class A foam creates a protective blanket

In addition to cooling the fuel of a fire, the foam solution can also separate the fuel from receiving oxygen by creating a vapor barrier. The barrier also insulates combustibles from radiant heat and flame impingement, can prevent ignition of pretreated exposures, and reduces the chance of re-kindling after fire suppression.

1.6.5 The foam is clearly discernible during and after application

Unlike water which is transparent, the foam is opaque and can be easily seen on treated areas. The nozzle operator can therefore protect more surfaces subject to radiant heat or flame impingement by eliminating application redundancy.

1.6.6 The foam adheres to most surfaces and is retained much longer than plain water

Water tends to run-off surfaces very easy providing short exposure protection, unless applied constantly. Class A foam has a much slower run-off time, and is even effective on sloped and vertical surfaces, providing longer exposure protection and less water damage. The foam solution

also penetrates Class A fuels much deeper than plain water, due to its reduced surface tension. The foam can also cling to water resistant materials, such as vinyl, glass, and paint.

1.6.7 CAFS hoselines are much lighter than water hoselines

As compared to plain water or aspirated foam hoselines of the same length and diameter, CAFS hoselines are lighter because they are mostly filled with air. This reduces stress and fatigue on firefighters, and allows for more maneuverable attack lines. Larger diameter CAFS lines can also be easily handled.

1.6.8 The foam may increase preservation of fire forensic evidence

Class A foam solutions can penetrate and extinguish deep-seated Class A fires, due to its wetting ability. This can amount to less agent used in overhaul, and therefore less damage caused by the hose stream impact, better preserving the area for investigators to determine the source of the fire. The foam will also evaporate over time, uncovering additional evidence.

1.6.9 Class A foam supports wildland/urban interface attack

Class A type foams were first designed to fight wildland fires and control interface fires. It has been adapted for portable use, brush and fire engines, and aerial platforms (fixed wing and rotary aircraft).

1.6.10 Class A foam may provide long term financial savings and less severe property damage

Although not conclusively documented, it is believed that savings can come from shorter deployments of fire department resources and reduced property damage that would normally occur by using plain water. Quicker extinguishment and exposure protection, as a result of using foam, would tie up less operators and cause less water damage to property.

1.6.11 The foam may help reduce stress and fatigue on firefighters

Shorter fireground operation durations in suppression, overhaul, and company turn-around could reduce physical stress on firefighters. Lighter CAFS hoselines enhance this effect, due to their easier maneuverability.

1.6.12 Class A foam enhances the cooling ability of water

Plain water's primary fire extinguishing ability is to cool the fuel of a fire, but is not that efficient in doing so due to its natural properties. The U.S. Department of Agriculture estimates that less than ten percent (10%) of water applied to an unconfined fire contributes to extinguishment. Class A foam's surfactant properties, which decreases the water molecule's surface tension and enables water to penetrate fuel, allows CAFS to increase the water's cooling ability to eighty percent (80%).

1.6.13 CAFS has a much longer throw distance than plain water

The compressed air pump generates additional forces within the hose stream, propelling the suppression agent much further. The International Fire Safety Training Association estimates the fire stream can reach twice as far as plain water or nozzle-aspirated foam. Four (4) break-horsepower is generated from 40-gpm of water. Adding 20-cfm of air to 40-gpm of water will add ten (10) break-horsepower, which will increase stream flow by a factor of three (3). A 100-ft CAFS stream has been reported from a 25-gpm to 50-gpm flow, and a 200-ft CAFS stream from a 180-gpm (1 1/2-inch deck gun) flow. With this increased throw distance, fire crews can safely attack a structure fire from the exterior at much further standoff distances.

1.6.14 CAFS has a lower impact on the environment and equipment

Less knockdown time and suppression agent quantity is characteristic of CAFS, and as a result, reduces the amount of toxic and unburnt products released into the air and collected in run-off water. CAFS also allows fire engines to idle at lower revolutions per minute, produces no water hammer within hoselines as a result of mixture compression, and requires less operating

pressure due to the lack of friction; all of which reduces the wear and tear on firefighting equipment.

1.7 Claimed Disadvantages

The primary limitations and claimed disadvantages of CAFS, as discussed in Taylor's (1997) applied research project, include increased corrosion, increased slip hazards, slug flow, water contamination, and increased cost. Other drawbacks to CAFS found in the literature are: line bursts, nozzle reaction force, and kinking potential.

1. Class A foam concentrate is mildly corrosive
2. Class A foam can be more slippery than plain water
3. Slug flow can result from a CAFS malfunction
4. Class A foam concentrate may be hazardous to the environment
5. CAFS may be too expensive to implement
6. CAFS hoselines exposed to radiant heat are more prone to burst failure
7. CAFS produces a greater nozzle reaction force
8. CAFS may have a greater tendency to kink hoselines

1.7.1 Class A foam concentrate is mildly corrosive

It is comparable to a triple strength dish detergent. Exposure can cause bodily irritation (to the skin, eyes, and upper respiratory tract), contact dermatitis, and sensitization dermatitis. It may be corrosive to metals components, such as tanks and pump parts, and apparatus paint and finishes. It can also reduce the use life of leather gear. Wearing full turnout gear and a self-contained breathing apparatus is advised when using Class A foams, and should be cleaned whenever exposed to foam concentrate.

1.7.2 Class A foam can be more slippery than plain water

Some fire departments have reported Class A foam concentrate as a falling or slipping hazard. Others indicate that the foam only creates a slight increase in slip hazard, compared to plain water, or no additional hazard whatsoever.

1.7.3 Slug flow can result from a CAFS malfunction

This condition occurs when water and compressed air separates within the hoseline, because air is unable to bond with the water due to insufficient surfactant. This causes a violent serpentine hose motion or pulsation, and an inadequate suppression agent mixture (Darley, 1995; Taylor, 1997). To reduce the chance of slug flow, CAFS systems should be selected with a mechanical fail-safe that shuts down the air pump when foam does not flow. Some evidence also suggests that slug flow may wear out hoselines faster, resulting in earlier separation of interior hoseliners or coupling failure. In the event of a hoseline burst or coupling blow off failure, the broken hoseline ends will be much more hazardous than a ruptured plain water hoseline, as the built up CAFS pressure from air compression due to hoseline shutoff causes greater whipping/moving forces (Fornell, 1991). This may have been a factor that contributed to the death of two (2) German firefighters in 2005, and will be discussed later. All hoselines, therefore, should be approved for CAFS use by the manufacture.

1.7.4 Class A foam concentrate may be hazardous to the environment

Finished foams (foam solutions that are properly proportioned with water and foam concentrate) are considered biodegradable, when the concentrate is approved by the USDA Forrester Service and NFPA 1150; although long term impacts have not been documented. Ground water can become contaminated, however, when it comes in contact with foam concentrate. Care should be taken whenever the concentrate is handled.

1.7.5 CAFS may be too expensive to implement

New equipment, training, and maintenance will likely incur expenditures that are too difficult to justify. The cost for a new CAF system can be as high as \$50,000 to \$35,000 per engine (Lyon, 2009; Stern and Routley, 1996) or fifteen percent (15%) of the engine base price (Duncan, 1994). Foam concentrate is nearly \$18 per gallon, which can add up when proportioned at higher percentages (as high as 1.0% for some applications). Training and system maintenance may also present high costs that cannot easily be predicted.

1.7.6 CAFS hoselines exposed to radiant heat are more prone to burst failure

One of the most dangerous faults with CAFS became infamous in 2005 when two (2) German firefighters were killed after becoming trapped during a fire. Although the main cause of death was carbon monoxide poisoning, as a result of the historical wooden construction and more recent renovations that did not remove the stairwell from other rooms, it presented new concerns for using CAFS. While stuck on the upper floor, their CAFS line became exposed to radiant heat from the fire involved story below. This led to a hoseline burst, which would have happened several minutes later, had they been using a plain water line. Post incident testing confirmed that a CAFS line exposed to radiant heat or glowing embers will fail much faster than a water line due to the foams reduced heat capacity (de Vries, 2007).

1.7.7 CAFS produces a greater nozzle reaction force

One of the lessons learned from the Los Angeles Fire Department during their field experiments was that a fully charged CAF line has a very strong nozzle reaction. They recommend using pistol-grips, or other auxiliary support devices, with CAFS as the hose stream has enough energy to kick up loose objects. They also suggest wearing eye protection when working up close (Cavette, 2001). Another set of tests by the Morristown Fire Bureau concluded the same thing, that CAFS lines produce greater nozzle reactions when trying to achieve the same gallons per minute of solution as plain water hoselines (Taylor, 1997).

1.7.8 CAFS may have a greater tendency to kink hoselines

CAFS hoselines can become kinked due to the air and foam mixture making up two-thirds (2/3) of the product content. A survey reported that thirty-seven (37) out of seventy (70) firefighters had problems with kinking during training or firefighting. Slug flow may also develop when a hoseline kinks, as the consistency of the foam is changed by the restricted flow. One article claims that kinked hoselines will actually improve the finished foam product. Another suggests that kinking is normally caused by improperly deployed hoselines, not specifically caused by the CAFS agent (Lyon, 2009). During 146 field tests using CAFS, the Boston Fire Department had only two (2) cases of hoseline kinks (Routley, 1994), indicating that kinking is not as big of a problem as some may believe.

2 LITERATURE REVIEW OF PRIOR TESTING

2.1 Comparison between Mock-Up and Acquired Structure Testing

The only way to know whether the claims about CAFS are true is through well documented live fire field testing. Field testing is most commonly performed using constructed mock-up structures or acquired structures. With a mock-up structure, one or more rooms are constructed using noncombustible material, and are filled with fuel packages that can consist of wall boards, carpet, furniture, wooden pallets, or wood cribs. The benefit of a mock up structure is that multiple tests can be conducted using the same room configuration, as the spent fuel is replaced with identical fuel loads. The drawback to this method is that it is not a real building, and lacks structural features such as an attic space or other rooms where a fire could spread. Testing in acquired structures offers the most realistic method for testing the effectiveness of CAFS, as it creates a fire scenario that is as close to an actual 911 call as possible. The structures burned are typically slated for demolition; therefore, there is usually some degree of dilapidation within the structure. These buildings, unless lined with noncombustible material, can only be used once. Repeat testing is usually not an option or is limited. Finding buildings with identical floor plans can also be a limitation. Several articles documenting the effectiveness of CAFS verses plane water using either mock-up structures or real buildings are summarized below.

2.2 Constructed Mock-Up Structures

The following are interior structural fire suppression tests that compare foam agents against water, conducted in test rooms built specifically for multiple experiments. These tests are better representations of an actual fire than open air wooden crib or hydrocarbon pan fire tests (of which there are many published), as the hot gases produced by the fire are confined to the test room. The hot gases can pose an extreme hazard to building occupants and emergency responders, and are therefore important test parameters. The tests included in the literature review are:

- Underwriters Laboratories, 1994
- Ingolstadt, 1998

- Dortmund, 1998
- Underwriters Laboratories, 2008
- National Research Council of Canada, 2009
- Carlow County Fire and Rescue Service, 2010
- Grand Rapids Fire Department, 2011

Underwriters Laboratories, 1994

In 1994, the Fire Protection Research Foundation (FPRF) performed a series of tests at the Underwriters Laboratories (UL) in Northbrook, Illinois comparing water, Class A foam solution, and Class A compressed air foam (CAF). The test enclosure measured 8-ft by 12-ft by 8-ft high, and was adjacent to an 8-ft by 8-ft calorimeter collection hood positioned over the doorway opening. The walls of the structure were fitted with plywood, while the ceiling was covered in tiles. The first series of tests (Series I) used a residential fuel package, consisting of a wood crib and simulated furniture made of polyether cushions with wooden support frames. The second series of tests (Series II) used a corner style upholstered sofa scenario, made of polyether mattresses to simulate the cushions on a steel frame. For each series the heat release rate was recorded verses time, as well as the time and quantity of agent required to reduce the rate of heat release to 500-kW. Thermocouples measured the heat while the rate of heat release was measured by oxygen consumption calorimetry. Additional instrumentation was also set up to record foam solution/water flow rate, smoke density, and heat flux. Data demonstrated that both the Class A foam solution and CAF provided enhanced structural fire suppression performance compared to water alone.

Series I tests produced the following findings for seven (7) total experiments (one [1] free burn, two [2] tests using water indirectly and directly, two [2] tests using Class A foam solution indirectly and directly, and two [2] tests using CAF indirectly; all using a 5-gpm flow rate). The Class A foam solution applied directly to the fuel took slightly less time to suppress, used a little less quantity of agent, and had a somewhat lower total heat release (from agent application until rate of heat

release was reduced to 500-kW) than plain water suppression. Applied indirectly, water and the Class A foam solution had near identical: suppression times, quantity of agent used, and total heat release (from application until rate reduced to 500-kW). The CAF direct suppression time and quantity of agent used mimicked the water and Class A foam solution values for one run, but were slightly more for the second run, and had higher total heat release for both runs.

Series II tests yielded the following discoveries for seventeen (17) total experiments (four [4] tests applying water indirectly, three [3] times at 10-gpm and once [1] at 7-gpm; six [6] tests applying each type of foam indirectly, two [2] times at 10-gpm and once [1] at 7-gpm; six tests [6] applying each agent directly, two [2] times at 7-gpm; one [1] test applying water directly at a flow rate greater than 30-gpm). Compared to water only suppression, the Class A foam solution and CAF generally produced a lower amount of total heat released. Class A foam solution applied indirectly to the fuel at a flow rate of 10-gpm took less time and quantity of agent to reduce the rate of heat release to 500-kW compared to CAF or water. CAF applied directly at a flow rate of 7-gpm had the shortest suppression time and lowest quantity of agent used to reduce the rate of heat release to 500-kW. Although the direct application of water at a flow rate of greater than 30-gpm had the fastest suppression time, the lowest total heat release rate, and least amount of property damage, it was at least three (3) times higher than the flow rate of the Class A foam solution and CAF. Direct suppression of fuel using water, Class A foam solution, or CAF provides for reduced amount of total heat release and less property damage compared to indirect suppression under similar conditions (Pabich and Carey, 1994).

Table 2-1 UL 1994 Series I

Series I				From Agent Application Until RHR Was Reduced to 500-kW		
Test No.	Agent	Application Method	Flow (gpm)	Time (sec)	Quantity of Agent (gal)	Total Heat Released (MJ)
1	None	-	-	-	-	-
2	H ₂ O	Direct	5	26	2.2	58
3	Class A	Direct	5	24	2.0	54
4	H ₂ O	Indirect	5	36	3.0	72
5	Class A	Indirect	5	36	3.0	72
6	CAFS	Indirect	5	36	3.0	86
7	CAFS	Indirect	5	39	3.3	92

Table 2-2 UL 1994 Series II

Series II				From Agent Application Until RHR Was Reduced to 500-kW		
Test No.	Agent	Application Method	Flow (gpm)	Time (sec)	Quantity of Agent (gal)	Total Heat Released (MJ)
14	H ₂ O	Direct	7	48	5.6	85.0
13	H ₂ O	Direct	7	60	7.0	115.9
15	Class A	Direct	7	39	4.6	75.6
12	Class A	Direct	7	45	5.3	72.9
16	CAFS	Direct	7	27	3.2	42.7
11	CAFS	Direct	7	36	4.2	52.9
3	H ₂ O	Indirect	7	169	19.7	224.1
9	Class A	Indirect	7	70	8.2	116.5
10	CAFS	Indirect	7	66	7.7	111.5
2	H ₂ O	Indirect	10	54	9.0	97.3
8	H ₂ O	Indirect	10	60	10.0	108.6
1 ⁺	H ₂ O	Indirect	10	72	12.0	102.7
5	Class A	Indirect	10	39	6.5	50.4
4	Class A	Indirect	10	45	7.5	75.2
7	CAFS	Indirect	10	48	8.0	87.2
6	CAFS	Indirect	10	51	8.5	96.9
17	H ₂ O	Direct	>30	18	9.0	35.8

+ Different indirect application method

Ingolstadt, 1998

In 1998, four (4) test burns were conducted comparing water and compressed air foam systems (CAFS) at the former Royal Bavarian Artillery Factory in Ingolstadt, Germany. The test room was constructed using a steel intermodal shipping container measuring 20-ft long by 8-ft wide by 8-ft tall. For each test the container was loaded identically with fifteen (15) wooden pallets, set up as

a shelf and a bed frame, two (2) car seats, one (1) mattress, and two (2) bales of straw distributed over the contents. Four (4) square holes were cut into the side walls of the container to simulate windows for proper ventilation. Twelve (12) thermocouples were installed, six (6) were placed 3-ft above the floor, and six (6) were placed 6-ft above the floor. Only eight (8) thermocouples, however, produced results for all four (4) tests. Two (2) tests using water averaged eighty-two (82) total gallons of agent for an average suppression time of six minutes and thirty-eight seconds (6:38). Two (2) tests using CAFS averaged twenty-three (23) total gallons of agent for an average suppression time of three minutes and forty seconds (3:40). The time to extinguishment was measured by nozzleman's "gut feeling," therefore the suppression time results are not consistent. No in depth analysis was conducted for the thermocouple temperature data (de Vries, 1998).

