Evaluation of Water Additives for Fire Control and Vapor Mitigation

Phase I
Final Report

Prepared by:

Joseph L. Scheffey
Eric W. Forssell
Jarrod T. Childs

Hughes Associates, Inc.
Baltimore, MD 21227

THE FIRE PROTECTION RESEARCH FOUNDATION

FIRE RESEARCH

THE FIRE PROTECTION RESEARCH FOUNDATION
ONE BATTERYMARCH PARK
QUINCY, MASSACHUSETTS, U.S.A. 02169-7471
E-MAIL: Foundation@NFPA.org
WEB: www.nfpa.org/Foundation

(This page left intentionally blank)

FOREWORD

Various water additives are available in today's marketplace that claim to provide advantageous performance characteristics for fire control and vapor mitigation. Of particular interest are additives that report to provide superior fire suppression capabilities through emulsification or encapsulation. However, a scientific assessment of these various additives is lacking, and the fire protection community would benefit from an evaluation of the various available water additives for fire control and vapor mitigation.

The goal of this project is to provide a comprehensive evaluation of water additives used for fire control and vapor mitigation, with the intent to clarify the fire protection benefit of using water with additives for fire suppression versus water without additives. The project objectives to achieve this goal include providing a comprehensive review of the literature, identification of key performance characteristics, review of candidate test agents, and formulation of a detailed test plan that would be implemented in a potential second phase (not included in the scope of this effort).

The Research Foundation expresses gratitude to the report authors Joseph L. Scheffey, Eric W. Forssell, and Jarrod T. Childs, all with Hughes Associates, Inc. Appreciation for their on-going guidance is expressed to the Project Technical Panelists and all others who contributed to this research effort. Special thanks are expressed to the following project sponsors for providing the funding for this project: AEGIS Insurance Services Inc; AES Global Insurance Company; Global Risk Consultants; Hazard Control Technologies Inc; MX Fire Solutions Inc; PPL Generation LLC; PRB Coal Users Group; and Xcel Energy Inc.

The content, opinions and conclusions contained in this report are solely those of the author.

(This page left intentionally blank)

PROJECT TECHNICAL PANEL

Mark Boone, Dominion Resources Services Inc (VA)

Jeff Harrington, Harrington Group Inc (GA)

Dave Snell, Luminant Power & NFPA 850 Chair (TX)

Blake Shugarman, UL (IL)

Sandra Stanek, NFPA 18A Staff Liaison (MA)

Benjamin Truchot, INERIS (France)

PROJECT SPONSOR REPRESENTATIVES

Jim Biggins, Global Risk Consultants (IL)

Tracy Browder, Xcel Energy Inc (CO)

Brian Crain, MX Fire Solutions Inc (CO)

Brian Foster, AEGIS Insurance Services Inc (NC)

Michael Greiner, Hazard Control Technologies Inc (GA)

David Miller, Alternate for AEGIS Insurance Services Inc (NJ)

John Reiter, AES Global Insurance Company (VA)

Thomas Roche, Xcel Energy Inc (CO)

Rick Schartel, PPL Generation LLC (PA)

Robert Taylor, PRB Coal Users' Group (IN)

(This page left intentionally blank)

HAI Project #1JLS00032.000

Evaluation of Water Additives for Fire Control and Vapor Mitigation

Prepared for:
The Fire Protection Research Foundation
One Battery Park Plaza
Quincy, MA 02169

Prepared by:

Joseph L. Scheffey
Eric W. Forssell
Jarrod T. Childs
Hughes Associates, Inc.
3610 Commerce Drive, Suite 817
Baltimore, MD 21227
Ph. 410-737-8677 FAX 410-737-8688
www.haifire.com

May16, 2013

CONTENTS

EVALUATION OF WATER ADDITIVES
FOR FIRE CONTROL AND VAPOR MITIGATION

1.0 BACKGROUND

Various water additives are available in today's marketplace that claim to provide advantageous performance characteristics for fire control and vapor mitigation. Of particular interest are additives that report to provide superior fire suppression capabilities through emulsification or encapsulation. However, a scientific assessment of these various additives is lacking, and the fire protection community would benefit from an evaluation of the various available water additives for fire control and vapor mitigation.

2.0 OBJECTIVES

The goal of this project is to provide a comprehensive evaluation of water additives used for fire control and vapor mitigation, with the intent to clarify the fire protection benefit of using water with additives for fire suppression versus water without additives.

3.0 APPROACH

To achieve the stated objective, a comprehensive review of the literature review was performed. The requirements of the two existing NFPA standards related to water additives was included in this review. Commercial products were identified, along with associated assertions of the agent performance and mechanisms used to achieve the performance. The identification of commercially available products might also be used to select representative agents for further testing. Based on this information, key performance characteristics were identified. These parameters were used to formulate proposed test approaches, from which a detailed test plan will be developed. Tests would be performed in a potential second phase of the project.

This project is focused in the fire performance characteristics of water additives. Other parameters that might be included in a performance or material specification, such as physical properties, compatibility of materials, proportioning, environmental impact, and quality assurance, are not considered.

The project technical panel guiding the project emphasized Class B fire suppression, and suppression of deep-seated Class A fires such as burning coal in storage or on conveyor belts. Other Class A scenarios were not emphasized, but they were hard to avoid in the assessment since many agents purport to have superior Class A fire suppression performance compared to water alone. Compressed air foam systems (CAFS) are an example of this. "Sticky" water, which might be applied to combustible horizontal barriers as a thermal radiation barrier, and hypergolic fuel vapor suppressants, were identified but not emphasized.

4.0 HISTORY AND DEFINITIONS

A project directive was to "provide baseline definitions of water additives whose performance is based on the fire control concepts of emulsification and encapsulation, and utilize these definitions to clarify the additives included within the scope of this study." Since this study was initiated, at least in part, due to interest from the NFPA Technical Committee on Water

Additives for Fire Control and Vapor Mitigation, it is useful to start with a review and history of the applicable NFPA standards:

- NFPA 18A – S*tandard on Water Additives for Fire Control and Vapor Mitigation,* 2011 Edition; and,

- NFPA 18 – *Standard on Wetting Agents*, 2011 Edition.

Since NFPA 18 was the precursor to NFPA 18A, it is appropriate to start with its history, documented in the "Origin and Development" section of the Standard. This standard was originally sponsored by the NFPA General Committee on Special Extinguishing Methods and prepared by the NFPA Committee on Wetting Agents. Initiated and tentatively adopted in 1949, it was officially adopted in 1951. Extensive revisions, most of which were concerned with the use of wetting agent foam, were adopted in 1955. Subsequently, in 1959, responsibility for this standard was transferred to the Committee on Foam, and the standard was amended in 1972 and 1979. The 1986 and 1990 Editions of the standard were reconfirmations of the 1979 Edition. The 1995 Edition of the document also was a reconfirmation. However, some editorial changes were incorporated in an effort to make the document more user-friendly.

The 2006 Edition underwent extensive revisions, both technical and editorial. Technical changes included clarifying the definition of wetting agents and their use on specific types of fires. Specific requirements for wetting agents and the methods for testing were included, along with packaging requirements and inspection, testing, and maintenance requirements for systems using wetting agents. The 2011 Edition added limits for aquatic toxicity.

NFPA 18 is intended to address qualification tests, methods of evaluation, and general rules for application of wetting agents and wetting agent solutions as related to fire control and extinguishment. NFPA 18 defines an **additive** as "a liquid such as foam concentrates, emulsifiers, and hazardous vapor suppression liquids and foaming agents intended to be added to the water." **Wetting agents** are defined as "a concentrate that when added to water reduces the surface tension and increases its ability to penetrate and spread."

With such a long history, many agents are Listed by Underwriters Laboratories as a Wetting Agent in accordance with the test parameters in NFPA 18.

In 1998, the NFPA Standards Council approved the formation of the Technical Committee on Water Additives for Fire Control and Vapor Mitigation. The committee was tasked with having primary responsibility for documents on the manufacture, testing, application, and use of water additives for the control and/or suppression of fire and flammable vapor mitigation, including water additives used to prevent or reduce the spread of fire and the use of water additives in fixed, semi-fixed, mobile, and portable fire suppression systems. The standard they were given was NFPA 18, *Wetting Agents*. Initially, the committee proposed to combine wetting agents and water additives under one standard. This effort was returned to the committee by Association action in June 2003. As a result, the committee decided to divide this work into two subject areas and standards, retaining and revising NFPA 18 and creating a new standard addressing water additives, NFPA 18A, the first edition of which was issued in 2007. Changes in the 2011 Edition include test procedures and criteria.