Table 2-3 Ingolstadt 1998

Test No.	Agent	Time (min:sec)	Quantity of Agent (gal)
1	H ₂ O	7:45	100
2	H ₂ O	5:30	64
3	CAFS	2:50	17
4	CAFS	4:30	28

Dortmund, 1998

In 1997 and 1998, twenty-one (21) burn room tests were performed in a tunnel of the former research mining field Tremonia of Deutsch Montanttechnik, in Dortmund, Germany, to compare water, Class A foam, and a sodium polyacrylic additive. The test room measured 16.4-ft deep in the 9.8-ft wide by 9.8-ft high tunnel. Two (2) walls made of magnesia-silicate board were erected on 2-inch steel C frames. The dry wall construction had a fire rating of ninety (90) minutes. One wall had a window, and the other a door opening with two (2) small hatches for video recording and ventilation. The room was instrumented with twenty-four (24) thermocouples, spaced in a three (3) dimensional grid. Eight (8) equally spaced thermocouples were installed at 8.2-ft, 4.9-ft, and 1.6-ft above the floor. Each test had a fuel load consisting of a mattress, a wooden table, fourteen (14) wooden pallets, two (2) car seats, three (3) wooden chairs, shredded newspaper, and cotton-polyester fabric, weighing a total of 680-lbs. The overall energy release was estimated

between 2.9 and 4.1 megawatts (MW). A fifteen (15) minute preburn time allowed the room to become fully involved before suppression was administered. Plain water, aspirated Class A foam (proportioned at 0.5%), and sodium polyacrylic additive (SPA) gel (proportioned at 3%), were used as suppression agents. A Quadra-Fog 40-gpm nozzle by Task Force Tips and a 1-inch attack line were used for fire suppression. Most trials were extinguished using an indirect attack method, while some water tests used a direct method. Of the twenty-one (21) tests performed, only seventeen (17) were considered comparable. The results indicate that on average plain water took ten (10) minutes to extinguish the fire, while using an average of sixty-six (66) gallons of agent. Class A foam was able to suppress the fire in an average of nine (9) minutes, averaging forty (40) gallons of agent. The only usable trial with the gel extinguished the fire in nine (9) minutes, using fifty-four (54) gallons of agent. Foam averaged a slightly faster extinguishing time over water (by one [1] minute) using considerably less quantity of agent (twenty-six [26] gallons less). The results for the gel weren't as conclusive due to the single comparable trial (de Vries, 1999).

Table 2-4 Dortmund 1998

Trial No.	Agent	Application Method	Time (min)	Quantity of Agent (gal)
1	Water	Indirect	7	81
2	Water	Indirect	8	67
3	Water	Indirect	14	106
5	Water	Indirect	8	74
7	Water	Indirect	11	95
8	Water	Indirect	17	59
9	Water	Indirect	9	35
15	Water	Direct	6	64
16	Water	Direct	12	44
18	Water	Direct	8	56
19	Water	Direct	5	49
13	SPA Gel	Indirect	9	54
10	Class A Foam	Indirect	5	34
11	Class A Foam	Indirect	10	41
14	Class A Foam	Indirect	8	46
17	Class A Foam	Indirect	12	30
21	Class A Foam	Indirect	11	47

Underwriters Laboratories, 2008

In 2008, funded by a United States Department of Homeland Security Assistance to Firefighter Grant Program (awarded in 2006), UL completed a project for the United States Fire Administration to evaluate the performance of special extinguishing agents, including wetting agents and Class A foams, as compared to traditional water application for firefighter use. The testing room consisted of a 14-ft by 14-ft by 8-ft tall living space with an attached 14-ft long by 6-ft wide by 8-ft high corridor. The living space was loaded with a sofa, loveseat, coffee table, end tables, entertainment center, and carpet. A trash can filled with shredded office paper was used for ignition. Thirty (30) seconds after flashover was achieved, when the convective heat release rate reached 1900-kW, measured by oxygen consumption calorimetry through the collection hood, each fire was attacked by the handline operator. Thermocouples and radiometers positioned throughout the living space and corridor measured the temperature and heat flux. The gas products (CO, CO₂, and O₂) and smoke obscuration were also measured. Two (2) different hose streams (straight stream and wide spray) were used for each of the six (6) agents and one (1) water trial, for fourteen (14) total comparison tests. The straight stream nozzle produced 22-gpm of solution, while the wide spray nozzle produced 15-gpm of solution. In measuring the time to reduce the heat release rate of the room fire, the various one percent (1%) concentration water additives were found to be marginally quicker than plain water when using the 15-gpm wide spray pattern nozzle. No significant differences were discovered in using the 22-gpm straight stream nozzle (Steppan and Pabich, 2008).

Table 2-5 UL 2008

Test No.	Flow (gpm)	How much quicker (time) than H ₂ O at reducing HRR?
1-7	15 – wide stream	Marginally
8-14	22 – straight stream	No significant difference

National Research Council of Canada, 2009

In 2009, the National Research Council (NRC) of Canada administered three (3) tests to evaluate the effectiveness of a foam-water solution and compressed air foam against typical water for fire suppression. They constructed a compartment with wooden studs and a gypsum wallboard interior measuring 14-ft by 12-ft by 8-ft tall, with a 7.5-ft by 12-ft attached hallway and 1.3-ft by

1.6-ft simulated window. Each compartment trial was loaded with two (2) wood cribs, a mock up sofa made from OBS boards and polyester blankets, and interspersed OBS sheets for a total rated heat release of 5.6-MW. Thermocouples were instrumented inside the building, along with a heat flux meter, and a gas sampling tube (to measure smoke obscuration and CO, CO₂, and O₂ concentrations) in the hallway. The temperature and water consumption data produced the only significant results. To reach a critical temperature of 200°C it took the foam-solution forty-five (45) seconds and CAFS thirty-five (35) seconds, verses sixty (60) seconds for plain water. CAFS also used a much lower flow rate of 25-gpm, whereas foam-water solution and water suppression had a flow rate of 95-gpm. CAFS used a total of six (6) gallons of water compared to fifteen (15) gallons by the foam-water solution, and thirty (30) gallons used by water only suppression. CAFS extinguished the flame faster, at a lower flow rate, and with less quantity of agent, making it the most effective suppressant (Kim and Crampton, 2009).

Table 2-6 NRC 2009

Test No.	Agent	Flow (gpm)	Average room temp time to drop to critical temp of 200°C (sec)	Quantity of Agent (gal)
6	H ₂ O	95	60	30
8	Class A	95	45	15
10	CAFS	25	35	6

Carlow County Fire and Rescue Service, 2010

In 2010, personnel from the Institute of Fire Safety Engineering Research and Technology Centre at the University of Ulster and the Carlow County Fire and Rescue Service in Ireland participated in an assessment of the gas cooling capabilities of water mist and compressed air foam systems. Two (2) fuel-controlled tests were conducted in a 39.4-ft long by 7.9-ft wide by 7.9-ft tall shipping container, while three (3) ventilation-controlled tests (one [1] of which was a free burn) were performed in a similar 19.7-ft long by 7.9-ft wide by 7.9-ft tall container. Three (3) thermocouples took temperature measurements at varying heights in each container. Wooden pallets and chipboards were used as fuel. The fuel-controlled test used eight (8) total chipboard sheets mounted on the walls and ceiling as fuel, and initiated suppression at a flow rate of 60-L/min (16-gpm) after a temperature of 350°C was achieved. CAFS reduced the ceiling temperature by 164°C, compared to water by 83°C, both in the duration of 2.5 minutes after initial attack. CAFS

was superior in reducing the room temperatures in fuel controlled fires. The ventilation-controlled test used two (2) chipboard sheets mounted on the walls and a wood crib made of eight (8) pallets as fuel, and allowed a fire to develop for six (6) minutes before shutting all openings for an additional four (4) minutes to limit ventilation. Water mist/CAFS was applied through a side door for four (4) minutes, and then a backdraft was developed by closing the side door while simultaneously opening the front door. Each ventilation-controlled test used 50-L (thirteen [13] gallons) of water for suppression through the side window. Neither CAFS nor water alone had important effects in mitigating backdraft, as the supposed development of the fire is controlled by ventilation. The thermocouple readings were also almost identical after the application of CAFS or water, therefore neither can be said to be more effective than the other. It is worth noting, however, that the results show the presence of compressed air in the CAFS did not contribute to or cause backdraft (Zhang *et al.*, 2011).

Table 2-7 Carlow County 2010

Fuel-Controlled			Net temp drop from 350°C after 2.5 min of suppression (°C)
Test No.	Agent	Flow (gpm)	
1	H ₂ O	16	83
2	CAFS	16	164

Grand Rapids Fire Department, 2011

In 2011, the City of Grand Rapids Fire Department Strategic Planning Office, with assistance from ATF Special Agent/Certified Fire Investigator Mark Marquardt, organized ten (10) total live fire tests to study the effectiveness and feasibility of using compressed air foam systems and/or positive pressure attack ventilation for structural firefighting. They constructed a temporary wood frame building measuring 24-ft by 32-ft on a concrete slab. The building was subdivided into five (5) rooms, each with its interior walls and ceiling finished with two (2) layers of 5/8-inch drywall. Wooden pallets, straw, and sometimes chairs, couch cushions, or tables, were used as fuel. Each room was also instrumented with five (5) thermocouples at varying levels. The only tests that appeared to be identical were the CAFS and water tests (test number five [5] and six [6] respectively) in room three (3) due to their identical fuel loads, location of fire origin, configuration

of the interior doors being opened or closed, and the suppression method from the exterior of the building. All ten (10) tests seemed to be conducted for fireground evolutions, not for precision quantitative analysis, therefore no significant conclusions should be drawn from this data. The suppression times for tests five (5) and six (6) look to be similar from the graph outputs. Test five (5) used fifty-six (56) total gallons of water, while test six (6) used seventy-five (75) total gallons of water. CAFS was only more effective at using less quantity of agent to suppress the fire (Marquardt, 2011).

Table 2-8 Grand Rapids 2011

Test No.	Agent	Quantity of Agent (gal)
6	H ₂ O	75
5	CAFS	56

2.3 Acquired Structures

The following tests compare foam agents against water in acquired structures. These tests have an advantage over constructed mock-up structures, in that they were not specifically build for experimentation and better represent real fire conditions. Some of the tests, however, confine the fires to a single room, making them almost identical to the constructed test rooms. The literature review includes the following tests:

- Sikeston, 1990
- Salem, 1992
- Boston Fire Department, 1994
- Fairfax County Fire Department, 1994
- Public Safety Department of Matanuska-Susitna, 1997
- Los Angeles County Fire Department, 2001
- Montgomery County Fire Rescue Service, 2002

Sikeston, 1990

In 1990, Missouri fire instructors supervised comparison tests with water and Class-A foam solution at a vacant motel in Sikeston, Missouri. Four (4) identical rooms were instrumented with

thermocouples and identically loaded with wall coverings, a bed, pallets, a loveseat, and the existing wall panels and carpet. Two (2) tests (one [1] using water and one [1] using foam) used a flow rate of 30-gpm, while the other two (2) tests (one [1] using water and one [1] using foam) used a flow rate of 60-gpm. The fire was allowed to develop to a prescribed flashover temperature of 1000°F (538°C), and was extinguished down to a temperature of 200°F (93°C), then was allowed to rekindle until flashover before performing the final overhaul. At the 60-gpm flow rate it took water thirty-four (34) seconds to reduce the temperature from flashover to the ambient temperature of 105°F (41°C), using twenty-eight (28) gallons of water. With the same flow rate it took the foam twenty (20) seconds to reduce the temperature from flashover to ambient, using twenty (20) gallons of water. The total amount of water used in overhaul at the 60-gpm flow rate was 214 gallons for water and fifty-seven (57) gallons for foam. At the 30-gpm flow rate, overhaul was achieved using 242 gallons of water for plain water and seventy-seven (77) gallons of water for foam. Researchers found that when using the Class A foam on these motel fires, suppression was achieved in twenty-nine percent (29%) to fifty-two percent (52%) less time than when using plain water. Less quantity of water was also used during knockdown, and especially during overhaul, when enhanced with a Class A foam (Almer, 1990; Fornell, 1991).

Table 2-9 Sikeston 1990

Test No.	Agent	Flow (gpm)	Time from 1000°F until 105°F (sec)	Knockdown Agent Quantity (gal)	Overhaul Quantity of Agent (gal)
1	H ₂ O	30	-	-	242
2	Class A	30	-	-	77
3	H ₂ O	60	34	28	214
4	Class A	60	20	20	57

Salem, 1992

In 1992, nine (9) live burn tests were conducted in Salem, Connecticut, to compare water, Class-A foam solution, and compressed air foam systems. A two (2) story wood frame single family dwelling was acquired and modified to house three (3) identical rooms measuring 11-ft by 10-ft by 8-ft tall on the first floor, each with their own door and window openings to have similar ventilation dynamics. Thermocouples were instrumented on the ceiling and at the 4-ft level to read fire temperatures. The fuel load for each test consisted of identical quantities of straw and wood

pallets. A fire was allowed to grow to flashover and then was suppressed for sixty (60) seconds targeting the ceiling at a flow rate of 20-gpm, followed by an additional sixty (60) second attack directly on the room contents. All nine (9) tests (three [3] using water, three [3] using the foam solution, and three [3] using CAFS) produced similar readings for temperature at both recoding heights for their respective suppressant agent. Ceiling temperature profiles for each suppression agent were nearly identical in each case, probably due to direct application impingement on the thermocouple. At the 4-ft level, each type of agent showed noticeable differences in temperature drop. On average it took 222.9 seconds for water to reduce the temperature from 1000°F (538°C) to 212°F (100°C), 102.9 seconds for the foam solution, and 38.5 seconds for CAFS, each using seventy-four (74), thirty-four (34), and thirteen (13) total gallons of water respectively. It is clear that CAFS used less quantity of agent, and had a quicker temperature reduction time, making it more effective than water (Colletti, 1993; 2006).

Table 2-10 Salem 1993

Test No.	Agent	Flow (gpm)	Time from 1000°F until 212°F (sec)	Quantity of Agent (gal)
1-3	H ₂ O	20	222.9	74
4-6	Class A	20	102.9	34
7-9	CAFS	20	38.5	13

Boston Fire Department, 1994

In 1994, the Boston Fire Department performed a series of controlled fires at the Massachusetts State Fire Academy to compare water against CAFS. Each interior test structure was loaded with the same quantity of fuel in identical configurations. Three (3) experiments each testing water and CAFS in slightly different scenarios were conducted to see if the effect of head pressure, ventilation and unrestricted air movement, and heat containment and oxygen deprivation, had any bearing on the performance of each suppression agent. In each test suppression began at a predetermined temperature and was terminated when the captain observed the fire was extinguished. The first experiment extinguished the fire using water in one minute and forty-eight seconds (1:48) using sixty-nine (69) gallons of agent, while CAFS took fifty-nine (59) seconds using thirty (30) gallons of agent. The second experiment yielded a suppression time of one minute and six seconds (1:06) for each agent, using 100 gallons for water and thirty-six (36)

gallons for CAFS. The last experiment took two minutes and forty-eight seconds (2:48) for water to suppress the flames and one minute and thirty-nine seconds (1:39) for CAFS, both using ninety (90) gallons of agent. It should be noted that not many details were provided for the test structure, type of fuel, and instrumentation. CAFS can be viewed as outperforming water in each experiment for either suppression time, total quantity of agent used, or both, but the fire department later viewed these tests as inconclusive. Despite their conclusion, this account does have some value for reference (Routley, 1994).