NFPA 18A is intended to provide the minimum requirements for water additives used for the control and/or suppression of Class A and Class B fires and the mitigation of flammable vapors. A **water additive** is defined as "an agent that, when added to water in proper quantities, suppresses, cools, mitigates fire and/or vapors, and/or provides insulating properties for fuels exposed to radiant heat or direct flame impingement." Water additives can materially reduce water's surface tension and increase its penetrating and spreading abilities; they also might provide enhanced cooling, emulsification, and foaming characteristics." Appendix material notes that **water additives** can materially reduce the surface tension of water and increase its penetrating and spreading abilities. They also might provide enhanced cooling, emulsification, and foaming characteristics. An **emulsifier** is defined as "a chemical or mixture of chemicals that along with some energy input promotes the formation of an emulsion." An **emulsion** is defined as "a heterogeneous system, consisting of at least one immiscible liquid dispersed in another in the form of droplets." **Emulsification** is defined as "the process of forming an emulsion." NFPA 18A provides no definition of an **encapsulator** or **encapsulation**. A **micelle** is defined as a basic building block of an emulsion. For purposes of the NFPA 18A standard, a **micelle** consists of a minute droplet of the hydrocarbon fuel surrounded by water and the emulsifying agent.

NFPA 1150 *Standard on Foam Chemicals for Fires in Class A Fuels, 2010 Edition*, is intended to address Class A foam and water enhancing gels, and their utilization for all wildland and structural firefighting. This excludes fixed fire protection systems. **Class A foams** are defined as "foam for use on fires in Class A fuels." **Wetting ability** is defined as "the ability of foam solution to penetrate and soak into a solid." **Exposure protection effectiveness** is defined as "the ability of a product to increase the time to ignition of a substrate subjected to a prescribed radiant heat source."

A general overview of wetting agents and water additives is provided by Frank [2008]. **Wetting agents** are defined as a concentrate that, when added to water, reduces the surface tension and increases its ability to penetrate and spread. While the definition would seem to imply use for Class A firefighting (i.e., surface tension reduction), the NFPA 18 standard includes tests for Class B threats, in addition to Class A fires. Frank notes that manufacturers have developed water additives that appear to be much more effective on Class A and Class B fires than traditional wetting agents. This is embodied in the performance parameters developed in NFPA 18A vs. NFPA 18, as described later in this analysis. Wetting agents evolved from foam technology, and are generally applied as foams. Their effectiveness on Class A fires relates to improved water efficiency, (via surface tension reduction) and water savings. They might be used on Class B fires, but their effectiveness is usually much less than from traditional Class B foam agents (NFPA 11), see Section 7 analysis. There are numerous chemicals that fulfill the primary function of a wetting agent, the primary purpose of which is to lower the surface tension of water.

A simple chemical definition of an emulsion is a mixture of two or more liquids that are normally immiscible. For fire protection purposes, the implication is that emulsification agents render the host fuel less flammable or more benign. A real-world example is Class K extinguishing agents which form a crust on the surface of cooking oil fires (also called saponification).

Frank [2008] describes an emulsion as being formed when immiscible liquids are agitated together and one of the liquids is dispersed throughout the others. He describes an active fire suppression process using water only. Extinguishment by this process might be achieved by applying water only (with no additives) to certain viscous flammable liquids, since the effect of cooling the surfaces of such liquids prevents the release of flammable vapors. With some viscous liquids (such as No. 6 fuel oil), the emulsification is a froth that retards the release of flammable vapors. Care must be used on liquids of appreciable depth, however, because frothing may spread the burning liquids over the sides of the container. A relatively strong, coarse water spray is normally used for this type of emulsification. A solid stream of water should be avoided, as it will cause violent frothing. Frank notes that these techniques are rarely used.

As used in NFPA 18A, the term emulsification implies the chemical and/or physical change of the hazardous fuel. The implication is that the flammability of the fuel is reduced, for example by limiting the production of ignitable vapors. One question is the effectiveness of emulsification before and during a fire. An agent applied before ignition might quantitatively reduce ignitable vapors, and might be readily quantified through laboratory testing (see Section 5 literature search, Reference A9, A20). It is unclear how emulsions interact with fuel once the material is ignited. The same question is applicable to encapsulators.

Certain types of fires, such as those in baled cotton, stacked hay, some rubber compounds, and some flammable liquids that do not ordinarily respond to treatment with water may be extinguished when a proper wetting agent is used. Frank notes that this may be attributed to an increase in the penetrating, spreading, and emulsifying capability of water due to lowered surface tension.

Agents known as Class A foams have become popular in recent years. NFPA 1150 covers these foams. Water efficiency (less solution used compared to plain water) is the primary advantage of these foams. For wildland/forest fire applications, improved water penetration through surface tension reduction is important.

NFPA 18A provides no definition of an **encapsulator** or **encapsulation**. A simple definition is an agent which isolates a fuel source. Fire resistive material applied to building structural elements is a classic example. The Class K agent described above could be said to encapsulate the exposed cooking oil surface.

5.0 LITERATURE REVIEW

A review of the literature is summarized in Table 1. Appendix A provides the citations and description of the public domain literature identified for this project. Additionally, there is one non-public domain presentation related to coal fire suppression and internal data from a utility on tests conducted using an encapsulator.

The literature reviewed is generally considered scientific, i.e., published in peer-reviewed technical journals or by independent test laboratories/organizations. Fire service trade magazines/journals have numerous articles, particularly related to Class A foam. The time and scope of this project limited efforts to document all of these sources.

Table 1 – Water Additives Literature Matrix

	Application									Type of Agent			Type of Application			
	Class A				Class B									Nozzle		
Technical Literature	**Structural**	**Wild land**	**Deep-Seated**	**Radiative Resistance**	**Pool/ spill**	**3D**	**Vapor Mitigation**	**Class K**	**R&D**	**Additive**	**Foam**	**Description**	**Mist**	**Fixed**	**Hose**	**Comments:**
A4, Evaluating the Performance of a Portable Water-Mist Fire Extinguishing System with Additives					X					X		Additive consisted of 97% fire retardant, 1.8% surfactant, 0.6% mint, and 0.6% camphor.	X		X	The additive solution volume and discharge angle plaed a significant role in fire extinction.
A22, Improvement Of Water Mist's Fire-extinguishing Efficiency With Mc Additive.	X				X				X	X		Multi-composition additive made up of CH3COONa, carbamide and N, N-dimethylformamide.	X	X		The MC additive greatly improves the fire extinguishing efficiency of the mist system
A14, Localized Protection of Flammable Liquid Hazards Utilizing Water Mist Nozzles with an AFFF Additive.					X	X (spray)					X	3% AFFF	X	X		The mist nozzle with AFFF was very effective in extinguishing the pool and spray fires, no case of water alone could extinguish the fires.
A8, Fire Protection of Heritage Structures: Use of a Portable Water Mist System under High-Altitude Conditions.					X			X (Ghee)		X		Multi-composition additive made up of a surfactant, a viscosity modifier, an organic metallic compound, carbamide, and N, N-dimethyl-formamide.	X		X	In all of the tests, the MC additive allowed for improved extinguishing times. Higher altitude negatively affected extinguishment times.
A1, Water Additives for Fighting Class A Fires: Summary Report	X									X	X	Multiple additives including Cold Fire, AFFF, Phos Chek, Chemguard, etc.			X	Studies of 11 additives found that there was no considerable improvement of extinguishment due to the use of the Class A additives, perhaps due to hose line application
A11, Preliminary Experiments on the Use of Water Additives for Friction Reduction in Fire Hose.									X	X		Used Polyethylene Oxide (PEO)			X	Fire hose water friction loss reducing additive
A18, The Effect of Additive on the Fire Extinguishing Improvement of Water Mist Spray.					X				X	X		Additive not explicitly named.	X	X		Larger droplet sizes of the additive solution had better extinguishment times than the smaller droplet sizes.
A5, Evaporation of a Small Water Droplet Containing an Additive									X	X		Used either potassium acetate or sodium iodide.				The addition of the salts decreased the average evaporation rates which may allow droplets to further penetrate a fire plume.
A16, On the Collision Dynamics of a Water Droplet Containing an Additive on a Heated Solid Surface									X	X		Water with 30% sodium acetate trihydrate.				For surface temperatures below 140^{o}C, the evaporation lifetime of the droplets with the additive were considerably longer than those without the additive.
A13, The Effect of Foam Additives on the Fire Suppression Efficiency of Water Mist	X				X						X	Class A (Silvex) and Class B (AFFF) foams.	X	X		Class A and B foams greatly improved the performance of the water mist system for the pool fire, not the crib fire.
A15, Water Additives for Increased Efficiency of Fire Protection and Suppression	X			X					X		X	Four Class A foams used.		X		The reduced surface tension and increased contact with the fuel provide for increased fuel cooling and wetting.
A24, Experimental Research on Low Pressure Water Mist Extinguishing Systems in Cookroom with Micelle Encapsulator Additive								X		X		F-500 micelle encapsulator.	X	X		The encapsulating agent extinguished the cooking oil fire three to ten times faster than water mist alone.