Table 2-11 Boston 1994

Test No.	Exp. No.	Agent	Apparent Flow (gpm)	Time to Extinguishment (min:sec)	Quantity of Agent (gal)
1	1	H ₂ O	38.3	1:48	69
2	1	CAFS	30.6	0:59	30
3	2	H ₂ O	90.9	1:06	100
4	2	CAFS	32.7	1:06	36
5	3	H ₂ O	32.1	2:48	90
6	3	CAFS	54.5	1:39	90

Fairfax County Fire Department, 1994

In 1994, the Fairfax County Fire and Rescue Department, in conjunction with interested parties of the US Army and Navy, carried out three (3) evolutions consisting of two (2) fires each, one (1) extinguished with water, and the other with CAFS, at Fort Belvoir, Virginia. The first two (2) evolutions, or the scoping and full scale tests, took place in identical two (2) story World War II vintage barracks buildings, while the final evolution or demonstration test used two (2) one (1) story buildings positioned side by side. Each test used wooden cribs, wooden pallets, box spring mattresses, and bales of hay as fuel. The scoping test room measured 20-ft by 29-ft by 8-ft tall, with an additional 10-ft by 12-ft by 8-ft tall attached room, and was instrumented with thermocouples at the ceiling and 3-ft above the floor. The scoping water test had a preburn time of 116 seconds, a maximum temperature of 925°F (496°C) at the ceiling, and was extinguished in forty-six (46) seconds, at a flow rate of 124-gpm, using ninety-five (95) total gallons to achieve knockdown. The scoping CAFS test had a preburn time of 382 seconds, a maximum temperature of 990°F (532°C) at the ceiling, and was extinguished in forty-two (42) seconds, at a flow rate of

50-gpm (with 50-cfm of air), using thirty-five (35) total gallons of agent to achieve knockdown. The full scale test room measured 47-ft by 29-ft by 8-ft tall, and was instrumented with thermocouples and a heat flux gauge. The full scale water test had a preburn time of eighty-four (84) seconds, a maximum temperature of 1400°F (760°C) at the ceiling, a maximum heat flux of 65-kW/m², and was extinguished in seventy-six (76) seconds, at a flow rate of 124-gpm, using 157 total gallons to achieve knockdown. The full scale CAFS test had a preburn time of ninety (90) seconds, a maximum temperature of 1400°F (760°C) at the ceiling, a maximum heat flux of 55-kW/m², and was extinguished in seventy-six (76) seconds, at a flow rate of 50-gpm (with 50-cfm of air), using sixty-three (63) total gallons of agent to achieve knockdown. The demonstration test rooms measured 32-ft by 19-ft by 10-ft tall, and were instrumented with thermocouples, a heat flux gauge, and gas sampling tubes. The demonstration water test had a preburn time of 186 seconds, a maximum temperature of 1400°F (760°C) at the ceiling, a maximum heat flux of 80-kW/m², and was extinguished in fifty-three (53) seconds, at a flow rate of 53-gpm, using forty-seven (47) total gallons to achieve knockdown. The demonstration CAFS test had a preburn time of 660 seconds, a maximum temperature of 1700°F (927°C) at the ceiling, a maximum heat flux of 204-kW/m², and was extinguished in twenty-four (24) seconds, at a flow rate of 53-gpm, using twenty-one (21) total gallons of agent to achieve knockdown. The gas analysis for the demonstration fires yielded identical minimum concentration values for each test: seven percent (7%) to nine percent (9%) O₂, greater than 1.8% CO, and greater than 4.3% CO₂. CAFS appears to have performed better than water in all tests for total quantity of agent used, even in the fires with longer preburn times causing a more deeply seated fire, and for suppression time in two (2) out of three (3) evolutions (Duncan, 1994).

Table 2-12 Fairfax County 1994

Test No.	Exp.	Agent	Flow (gpm/cfm)	Knockdown Time (sec)	Quantity of Agent (gal)
1	Scope	H ₂ O	124/-	46	95
2	Scope	CAFS	50/50	42	35
3	Full Scale	H ₂ O	124/-	76	157
4	Full Scale	CAFS	50/50	76	63
5	Demo	H ₂ O	53/-	53	47
6	Demo	CAFS	53/50	24	21

Public Safety Department of Matanuska-Susitna, 1997

In 1997, the Public Safety Department of Matanuska-Susitna Borough in Wasilla, Alaska tested the Tri-Max Mobile 30 Fire Foam Systems against regular water fire suppression. Only two (2) structural suppression tests were conducted, one (1) using plain water, and the other with CAFS. Two (2) identical bedrooms in a two (2) story log structure were used as the test enclosures, measuring 11-ft by 13-ft by 8-ft high, each with two (2) 2-ft by 3.5-ft windows. The fuel load in each room consisted of a couch, a mattress with wooden headboard, and eight (8) thirty-five (35) gallon trash bags filled with crumpled newspaper. Each tests allowed the fire to grow until flashover before it was attacked. Water flowing at a rate of 84-gpm was able to knockdown a fire with a 147 second preburn time in seven (7) seconds. All visible flames were extinguished after an additional thirty-seven (37) second application for a total suppression time of forty-four (44) seconds. The water test used an estimated eighty (80) to 100 gallons of water. The Tri-Max 30 System flowing at a rate of 10-gpm was able to knockdown a fire with a 142 second preburn time in twenty-two (22) seconds. All visible flames were extinguished after an additional eighty-four (84) second application for a total suppression time of 106 seconds. The CAFS test used an estimated 12.5 to fifteen (15) gallons of solution. In this set of tests, typical plain water fire suppression was the superior method due to its faster extinguishment time, despite using much more quantity of agent. The Tri-Max 30 mobile CAFS system, however, is better dubbed as a mini-CAFS system, as it only has a thirty (30) gallon solution capacity and relatively low flow rate. It is more suited for preventing the ignition of a structure or small woodland area, not for interior fire suppression. A typical fire engine mounted CAFS, which is able to produce a higher flow rate with a larger capacity, likely would have produced more competitive results (Murdock, 1997).

Table 2-13 Matanuska-Susitna 1997

Test No.	Agent	Flow (gpm)	Knockdown Time (sec)	Knockdown + Overhaul Time (sec)	Total Quantity of Agent Used (gal)
1	H ₂ O	84	7	44	100
2	mini-CAFS	10	22	106	15

Los Angeles County Fire Department, 2001

In 2001, the Los Angeles County Fire Department led a series of controlled burns in three (3) identical one (1) story, wood-framed single-family dwellings using water, a Class A foam solution, and CAFS. Each unit had a 1,105-ft² floor plan with six (6) rooms, lath-and-plaster interior walls, and composition shingle roofs. The exterior stucco walls were removed due to asbestos contamination, and all window glass had been removed and replaced with plywood. The fuel load consisted of beds and bedding, dressers, wood dining room tables and chairs, bookcases, chairs, upholstered couches, coffee tables, various plastic items, magazines, and wall hangings. The carpets were removed as well, and thermocouples were installed at various locations. When temperatures reached between 550-850°F (288-454°C), the plywood windows were pulled back to simulate the heat failure of glass. After ventilating the fire for a short time, suppression began through open windows and doors. Using the Iowa formula, flow rates for water and the Class A foam solution were calculated to be 90-gpm; the CAFS attack also used the 90-gpm flow rate with 30-cfm of air. The water suppression took fifty (50) seconds to knockdown the fire, using seventy-five (75) gallons, and dropped the temperature from 600°F (316°C) to 200°F (93°C) in six minutes and three seconds (6:03). Similarly, the Class A solution results were twenty-five (25) seconds, forty-four (44) gallons, and one minute and forty-five seconds (1:45), while the CAFS values were eleven (11) seconds, sixteen (16) gallons, and one minute and twenty-eight seconds (1:28). In terms of knockdown time, the total gallons required for knockdown, and time to cool the building from 600°F to 200°F, CAFS was four (4) times more effective than water (Cavette, 2001).

Table 2-14 Los Angeles 2001

Test No.	Agent	Flow (gpm/cfm)	Knockdown Time (sec)	Temp drop from 600°F to 200°F (min:sec)	Knockdown Quantity of Agent (gal)
1	H ₂ O	90/-	50	6:03	75
2	Class A	90/-	25	1:45	44
3	CAFS	90/30	11	1:28	16

Montgomery County Fire Rescue Service, 2002

In 2002, the Montgomery County Fire & Rescue Service (MCFRS) set up eight (8) test fires to assess the effectiveness of CAFS and a Class A foam solution against water. A vacant seven (7)

story high-rise office building was used for testing. The fifth floor was modified to house a 29-ft by 9-ft by 9.5-ft tall burn room made of double layer 1/2-inch plywood under 1/2-inch gypsum board held in place with ceiling anchors. Eight (8) thermocouples were installed throughout the room. Each agent was to suppress its respective fire using the calculated flow rate of 50-gpm. The attack hoseline was connected to the building's standpipe that was supplied suppressant by the fire engine and local hydrant. The fuel package was composed of three (3) identical sets of six (6) wooden pallets and three (3) bales of straw. Soon after temperatures peaked each fire was suppressed. The evaluation of the effectiveness of all three (3) agents was not fully achieved for a number of reasons. Testing could only be conducted for a single day due to staffing limitations, and the difficult labor involved in preparing each test condensed the total number of runs to eight (8). Synthetic fuels were not allowed, neither were heavy fuel loads, and all exterior window glass was to remain intact, resulting in unchallenging fires and statistically insignificant data. The burn room was also under ventilated, yielding peak fire temperatures with very short durations, and a significant amount of un-burnt fuel which failed to bring the room to flashover. For one or more of these reasons, four (4) of the eight (8) tests were considered failures.

The following tests were deemed successful. Burn number five (5) was the hottest burning water suppressed fire, using sixty (60) gallons of agent flowing for a total of eighty (80) seconds, with a preburn time of 300 seconds, and a peak temperature of 1420°F (771°C). It took the ceiling temperature 150 seconds to drop to 300°F (149°C), and the 4-ft level temperature ninety-five (95) seconds to fall to 212°F (100°C). Burn number seven (7) was the hottest burning CAFS suppressed fire, using eighteen (18) gallons of agent flowing for twenty-five (25) seconds, with a preburn time of 340 seconds, and a peak temperature of 1390°F (754°C). It took the ceiling temperature sixty-five (65) seconds to lower to 212°F (100°C), and the 4-ft level temperature forty (40) seconds to descend to 212°F (100°C). Burn number eight (8) used CAFS to extinguish the fire, with twenty-two (22) gallons of agent, and a maximum temperature of 1160°F (627°C). Burn number six (6) used a Class A foam solution to extinguish the fire, with forty-six (43) gallons of agent, and a maximum temperature of 1200°F (649°C) that decayed very quickly. Test number

six (6) also had similar temperature drops to test number seven (7). The hottest burning water suppression and the hottest burning CAFS suppression tests confirm previously documented experience with CAFS, in which it uses less quantity of agent, takes less time to suppress a fire, and cools the room much faster than water alone (Lohr, 2002).

Table 2-15 Montgomery County 2002

Test No.	Agent	Flow (gpm)	Nozzle Flow Time (sec)	Ceiling Temp Drop Time to 100°C (sec)	4-ft Temp Drop Time to 100°C (sec)	Total Quantity of Agent (gal)
5 ⁺	H ₂ O	50	80	150	95	60
6	Class A	50	-	~65	~40	43
7 ⁺	CAFS	50	25	65	40	18
8	CAFS	50	-	-	-	22

+ Hottest fire for its respective suppression agent

* Ceiling temperature drop time to 149°C, not 100°C

2.4 Summary of Prior Testing

Nearly all of the published live fire testing suggests that CAFS is at least equal to if not more effective than water at suppressing a structural fire. The most common metrics for evaluating effectiveness are the time it takes to suppress a fire and the quantity of agent used to suppress the fire. A more specific effectiveness criteria is the time it takes to reduce the temperature from a prescribed high or peak value to a prescribed low value; similarly with the chemical or convective heat release rate. Other measurements not fully evaluated, or that is typically too similar to draw any conclusion, are the gas concentrations of oxygen, carbon monoxide, and carbon dioxide, smoke obscuration, smoke density, and heat flux.

3 FIREGROUND EVOLUTIONS

In conjunction with the fire suppression tests, the first round of CAFS fireground evolutions was completed in June 2012 by a Cal Poly mechanical engineering senior project team. Their objective was to produce data to evaluate the safety of hoseline handling properties for CAFS, compared to plain water. The parameters of this project were: nozzle reaction force, hose kinking, stream throw, steam distribution, and surface friction. Through field testing in partnership with the Cambria Community Service District Fire Department, they were able to draw preliminary conclusions which are documented in their technical report (see LaPolla *et al.*, 2012). A second senior project team improved these experiments during the winter and spring of 2013. Their results will be made available on the Cal Poly Digital Commons later this year.

4 GAS COOLING EXPERIMENTS

4.1 Description of Gas Cooling Test

The gas cooling tests conducted on September 25th, 26th, and 27th, 2012 at the Delaware County (DELCO) Emergency Services Training Center were performed in the facility's burn building (Figure 4-1). This test was intended to document the mass flow rate and cooling effects of plain water compared to aspirated foam and CAFS. Only the ground floor was utilized in this three (3) story structure, which contains three (3) rooms pictured in the floor plan (Figure 4-2). Looking at the floor plan, the bottom two (2) rooms were used in the testing, while the top room was closed. A fire was built up in the fire room by burning wooden pallets and tinder (Figure 4-3), while hot gases were allowed to develop in the adjacent smoke room. The hot gases in the smoke room were suppressed by each agent type, using a variety of flow configurations.

Figure 4-1 Burn Building

Figure 4-2 Burn Building Floor Plan

Figure 4-3 Burning Wooden Pallets

4.2 Instrumentation

The burn building is equipped with a thermal protective interior lining that keeps the structure free from fire damage (Figure 4-4). Both the fire room and smoke room measures 12.5-ft by 18.5-ft by 11-ft tall. Three (3) thermocouple arrays were placed in each corner of the smoke room, a fourth in the fire room, and a fifth in the doorway of the smoke room which leads to the outside (Figure 4-5). Each array took temperature measurements at the ceiling level and at every foot below the ceiling (BC); see Figure 4-6. The lowest thermocouple on each array sat 10-ft below the ceiling, or 1-ft above the floor in the 11-ft tall room. At the doorway to the exterior in the smoke room, array 5 took thermal data with thermocouples and mass flow rates using the bi-directional probes at 0.5-ft, 1-ft, 2-ft, 3-ft, 4-ft, and 5-ft below the soffit (BS) of the door (Figure 4-7).

Figure 4-4 Burn Building Interior

Figure 4-5 Burn Building Instrumentation

Figure 4-6 Thermocouple Arrays and Heat Flux Gauge/Radiometer

Figure 4-7 Doorway Instrumentation

Each thermocouple used to record temperature was a 1/8-inch diameter Type-K Inconel shielded thermocouple (Figure 4-8). These thermocouples are factory calibrated by the manufacturer. The uncertainty associated with this type of thermocouple is due to the device itself (0.75% according to the Omega website for Type-K thermocouples) and due to radiation error. In any case it is an estimate, typically about 15% (value used by NIST), but could possibly be less because there was no flaming combustion (hence limited radiation) in the smoke room where most of the data was collected.

Figure 4-8 Type-K Inconel Shielded Thermocouples

The bi-directional probes allow for measuring velocity data of the gases as they are pushed from the smoke room to the outside air. The intent was to see if there was a significant push out of the door during steam conversion. This was not observed, and therefore this data is not used for analysis.

A total heat flux gauge and a radiometer were also setup in the middle of the smoke room to record the total and radiant heat flux of the hot gas layer. Their position is depicted in Figures 4-5 and 4-6. The data produced from these sensors were not available to the author during this analysis, and therefore are not contained in this thesis. Future analysis by NIST should provide some details about the impact of these readings.

Video equipment was also setup to document the tests. Infrared thermal imaging cameras were setup to observe the hot gas plumes and the effect of the suppression agents. High definition video cameras were also used to record in the visual spectrum.

4.3 Nozzle Types and Settings

Five (5) different nozzle hose stream patterns were used in the gas layer cooling experiments. Throughout this report they are referred to in short hand as: 7/8" Solid, 1 3/8" Solid, SS, 30 Fog, and 60 Fog. The 7/8-inch solid and 1 3/8-inch solid are both smooth bore streams produced using the Valve Integral Tip Nozzle 1.5" NH (Part No: H-VIT by Task Force Tips). The 7/8-inch insert produces a solid stream of water, aspirated foam solution, or CAFS, from a 1 3/4-inch diameter hoseline that was used during testing. With no insert, the nozzle creates a 1 3/8-inch waterway which is optimal for CAFS while fed from the same 1 3/4-inch hoseline. The SS, 30 Fog, and 60 Fog are setting of the Metro 1 Tip 1.5" NH (Part No: ME1-TO by Task Force Tips) combination nozzle. This nozzle is screwed onto the Valve Integral Tip Nozzle, and can produce a variety of patterns, much like special fittings on a garden hose or a shower head. The SS setting refers to a straight stream setting, which is like the solid stream produced by the smooth bore tips. The 30 Fog and 60 Fog are angled fog patterns, which cover a wider range, but with limited reach. Water, aspirated foam, and CAFS can be used with all three combination nozzle settings when also fed from a 1 3/4-inch diameter hoseline. Below is summary table of the different nozzles and settings (Table 4-1), and a depiction of the different spray patterns (Figure 4-9).