	Application									Type of Agent			Type of Application			
	Class A				Class B									Nozzle		
Technical Literature	**Structural**	**Wild land**	**Deep-Seated**	**Radiative Resistance**	**Pool/ spill**	**3D**	**Vapor Mitigation**	**Class K**	**R&D**	**Additive**	**Foam**	**Description**	**Mist**	**Fixed**	**Hose**	**Comments:**
A7, Multipurpose Overhead Compressed-Air Foam System and Its Fire Suppression Performance	X				X				X		X	Class A (Silvex) and Class B (AFFF) foams used with CAFS.		X		The CAFS outperformed water mist and sprinkler systems when extinguishing wood crib fires, while performing equally as wel as the water mist for pool fires.
A17, Foam as a Fire Suppressant: An Evaluation	X	X									X	Class A foam with and without CAFS.		X	X	Synthetic foams used with CAFS are the most effective tools they tested.
A6, A New Fire Suppression Technology Introducing Fixed-Pipe Compressed Air Foam Systems, an Important Innovation in Fire Suppression System Design	X				X						X	Class A (Silvex) and Class B (AFFF) foams with CAFS.		X		The Class A foam performed well in both open and closed space tests.
A23, Assessment of Gas Cooling Capabilities of Compressed Air Foam Systems in Fuel and Ventilation Controlled Compartment Fires	X										X	Class A foam (Angus Forexpan S) with CAFS.	X		X	CAFS was superior to water mist in fuel-controlled environments. No difference observed in ventilation-controlled scenarios.
A20, Determination of the Burning Characteristics of a Slick of Oil on Water.					X		X		X	X		Emulsifier				Ignition efficiency decreases as water is addedd to emulsified oils.
A9, Flame Suppression over Liquid Pool by W/O Emulsification					X		X		X	X		Emulsifier				R&D that indicates that emulsification can reduce the fire hazard of oil
A2, The Use of Wetting Agents for Firefighting II: The Extinction of Fires in Fibrous Materials	X		X							X		Aqueous solution of an alkyl-phenyl substituted polyethylene glycol.		X		Wet water was more effective than the plain water in more tightly packed bales of straw, while there was no difference in the loosely packed bales.
A3, Fire Protection Foam Behavior in a Radiative Environment				X					X		X	Protein based foam.				The temperature gradient of the protected surface decreases with an increasing foam expansion ratio.
A19, Fire Protection Foam Thermal Physical Properties									X		X	Four synthetic hydrocarbon based foams and one protein based foam.				Tried to establish a testing procedure to evaluate the relevant properties of fire fighting foam.
A12, Evaluation of the Fire Suppression Effectiveness of Manually Applied Compressed-Air Foam (CAF) System	X										X	CAFS and ordinary foam-water solution.			X	A CAF system cooled a compartment fire the fastest, followed by the foam-water, followed by the water alone. Also, the CAF used 80% less water to control the fire.
A10, On the Action of Wetting Agents in the Extinction of Wood Fires	X									X		Additives tested were Nonyl Phenol Ethylene Oxide, Nonyl Phenol Ethylene Oxide and Dioctyl Sodium Sulphosuccinate, and Alcohol Alkoxylate.		X		Alcohol alkoxylate allowed for the fastest cooling time, taking almost half as long as plain water to cool it.
A.26 Evaluation of Novel Fire Suppression Systems for Conveyor Belt Fires in Underground Coal Mines	X		X						X	X	X	Gel, foam and water mist		X		Gels no more effective than water applied from sprinkler system to conveyor belt fire scenario
A21, F-500 Encapsulator Technology: Sprinkler/Spray System Applications					X					X		F-500 micelle encapsulator.		X		The F-500 greatly improved the efficiency of water when compared to plain water against diesel pool fires.

5.1 Categorization

The literature reviewed was categorized based on the applicability to this project. The research which applied to Class A fires was broken down into four separate categories – structural, wildland, deep-seated, and radiative resistance. Research on Class B fires were broken down into pool/spill fires, three dimensional fires, and vapor mitigation. Class D and K fires were assigned their own categories.

The structural category applied to all scenarios that could be classified as standard Class A fires involving cellulosic fires, and would be associated with tests involving wood crib fires or compartment fires. The wildland category applies to fuels associated with forest fires and the urban/wildland interface. Deep-seated application applies to research concerning fires burning below the fuel surface, as opposed to surface fires (e.g., associated with wood panel fire tests). It also applies to Class A fires where agent application to the fuel is restricted (e.g., the coal storage fire scenario). Radiative resistance applications apply to research on the additives' ability to protect against impinging fire and radiation.

The Class B pool/spill category applies to research conducted on two-dimensional (2D) Class B pool or spill fires. Three dimensional (3D) scenarios are those where a liquid fire flows freely from a vertical height, falling on associated equipment or structure down to a static pooled surface fire. The liquid in this case may be falling under gravity, or it may be pressurized. Vapor mitigation applies to research that was conducted on how effective agents were in neutralizing the vapors of flammable liquids.

5.2 Summary of the Literature

Much of the identified literature related to agents tested in a water mist system. This approach is not ideal for assessing additives for their generic effectiveness. While mist systems have their own benefits and detriments, it could be considered as an optimum application of a fixed system. Mist data is not readily amenable to manual firefighting applications, which are common for many of the applications of interest.

Regardless of the delivery method of the agents, the general consensus of the research is that water additives and wetting agents do have beneficial effects on the firefighting capabilities of water. Many different types of additives are represented in the literature, from multi-composition additives (MC) to ordinary AFFF. Nevertheless, the majority of the research shows that additives and wetting agents are beneficial.

5.3 Effectiveness of Additives

A majority of the studies indicated that wetting agents and water additives improve the fire suppression performance of water. A number of the studies identified many positive attributes of certain additives. For example, Bowes and Skeet [A2] showed how an aqueous solution of alkyl-phenyl and polyethylene glycol was far superior to plain water when extinguishing a deep-seated fire in a bundle of tightly packed straw. In their study, they found that the additive tested was more effective than plain water in extinguishing a fire in a relatively tightly packed bail. Ultimately, they concluded that the surfactant abilities of the water additive allow the solution to be more effective than plain water for the extinction of fire in fibrous materials (deep-seated fires).

Additionally, newer additives like emulsifiers have been shown to have beneficial firefighting capabilities. For example, Ishida and Watanabe [A9] studied the effects of emulsification on a pool fire of oil. They found that a water-in-oil type emulsification has the potential to reduce flame spread velocity over the pool by up to one half and that the flash point of the emulsification becomes reduced as well. This type of emulsion property has the potential to be a useful tool in Class B fires and areas requiring vapor mitigation.

In tests of CAFS manually applied to a compartment fire, Kim [A12] found that the CAFS was more effective (faster cooling, less water used) than water alone.

The literature does not universally support the improved effectiveness of additives. A study conducted by Kirsty Bosley for the Central Fire Brigades Advisory [A1] determined that, for a Class A fire scenario, "no significant distinction could be drawn between the extinguishing performance of water with any of the additives, and water alone." In this investigation, the capabilities of 13 different additives extinguishing capabilities against Class A fires was assessed. Two rounds of tests were conducted: the first to give a broad initial view of the additives; and the second was performed to repeat the initial testing under more strictly controlled conditions. Each fire test consisted of 56 wooden pallets arranged in a square of four stacks with a tray of heptane ignited beneath them to ignite the fire. The pallets were allowed to burn until a steady fire was achieved, at which point the firefighting would occur. The additives were premixed to manufacturers' specifications and applied via a hose reel at roughly 13 gallons per minute (50 liters per minute). The firefighter's discretion was the sole determinant on when to cease firefighting.

In both sets of tests, the conclusion was the same: the additives failed to show any improvement in extinguishing effectiveness over water alone. The investigation went on to further conclude that in a real fire, "there are so many uncontrollable variable affecting the fire that any change in firefighting performance that may potentially result from the use of Class A additives would probably be rendered unnoticeable."

The Bosley study is not the only one to conclude that the additives may not improve performance against Class A fires. A study conducted by Andrew Kim, et al. [A13] aimed to test the effectiveness of film-forming and foam-forming agents in a water mist system against various pool fires and a wood crib fire. These tests utilized a 0.9 meter diameter heptane and diesel pan fires, heptane and diesel pool fires, and a 0.6 x 0.6 x 0.3 m high pine wood cribs for the Class A test. One or two nozzles were used to dispense the solution at varying angles. The additives tested were a foam-forming Class A concentrate (Silvex) and a film-forming Class B concentrate (AFFF). It was concluded that "adding a small quantity of Class A or B foam concentrates to the water mist significantly improved the performance of the water mist system in suppressing liquid pool fires; in crib fire tests, the addition of a small amount of foam additive to the water mist did not significantly change the performance of the suppression system." The investigators determined that a thick foam layer is required to stop the crib from burning, which small amounts of the concentrates did not produce.

Tests were conducted by NIOSH on water gel additives applied through a standard sprinkler system used for conveyor belt protection [A.26]. The fire scenario was a belt fire. Foam and water mist were also evaluated. The results were compared against baseline tests using water. The general conclusion was that the three novel fire suppression systems were no more efficient than water. Ventilation, water supply, and sprinkler nozzle placement were found to be key factors.

No public domain literature was identified which showed comparative effects of manually applied water additives or wetting agents to Class B fires. Micelle encapsulating additives like F-500 are heavily endorsed by the Powder River Basin (PRB) Coal Users' Group [A25]. Bunker fires in PRB coal facilities are special risks because the coal creates a very porous environment. The extinguishing agent must penetrate this before it can suppress the deep-seated base of the fire. Because of this unique challenge, the PRB Group considered many different types of agents including wetting agents, foams, gases, and micelle-encapsulating agents. The Group determined that foams were not the most effective agent against coal fires because they take a particularly long time to smother. Foams are effective at excluding air from a fire source if a blanket is maintained, which is nearly impossible to do in a deep-seated coal fire. Encapsulating agents are chosen as the agent-of-choice not only because of the surface tension reduction, but also because of their ability to encapsulate fuel molecules and render them non-flammable. This special component of micelle encapsulating agents makes them uniquely effective.

The power utility Dominion provided video tapes of comparative testing of water compared to an encapsulating agent. Various size diesel fuel fires up to 120 square feet were performed. One pair of tests is particularly noteworthy. A single sprinkler was positioned above a 12 ft x 10 ft steel pan filled with 33 gallons of diesel fuel. The sprinkler discharged agent at 36 gpm to provide an application rate of 0.30 gpm/ft^2. The test fire was ignited and reached full involvement in about 45 seconds, after which the sprinkler was activates at about one minute. The results are shown in Table 2. While fire knockdown times were similar (qualitatively assessed from the videos as 90% control of the fire area), the total extinguishment time was significantly better for the encapsulator

Table 2 – Comparison of Water vs. Encapsulator for Suppression of 120 ft2 Diesel Pan Fire (Dominion Power Tests)

Agent	Application Rate (gpm/ft^2)	90% Control Time (sec)	100% Extinguished Time (sec)
Water	0.30	29	117
Encapsulator	0.30	10	36

5.4 Discussion of Test Methods Used

Of the literature that was reviewed, it was found that a large number of fixed nozzle mist systems were used to evaluate the effectiveness of the additives. While appropriate for actual fixed system applications, the mist systems may not necessarily be the best tool to evaluate the performance of an additive in all fire scenarios. For Class B fires, water mist alone has been shown to be sufficient to extinguish Class B fires. Additives may offer some advantage, particularly manual applications. In the reviewed Class A water mist fire tests, the additives have shown limited improvement in suppression effectiveness. It is postulated that the droplets that are dispersed by the mist system do not have the necessary momentum required to effectively penetrate a Class A fire, let alone a deep-seated one.

Few of the studies actually used hoses and standard spray systems. The test methods used in the literature for additives have limited applicability to the scenarios of interest for this project.

The Dominion tests suggest that encapsulator agents may be more effective than water, using the 0.30 gpm/ft^2 typically used by utilities for water suppression of Class B pool fires.

6.0 COMMERCIALLY AVAILABLE AGENTS

Commercially available water additives were identified as shown in Table 3. A total of 34 agents were identified that claim to be a water additive of some kind. While this is not an all encompassing list of every agent on the market, it gives a representative sample of what is available and what the manufacturers say that their products can do.

Of the agents listed, a majority are for either Class A or Class B fires: eight are for Class A fires only: seven are for Class B fires only: eleven are for both Class A and B fires; three are for Class A, B, and D fires; one is for Class A, B, and K fires; four are for Class A, B, D, and K fires; and four are for radiation resistance. NFPA 18 and 18A do not evaluate agent effectiveness on Class D or K fires.

The additives that are listed in the table were selected based on their purported firefighting abilities and characteristics. Novel additives effective against a broad range of different types of fires were emphasized in the search. An effort was made to refrain from including the more common Class A firefighting foams, “wetting agents,” and the more conventional types of foams. Additives which were identified as having unique chemical or physical properties, such as an encapsulating agent or emulsifying agent, were emphasized and included in the table. These relatively unique additives represent new technology, not necessarily explicitly addressed in the current standards. They tend to have the least amount of public domain firefighting effectiveness research. Environmental impact data is available from their MSDS sheets.

The following terminology, among others, is used by the producers to describe their agent properties and affects: microencapsulating, micelles, free-radical elimination, enhancing gel, water enhanced, endothermic reactions, macromolecule structure reduction, sticks to surfaces, increased viscosity, increased wetting and penetration ability, emulsifying, encapsulating, micelle encapsulating, vapor and odor suppression, render non-volatile, chemical shearing of hydrocarbon strings, surfactant, water enhancer, and flash preventer. These terms are used to describe both the physical actions of the agents and the intended results. All are presumably consistent with the proposed fire suppression application.

Agents that were identified, but ultimately not included in the table, include: Bio for C/N, First Class, Knockdown, Trimax, Silvex, and Fomtec. These additives and foams tended to be of the more traditional Class A type foams which are not the emphasis of this project.

Table 3 – Water Additives Agent Matrix

		Application										Type of Agent		
		Class A				Class B								
Product	UL Listed to NFPA 18	Structural	Wildland	Deep-Seated	Radiative Resistance	Pool/ Spill	3D	Polar Solvents	Vapor Mitigation	Class D	Class K	Additive	Foam	Description
Biosolve		X				X			X			X		Encapsulator and emulsifier. "BioSolve is a proprietary, water-based, biodegradable formulation of surfactants and performance additives that work together to provide unique functionality encapsulating and emulsifying hydrocarbons, and suppressing harmful odors and vapors."
Bioversal QF		X				X						X	X	Encapsulator and emulsifier. Prevents flashback. - Uses a micelle encapsulating mechanism, but also foams to act on all areas – taking away the fuel, temperature and oxygen.
BlazeTamer			X											"the BlazeTamer solution undergoes an endothermic reaction that produces a rapid cooling effect."
Boldfoams		X				X		X						
Cold Fire	X	X				X		X		X	X	X	X	"Cold Fire cools 21 times faster than water, and works to remove heat and the fuel sources from the fire tetrahedron, preventing reignition."
Denko Emulsifier									X			X		Emulsifier.
drench		X				X						X		"drench is a blend of four distinctly different chemical technologies maximizing the performance of several element of the water. Penetration is increased up 400%, friction loss is reduced by as much as 45% and vaporization takes place twice as fast."
Emulsi Flash									X			X		Emulsifier. Breaks petroleum products down into a detergent type solution where small particles become trapped by a coat of the emuslifier.
F-500	X	X		X		X				X		X		Encapsulator. Additive of choice in PRB Coal Industry for deep-seated coal fires.
First Class	X	X	X	X		X							X	Class A foam which reduces surface tension of water, produces foam, can be used with medium expansion nozzles on Class B flammable liquids
Fire Blockade	X	X				X				X			X	"Blended with unique penetrating, cooling components and a proprietary food grade protein retardant that renders fires extinguished upon application."
Fire Cap Plus	X	X				X			X			X		"Fire Cap Plus acts as an emulsifier that separates the chemical make-up of a contaminent and then renders it non-volatile."
Fire Out!						X			X			X		Encapsulator and emulsifier. "Specifically formulated to deliver a 'quick knockdown' of fires while emulsifying and encapsulating the hydrocarbons…creating a non-flammable solution." "Not a foam, but applies like water…"
FireAde 2000	X	X				X				X	X		X	"offers the simplicity of using one product to extinguish multiple classifications of fire."
FireIce			X		X							X		Gelling agent. - "FireIce breaks the fire triangle by suffocating the oxygen from the fuel by cooling the heat source, thus breaking the thermal barriers of fire."
Flame Freeze		X				X		X		X	X	X	X	Foam along with encapsulator. "5-in-1 technology: hydrocarbon encapsulator, penetrating agent, foaming agent, cooling agent, wetting agent"
Flameout	X	X				X						X		Encapsulator that breaks down hydrocarbons. "Chemically shears the hydrocarbon strings, rendering the fuel source inert."
Fomtec Foams		X				X		X					X	
Hi Combat A	X	X			X	X						X	X	Emulsifier. "A coating of Class A foam may also be used for exposure protection to prevent fuels from igniting…"
Hydrex		X			X							X		Gelling agent.

		Application										Type of Agent		
		Class A				Class B								
Product	**UL Listed to NFPA 18**	**Structural**	**Wildland**	**Deep-Seated**	**Radiative Resistance**	**Pool/ Spill**	**3D**	**Polar Solvents**	**Vapor Mitigation**	**Class D**	**Class K**	**Additive**	**Foam**	**Description**
HydroLock Vapor Encapsulator									X			X		Encapsulator. "a unique encapsulator agent formulation that neutralizes flammable liquids and vapors, as well as emulsifying hydrocarbon sludge and residue."
KV Foams		X				X		X	X		X		X	
Micro-Blaze Out	X	X				X						X		Microbial agent that breaks down hydrocarbons and prevents reignition.
Novacool UEF	X	X				X	X		X	X				"The oxygen, heat, fuel, and chemical reaction (free radicals) are eliminated with Novacool UEF Foam."
Penetro Wet		X										X	X	"A mixture of wetting agents, foaming agents, emulsifiers, and rust inhibitors formulated expressly for the fire service." Can also be an emulsifier on light petroleum spills.
Petromist		X				X			X			X		Encapsulator. "…attack fires, the gases surrounding fires, and the fuel that perpetuates fires…FOS has the only quick, microencapsulating, nontoxic, fire-elimination products in the world…"
Phos-Chek Aquagel-K			X		X							X		Gelling agent. Absorbs water many times its own weight in water and forms a gel producing increased droplet sizes that reduce drift and evaporation
PinkWater						X			X					Encapsulator and emulsifier. "PinkWater plays a dual role in efficiently knocking down the flame and neutralizing the hydrocarbon source."
Pyrocool		X				X				X	X		X	
PMA-RTU						X			X			X		Encapsulator and emulsifier. "PMA-RTU's ability to solublize and emulsify oils surpasses simple wetting agents and emulsifiers that reduce surface tension to fight a fire."
STHAMEX ultraWet		X										X		"extinguishes without foaming"
TetraKO		X	X									X		Gel. Smothers flame to prevent re ignition. - "TetraKO™ water enhancer transforms water into a liquid that sticks to vertical and ceiling surfaces and can be pumped through standard fire equipment."
uniMUL									X			X		Emulsifier.
Water Wetter		X										X		"Water Wetter is a special chemical additive that increases the wetting and penetrating ability of water…for use in fighting stubborn, smoldering fires, it reduces the surface tension of water to allow it to penetrate faster and reduced the total amount of water needed."