Table 4-1 Nozzles and Settings

Part No.	Insert/Setting	Coupling Size	Hoseline Diameter
H-VIT	7/8-inch	1 1/2-inch	1 3/4-inch
H-VIT	1 3/8-inch	1 1/2-inch	1 3/4-inch
ME1-TO	SS	1 1/2-inch	1 3/4-inch
ME1-TO	30 Fog	1 1/2-inch	1 3/4-inch
ME1-TO	60 Fog	1 1/2-inch	1 3/4-inch

Figure 4-9 Nozzle Types and Spray Patterns

The following pictures are the real spray patterns and nozzles used during testing (Figures 4-10 through 4-13).

Figure 4-10 Typical 7/8" and 1 3/8" Solid Stream

Figure 4-11 Straight Stream (SS)

Figure 4-12 30 Fog

Figure 4-13 60 Fog

4.4 Procedure

A total of eighty-eight (88) hot gas layer cooling tests were performed over three days, between September 25th and 27th, 2012. The smoke layer temperatures were allowed to peak, and when temperatures started to drop a fifteen (15) second suppression was administered using water, aspirated foam, or CAFS. Each gas cooling suppression is considered a test, and some were performed in short succession. A chronological list experiments is provided in Appendix A, which details the agent type, nozzle type, water/air flow rate, and cooling impact position for each test.

The cooling impact position relates to where the monitor (located outside the doorway) was directed toward the hot gas layer (Figure 4-14). In both “mid” and “full back” positions the nozzle was angled toward thermocouple array 2. The “mid” position aimed the nozzle to hit the middle of the ceiling, approximately 6-ft from the side and 9-ft from the rear. The “full back” position aimed the nozzle as high as it could be pulled up or as far back as it would go, resulting in the nozzle aimed to hit the ceiling about 13-ft from the rear wall, or approximately 5-ft from the front wall.

The "hand held" position refers to application without the use of a monitor, where the firefighter rotates the nozzle toward the hot gas layer (Figure 4-15).

Figure 4-14 Hoseline/Nozzle Monitor

Figure 4-15 Hand Held Position

Data from thermocouple arrays 1, 2, 3, and 5 were chosen to be the main focus of the analysis, as they best represent conditions in the smoke room. The data produced by thermocouple array 4 is useful to confirm that temperature decreases in the smoke room correlate with activation of the nozzle, and not the opening of a window for fuel reloading. The data is further narrowed to the 1-ft, 2-ft, 6-ft, and 9-ft thermocouple levels below the ceiling at arrays 1, 2, and 3. In the doorway at array 5, only the 2-ft and 5-ft levels below the soffit were analyzed. These 2-ft and 5-ft thermocouples below the soffit are at about the same height as the 6-ft and 9-ft thermocouples below the ceiling in the smoke room. See Figure 4-16 for clarification.

Figure 4-16 Thermocouple Locations and Heights That Were Analyzed

These specific thermocouple heights were chosen to model three things:

1. Hottest gas layer temperatures
2. Head height tenability
3. Crouched position conditions

The hottest gas layer temperatures occur at 1-ft and 2-ft below the ceiling. This high heat area shows the most dramatic drops in temperature due to suppression. The 6-ft level below the ceiling best represents a person standing in the room. This level is 5-ft above the floor, which would certainly be at head height for most people, and directly relates to thermal tenability. The lowest level of 9-ft below the ceiling (2-ft above the floor) simulates someone crawling out of the building, or a firefighter crawling in to begin attacking the fire. This last scenario would be relevant when much of the room is obscured by smoke.

4.5 Data Analysis and Results

Graphs of the temperatures recorded by each thermocouple array are provided for each test series (see Appendix B), which contain multiple experiments. The series relate to the sets of data between turning the data acquisition system. Starting the data acquisition begins with series 1. If the acquisition system crashes or the operator shuts it down, this ends series 1. Every plot color codes the thermocouple height, and has been marked to easily distinguish the peak high and low temperatures associated with the agent suppression.

Example nomenclature for the graph legends is as follows:

GC1_0-30mBC → **G**as **C**ooling Experiment, Thermocouple Array **1**, **0.30 meters Below Ceiling**

GC5_1-52mBS → **G**as **C**ooling Experiment, Thermocouple Array **5**, **1.52 meters Below Soffit**

Below are height conversions for the thermocouple levels:

- 0.30m = 1-ft
- 0.61m = 2-ft
- 1.52m = 5-ft
- 1.83m = 6-ft
- 2.74m = 9-ft

The temperature drops displayed on the graphs were measured digitally, using Adobe Photoshop CS6, and scaled to approximate the magnitude of each drop. Each temperature drop for every test, at every height, was calculated and is tabulated in Appendix C. For each respective thermocouple level, the temperature drops were averaged to produce a uniform room temperature by height. These uniform temperatures were then averaged again to compare the three agent types (H₂O, aspirated foam, and CAFS) against their nozzle type, flow rate, and cooling impact position. A final comparison was also made of all tests by agent type, regardless of nozzle type, flow rate, and cooling impact position. Analysis A includes tables that summarize these averaged temperature drops. Analysis B on the contrary, does not average these

temperature drops, but instead examines each thermocouple reading in Appendix C through statistical significance tests. Like analysis A, the statistical tests are also grouped by nozzle type, water flow rate, cooling impact position, and agent only.

4.5.1 Data Analysis A – Averaging Temperature Drops

The tables below contain averaged temperature drops for all the tests performed. Within the tables the number in parenthesis represents the quantity of tests averaged for that particular criteria and agent type. For example, thirty-four (34) total tests were performed using the 7/8-inch solid stream nozzle insert, twenty-one (21) using water, three (3) using aspirated foam, and ten (10) using CAFS. The numbers in the square brackets are the standard deviations for each respective temperature drop population. The values in red are the differences between the highest average temperature drop and the average temperature drop for that particular agent. All the data is provided for completeness, but only certain parts are relevant. The 7/8-inch solid, SS, and 30 degree fog nozzles tested all three agent types, making them comparable, whereas the 1 3/8-inch solid and 60 degree fog nozzles only ran CAFS and water respectively, and therefore are not comparable. Likewise for the water flow rates, the 110-gpm and 180-gpm tests cannot be compared to any other agent. Other tests are comparable to at least one other agent type, but have small sample sizes. The 150-gpm and 115-gpm water flow rates, for example, are not as conclusive as say the 120-gpm water flow rate tests.

1-ft Below the Ceiling

Table 4-2 Average Temperature Drops 1-ft Below Ceiling

Average Temperature Drop in Celsius by Nozzle Type			Average Temperature Drop in Celsius by Water Flow Rate			Average Temperature Drop in Celsius by Cooling Impact Position		
7/8" Solid (34)			120 gpm (75)			Mid (60)		
H2O (21)	AF (3)	CAFS (10)	H2O (37)	AF (12)	CAFS (26)	H2O (25)	AF (14)	CAFS (21)
131 [34]	122 [21]	125 [39]	105 [37]	119 [16]	118 [32]	101 [30]	113 [22]	122 [34]
	9	6	14		1	21	9	
SS (26)			150 gpm (4)			Full Back (20)		
H2O (10)	AF (6)	CAFS (10)	H2O (2)	AF (2)		H2O (14)		CAFS (6)
72 [17]	103 [22]	118 [32]	88 [28]	73 [2]		108 [43]		100 [14]
42	15			15				8
30 Fog (17)			115 gpm (3)			Hand Held (7)		
H2O (9)	AF (5)	CAFS (3)	H2O (2)		CAFS (1)	H2O (4)		CAFS (3)
99 [33]	118 [18]	143 [18]	92 [9]		84 [0]	143 [51]		143 [18]
44	25				8			
1 3/8" Solid (7)			110 gpm (3)			Average Temperature Drop in Celsius by Agent Only		
	CAFS (7)			CAFS (3)				
	104 [10]			143 [18]				
60 Fog (3)			180 gpm (2)			H2O (43)	AF (14)	CAFS (30)
H2O (3)			H2O (2)			107 [38]	113 [22]	120 [32]
82 [7]			181 [1]			13	7	

At the 1-ft height below the ceiling, foam agents (CAFS especially) seem to decrease temperatures the best all around. CAFS is the dominate suppression agent while using the straight stream and 30 degree fog nozzle settings. It dropped the temperature forty-two (42) and forty-four (44) degrees more than water, respectively. CAFS also outperformed water by twenty-one (21) degrees while in the mid cooling impact position. Aspirated foam and CAFS were able to cool the gas layer about the same at the 120-gpm water flow rate, which was thirteen (13) to fourteen (14) degrees more than water. Water lowered the temperature better in three (3) areas: while using the 7/8-inch solid stream nozzle insert, at the 115-gpm flow rate, and while in the full back position; however, the temperature differences were less than ten (10) degrees in each case. At the 150-gpm water flow rate, water did better than aspirated foam by fifteen (15) degrees. Hand held agent application was the same using water or CAFS. Comparing all tests by agent, CAFS performed the best, averaging thirteen (13) degrees over water, and seven (7) degrees over aspirated foam.

2-ft Below the Ceiling

Table 4-3 Average Temperature Drops 2-ft Below Ceiling

Average Temperature Drop in Celsius by Nozzle Type			Average Temperature Drop in Celsius by Water Flow Rate			Average Temperature Drop in Celsius by Cooling Impact Position		
7/8" Solid (34)			120 gpm (75)			Mid (60)		
H2O (21)	AF (3)	CAFS (10)	H2O (37)	AF (12)	CAFS (26)	H2O (25)	AF (14)	CAFS (21)
143 [26]	127 [16]	89 [26]	121 [37]	113 [18]	97 [28]	122 [27]	116 [19]	94 [27]
	16	54		8	24		6	28
SS (26)			150 gpm (4)			Full Back (20)		
H2O (10)	AF (6)	CAFS (10)	H2O (2)	AF (2)		H2O (14)		CAFS (6)
106 [30]	112 [21]	100 [28]	144 [8]	139 [5]		115 [39]		109 [23]
6		12		5				6
30 Fog (17)			115 gpm (3)			Hand Held (7)		
H2O (9)	AF (5)	CAFS (3)	H2O (2)		CAFS (1)	H2O (4)		CAFS (3)
106 [43]	116 [16]	141 [19]	95 [6]		92 [0]	153 [59]		141 [19]
35	25				3			12
1 3/8" Solid (7)			110 gpm (3)			Average Temperature Drop in Celsius by Agent Only		
	CAFS (7)			CAFS (3)				
	104 [25]			141 [19]				
60 Fog (3)			180 gpm (2)			H2O (43)	AF (14)	CAFS (30)
H2O (3)			H2O (2)			123 [37]	116 [19]	102 [30]
89 [7]			171 [0]				7	21

At 2-ft below the ceiling, the results favor suppression by water. Water dropped the temperature greater than any other agent under the following criteria: while using the 7/8-inch solid stream nozzle insert, at the 115-gpm, 120-gpm, and 150-gpm water flow rates, at all cooling impact positions, and when comparing all tests by agent type. The greatest temperature drops using water over CAFS were fifty-four (54), twenty-eight (28), and twenty-four (24) degrees, while using the 7/8-inch solid stream insert, in the mid position, and at the 120-gpm flow rate, respectively. CAFS had a notable temperature decrease over water, while again using the 30 degree fog pattern, by thirty-five (35) degrees. Aspirated foam outperformed water and CAFS, using the straight stream pattern. Regardless of nozzle type, flow rate, and cooling impact position, water was able to lower the temperature best, by seven (7) degrees over aspirated foam, and twenty-one (21) degrees over CAFS.

6-ft Below the Ceiling / 2-ft Below the Soffit

Table 4-4 Average Temperature Drops 6-ft Below Ceiling / 2-ft Below Soffit

Average Temperature Drop in Celsius by Nozzle Type			Average Temperature Drop in Celsius by Water Flow Rate			Average Temperature Drop in Celsius by Cooling Impact Position		
7/8" Solid (34)			120 gpm (75)			Mid (60)		
H2O (21)	AF (3)	CAFS (10)	H2O (37)	AF (12)	CAFS (26)	H2O (25)	AF (14)	CAFS (21)
110 [23]	79 [12]	83 [27]	102 [23]	79 [25]	81 [22]	96 [17]	77 [24]	81 [24]
	32	27		23	21		19	15
SS (26)			150 gpm (4)			Full Back (20)		
H2O (10)	AF (6)	CAFS (10)	H2O (2)	AF (2)		H2O (14)		CAFS (6)
91 [11]	60 [6]	83 [22]	99 [9]	64 [5]		109 [22]		85 [16]
	31	8		35				24
30 Fog (17)			115 gpm (3)			Hand Held (7)		
H2O (9)	AF (5)	CAFS (3)	H2O (2)		CAFS (1)	H2O (4)		CAFS (3)
105 [24]	97 [28]	92 [13]	105 [2]		106 [0]	128 [24]		92 [13]
	8	13	1					36
1 3/8" Solid (7)			110 gpm (3)			Average Temperature Drop in Celsius by Agent Only		
	CAFS (7)			CAFS (3)				
	79 [12]			92 [13]				
60 Fog (3)			180 gpm (2)			H2O (43)	AF (14)	CAFS (30)
H2O (3)			H2O (2)			103 [22]	77 [24]	83 [22]
90 [15]			123 [2]				26	20

Suppression by water at the 6-ft level below the ceiling, and at the 2-ft level below the soffit of the door, drops the temperature better than aspirated foam and CAFS in nearly all configurations. The only condition where water is not the best suppressant is at the 115-gpm flow rate, where CAFS is only slightly better at reducing the temperature by one (1) degree. Water drops the temperature by thirty-one (31), thirty-one (31), twenty-three (23), and thirty-five (35) degrees while using the 7/8-inch solid stream insert, the straight stream setting, and at the 120-gpm and 150-gpm flow rates over aspirated foam respectively. It also drops the temperature lower than CAFS by twenty-seven (27), twenty-one (21), twenty-four (24), and thirty-six (36) degrees while using the 7/8-inch smooth bore, at the 120-gpm flow rate, and in the full back and hand held impact positions respectively. Comparing strictly by agent type yields a preference for water over aspirated foam by twenty-six (26) degrees and over CAFS by twenty (20) degrees.

9-ft Below the Ceiling / 5-ft Below the Soffit

Table 4-5 Average Temperature Drops 9-ft Below Ceiling / 5-ft Below Soffit

Average Temperature Drop in Celsius by Nozzle Type			Average Temperature Drop in Celsius by Water Flow Rate			Average Temperature Drop in Celsius by Cooling Impact Position		
7/8" Solid (34)			120 gpm (75)			Mid (60)		
H2O (21)	AF (3)	CAFS (10)	H2O (37)	AF (12)	CAFS (26)	H2O (25)	AF (14)	CAFS (21)
14 [3]	15 [1]	16 [5]	15 [3]	11 [3]	16 [4]	14 [3]	11 [3]	16 [4]
2	1		1	5		2	5	
SS (26)			150 gpm (4)			Full Back (20)		
H2O (10)	AF (6)	CAFS (10)	H2O (2)	AF (2)		H2O (14)		CAFS (6)
14 [3]	8 [2]	15 [3]	12 [2]	11 [1]		15 [3]		15 [4]
1	7			1				
30 Fog (17)			115 gpm (3)			Hand Held (7)		
H2O (9)	AF (5)	CAFS (3)	H2O (2)		CAFS (1)	H2O (4)		CAFS (3)
15 [2]	12 [1]	20 [4]	15 [2]		9 [0]	15 [2]		20 [4]
5	8				6	5		
1 3/8" Solid (7)			110 gpm (3)			Average Temperature Drop in Celsius by Agent Only		
	CAFS (7)			CAFS (3)				
	16 [3]			20 [4]				
60 Fog (3)			180 gpm (2)			H2O (43)	AF (14)	CAFS (30)
H2O (3)			H2O (2)			15 [3]	11 [3]	16 [4]
15 [4]			13 [1]			1	5	

At the lowest height in the analysis, CAFS lowers the heat the best, but only slightly better than water and aspirated foam. CAFS has the largest temperature drops while using the 7/8-inch smooth bore nozzle insert, the straight stream and 30 degree fog patterns, at the 120-gpm flow rate, and at the mid and hand held cooling impact positions. The biggest CAFS differentials are only seven (7), eight (8), five (5), and five (5) degrees, however, while using the straight stream setting, the 30 degree fog pattern, the 120-gpm flow rate, and at the mid position, over aspirated foam, respectively. When CAFS drops the temperature better than water, the differences are only between one (1) and five (5) degrees. Water does better than CAFS by six (6) degrees at the 115-gpm flow rate, and by one (1) degree at the 150-gpm flow rate. In the full back position, both water and CAFS reduces the heat the same. When comparing all tests by agent, CAFS outperforms water by one (1) degree and aspirated foam by five (5) degrees.