NOTE: Not all NFPA 18 Listed wetting agents included in this summary.

6.1 UL Listed Agents and Their Uses

Of the 34 agents identified, 10 are UL Listed as "Wetting Agents." In total, 14 products are UL Listed as wetting agents, in accordance with NFPA 18. There are currently no products currently UL Listed as a water additive in accordance with NFPA 18A.

All of the products Listed as wetting agents under UL are Listed for both Class A and Class B fires. The listings themselves show two separate concentrations of the product that are applicable to either Class A or Class B fires. While many of products are not UL Listed or FM Approved, they all claim to be effective at extinguishing a certain type of fire – many of them claim to be effective against multiple classes of fires.

7.0 TESTING AND PERFORMANCE PARAMETERS

7.1 NFPA Criteria

Frank [2008] says that manufacturers have developed water additives that appear to be much more effective on Class A and Class B fires than traditional wetting agents. These manufacturers often promote the environmental benefits of their agents as well. The Technical Committee on Water Additives for Fire Suppression and Vapor Mitigation developed NFPA 18A that reflects their perceived differences between wetting agents (traditionally an offshoot of foam), and water additives. The challenge for the committee was how to quantify the improvements that these agents purport to offer.

For NFPA 18, an agent is listed either for Class A or B fire scenarios, or both. It appears that all UL Listed agents are Listed for both Class A and B fires. Different agent concentrations are typically used for Class A and Class B. The test scenarios include:

- Class A – wood crib fire extinguishment test, deep-seated fire test (including extinguishment with less runoff than water), and a wood panel fire test (with less weight loss of the source fuel and less runoff compared to water).
- Class B – flammable liquid pool fire test

For NFPA 18A, these scenarios include:

- Class A scenarios – an agent must pass both a wood panel and wood crib fire extinguishment test
- Class B scenarios – an agent is to be tested against one or more of the following: flammable liquid spill, pool, or three-dimensional (3D) fire. Fuel-in-depth fire and polar solvent extinguishment tests are anticipated.

The fire tests have clear performance parameters in terms of mass application rate, fuel to be used, maximum extinguishment times, and, for the two dimensional Class B fires, burnback resistance. A Class B agent is to be tested and listed in accordance with one or more of the test procedures.

7.1.1 Two Dimensional Class B Pool Fire Suppression

Table 4 shows the differences in Class B fire extinguishment performance between NFPA 18 and the two NFPA 18A tests. The NFPA 18A spill fire test is much more difficult than the pool fire test. The extinguishment application density is 0.15 gal/sq ft for the spill test compared to 0.50 gal/sq ft for the pool fire test.

Table 4 – Comparison of Class B Pan Fire Test Criteria and Requirements

Standard	Nozzle Discharge Rate (gpm)	Application Rate (gpm/ft^2)	Maximum Extinguishment Time (minutes)	Extinguishment Density (gal/ft^2)	Listing Application Rate (gpm/ft^2)
NFPA 18	10	0.20	5	1.0	Not specified
NFPA 18A Spill Fire test	5	0.10	1.5	0.15	0.17
NFPA 18A Pool Fire Test	5	0.10	5	0.50	0.25
Constants – 50 sq. ft. heptane fire, 60 second preburn					

There is a test under the Class B assessment for emulsification: this demonstrates the ability of the agent to inert flammable and combustible liquids, that is, prevent liquid fuel ignition from an exposing flame. There are no tests for encapsulation.

7.1.2 Three Dimensional Class B Fire Suppression

A 3D test article has been adopted in NFPA 18A. NFPA 18A, Annex D provides details on the dimensions of the test article; see photo and description in Section 7.4.3. For aviation applications, Jet-A fuel is to be used, with a 64 ft^2 pan collecting a 3.5 gpm fuel flow cascading down a 6 ft high tray assembly. A 45 second preburn is specified. For the aviation fire scenario, the water additive discharge rate is 40 gpm, and extinguishment must occur in 20 seconds or less. For industrial applications, heptane is to be used as the test fuel, the water additive discharged at 60 gpm, and extinguishment must occur in 45 seconds.

7.1.3 Class A Deep-Seated Fire Suppression

A Class A agent for water additives must pass the minimum extinguishment times of the Class A crib and panel fire test methods. Unlike the NFPA 18 requirements, improvement over plain water is not required.

NFPA 18 requires the extinguishment of a UL 3-A wood crib using agent discharged from a 2.5 gallon portable extinguisher. There is also a deep-seated fire test involving a 7 in. high column of cotton and a wood panel. Fires must be extinguished, with less agent used than with plain water.

NFPA 1150 has only one performance test, related to the wetting ability of the agent for a Class A fuel. The ability to wet a cotton skein is determined in accordance with ASTM D 2281, *Standard Test Method for Evaluation of Wetting Agents by the Skein Test,* as modified. Users interested in wetting ability, i.e. the rural/forestry fire service, have a baseline parameter for agents to meet which correlates to the desired scenario, i.e. a wildland fire. Users of Class A foam or CAFS for structural firefighting are left on their own since no performance fire test is provided.

7.2 Approach to Performance Parameters

There are two potential assessment approaches to establishing performance parameters. One involves describing agents based on their physical attributes. This is sometimes used by the agent vendors to promote niche markets. These markets include: petrochemical; aircraft rescue and firefighting (ARFF); aircraft hangar protection; nuclear power; fossil fuel power; civilian and industrial firefighting; and hazardous material handling. Terms described in Section 6.0 are used in describing the overall performance characteristics of the agent.

The alternative approach involves establishing fundamental fire suppression mechanics, and applying this knowledge to a given hazard. Class B suppression could be assessed for: two-dimensional (pool) fires; three-dimensional (spill/running fuel or pressurized spray) fires; and, vapor suppression to prevent ignition or reflash. The baseline for comparison is Class B firefighting foams, currently Listed in accordance with UL 162 or Approved using FM 5130.

As an example, traditional foams can be considered. AFFF is a “film-former,” i.e., it creates an aqueous surface tension-reducing solution which allows foam solution to float on a hydrocarbon fuel surface. Film-forming fluorprotein foam creates surface tension reduction, but generally not as great as AFFF. A spreading coefficient test is performed in foam test regulations to establish the category of AFFF (or film-formers). But, no direct correlation has been established between spreading coefficient and fire suppression performance [Scheffey, 1994]. It may be more appropriate to classify foams in terms of performance (see Section 7.3) instead of physiochemical attributes. The same approach could be used to eliminate the need to categorize water additives as “encapsulators,” “emulsifiers,” “gels,” “vapor suppressants,” “micelles,” etc. This does not eliminate the option to have a physiochemical test, say for an emulsifier, as is performed for spreading coefficients of film-forming foams. There may be no need to directly tie this into fire suppression performance.

Categorizing Class A fire suppression capabilities is more challenging. Potential suppression capabilities generally relate to reported advantages compared to plain water. These include: greater efficiency than water; faster knockdown/control; less water usage; greater cooling capability (both in suppression and ignition prevention or boundary cooling); and, less water run-off, i.e. greater fuel penetration.

Inerting to prevent an initial ignition is a special situation. For now this is not considered.

7.3 Levels of Performance

Similar issues regarding categorizing agents have occurred with traditional Class B firefighting foams. Protein foam was originally used for Class B combustible and flammable liquid two-dimensional pool (spill) fires. It requires air-aspiration to float foam on top of a fuel to suppress vapors and ultimately extinguish a fire. This vapor suppression also limited reignition potential from hot surfaces. Fluorprotein foam was an advancement, where chemicals were added to reduce the agent surface tension, making the foam easier to "skim" over the fuel surface. Aqueous film forming foam (AFFF) uses fluorocarbon surfactants to reduce the agent surface tension. Fuel fires were extinguished more rapidly than with fluorprotein foam, which in turn extinguished fires more rapidly than protein foam.

Historically, these foams have been categorized by their physical composition and attributes: protein (derived from hydrolyzed natural proteins); fluorprotein (proteins plus surface active chemicals); and AFFF (synthetic with fluorosurfactants). But this categorization has become more difficult as more commercial derivatives were developed, including film-forming fluorprotein (FFFP) and fluorine-free foam (FFF).

In European aviation foam regulations, this categorization has been replaced with foam levels of performance. Using a constant nozzle flow rate on increasing fire sizes, different levels of performance are established for a maximum one-minute extinguishment time, as shown in Table 5.

Table 5–Levels of Foam Performance in International Civil Aviation Organization (ICAO) Tests

Performance Level	Fire Size (ft^2)	Nozzle Discharge Rate (gpm)	Application Rate (gpm/ ft^2)	Extinguishment Application Density (gal/ ft^2)
A	30	3	0.10	0.10
B	48	3	0.06	0.06
C	79	3	0.04	0.04

For equivalent fire performance, users selecting performance Level A must provide more agent compared to users selecting Levels B or C. Likewise, Level B users must provide more agent than users selecting Level C. Level C agents typically cost more, so there is a cost/benefit judgment that the user must make.

Particularly for Class B pool fire suppression, this type of categorization, based strictly on fire performance, could be used to discriminate between alternative water additives. The current NFPA 18A provides two levels of performance for two dimensional Class B fire suppression.

The problem is more challenging for Class B three-dimensional and Class fire A scenarios, where standardized testing, based on years of small and large-scale tests (as with foam) has not been established. NFPA 18A provides two levels of extinguishing performance for the 3D Class B fire scenario.

7.4 Fundamental Measures of Performance and Scaling of Test Fires

7.4.1 General Performance Criteria

The fundamental measures of performance for comparative agent performance should be based on:

- Speed of fire control and extinguishment
- Time provided before the fuel package reignites and self sustains combustion

These times can be used by themselves for individual agent comparison. Using time as a measure, agent mass flow rate and fire size should be held constant. Alternately, as is used in standardized regulatory tests, a maximum time is established. The mass flow rate of agent or fire size is typically varied to establish performance variations between agents. This is demonstrated in the ICAO example in Table 5.

7.4.2 Class B Two Dimensional Pool Fires

Fire suppression for Class B pool fires is readily scalable in the 25–50 sq ft range. This scale could go as low as 3 feet in diameter (i.e., hydrocarbon quasi-steady state burning rate). The challenge has been the scalability of the application discharge device. For foam, reduced-scale nozzles and 25-50 sq ft fire tests have a documented history of scalability [Scheffey, 1994]. Vendors of water additives have been critical of this approach since it may not factor in necessary physical properties required for their agent/ application. This could relate to: pressure (CAFS is an example which has yet to be simulated at reduced scale); agitation not related to foaming (forming of micelles); and application onto fuel surfaces (too gentle or forceful). Prior experience has shown that moderate scale pool fire tests on the order of 1000 sq ft should allow for performance discrimination with the use of actual vendor discharge hardware. Sixty gallons per minute (60 gpm) is near the low end of standard manual firefighting nozzles/discharge devices. Assuming a baseline of about one minute fire control/extinguishment time at 60 gpm, an extinguishment application density of 0.06 gal/ft^2 might be established as a baseline. Reignition potential (burnback resistance) should be included to assess the degree of suppression of post-fire vapors. This can be done using relatively standardized methods which assess time to reignition or burnback fire area.

Fuel type is an important parameter in Class B tests. Volatile, low flash point fuels are more difficult to extinguish than high flash point fuels. A higher application rate and/or longer extinguishment time may be needed for low flash point fuels. Lower flashpoint fuel (e.g. heptane) is generally used as a non-miscible test fuel in standardized tests. Polar solvents would require use of the fuel to be protected.

The factor of safety applied in a regulatory code or standard is an important consideration. The Annex of NFPA 18A describes how a factor of safety has been applied to establish minimum application rates for the 2D Class B scenario. This is evident in the two levels of required application rate in the NFPA18A tests. In fire demonstrations, this factor of safety may not be apparent or emphasized. For example, it is unlikely that a substantial performance difference would be evident on a 1000 square foot diesel fuel fire, with a short preburn, with agents applied at 100 gpm. If the application rate was reduced by two-thirds, and gasoline or heptane was used, the performance discrimination would be more likely.

7.4.3 Three Dimensional Class B Fires

It is difficult to predict the fire size and configuration of a potential fuel spill fire. It is even more difficult to predict and quantify three-dimensional, running fuel or spray fires which may occur in an accident or catastrophic event. This is true even if the hazard type is limited, e.g., to transformers. Pressurized fuel spray fires are likely beyond the capability of a water additive, except maybe for fixed systems, so are not included in this discussion.

The focus should be on gravity fed 3D fires, such as a transformer fire. The transformer fire scenario will be used as the scenario of interest. The control of a plasma arc situation is well beyond agent capabilities, so the scenario is limited to the post-initiating event where liquid under very low or no pressure, cascades down a transformer assembly, e.g., from a day tank. This scenario is sometimes called a running fuel fire.

Dry chemical agents, carbon dioxide/clean agents, and fixed water mist are normally used for larger, three-dimensional running fuel fires. Unlike foam, these agents do not secure the residual fuel surface against re-ignition. Re-ignition (re-flash) may occur, so the “burnback resistance” is important. AFFF, while generally considered ineffective on three-dimensional fires, provides cooling. The original AFFF/potassium bicarbonate (PKP) “twin agent” concept from the 1960s was based on the cooling and vapor-securing of foam, combined with the three-dimensional suppression capability of dry chemical. The need for a complementary agent should be considered when investigating additives for 3D fire manual firefighting capability.

A three-dimensional test article has been developed to assess extinguishing agents as shown in Figure 1. Reportedly, it was constructed as part of the development and assessment of the dry chemical agent MONEX® by the UK Civil Aviation Authority (CAA). This test article has been adopted in NFPA 18A. NFPA 18A, Annex D provides details on the dimensions of the test article. NFPA 18A specifically indicates that this test method should be used for evaluating water additives for aviation or industrial applications. Fuel is pumped to top of 6 ft high cascade tower and flows down over shelves into bottom pan. The pan is 6 ft by 6 ft with 12 inch high sides. The fuel, selected based on the hazard, is discharged at 3.5 gpm.

Figure 1 – 3D cascade fire test apparatus specified in NFPA 18A.

Other 3D fire scenarios have been developed and are in fairly common use. Most of these are used to simulate military incidents involving aircraft or ship crash/engine/fuel leak situations [Back, et al., 2000]. Appendix C provides additional details.

Tests have been performed with a fixed water mist system on a transformer mock up [Kim, 2006].

The currently specified test article in NFPA 18A or the military test article appear to be a reasonable starting point to generally assess comparative 3D fire extinguishing performance of water additives. A transformer 3D mock up could be used to create a representative situation if this scenario is of specific interest.

7.4.4 Class A Deep Seated Fires

The crib geometry and lengthy preburn makes the NFPA18A crib test article challenging. Agent must be directed into the core of the crib, which has a burning char layer that is difficult to completely extinguish. But, the manual application allows agent to ultimately be applied directly on the burning surface, so it is usually a question of having sufficient agent quantity and discharge rate for a given crib size. The literature has shown that it is difficult to correlate standard crib suppression with real scale fire scenarios [Scheffey, 1991].

The NFPA 18A wood panel test represents a surface burning condition and is not of interest for this project.

Creating a set of Class A extinguishment tests is more challenging and is scenario-specific. If an agent is designed to be more “efficient” than water, then wood crib, wood panel, or compartment fire testing might be performed. The history of this comparative testing is not encouraging. NIST [Madrzykowski, 1998] has investigated compartment fires using water additives. The limitation is that while subtle differences might be identified, these tend to become irrelevant in actual firefighting. Much, much larger quantities of water tend to be used in actual manual firefighting, compared to controlled experimental results [Scheffey, 1991]. Water retention test techniques have been reported in the literature and are included in NFPA 18. Scaling to real world applications has not been demonstrated; presumably, agents that penetrate Class A material more effectively would suppress deep seated Class A fires more readily than water. The availability of scaled nozzles or scaled application technique, or lack thereof, will determine the scale of Class A comparative tests.

Since correlations between small scale water penetration tests and real scale suppression has not been clearly established, deep-seated fire scenarios should be tested in a representative fuel/geometry configuration. A fire fueled with coal could be evaluated with a relatively small scale test apparatus, Figure 2. This test apparatus would consist of a 55 gal steel drum with both ends removed. A fine mesh steel screen would be supported above the open bottom end. The coal would be placed on top of the screen filling the drum to within 10 cm (4 in) of the top of the drum. The drum would be raised off the ground to allow air to enter the coal pile from below and to prevent the build-up of water at the bottom of the drum. The coal would be ignited with a tubular heater inserted into the pile below the center of the pile. The burning of the coal would be monitored with thermocouples inserted throughout the pile.

The water or water with additive would be sprayed onto the pile from above after the burning of the coal had become well established. The flow-rate of the water or water with additive would be varied over successive tests until a minimum flow-rate to cause extinguishment has been established. The water flow would be facilitated by pressurizing the cylinder with nitrogen. Otherwise, application should not be sensitive to actual nozzle discharge characteristics. In reality, the agent would have to penetrate by gravity though a relatively long column of coal. The primary challenge in using this apparatus will be in maintaining a consistent coal sizing through successive tests. Previous tests by the U.S. Coast Guard [Schultz, et al., 1990] have shown that penetration of the suppression agent throughout the pile is a key to effectiveness and is effected by the size of the coal briquettes utilized.