4.5.2 Data Analysis B – Statistical Significance

A statistical analysis at every thermocouple is included to give better resolution of the data than the previous analysis, but will be much harder to make generalizations about the results. It is included to give a more complete picture of what is going on at each thermocouple location.

An analysis of variance (ANOVA) was performed by nozzle type, water flow rate, cooling impact position, and agent only (regardless of nozzle type, water flow rate, and cooling impact position). Each ANOVA generated p-values for the selected thermocouple criteria at their respective location and height. Any p-value below the 0.05 chosen level means that the data shows statistically significant differences between agent types with 95% confidence. Using this 0.05 confidence level, however, comes with a word of caution. Any time numerous statistical tests are performed using this value, we can expect one (1) test out of every twenty (20) tests to be a false positive; showing statistical significance when in fact the data is only significant due to chance variation.

Each analysis by height has two tables. The first table provides the p-values that show which tests have statistically significant differences. The second table contains the mean temperature drop values, standard error (SE), and connecting letter reports, all by agent type, of those tests deemed statistically significant. Agent levels not connected by the same letter are significantly different. The connecting letter reports were produced by JMP Pro 10 statistical software. The Tukey-Kramer HSD (honestly significant difference) test was used to create the reports grouped by nozzle type, water flow rate, and cooling impact position, and the least squares method was used to make the reports by agent only, both using the same 0.05 confidence level. The analysis is organized by thermocouple height to be consistent with data analysis A.

Experiment number one (1) and twelve (12; see Appendix A and C) are omitted from analysis. Because the nozzle kicked left during test one (1), the readings for thermocouples arrays 1 and 2 became statistical outliers, and therefore inconsistent. Test number one (1) is therefore removed

from the statistical analysis, but left in the previous analysis because the values were averaged over the height of the thermocouples. Test number twelve (12) could not be determined from the temperature drop graphs (Figures B-5 through B-8), and is therefore also absent from the data.

Certain test configurations are omitted from the statistical analysis. The 1 3/8" solid stream smooth bore nozzle, 60 degree fog nozzle setting, 110-gpm, and 180-gpm flow rates were excluded because only a single agent was tested with each criterion. The 115-gpm flow rate was also left out because only one (1) data point represents the CAFS agent. The 150-gpm flow rate probably should have been excluded, as it has a relatively small sample size (two [2] tests for water and two [2] tests for aspirated foam), but is left in for reference.

1-ft Below the Ceiling

Table 4-6 P-Values 1-ft Below Ceiling

		TC-1	TC-2	TC-3
Nozzle	7/8" Solid	0.1236	0.6585	0.4252
	SS	0.0001	0.0030	0.0017
	30 Fog	0.0186	0.0213	0.1400
Water Flow Rate	120-gpm	0.0091	0.0104	0.0029
	150-gpm	0.5105	0.7091	0.6540
Cooling Impact Position	Mid	0.0030	0.0565	0.0027
	Full Back	0.1971	0.3287	0.1705
	Hand Held	0.2515	0.7374	0.6928
Agent Only		<0.0001	0.0040	0.0010

At 1-ft below the ceiling the 7/8-inch solid nozzle, 150-gpm water flow rate, full back, and hand held cooling impact positions do not show significant differences at any thermocouple. TC-3 using the 30 fog nozzle, and TC-2 at the mid cooling impact position, do not show significance either. Everywhere else, statistical significance is observed.

Table 4-7 Statistically Significant Tests 1-ft Below Ceiling

		TC-1				TC-2				TC-3			
		Level	Mean	SE		Level	Mean	SE		Level	Mean	SE	
Nozzle	SS	CAFS	A	84	7	Class A Foam	A	246	29	CAFS	A	89	8
		Water	B	49	7	CAFS	A B	180	23	Water	A B	64	8
		Class A Foam	B	27	9	Water	B	105	23	Class A Foam	B	37	10
	30 Fog	CAFS	A	159	21	Class A Foam	A	215	28				
		Water	B	94	12	CAFS	A B	162	36				
		Class A Foam	B	73	16	Water	B	105	21				
Water Flow Rate	120 gpm	CAFS	A	79	5	Class A Foam	A	257	25	CAFS	A	85	5
		Water	A B	68	5	CAFS	A B	191	17	Water	A	79	5
		Class A Foam	B	48	8	Water	B	167	14	Class A Foam	B	52	8
Cooling Impact Position	Mid	CAFS	A	77	5					CAFS	A	83	5
		Water	A B	60	5					Water	A B	71	5
		Class A Foam	B	46	7					Class A Foam	B	53	7
Agent Only		CAFS	A	110	6	Class A Foam	A	235	28	CAFS	A	102	6
		Water	B	84	5	CAFS	B	161	19	Water	B	87	6
		Class A Foam	B	70	9	Water	B	149	17	Class A Foam	C	69	9

Levels not connected by same letter are significantly different

There is an obvious trend favoring foam agents that depends on the location of the thermocouple, and is consistent regardless of nozzle, flow rate, cooling impact position, or agent only. At every configuration TC-1 and TC-3 have the same pattern in descending order of mean temperature drop: CAFS, water, and Class A foam (aspirated foam). At these locations CAFS is always more significant than aspirated foam. At TC-1 CAFS is clearly more significant than water using the SS and 30 fog nozzle setting, and by comparing agent only, but not as significant for the 120-gpm flow rate or the mid position. At TC-3 CAFS is not significantly different than water for the SS nozzle setting, 120-gpm flow rate, or mid position, but is for agent only. At TC-2 the profile in descending average temperature drop is: aspirated foam, CAFS, and water. Here aspirated foam is clearly better at dropping the temperature than water, but only marginally better than CAFS (except by agent only). Similar to the 1-ft height below the ceiling results of data analysis A, the tests seem to have larger and more significant temperature drops with CAFS or aspirated foam than with water.

2-ft Below the Ceiling

Table 4-8 P-Values 2-ft Below Ceiling

		TC-1	TC-2	TC-3
Nozzle	7/8" Solid	0.1473	<0.0001	0.3535
	SS	0.0021	0.0132	0.0031
	30 Fog	0.2509	0.0212	0.1296
Water Flow Rate	120-gpm	0.0449	0.0005	0.0017
	150-gpm	0.4625	0.8509	0.6586
Cooling Impact Position	Mid	0.0794	<0.0001	0.0017
	Full Back	0.3521	0.5353	0.5985
	Hand Held	0.9639	0.7666	0.6764
Agent Only		0.1068	<0.0001	0.0022

2-ft below the ceiling does not show significant differences at any location for the 150-gpm water flow rate, nor for the full back and hand held cooling impact positions. The SS nozzle setting shows significance at all locations, while the 7/8-inch solid and 30 fog nozzle settings are only significant at TC-2. The mid cooling impact position and agent only comparison show differences at TC-2 and TC-3.

Table 4-9 Statistically Significant Tests 2-ft Below Ceiling

		TC-1					TC-2					TC-3				
		Level	Mean			SE	Level	Mean			SE	Level	Mean			SE
Nozzle	7/8" Solid						Water	A		266	12					
							Class A Foam	A		261	30					
							CAFS	B		119	16					
	SS	CAFS	A		86	8	Class A Foam	A		266	33	CAFS	A		82	7
		Water	A B		61	8	Water	A B		191	25	Water	A B		65	7
		Class A Foam	B		32	11	CAFS	B		133	25	Class A Foam	B		37	9
	30 Fog						Class A Foam	A		209	24					
							CAFS	A B		164	30					
							Water	B		116	18					
Water Flow Rate	120 gpm	Water	A		87	7	Class A Foam	A		234	22	CAFS	A		82	5
		CAFS	A B		76	8	Water	A		197	13	Water	A		78	4
		Class A Foam	B		54	11	CAFS	B		134	15	Class A Foam	B		50	7
Cooling Impact Position	Mid						Class A Foam	A		245	19	CAFS	A		80	5
							Water	A		220	15	Water	A		70	5
							CAFS	B		128	16	Class A Foam	B		51	6
Agent Only							Class A Foam	A		250	25	CAFS	A		98	6
							Water	B		202	15	Water	A		87	5
							CAFS	C		105	17	Class A Foam	B		69	9

Levels not connected by same letter are significantly different

The foams seem to have the highest mean temperature drops at 2-ft below the ceiling, but are not that significant over plain water. CAFS is clearly more significant than aspirated foam at TC-1 for the SS nozzle, and at TC-3 for the SS nozzle, 120-gpm flow rate, mid cooling impact position, and for agent only, but is not significantly different than water. Similarly, aspirated foam is significant over CAFS at TC-2 for the SS nozzle, the 120-gpm flow rate, mid cooling impact position, and by agent only, but not over water (except by agent only). Aspirated foam is more significant than water while using the 30 fog nozzle and by agent only at TC-2. Water is significant over CAFS and aspirated foam using the 7/8-inch solid nozzle at TC-2 and at the 120-gpm flow rate at TC-1 respectively. It is hard to say whether foam is overall more significant at dropping temperatures than plain water at this height, but the odds are definitely leaning towards either CAFS or aspirated foam due their higher mean values. Data analysis A favored water for suppression at the 2-ft level, but in this analysis foams are given a bit more precedence.

6-ft Below the Ceiling / 2-ft Below the Soffit

Table 4-10 P-Values 6-ft Below Ceiling / 2-ft Below Soffit

		TC-1	TC-2	TC-3	TC-5
Nozzle	7/8" Solid	0.0247	0.0009	0.4813	0.0987
	SS	0.3193	0.0031	0.0057	0.0417
	30 Fog	0.3245	0.5449	0.2721	0.2690
Water Flow Rate	120-gpm	0.0005	0.0004	0.1083	0.0739
	150-gpm	0.5460	0.0394	0.3538	0.3824
Cooling Impact Position	Mid	0.0043	0.0104	0.0254	0.0531
	Full Back	0.8444	0.0062	0.7310	0.0500
	Hand Held	0.0037	0.4828	0.4639	0.1789
Agent Only		0.0552	0.0002	0.0938	0.0030

The 30 fog nozzle setting is the only configuration with no significant differences at all locations, 6-ft below the ceiling or 2-ft below the soffit. The 7/8-inch solid nozzle is significant at TC-1 and TC-2. The SS nozzle setting is only insignificant at TC-1. The water flow rates are significant at TC-1 for 120-gpm, and at TC-2 for 120-gpm and 150-gpm. The mid cooling impact position is

only negligible at TC-5. TC-2 and TC-5 only show major differences with the full back position, and by agent only. The hand held position is only considerable at TC-1.

Table 4-11 Statistically Significant Tests 6-ft Below Ceiling / 2-ft Below Soffit

		TC-1				TC-2				TC-3				TC-5						
		Level	Mean		SE	Level	Mean		SE	Level	Mean		SE	Level	Mean		SE			
Nozzle	7/8" Solid	Water	A	94	7	Water	A	229	12											
		Class A Foam	A	B	70	19	Class A Foam	A	B	161	31									
		CAFS	B		59	10	CAFS	B		144	17									
	SS					Water	A	179	13	CAFS	A	72	4	CAFS	A	73	10			
						CAFS	B		117	13	Water	A	B	64	4	Water	A	B	53	10
						Class A Foam	B		112	17	Class A Foam	B		51	5	Class A Foam	B		27	13
Water Flow Rate	120 gpm	Water	A	91	5	Water	A	196	10											
		Class A Foam	B		62	9	Class A Foam	A	B	161	17									
		CAFS	B		61	6	CAFS	B		134	11									
	150 gpm					Water	A	223	17											
						Class A Foam	B		108	17										
	Cooling Impact Position	Mid	Water	A	80	4	Water	A	186	12	CAFS	A	74	3						
Class A Foam			B		61	6	Class A Foam	A	B	154	15	Water	A	B	68	3				
CAFS			B		60	5	CAFS	B		133	12	Class A Foam	B		60	4				
Full Back						Water	A	215	15					Water	A	55	3			
						CAFS	B		130	23					CAFS	B		45	4	
Hand Held		Water	A	197	12															
		CAFS	B		101	14														
Agent Only						Water	A	177	12					CAFS	A	47	6			
						Class A Foam	B		140	20					Water	A	36	6		
						CAFS	B		115	13					Class A Foam	B		15	10	

Levels not connected by same letter are significantly different

Water appears to be the dominate suppression agent at this height. At TC-1 and TC-2, under all test configurations, water shows significant differences over CAFS, aspirated foam, or both. Water is not statistically significant over aspirated foam, however, while using the 7/8-inch Solid nozzle at TC-1 and TC-2, and additionally while using the 120-gpm flow rate and mid cooling impact position at TC-2. Water also has significant temperature drops over CAFS in the full back position and over aspirated foam for agent only, both at TC-5. As for the rest of the configurations at TC-3 and TC-5 (SS, mid, and agent only), CAFS displays significant differences greater than aspirated foam, but are not statistically significantly different than water. This analysis is in agreement with data analysis A, which preferred water over the foam agents at the 6-ft below the ceiling/2-ft below the soffit level.

9-ft Below the Ceiling / 5-ft Below the Soffit

Table 4-12 P-Values 9-ft Below Ceiling / 5-ft Below Soffit

		TC-1	TC-2	TC-3	TC-5
Nozzle	7/8" Solid	0.6028	0.6318	0.0761	0.0252
	SS	0.0022	0.0014	0.2195	0.0269
	30 Fog	0.0578	0.9412	0.6400	0.0136
Water Flow Rate	120-gpm	0.0010	0.1562	0.0453	0.0006
	150-gpm	0.7818	0.1448	0.7218	0.1607
Cooling Impact Position	Mid	0.0099	0.0722	0.0155	0.0003
	Full Back	0.3715	0.4183	0.9599	0.4195
	Hand Held	0.2976	0.0445	0.8348	0.0781
Agent Only		0.0085	0.1386	0.0569	<0.0001

Looking at different nozzle configurations, TC-5 was significant using all three types at 5-ft below the soffit. The TC-1 and TC-2 temperature drops were significant using the SS nozzle pattern at 9-ft below the ceiling. No location was notable while using the 150-gpm flow rate or full back cooling impact position; however, all locations except TC-2 show differences at the 120-gpm rate and mid position. The hand held position was only considerable at TC-2. Looking at agent only, TC-1 and TC-5 show significant results.

Table 4-13 Statistically Significant Tests 9-ft Below Ceiling / 5-ft Below Soffit

		TC-1				TC-2				TC-3				TC-5					
		Level	Mean	SE		Level	Mean	SE		Level	Mean	SE		Level	Mean	SE			
Nozzle	7/8" Solid													CAFS	A	9	1		
														Water	A	B	7	1	
														Class A Foam		B	2	2	
	SS	CAFS	A	23	2	Water	A	18	1					CAFS	A	8	1		
		Water	A	21	2	Class A Foam	B	15	1					Water	A	8	2		
		Class A Foam		B	9	3	CAFS	B	14	1					Class A Foam		B	2	1
	30 Fog													CAFS	A	15	3		
														Water	A	B	8	1	
														Class A Foam		B	4	2	
Water Flow Rate	120 gpm	CAFS	A	24	1					CAFS	A	16	2	Water	A	8	1		
		Water	A	22	1					Water	A	12	1	CAFS	A	8	1		
		Class A Foam		B	15	2					Class A Foam	A	11	2	Class A Foam		B	3	1
Cooling Impact Position	Mid	CAFS	A	22	1					CAFS	A	17	2	Water	A	9	1		
		Water	A	B	21	1					Class A Foam	A	B	11	2	CAFS	A	8	1
		Class A Foam		B	16	2					Water		B	10	2	Class A Foam		B	3
	Hand Held					CAFS	A	15	1										
						Water		B	13	1									
Agent Only		CAFS	A	25	2									CAFS	A	9	1		
		Water	A	23	2									Water	A	8	1		
		Class A Foam		B	18	3									Class A Foam		B	2	2

Levels not connected by same letter are significantly different

CAFS and water seem to perform the same, except in a few cases. CAFS and Water are not significantly different from each other, but are both significantly greater than aspirated foam while using the SS nozzle setting, 120-gpm water flow rate, and by agent only at TC-1 and TC-5, and while in the mid cooling impact position at TC-5. CAFS shows major differences over aspirated foam, but not water, when using the 7/8-inch Solid and 30 Fog nozzles at TC-5, and while in the mid position at TC-1. CAFS is has considerable temperature drops greater than water at TC-3 using the mid position, and at TC-2 using the hand held application. Water is better than the foams in only one case, while using the SS nozzle setting at TC-2. Using 120-gpm, TC-3 read insignificant differences between agents, but registered a p-value of less than 0.05; this could have been a false positive. Looking back at data analysis A, the statistical analysis seems to match, as CAFS shows slightly higher mean temperature drops in most areas, but isn't significantly different than water for the most part.