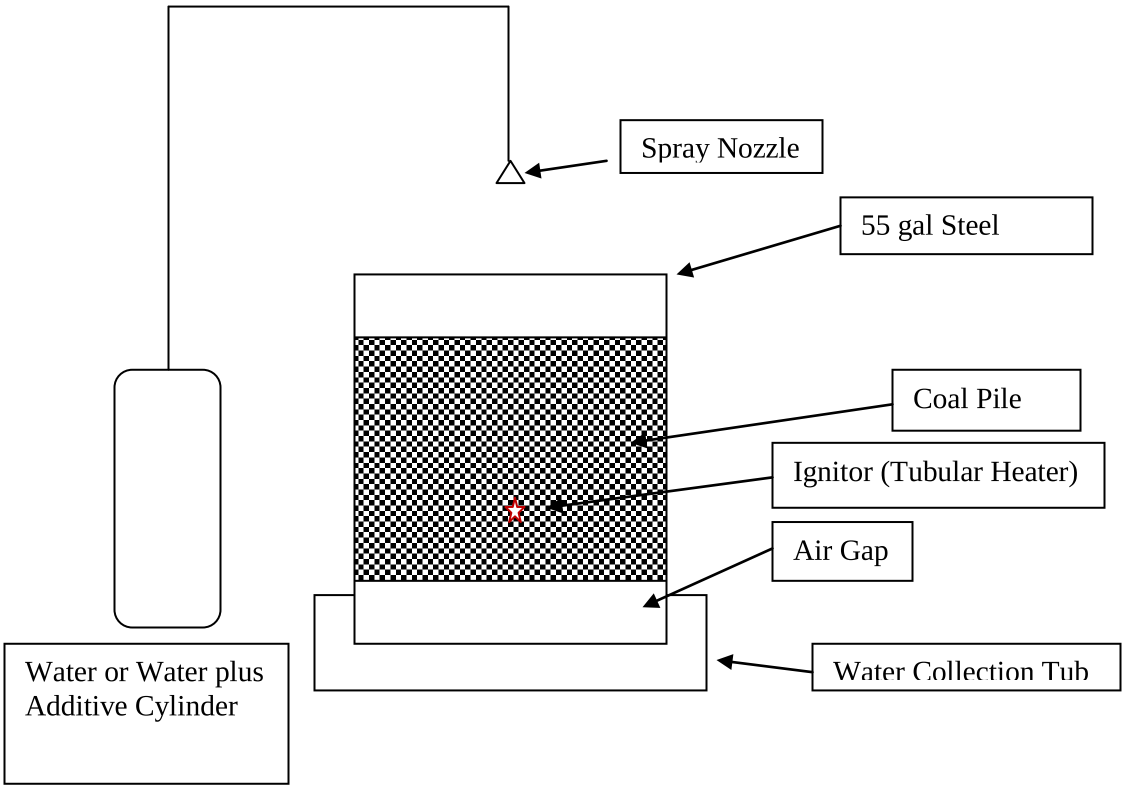

Figure 2 – Potential small scale coal fire suppression apparatus.

8.0 TEST PLANNING AND PATH FORWARD

8.1 General Parameters

Preliminary test plans were prepared for Class A and B tests as shown in Appendices B and C, respectively. The plans were distributed to the Sponsors and Technical Panel. Their input was reviewed in a conference call and subsequent test plan meeting. The following summarizes the results of these reviews and decisions on a path forward for a testing program to be performed in a follow-on phase.

It was generally concluded that the tests should be designed to focus on developing comparative fire suppression performance data between water and water additives. The overall objective is to quantify the improvement when using wetting agents. Development of specific design criteria, hardware requirements and potential listing/approval criteria would be developed after the fundamental performance data is derived in the first testing phase. In the performance comparative tests, agents will likely be premixed so that agent-specific proportioning and equipment details are not variables. Likewise, to the extent possible, generalized spray or sprinkler application techniques will be adopted using a commercially available non-air aspirating spray or sprinkler nozzles. It is assumed that most agents will not require special discharge or proportioning equipment. If so, that would be a limitation when considering that particular agent for an installation.

Scaling was considered, in particular whether smaller scale approaches compared to those described in Section 7 and Appendices B and C, could or should be used. It was concluded that the scale of the tests proposed in Appendices B and C probably represent the low end of the size needed for valid comparative data. Correlation to bench scale tests, particularly related to penetrability, might ultimately be developed. It was also concluded that scaled-up validation tests will likely be required, dependent on the specific scenario.

At least thirty-four agents are available for testing and evaluation. An approach was adopted to limit the agents for testing to an affordable number:

1. Agents should already be UL Listed as a wetting agent; this affords some prior pedigree that the agent has been evaluated for fuel penetration and fire suppression capability;
2. A mix of agents as defined by their published extinguishing mechanisms should be used, including ecapsulators and emulsifiers;
3. Agent produced by any project sponsor should be tested; and
4. Any agent can subsequently be tested if test funding is provided by a manufacturer.

The agents will be tested and reported in a blind manner.

8.2 Class A Tests

The focus of the Sponsors was on coal fire hazards, although the results of testing may have applicability to other deep-seated Class A fires such as grain silos (including the ethanol industry) and rubber manufacturing/storage.

Three coal storage and handling scenarios of interest were discussed:

1. Coal bin/bunker/silo storage;
2. Coal handling via conveyors; and
3. Coal dust control/suppression.

For coal bins, bunkers, or silos, there are currently no design criteria. NFPA 850 provides general manual fire fighting guidance, but no specifics other than the potential positive effects of water additives for penetration of deep-seat coal fires resulting from self-heating. Large volumes of water have significant drawbacks, including:

1. Potential failure to penetrate to the hot spot because of the high water surface tension – water additives will reduce surface tension to improve penetrability;
2. Potential to cause structural failure of the containment facility due to the weight of water;
3. Inadequate protection due to poor water supply capacity;
4. Relatively small deluge zones because of the water discharge rate required - use of less water using an additive might allow more practical and cost effective zoning of fixed deluge systems; and
5. Potential to cause a steam explosion;

The use of a sprinkler at the top of a facility is uncommon. The discharging of air through the dry pipe prior to agent application may create suspended coal dust, susceptible to an explosion. It was concluded that the coal storage scenario of was of primary importance to the Sponsors.

The conveyor situation is not necessarily a coal-in-depth scenario. Water additives would have an advantage compared to plain water if they provide more rapid fire extinguishment. The ignition scenario usually involves a combustible conveyor belt. Even without coal, a minimum sprinkler application rate is required for the belt, e.g., 0.25 gpm/ft^2 as recommended by NFPA 850.

Dust suppression was considered a lower priority at this stage of the project, and will not be explicitly evaluated in the next phase.

It was concluded that the coal-in-depth scenario is appropriate for agent comparative purposes. The moderate scale test apparatus proposed in Figure 2 should be used. The measures of performance will be:

1. Ability of agent to penetrate a coal pile; and
2. Suppression (e.g., cooling of fire temperatures by 90%) and total extinguishment of a deep-seated coal fire. A critical agent application rate (or flux) will be determined, which is the minimum rate need for extinguishment.

The type of coal to be experimentally evaluated was discussed. The three coal types of primary interest are:

1. Bituminous;
2. Sub-bituminous; and
3. Lignite.

There was strong interest to test all three types of coal, since this is a key variable identified in Section 7.4.4. It was recognized that this will add considerably to the initial test costs by essentially tripling the number of tests. It was decided to:

1. Use sub-bituminous for the baseline comparative tests;
2. Obtain the coal from a single source/lot, thereby further reducing variability in the coal characteristics, including geometry; and
3. Use weight/density in the experimental setup as a de facto control of the coal geometry, e.g., each initial test weight should be the same, ± 10%.

Appendix B is predicated on establishing a fixed deep-seated fire scenario. As a baseline measure of performance, non-fire penetration tests will be performed. This will involve application of water and the additives to the coal column as shown in Figure 2. The liquid collected at the bottom of the apparatus as a function of time will provide an indicator of penetrability and, potentially, absorption.

The test plan will be refined to optimize the number of tests:

1. Initial scoping tests will be needed to define the fire size, location, and duration prior to agent application;
2. Water plus one representative agent will be used at three application rates (gpm/ft^2 surface area or gpm/ft^3 of coal volume, TBD) to bound discharge rates; and
3. Tests with additional water additives might be performed using two application rates in order to identify the critical rate.

It is anticipated that these tests will provide a quantitative comparison of water alone compared to water additives. Several scaled-up validation tests may need to be performed to determine if the column height affects the critical agent application determined using the Figure 2 apparatus. These validation tests are not included in the initial test series.

The results should be applicable to coal suppression in the conveyor scenario. It is recognized that a minimum suppression application rate is required for the belt material. While the moderate scale test apparatus might be adapted for a thin coal layer supported by belt material, it was decided to initially forego this specific scenario until after the baseline data is collected.