4.6 Discussion

Each interpretation of the temperature drops seems to draw similar results in general. At the 1-ft height below the burn building ceiling, either CAFS or aspirated foam performed better than water in analysis A and B. This could very well be due to foams ability to cling to surfaces much better than plain water, resulting in reduced re-radiation from the ceiling impinging on the thermocouples. Looking at the next layer down, 2-ft below the ceiling, there is contention between agent types. Data analysis A favors gas layer cooling by plain water, but analysis B makes the case for foam agents being slightly better. Moving further down the room, the 6-ft height below the ceiling and 2-ft height below the soffit level yields water as having the strongest temperature drops in both analyses. Near the very bottom of the room, at 9-ft below the ceiling and 5-ft below the soffit, analysis A and B are in agreement that CAFS produces the best temperature drops, but is only marginally better than water.

Neither foam nor plain water works best to lower the temperature throughout the entire room. The foam agents and water perform arguably the same at 2-ft and 9-ft below the ceiling. Foam

appears to work best closest to the ceiling (1-ft down), while water has the greatest effect at the head height (6-ft below the ceiling). These results make it difficult to determine the best all-around suppression agent. In many cases statistical significance was not observed between agent types under various suppression configurations; see the p-values in black at tables 4-6, 4-8, 4-10, and 4-12. This is probably a testament to the fact that there really is not a big enough difference between the ability of CAFS, aspirated foam, or plain water to cool the hot gas layers in such a small room. Since there is no obvious agent that sticks out above the rest in a majority of the tests, the results from the temperature data of the gas cooling experiments are inconclusive. The CAFS Project Technical Panel made a similar assessment during their workshop on December 10th, 2012. They recommended that in order to make a conclusive assessment, more challenging fires needed to be conducted to determine if the mechanical changes to the properties of water and the delivery energy make a difference.

5 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Other Experiments

DELCO Testing September/October 2012

Aside from the gas cooling tests conducted in the burn building, three (3) other tests were conducted at the Delaware County facility. Two (2) of the tests were spray distribution tests, one (1) in the smoke room of the burn building and the other in the burn room of one (1) of the two (2) fire suppression buildings (Figures 5-1 and 5-2). These tests used overlapping buckets to collect the distribution of water or foaming agent using different nozzle configurations (Figures 5-3 and 5-4). Each bucket was pre-weighed so that the net weight of agent could be recorded. These tests allowed researchers to see the distribution of water or foam agent, in the same nozzle configurations and settings as the live fire tests. Although the practical side of these results is still being interpreted, they do give insight into the placement of thermocouples so that they are out of the main flow of agents.

Figure 5-1 Fire Suppression Buildings

Figure 5-2 Fire Suppression Building Floor Plan

Figure 5-3 Burn Building Spray Pattern

Figure 5-4 Fire Suppression Building Spray Pattern

The final set of tests was conducted in the multi-compartment fire suppression buildings (Figures 5-1 and 5-2). The building's interior was lined with non-combustible cement board to allow for repeat testing. The fuel load consisted of synthetic plastic chairs and sofas, carpet with a layer of polyurethane foam underneath, and medium density fiber-board wall paneling to simulate the fuel load of a single family living room (Figure 5-5). Two monitors were setup to reduce the temperature of the hot gas plumes, one at the end of the corridor closest to the burn room, and the other in the top right corner of the burn room, while looking at the plan view (Figures 5-2 and 5-6). Different nozzles and settings were used to test the effectiveness of both water and CAFS at cooling the hot gas layers produced by the fire. The building was instrumented with two (2) thermocouple arrays, multiple heat flux gauges, and two (2) arrays of bi-directional probes. Thermal and high definition video cameras also documented the tests.

Figure 5-5 Burn Room Fuel

Figure 5-6 Dual Monitors

The last two experiments conducted in the fire suppression buildings used wooden pallets and tinder as fuel to build a fire large enough to spread into the attic (Figure 5-7). Holes were cut in the ceiling of each burn room to allow the fire to spread there. One (1) test was suppressed using plain water and the other using CAFS. Only one (1) thermocouple array in each building was used for instrumentation. High definition and thermal image cameras also recorded footage of the tests. The spray distribution and fire suppression experiments were not analyzed in this report, but will be published by NIST at a later time.

Figure 5-7 Attic Fire Test

DELCO Testing May 2013

More testing was conducted at the Delaware County facility in May 2013. Four (4) more runs were performed, two (2) using plain water suppression, and two (2) using CAFS suppression. Similar to the previous attic tests, two identical fire suppression buildings were constructed (Figure 5-8). After the first set of buildings was burned, each was reconstructed to allow for repeat testing. The wooden crib fueled fires simulated basement fires, instead of attic fires, with much longer preburn times. The buildings were also instrumented with similar equipment as the previous multi-compartment fire suppression building tests; with thermocouple arrays, heat flux gauges, bi-directional probes, and thermal and high definition video cameras. The results of these experiments will also be published by NIST.

Figure 5-8 Basement Buildings

5.2 Conclusion

The results from the temperature readings of the gas cooling experiment do not make a strong enough case for or against foaming agents as a superior alternative to plain water in structural fire suppression. Each suppression agent was testing using different nozzle spray patterns, at mostly the same flow rate, and in different application positions, to cool the hot gases produced by fire fueled with wooden pallets. Each agent was able to perform better than one another at isolated locations and room heights, but no one agent could claim to produce the most significant temperature drops at a majority of selected thermocouples. The severity of the fires, or lack thereof, is believed to be the cause of the insignificant results. Further research may better

determine the significance of using compressed air foam systems over plain water for hot gas layer cooling in structural firefighting.

5.3 Recommendations

Improving upon the gas cooling experimental procedure or a re-examination of the temperature data could produce more meaningful results. One large drawback to the results was the unequal sample sizes for each test variable (agent type, nozzle type, water flow rate, and cooling impact position). If the sample sizes were uniform then the interactions between each criterion could be statistically analyzed for significance. This would add greater depth to the results, and identify optimal configurations for each agent type. In addition, as suggested by the Project Technical Panel on December 10th, 2012, more challenging fire could also help to better distinguish each agent type in the data. Re-testing may not be necessary; however, as not all of the temperature data was analyzed. Only fourteen (14) thermocouples out of thirty-nine (39) were chosen in this thesis to draw conclusions. Looking at more thermocouple locations could change the outcome of the results.

LIST OF REFERENCES

- (Almer, 1990) Almer, S, prod. *American Heat: Class A foam tests: Sikeston, MO [Video magazine]*. Edit. C Emg, and C Wilson. 1990. Videocassette. 17 Feb 2013.
- (Cavette, 2001) Cavette, Chris. "Bubbles beat water." *Fire Chief*. 01 JUL 2001: n. page. Web. 22 Feb. 2013. <http://firechief.com/suppression/foam/firefighting_bubbles_beat_water>.
- (Colletti, 1993) Colletti, Dominic. "Quantifying the Effects of Class A Foam in Structure Firefighting: The Salem Tests." *Fire Engineering*. 01 Feb 1993: 41-44. Print. <[http://www.cafs institute.org/pdf/Salem Tests.pdf](http://www.cafs institute.org/pdf/Salem_Tests.pdf)>.
- (Colletti, 2006) Colletti, Dominic. *The Compressed Air Foam Systems Handbook*. 1st. Royersford: Lyon's Publishing, 2006. 113-118. Print.
- (Darley, 1995) Darley, Paul. "The Use of Class "A" Foam and Compressed Air Foam Systems (CAFS) in Firefighting." *Foam Applications for Wildland & Urban Fire Management*. 7. Boise: 1995. 15-22. Print.
- (de Vries, 1998) de Vries, Holger. "CAFS goes to Germany." *Fire Chief*. 42.8 (1998): 116-121. Print.
- (de Vries, 1999) de Vries, Holger. "Foam follow function: The Tremonia and Wattenscheid trials." *Fire Chief*. 01 Aug 1999: 110-118. Print. <http://firechief.com/suppression/foam/firefighting_foam_follow_function>.
- (de Vries, 2007) de Vries, Holger. "Heat Stress." *Fire Chief*. 01 OCT 2007: 60-70. Print. <http://firechief.com/suppression/foam/firefighting_heat_stress>.
- (Duncan, 1994) Duncan, Samuel. "Evaluation of NDI Compressed Air Foam Systems (CAFS) Applied as a Retrofit." *Defense Technical Information Center*. U.S. Army Tank-Automotive Command, Development and Engineering Center, 28 Sep 1994. Web. 19 Feb 2013. <<http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA284942>>.
- (Fornell, 1991) Fornell, David. *Fire Stream Management Handbook*. 1st. Saddle Brook: Fire Engineering, 1991. 301-328. Print.
- (Kim and Crampton, 2009) Kim, Andrew, and George Crampton. "Evaluation of fire suppression effectiveness of manually applied compressed air-foam (CAF) system." *Foams*. Quincy: The Fire Protection Research Foundation, 2009. 1-3. Web. 15 Feb. 2013.

- <http://www.nfpa.org/assets/files//2009proceedings/Evaluation_of_the_Fire_Suppression_Effectiveness_of_Manually.pdf>.
- (LaPolla *et al.*, 2012) LaPolla, Justin, Alexander Morano and Vincent Luchsinger. "Compressed Air Foam Firegrounds Evolution Tests." Diss. California Polytechnic State University, 2012. Web. <<http://digitalcommons.calpoly.edu/mesp/110/>>.
- (Lohr, 2002) Lohr, Steven. "The Use of Compressed Air Foam to Enhance Fire Fighting Water Supplies in Montgomery County, MD." *United States Fire Administration*. National Fire Academy, 01 Jun 2002. Web. 23 Feb 2013. <<http://www.usfa.fema.gov/pdf/efop/efo34560.pdf>>.
- (Lyon, 2009) Lyon, Tracy. United States. Fire Administration. *Tactical Use of Compressed Air Foam*. Emmitsburg, 2009. Web. <<http://www.usfa.fema.gov/pdf/efop/efo43975.pdf>>.
- (Madrzykowski, 1988) Madrzykowski, Daniel. United States. Department of Commerce. *Study of the Ignition Inhibiting Properties of Compressed Air Foam*. Gaithersburg: National Institute of Standards and Technology, 1988. Web. <http://www.nist.gov/manuscript-publication-search.cfm?pub_id=910351>.
- (Marquardt, 2011) Marquardt, Mark. Grand Rapids, Michigan. Fire Department. *GRFD Live Burn Demonstration and Testing CAFS and PPA*. Grand Rapids: Strategic Planning Office, 2011. Web. <<ftp://ftp.grand-rapids.mi.us/>>.
- (McKenzie, 1992) McKenzie, Dan. United States. Department of Agriculture. *Compressed Air Foam Systems for Use in Wildland Fire Applications*. San Dimas: Technology and Development Center, 1992. Print.
- (Murdock, 1997) Murdock, Johnny I. Compressed Air Foam Systems: a Project Pertaining to an Adoption Decision. Emmitsburg, MD: National Fire Academy, 1997. Print.
- (National Fire Service Research Agenda Symposium, 2005) *Report of the National Fire Service Research Agenda Symposium*. Emmitsburg: National Fallen Firefighters Foundation, 2005. 33. Web. 8 May. 2013. <<http://www.everyonegoeshome.com/symposium/report.pdf>>.
- (National Wildfire Coordinating Group, 1993) United States. Forest Service. *Foam vs Fire - Class A Foam for Wildland Fires*. Boise: The National Wildfire Coordinating Group, 1993. Web. <http://www.fs.fed.us/t-d/php/library_card.php?p_num=9351_1208>.
- NFPA 1145, *Guide for the Use of Class A Foams in Manual Structural Fire Fighting* (National Fire Protection Association 2011)

- (Pabich and Carey, 1994) Pabich, Martin, and William Carey. "Class A Foam for Structural Fire Fighting - Room Burn Tests." *National Fire Protection Association*. National Fire Protection Research Foundation, n.d. Web. 12 Feb 2013. <http://www.nfpa.org/assets/files/PDF/Research/Class_A_Foam_for_Structural_Fire_Fighting.pdf>.
- (Routley, 1994) Routley, J. "Compressed Air Foam for Structural Fire Fighting: A Field Test." *United States Fire Administration*. United States Fire Administration, 01 Jan 1994. Web. 19 Feb 2013. <<http://www.usfa.fema.gov/downloads/pdf/publications/tr-074.pdf>>.
- (Steppan and Pabich, 2008) Steppan, Daniel, and Martin Pabich. "Performance of Special Extinguishment Agents for Firefighter Use." *Underwriters Laboratories*. Underwriters Laboratories, 30 Sep 2008. Web. 15 Feb 2013. <[http://www.ul.com/global/documents/offerings/industries/buildingmaterials/fireservice/extinguishingagents/DHS Grant Final Report - Project 07CA42526 - Performance of Special Extinguishment Agents for Fire Fighter Use - Sept. 30_2008.pdf](http://www.ul.com/global/documents/offerings/industries/buildingmaterials/fireservice/extinguishingagents/DHS_Grant_Final_Report_-_Project_07CA42526_-_Performance_of_Special_Extinguishment_Agents_for_Fire_Fighter_Use_-_Sept._30_2008.pdf)>.
- (Stern and Routley, 1996) Stern, Jeff, and J. Gordon Routley. United States. Fire Administration. *Class A Foam for Structural Firefighting*. Emmitsburg: U.S. Fire Administration, 1996. Web. <<http://www.usfa.fema.gov/downloads/pdf/publications/tr-083.pdf>>.
- (Taylor, 1997) Taylor, Robert. United States. Fire Administration. *Compressed Air Foam Systems in Limited Staffing Conditions*. Emmitsburg: U.S. Fire Administration, 1997. Web. <http://www.usfa.fema.gov/downloads/pdf/tr_98rt.pdf>.
- (Tinsley, 2002) Tinsley, Michael. United States. Fire Administration. *Compressed Air Foam Systems: Live Fire Application and Corresponding Temperature Degradation*. Emmitsburg: U.S. Fire Administration, 2002. Web. <<http://www.usfa.fema.gov/pdf/efop/efo33907.pdf>>.
- (Zhang *et al.*, 2011) Zhang, Jianping, Michael Delichatsios, and Alan O' Neill. "Assessment of gas cooling capabilities of compressed air foam systems in fuel and ventilation-controlled compartment fires." *Journal of Fire Sciences*. 29.6 (2011): 543–554. Web. 16 Feb. 2013. <<http://jfs.sagepub.com/content/29/6/543>>.

APPENDIX A – EXPERIMENTAL LISTING

Table A-1 Gas Cooling Experiment Listing

Test #	Date	Agent	Nozzle	Water Flow Rate (gpm)	Air Flow Rate (CFM)	Cooling Impact Position	Comments
1	09/25/12	Water	7/8 " Solid	120	0	mid	nozzle kicked left
2	09/25/12	Water	7/8 " Solid	120	0	mid	handheld
3	09/25/12	Water	7/8 " Solid	120	0	mid	
4	09/25/12	Water	7/8 " Solid	120	0	mid	
5	09/25/12	CAFS	7/8 " Solid	120	60	mid	fluctuation
6	09/25/12	CAFS	7/8 " Solid	120	60	mid	
7	09/25/12	CAFS	7/8 " Solid	120	60	mid	
8	09/25/12	Water	7/8 " Solid	120	0	mid	beginning with CAFS
9	09/25/12	Water	7/8 " Solid	120	0	mid	
10	09/25/12	CAFS	7/8 " Solid	120	60	mid	
11	09/25/12	CAFS	7/8 " Solid	120	60	mid	end 1st data file
12	09/25/12	CAFS	SS	120	60	full back	nozzle kicked left
13	09/25/12	CAFS	SS	120	60	full back	
14	09/25/12	CAFS	SS	115	60	full back	
15	09/25/12	Water	SS	120	0	mid	
16	09/25/12	Water	SS	120	0	mid	end 2nd data file
17	09/26/12	Water	7/8 " Solid	120	0	mid	
18	09/26/12	Water	7/8 " Solid	120	0	mid	
19	09/26/12	Water	7/8 " Solid	120	0	mid	
20	09/26/12	Water	SS	120	0	mid	
21	09/26/12	Water	SS	120	0	mid	
22	09/26/12	Water	SS	120	0	mid	
23	09/26/12	Water	30 Fog	120	0	mid	
24	09/26/12	Water	30 Fog	120	0	mid	
25	09/26/12	Water	30 Fog	120	0	mid	
26	09/26/12	Water	60 Fog	120	0	mid	
27	09/26/12	Water	60 Fog	120	0	mid	
28	09/26/12	Water	60 Fog	120	0	mid	
29	09/26/12	Water	SS	120	0	full back	
30	09/26/12	Water	SS	120	0	full back	
31	09/26/12	Water	SS	120	0	full back	
32	09/26/12	Water	30 Fog	120	0	full back	started on SS
33	09/26/12	Water	30 Fog	120	0	full back	
34	09/26/12	Water	30 Fog	120	0	full back	

35	09/26/12	Water	7/8 " Solid	120	0	full back	
36	09/26/12	Water	7/8 " Solid	120	0	full back	
37	09/26/12	Water	7/8 " Solid	120	0	full back	
38	09/26/12	Water	7/8 " Solid	180	0	full back	
39	09/26/12	Water	7/8 " Solid	180	0	full back	
40	09/26/12	Water	SS	150	0	mid	
41	09/26/12	Water	SS	150	0	mid	
42	09/26/12	Class A Foam	SS	150	0	mid	
43	09/26/12	Class A Foam	SS	150	0	mid	
44	09/26/12	CAFS	SS	120	60	mid	80 gpm?
45	09/26/12	CAFS	SS	120	60	mid	
46	09/26/12	CAFS	SS	120	60	mid	
47	09/26/12	CAFS	SS	120	60	mid	
48	09/26/12	CAFS	SS	120	60	mid	
49	09/26/12	CAFS	SS	120	60	mid	
50	09/26/12	CAFS	SS	120	60	mid	
51	09/26/12	CAFS	SS	120	60	mid	
52	09/26/13	CAFS	7/8 " Solid	120	60	mid	
53	09/26/13	CAFS	7/8 " Solid	120	60	mid	
54	09/26/13	CAFS	7/8 " Solid	120	60	mid	
55	09/26/13	CAFS	7/8 " Solid	120	60	mid	
56	09/26/13	CAFS	7/8 " Solid	120	60	mid	
57	09/26/12	CAFS	30 Fog	110	80	hand held	
58	09/26/12	CAFS	30 Fog	110	80	hand held	
59	09/26/12	CAFS	30 Fog	110	80	hand held	
60	09/26/12	Water	30 Fog	115	0	hand held	
61	09/26/12	Water	30 Fog	115	0	hand held	
62	09/26/12	Water	7/8 " Solid	120	0	hand held	
63	09/26/12	Water	30 Fog	120	0	hand held	
64	09/27/12	Class A Foam	7/8 " Solid	120	0	mid	
65	09/27/12	Class A Foam	7/8 " Solid	120	0	mid	end of data file
66	09/27/12	Class A Foam	7/8 " Solid	120	0	mid	
67	09/27/12	Class A Foam	SS	120	0	mid	
68	09/27/12	Class A Foam	SS	120	0	mid	
69	09/27/12	Class A Foam	SS	120	0	mid	
70	09/27/12	Class A Foam	SS	120	0	mid	
71	09/27/12	Class A	30 Fog	120	0	mid	

		Foam					
72	09/27/12	Class A Foam	30 Fog	120	0	mid	
73	09/27/12	Class A Foam	30 Fog	120	0	mid	
74	09/27/12	Class A Foam	30 Fog	120	0	mid	
75	09/27/12	Class A Foam	30 Fog	120	0	mid	
76	09/27/12	CAFS	1 3/8" Solid	120	60	mid	
77	09/27/12	CAFS	1 3/8" Solid	120	60	mid	
78	09/27/12	CAFS	1 3/8" Solid	120	60	mid	
79	09/27/12	CAFS	1 3/8" Solid	120	60	full back	
80	09/27/12	CAFS	1 3/8" Solid	120	60	full back	
81	09/27/12	CAFS	1 3/8" Solid	120	60	full back	
82	09/27/12	CAFS	1 3/8" Solid	120	60	full back	
83	09/27/12	Water	7/8 " Solid	120	0	mid	
84	09/27/12	Water	7/8 " Solid	120	0	mid	
85	09/27/12	Water	7/8 " Solid	120	0	mid	
86	09/27/12	Water	7/8 " Solid	120	0	full back	
87	09/27/12	Water	7/8 " Solid	120	0	full back	
88	09/27/12	Water	7/8 " Solid	120	0	full back	

APPENDIX B – TEMPERATURE GRAPHS

Figure B-1 Thermocouple Array 1, 25th Sept. 2012, Series 1 (Tests 1-11)

Figure B-2 Thermocouple Array 2, 25th Sept. 2012, Series 1 (Tests 1-11)

Figure B-3 Thermocouple Array 3, 25th Sept. 2012, Series 1 (Tests 1-11)

Figure B-4 Thermocouple Array 5, 25th Sept. 2012, Series 1 (Tests 1-11)

Figure B-5 Thermocouple Array 1, 25th Sept. 2012, Series 2 (Tests 12-16)

Figure B-6 Thermocouple Array 2, 25th Sept. 2012, Series 2 (Tests 12-16)

Figure B-7 Thermocouple Array 3, 25th Sept. 2012, Series 2 (Tests 12-16)

Figure B-8 Thermocouple Array 5, 25th Sept. 2012, Series 2 (Tests 12-16)

Figure B-9 Thermocouple Array 1, 26th Sept. 2012, Series 1 (Tests 17-32)

Figure B-10 Thermocouple Array 2, 26th Sept. 2012, Series 1 (Tests 17-32)

Figure B-11 Thermocouple Array 3, 26th Sept. 2012, Series 1 (Tests 17-32)

Figure B-12 Thermocouple Array 5, 26th Sept. 2012, Series 1 (Tests 17-32)

Figure B-13 Thermocouple Array 1, 26th Sept. 2012, Series 2 (Tests 33-56)

Figure B-14 Thermocouple Array 2, 26th Sept. 2012, Series 2 (Tests 33-56)

Figure B-15 Thermocouple Array 3, 26th Sept. 2012, Series 2 (Tests 33-56)

Figure B-16 Thermocouple Array 5, 26th Sept. 2012, Series 2 (Tests 33-56)

Figure B-17 Thermocouple Array 1, 26th Sept. 2012, Series 3 (Tests 57-63)

Figure B-18 Thermocouple Array 2, 26th Sept. 2012, Series 3 (Tests 57-63)

Figure B-19 Thermocouple Array 3, 26th Sept. 2012, Series 3 (Tests 57-63)

Figure B-20 Thermocouple Array 5, 26th Sept. 2012, Series 3 (Tests 57-63)

Figure B-21 Thermocouple Array 1, 27th Sept. 2012, Series 1 (Tests 64-65)

Figure B-22 Thermocouple Array 2, 27th Sept. 2012, Series 1 (Tests 64-65)

Figure B-23 Thermocouple Array 3, 27th Sept. 2012, Series 1 (Tests 64-65)

Figure B-24 Thermocouple Array 5, 27th Sept. 2012, Series 1 (Tests 64-65)

Figure B-25 Thermocouple Array 1, 27th Sept. 2012, Series 2 (Tests 66-75)

Figure B-26 Thermocouple Array 2, 27th Sept. 2012, Series 2 (Tests 66-75)

Figure B-27 Thermocouple Array 3, 27th Sept. 2012, Series 2 (Tests 66-75)

Figure B-28 Thermocouple Array 5, 27th Sept. 2012, Series 2 (Tests 66-75)

Figure B-29 Thermocouple Array 1, 27th Sept. 2012, Series 3 (Tests 76-88)

Figure B-30 Thermocouple Array 2, 27th Sept. 2012, Series 3 (Tests 76-88)

Figure B-31 Thermocouple Array 3, 27th Sept. 2012, Series 3 (Tests 76-88)

Figure B-32 Thermocouple Array 5, 27th Sept. 2012, Series 3 (Tests 76-88)

APPENDIX C – TEMPERATURE DROPS

Table C-1 Color Code

H2O	
Aspirated Foam	
CAFS	

Table C-2 Temperature Drops 1-ft Below Ceiling

Test No.	Temp Drop (inches)			Temp Drop (C)			
	TC1	TC2	TC3	TC1	TC2	TC3	AVG
Scale (deg/in)	70.7	70.7	70.7				
1	3.157	0.980	0.837	223	69	59	117
2	0.987	4.133	1.160	70	292	82	148
3	0.723	3.407	0.830	51	241	59	117
4	0.630	4.350	0.823	45	308	58	137
5	1.070	3.733	1.000	76	264	71	137
6	0.947	3.963	0.940	67	280	66	138
7	0.803	1.873	0.900	57	132	64	84
8	0.747	4.223	0.920	53	299	65	139
9	0.780	4.507	0.973	55	319	69	148
10	1.200	4.430	1.303	85	313	92	163
11	1.167	3.843	1.257	83	272	89	148
Scale (deg/in)	70.7	70.7	70.7				
12							
13	0.963	1.033	1.290	68	73	91	77
14	1.380	1.150	1.020	98	81	72	84
15	1.167	1.080	1.343	83	76	95	85
16	0.880	1.220	1.177	62	86	83	77
Scale (deg/in)	79.7	79.5	70.7				
17	0.770	3.740	0.963	61	297	68	142
18	0.707	3.747	1.057	56	298	75	143
19	0.730	3.387	1.153	58	269	82	136
20	0.397	1.583	0.640	32	126	45	68
21	0.430	1.433	0.613	34	114	43	64
22	0.450	1.600	0.620	36	127	44	69
23	1.123	1.237	1.280	90	98	91	93
24	1.077	0.993	1.127	86	79	80	82
25	0.940	1.277	1.423	75	102	101	92
26	1.163	0.983	1.350	93	78	95	89
27	0.923	0.840	1.090	74	67	77	72
28	1.040	1.057	1.257	83	84	89	85
29	0.607	0.680	1.387	48	54	98	67
30	0.617	0.960	0.927	49	76	66	64
31	0.567	0.973	0.640	45	77	45	56
32	1.033	1.233	1.043	82	98	74	85

Scale (deg/in)	79.5	79.6	79.6				
33	0.860	1.033	0.930	68	82	74	75
34	1.127	1.183	0.967	90	94	77	87
35	0.750	3.920	0.890	60	312	71	147
36	0.670	3.750	1.003	53	298	80	144
37	1.097	3.493	1.250	87	278	99	155
38	1.507	4.157	1.197	120	331	95	182
39	1.490	4.150	1.180	119	330	94	181
40	0.470	1.163	0.623	37	93	50	60
41	0.777	2.713	0.887	62	216	71	116
42	0.573	1.563	0.700	46	124	56	75
43	0.363	1.653	0.680	29	132	54	72
44	0.610	2.097	0.843	49	167	67	94
45	1.010	4.300	1.223	80	342	97	173
46	0.867	2.520	0.880	69	201	70	113
47	0.897	3.337	0.837	71	266	67	134
48	0.527	2.003	0.583	42	159	46	83
49	1.450	1.987	1.557	115	158	124	132
50	1.503	1.990	1.417	120	158	113	130
51	1.663	2.490	1.853	132	198	147	159
52	0.917	1.880	0.940	73	150	75	99
53	0.670	1.953	0.857	53	155	68	92
54	0.697	1.730	0.833	55	138	66	86
55	0.737	2.153	0.760	59	171	60	97
56	1.400	4.313	2.200	111	343	175	210
Scale (deg/in)	79.7	79.7	79.7				
57	1.663	1.747	1.293	133	139	103	125
58	2.220	2.447	1.643	177	195	131	168
59	2.083	1.893	1.207	166	151	96	138
60	1.237	1.400	1.153	99	112	92	101
61	0.867	1.157	1.103	69	92	88	83
62	1.483	4.450	1.463	118	355	117	196
63	2.333	2.390	2.440	186	190	194	190
Scale (deg/in)	70.8	70.9	62.0				
64	0.487	2.753	0.830	34	195	51	94
65	0.657	4.050	1.020	47	287	63	132
Scale (deg/in)	70.7	70.7	70.7				
66	0.650	4.303	1.033	46	304	73	141
67	0.357	4.253	0.413	25	301	29	118
68	0.177	4.450	0.377	13	315	27	118
69	0.340	3.983	0.373	24	282	26	111
70	0.320	4.577	0.450	23	324	32	126
71	1.400	1.943	0.857	99	137	61	99
72	1.177	1.700	1.047	83	120	74	93
73	1.747	2.310	1.487	124	163	105	131
74	0.380	4.610	0.560	27	326	40	131
75	0.427	4.683	0.627	30	331	44	135
Scale (deg/in)	79.7	79.7	70.7				

76	1.120	1.900	1.040	89	152	74	105
77	0.573	1.810	0.797	46	144	56	82
78	0.967	1.990	0.903	77	159	64	100
79	0.973	2.043	1.310	78	163	93	111
80	1.190	1.690	1.270	95	135	90	106
81	1.207	1.713	1.430	96	137	101	111
82	1.257	1.690	1.360	100	135	96	110
83	0.497	1.547	0.780	40	123	55	73
84	0.763	2.050	1.030	61	163	73	99
85	0.613	1.607	0.700	49	128	50	76
86	0.980	1.380	1.070	78	110	76	88
87	0.877	1.290	1.207	70	103	85	86
88	1.027	1.357	1.370	82	108	97	96

Table C-3 Temperature Drops 2-ft Below Ceiling

Test No.	Temp Drop (inches)			Temp Drop (C)			
	TC1	TC2	TC3	TC1	TC2	TC3	AVG
Scale (deg/in)	70.7	70.7	70.7				
1	2.823	1.020	0.863	200	72	61	111
2	0.960	3.923	1.173	68	277	83	143
3	0.790	3.277	0.840	56	232	59	116
4	0.770	4.077	0.883	54	288	62	135
5	0.990	1.557	0.977	70	110	69	83
6	0.860	1.597	0.953	61	113	67	80
7	0.650	1.287	0.877	46	91	62	66
8	0.897	4.090	0.917	63	289	65	139
9	0.993	4.297	0.967	70	304	68	148
10	1.060	2.013	1.313	75	142	93	103
11	1.027	1.687	1.230	73	119	87	93
Scale (deg/in)	70.7	70.7	70.7				
12							
13	1.013	1.100	1.063	72	78	75	75
14	1.673	1.197	1.040	118	85	74	92
15	1.550	1.160	1.207	110	82	85	92
16	1.347	1.547	1.130	95	109	80	95
Scale (deg/in)	79.7	79.5	70.7				
17	0.963	3.523	1.020	77	280	72	143
18	1.033	3.480	1.067	82	277	75	145
19	2.773	3.267	1.130	221	260	80	187
20	0.437	3.700	0.583	35	294	41	123
21	0.487	3.800	0.593	39	302	42	128
22	0.430	3.743	0.627	34	298	44	125
23	1.147	1.313	1.167	91	104	83	93
24	1.130	1.167	1.040	90	93	74	85
25	1.013	1.407	1.343	81	112	95	96
26	1.420	1.060	1.293	113	84	91	96
27	1.187	0.857	1.063	95	68	75	79

28	1.207	1.127	1.200	96	90	85	90
29	0.673	0.693	1.650	54	55	117	75
30	0.773	1.030	0.937	62	82	66	70
31	0.690	0.950	0.690	55	76	49	60
32	1.090	1.467	0.920	87	117	65	90
Scale (deg/in)	79.5	79.6	79.6				
33	0.923	1.237	0.930	73	98	74	82
34	1.080	1.357	0.943	86	108	75	90
35	1.000	3.737	0.943	80	297	75	151
36	0.903	3.790	1.030	72	302	82	152
37	1.270	3.980	1.220	101	317	97	172
38	1.387	3.873	1.187	110	308	94	171
39	1.420	3.813	1.217	113	303	97	171
40	0.643	3.893	0.613	51	310	49	137
41	0.953	3.767	1.007	76	300	80	152
42	0.713	3.633	0.693	57	289	55	134
43	0.560	4.147	0.727	45	330	58	144
44	0.620	1.343	0.800	49	107	64	73
45	1.057	1.970	1.193	84	157	95	112
46	0.970	1.780	0.900	77	142	72	97
47	0.823	1.663	0.843	65	132	67	88
48	0.520	1.137	0.577	41	90	46	59
49	1.387	2.103	1.330	110	167	106	128
50	1.430	2.020	1.210	114	161	96	124
51	1.630	2.593	1.593	130	206	127	154
52	0.920	1.377	0.917	73	110	73	85
53	0.620	1.367	0.857	49	109	68	75
54	0.730	1.180	0.773	58	94	62	71
55	0.727	1.300	0.770	58	103	61	74
56	1.407	2.493	2.180	112	198	173	161
Scale (deg/in)	79.7	79.7	79.7				
57	1.620	1.847	1.243	129	147	99	125
58	2.303	2.363	1.643	184	188	131	168
59	1.743	1.987	1.190	139	158	95	131
60	1.260	1.393	1.140	100	111	91	101
61	0.993	1.227	1.103	79	98	88	88
62	1.757	4.113	1.510	140	328	120	196
63	3.703	2.513	2.303	295	200	184	226
Scale (deg/in)	70.8	70.9	62.0				
64	0.610	3.243	0.830	43	230	51	108
65	0.913	3.610	0.870	65	256	54	125
Scale (deg/in)	70.7	70.7	70.7				
66	0.983	4.207	1.043	70	298	74	147
67	0.363	3.767	0.403	26	266	29	107
68	0.207	3.380	0.357	15	239	25	93
69	0.347	3.793	0.357	25	268	25	106
70	0.353	2.900	0.407	25	205	29	86
71	1.463	1.977	0.847	103	140	60	101

72	1.157	1.757	1.023	82	124	72	93
73	1.843	2.547	1.400	130	180	99	136
74	0.397	4.270	0.550	28	302	39	123
75	0.510	4.223	0.617	36	299	44	126
Scale (deg/in)	79.7	79.7	70.7				
76	0.963	1.593	1.050	77	127	74	93
77	0.553	1.130	0.780	44	90	55	63
78	0.947	1.450	0.910	76	116	64	85
79	1.087	1.993	1.293	87	159	91	112
80	1.210	1.893	1.270	96	151	90	112
81	1.173	3.200	1.370	94	255	97	149
82	1.120	2.067	1.327	89	165	94	116
83	0.600	3.730	0.807	48	297	57	134
84	1.053	4.077	1.070	84	325	76	162
85	0.657	2.713	0.730	52	216	52	107
86	1.100	1.673	1.110	88	133	79	100
87	1.233	1.677	1.240	98	134	88	107
88	1.253	1.960	1.410	100	156	100	119

Table C-4 Temperature Drops 6-ft Below Ceiling / 2-ft Below Soffit

Test No.	Temp Drop (inches)				Temp Drop (C)				
	TC1	TC2	TC3	TC5	TC1	TC2	TC3	TC5	AVG
Scale (deg/in)	70.7	70.7	70.7	44.2					
1	1.960	0.983	0.820	0.753	139	70	58	33	75
2	0.830	3.547	1.037	1.187	59	251	73	53	109
3	1.267	2.923	0.827	0.770	90	207	58	34	97
4	0.860	2.490	0.943	1.203	61	176	67	53	89
5	0.710	1.740	0.910	1.093	50	123	64	48	71
6	0.683	1.773	0.940	1.007	48	125	66	45	71
7	0.603	1.653	0.830	0.950	43	117	59	42	65
8	0.900	2.043	0.833	1.360	64	144	59	60	82
9	1.180	3.587	1.030	1.477	83	254	73	65	119
10	0.823	2.130	1.203	1.350	58	151	85	60	88
11	0.877	1.953	1.070	1.123	62	138	76	50	81
Scale (deg/in)	70.7	70.7	70.7	53.2					
12									
13	0.707	1.227	0.927	0.807	50	87	66	43	61
14	2.740	1.287	1.103	1.167	194	91	78	62	106
15	1.163	1.253	1.117	1.697	82	89	79	90	85
16	1.423	2.250	0.983	1.053	101	159	70	56	96
Scale (deg/in)	79.7	79.5	70.7	53.0					
17	0.927	3.127	1.027	1.320	74	249	73	70	116
18	0.870	3.043	0.950	0.967	69	242	67	51	107
19	1.580	2.900	0.970	0.823	126	231	69	44	117
20	0.693	2.970	0.687	0.907	55	236	49	48	97
21	0.830	1.883	0.780	0.753	66	150	55	40	78
22	0.677	3.077	0.793	0.813	54	245	56	43	99

23	0.913	2.960	1.077	1.047	73	235	76	56	110
24	0.963	1.603	0.987	0.877	77	127	70	47	80
25	1.043	2.530	1.170	1.113	83	201	83	59	107
26	1.347	1.290	1.157	2.250	107	103	82	119	103
27	0.967	0.963	1.013	0.997	77	77	72	53	70
28	2.137	1.180	1.050	0.970	170	94	74	51	97
29	0.817	1.187	0.963	0.983	65	94	68	52	70
30	0.960	1.870	0.830	1.360	77	149	59	72	89
31	0.710	2.807	1.087	0.727	57	223	77	39	99
32	0.833	3.430	0.920	1.100	66	273	65	58	116
Scale (deg/in)	79.5	79.6	79.6	53.2					
33	0.900	1.580	0.880	0.803	72	126	70	43	78
34	0.920	1.787	0.833	0.903	73	142	66	48	82
35	0.987	3.047	0.933	1.070	78	242	74	57	113
36	0.960	2.970	0.957	1.027	76	236	76	55	111
37	1.090	3.367	1.023	1.283	87	268	81	68	126
38	1.187	3.353	1.107	0.940	94	267	88	50	125
39	1.063	3.110	1.163	1.157	85	247	93	62	122
40	0.773	2.517	0.697	0.757	61	200	55	40	89
41	0.863	3.093	0.847	0.953	69	246	67	51	108
42	0.667	1.290	0.530	0.690	53	103	42	37	59
43	0.827	1.423	0.713	0.780	66	113	57	41	69
44	0.600	1.360	0.757	0.870	48	108	60	46	66
45	0.827	1.823	0.980	0.973	66	145	78	52	85
46	0.627	1.433	0.770	0.850	50	114	61	45	68
47	0.843	1.537	0.830	0.677	67	122	66	36	73
48	0.443	1.057	0.613	0.440	35	84	49	23	48
49	0.913	1.530	1.073	3.160	73	122	85	168	112
50	0.850	1.707	0.983	2.523	68	136	78	134	104
51	0.740	1.980	1.233	2.287	59	158	98	122	109
52	0.687	1.713	0.990	0.680	55	136	79	36	76
53	0.657	1.660	0.850	0.907	52	132	68	48	75
54	0.740	1.450	0.947	0.840	59	115	75	45	74
55	0.687	1.533	0.853	0.573	55	122	68	30	69
56	1.307	3.483	1.760	2.443	104	277	140	130	163
Scale (deg/in)	79.7	79.7	79.7	21.3					
57	1.167	1.787	1.107	0.977	93	142	88	21	86
58	1.603	2.127	1.520	0.863	128	170	121	18	109
59	1.013	1.740	1.143	0.300	81	139	91	6	79
60	2.673	1.413	1.117	0.630	213	113	89	13	107
61	2.567	1.440	1.063	0.413	205	115	85	9	103
62	2.007	3.433	1.760	0.170	160	274	140	4	144
63	2.610	3.260	2.057	0.260	208	260	164	6	159
Scale (deg/in)	70.8	70.9	62.0	35.5					
64	0.913	1.597	0.853	0.680	65	113	53	24	64
65	0.917	3.053	1.037	0.637	65	216	64	23	92
Scale (deg/in)	70.7	70.7	70.7	31.9					
66	1.117	2.167	1.013	0.823	79	153	72	26	83

67	0.590	1.447	0.763	0.567	42	102	54	18	54
68	0.560	1.413	0.680	0.670	40	100	48	21	52
69	0.627	2.030	0.727	0.730	44	144	51	23	66
70	0.647	1.577	0.767	0.750	46	112	54	24	59
71	1.417	3.537	1.057	3.227	100	250	75	103	132
72	0.983	2.783	0.917	1.923	70	197	65	61	98
73	1.423	3.203	1.290	1.480	101	227	91	47	116
74	0.567	1.373	0.793	0.283	40	97	56	9	51
75	0.677	3.153	0.847	0.537	48	223	60	17	87
Scale (deg/in)	79.7	79.7	70.7	44.2					
76	1.007	1.573	0.967	0.783	80	125	68	35	77
77	0.757	1.390	0.860	0.520	60	111	61	23	64
78	0.793	1.590	0.933	0.477	63	127	66	21	69
79	0.927	1.563	1.127	0.940	74	125	80	42	80
80	0.957	1.607	1.107	0.590	76	128	78	26	77
81	0.933	2.723	1.147	1.120	74	217	81	50	106
82	0.740	1.620	1.090	1.050	59	129	77	46	78
83	0.850	3.023	0.890	0.400	68	241	63	18	97
84	1.113	3.367	1.177	0.983	89	269	83	43	121
85	0.737	0.323	0.820	0.897	59	26	58	40	46
86	1.137	2.977	1.017	1.337	91	237	72	59	115
87	2.227	3.153	1.130	1.183	178	251	80	52	140
88	2.400	3.230	1.187	1.203	191	258	84	53	147

Table C-5 Temperature Drops 9-ft Below Ceiling / 5-ft Below Soffit

Test No.	Temp Drop (inches)				Temp Drop (C)				
	TC1	TC2	TC3	TC5	TC1	TC2	TC3	TC5	AVG
Scale (deg/in)	70.7	70.7	70.7	44.2					
1	0.313	0.323	0.150	0.180	22	23	11	8	16
2	0.373	0.263	0.507	0.350	26	19	36	15	24
3	0.220	0.210	0.237	0.100	16	15	17	4	13
4	0.270	0.223	0.173	0.230	19	16	12	10	14
5	0.237	0.167	0.467	0.167	17	12	33	7	17
6	0.333	0.280	0.047	0.147	24	20	3	7	13
7	0.300	0.287	0.333	0.127	21	20	24	6	18
8	0.330	0.290	0.230	0.220	23	21	16	10	17
9	0.330	0.297	0.040	0.123	23	21	3	5	13
10	0.290	0.237	0.353	0.480	21	17	25	21	21
11	0.310	0.200	0.343	0.287	22	14	24	13	18
Scale (deg/in)	70.7	70.7	70.7	53.2					
12									
13	0.220	0.190	0.230	0.137	16	13	16	7	13
14	0.203	0.113	0.063	0.160	14	8	4	9	9
15	0.303	0.257	0.247	0.367	21	18	17	20	19
16	0.283	0.267	0.053	0.137	20	19	4	7	12
Scale (deg/in)	79.7	79.5	70.7	53.0					
17	0.253	0.270	0.013	0.157	20	21	1	8	13

18	0.270	0.273	0.110	0.173	22	22	8	9	15
19	0.287	0.243	0.127	0.107	23	19	9	6	14
20	0.270	0.240	0.183	0.107	22	19	13	6	15
21	0.193	0.257	0.110	0.113	15	20	8	6	12
22	0.240	0.233	0.050	0.080	19	19	4	4	11
23	0.320	0.203	0.213	0.273	26	16	15	14	18
24	0.260	0.193	0.100	0.177	21	15	7	9	13
25	0.280	0.193	0.187	0.173	22	15	13	9	15
26	0.250	0.213	0.063	0.203	20	17	4	11	13
27	0.183	0.177	0.083	0.187	15	14	6	10	11
28	0.227	0.197	0.453	0.237	18	16	32	13	20
29	0.257	0.213	0.290	0.137	20	17	21	7	16
30	0.363	0.237	0.227	0.133	29	19	16	7	18
31	0.223	0.250	0.240	0.090	18	20	17	5	15
32	0.200	0.210	0.073	0.090	16	17	5	5	11
Scale (deg/in)	79.5	79.6	79.6	53.2					
33	0.387	0.273	0.137	0.160	31	22	11	9	18
34	0.403	0.177	0.190	0.127	32	14	15	7	17
35	0.277	0.190	0.077	0.097	22	15	6	5	12
36	0.350	0.390	0.143	0.190	28	31	11	10	20
37	0.287	0.147	0.037	0.160	23	12	3	9	11
38	0.260	0.160	0.167	0.153	21	13	13	8	14
39	0.297	0.160	0.063	0.100	24	13	5	5	12
40	0.230	0.227	0.013	0.090	18	18	1	5	11
41	0.300	0.187	0.100	0.177	24	15	8	9	14
42	0.260	0.160	0.147	0.040	21	13	12	2	12
43	0.240	0.167	0.030	0.060	19	13	2	3	9
44	0.260	0.177	0.233	0.093	21	14	19	5	15
45	0.487	0.150	0.263	0.037	39	12	21	2	18
46	0.427	0.167	0.187	0.070	34	13	15	4	16
47	0.340	0.267	0.050	0.033	27	21	4	2	14
48	0.223	0.187	0.097	0.083	18	15	8	4	11
49	0.347	0.227	0.317	0.300	28	18	25	16	22
50	0.243	0.140	0.153	0.277	19	11	12	15	14
51	0.190	0.153	0.240	0.260	15	12	19	14	15
52	0.183	0.177	0.113	0.077	15	14	9	4	10
53	0.347	0.293	0.127	0.120	28	23	10	6	17
54	0.140	0.197	0.070	0.090	11	16	6	5	9
55	0.240	0.147	0.137	0.117	19	12	11	6	12
56	0.430	0.130	0.533	0.210	34	10	42	11	25
Scale (deg/in)	79.7	79.7	79.7	21.3					
57	0.583	0.210	0.080	1.003	46	17	6	21	23
58	0.227	0.177	0.427	0.963	18	14	34	20	22
59	0.420	0.183	0.060	0.227	33	15	5	5	14
60	0.247	0.150	0.183	0.270	20	12	15	6	13
61	0.367	0.170	0.213	0.323	29	14	17	7	17
62	0.340	0.133	0.117	0.163	27	11	9	3	13
63	0.237	0.157	0.340	0.260	19	13	27	6	16

Scale (deg/in)	70.8	70.9	62.0	35.5					
64	0.320	0.270	0.253	0.057	23	19	16	2	15
65	0.300	0.207	0.263	0.020	21	15	16	1	13
Scale (deg/in)	70.7	70.7	70.7	31.9					
66	0.377	0.313	0.190	0.053	27	22	13	2	16
67	0.060	0.223	0.167	0.020	4	16	12	1	8
68	0.027	0.233	0.083	0.043	2	16	6	1	6
69	0.067	0.227	0.107	0.043	5	16	8	1	7
70	0.017	0.207	0.160	0.053	1	15	11	2	7
71	0.247	0.183	0.147	0.217	17	13	10	7	12
72	0.220	0.220	0.187	0.083	16	16	13	3	12
73	0.250	0.250	0.163	0.273	18	18	12	9	14
74	0.323	0.237	0.133	0.053	23	17	9	2	13
75	0.287	0.143	0.093	0.043	20	10	7	1	10
Scale (deg/in)	79.7	79.7	70.7	44.2					
76	0.293	0.213	0.217	0.163	23	17	15	7	16
77	0.137	0.187	0.247	0.050	11	15	17	2	11
78	0.297	0.137	0.240	0.073	24	11	17	3	14
79	0.510	0.240	0.197	0.197	41	19	14	9	21
80	0.470	0.220	0.133	0.170	37	18	9	8	18
81	0.350	0.223	0.103	0.203	28	18	7	9	15
82	0.357	0.187	0.307	0.060	28	15	22	3	17
83	0.190	0.187	0.077	0.163	15	15	5	7	11
84	0.337	0.143	0.040	0.087	27	11	3	4	11
85	0.267	0.160	0.023	0.113	21	13	2	5	10
86	0.313	0.203	0.183	0.163	25	16	13	7	15
87	0.327	0.190	0.180	0.117	26	15	13	5	15
88	0.297	0.190	0.247	0.120	24	15	17	5	15