Given the logistics and environmental considerations for fire testing of coal, conducting tests at an actual coal handling utility site was considered to be the best test site option.

8.3 Class B Fire Tests

The additives provide potential advantages for retrofitting existing systems which have insufficient capacity to achieve the 0.30 gpm/ft^2 water recommendation, and potential reduced water application rates where there are inadequate water supplies.

A number of potential Class B scenarios are described in Appendix C. All scenarios involve a 2D pool fire and 3D running fuel fire. These include:

1. Two generic 3D cascade fire test apparatus within a pan, which will create a 2D pool fire;
2. A simulated transformer mock-up, which included heat fuel; and
3. A multi-deck turbine pedestal mock-up with running fuel and pool fires.

A basic decision was made to use a test mock-up which will provide a generic, comparative analysis between water and water additives, and not replicate an exact installation scenario. It was decided to adopt the cascading fuel apparatus and associated pan/pool fire as shown in Figures 3 and 4. A fixed overhead sprinkler nozzle array will be evaluated, simulating current guidance to provide 0.30 gpm/ft^2 water application to Class B turbine pedestal situations and other associated Class B hazards in a power plant. The test grid will have closely spaced branch lines and blank outlets to readily vary application rate via increased or decreased nozzle spacing. This can also be varied through adjustment of nozzle pressure and/or orifice size. Application rate will be varied to determine the impact on suppression and extinguishment time.

The measure of performance will be 90% control and extinguishment time of the 2D and 3D fires as a function of application rate. A minimum application rate for 2D pool fire extinguishment will be established.

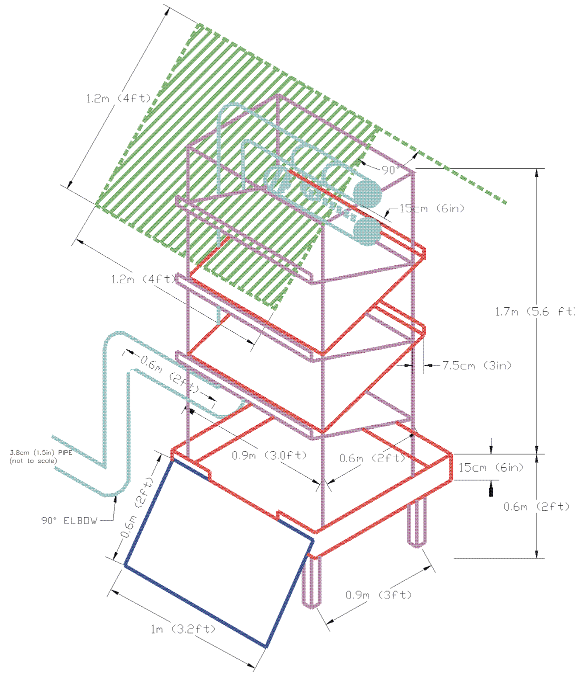

Figure 3 – Cascade fire apparatus, exact dimensions TBD.

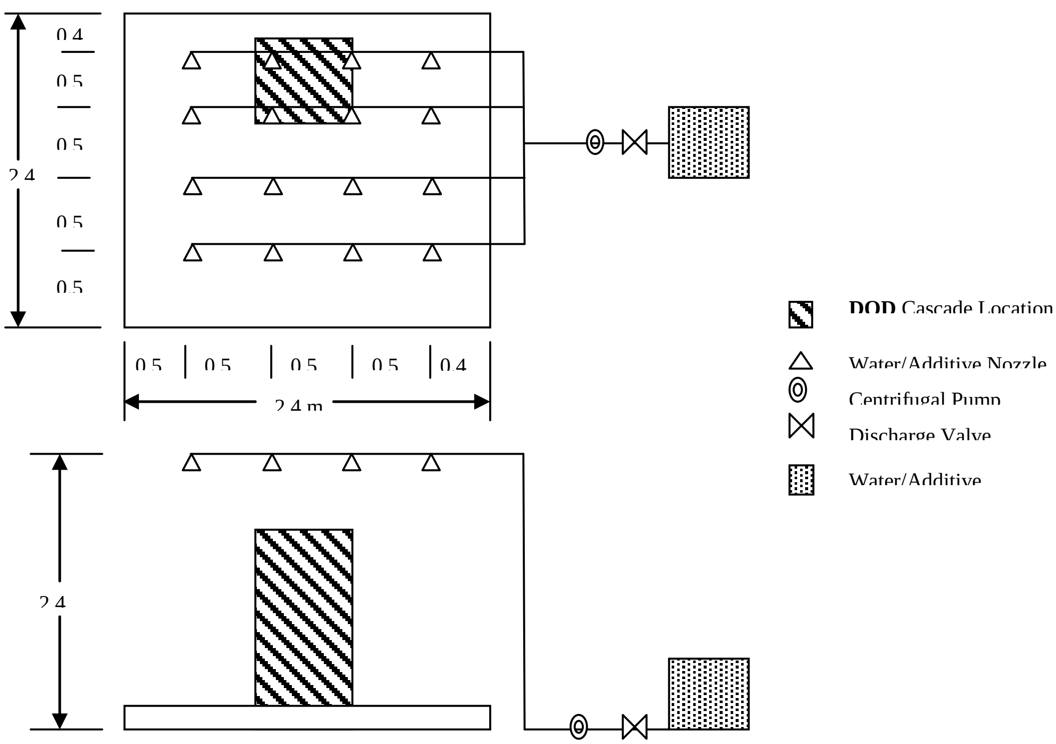

Figure 4 - Class B fire scenario plan and elevation views.

To limit test variables, low flashpoint fuels (less than 100°F) will be eliminated. Diesel fuel (flashpoint ~ 125-140°F) or a similar test fuel will be used to simulate transformer oil, hydraulic oil and lubricating fluid used in power generating and distribution equipment. Likewise, polar solvent fuels will not be investigated, although this is a variable which could be added.

The nozzle array will be fixed at approximately 8 ft above the deck/floor. The data collected should provide direct application to spill/pool scenarios for this height. It is recognized that extinguishing effectiveness is a function of sprinkler height above the floor. Validation tests will likely have to be performed for higher installations, e.g., nozzles installed at heights exceeding 20 ft above the floor.

The Technical Panel was in agreement to maintain the three-dimensional aspect for the test scenario. The effectiveness compared to water is of interest for this challenging scenario. The 3D fire also provides a reignition source for fuel that is extinguished.

A future variation of the system might be nozzles installed only at the perimeter of the test array, simulating a typical NFPA 15 water spray system protecting a transformer.

The agents used will be the same as those used for the coal fire tests.

The tests will likely have to be performed in an enclosed test facility. Outdoor tests might be performed, but they are highly susceptible to wind effects which should be eliminated for test respectability purposes. In real life, wind effects are addressed in the nozzle grid design (inclusion of upwind nozzles).

9.0 SUMMARY OF FINDINGS

Users of water additives have performance criteria for most scenarios of interest, as established by NFPA 18A. Interestingly, NFPA 18A does not address wetting ability or fuel wetting penetration, which is of interest to the Project Technical Panel and Sponsors. Those interested in wetting or penetration (which would be of interest in the coal storage scenario) currently must refer to NFPA 18 or NFPA 1150.

NFPA 18A has a set of screening fire tests for multiple applications. A user could request a test report from each vendor for the applicable fire scenario. Comparison of results from different vendors could allow for evaluation between agents. For Class B two- and three-dimensional fire suppression, two levels of performance are already established and are part of the Listing process. This could be used for comparative purposes, without the need to access individual test reports.

The current limitations of NFPA 18A are:

- No agents are listed/tested to this standard, so no comparison is readily available
- For at least one scenario of interest, suppression of deep-seated Class A fires, only the wood crib and wood panel fire tests are used, with no comparison to plain water. There is no assessment of water penetration or surface tension reduction. The current NFPA 18 and 1150 standards have assessment methods for this scenario.

- Except for Class B pool fire suppression, where scalability has been demonstrated, there is no demonstrated correlation between the small scale tests specified in NFPA 18A and real life scenarios of interest. The Class A tests provide an assessment of the magnitude of fire that can be suppressed. The Class B three dimensional test, which could be considered at or near full scale, has no basis of comparison, e.g., with an alternative agent such as water, dry chemical, CO_2, AFFF, or clean agent.

The scalability of the NFPA 18 and 1150 wetting agent test methods to real scale fire problems is unclear. The relative improvement of the wetting agents (and some water additives) on Class A fire scenarios has some (but not unequivocal) basis in larger scale fire testing, as demonstrated in the literature review. The practical value of such an improvement is left to the user to decide.

As with the initial technical challenge to create a separate standard for water additives, it is not always clear what the differences are between wetting agents and water additives for practical, real scale scenarios. In an effort to eliminate performance which is based on chemical/physical descriptions, levels of fire performance are proposed. NFPA 18A has established levels of performance for Class B 2D and 3D fire scenarios.

Based on the available data and the interests of the Sponsors and Technical Panel, a plan was developed to test representative water additives with fire scenarios of interest. These include a Class A deep-seated coal and combined 2D/3D Class B scenarios. The Class A coal scenario is a moderate scale adaptation of coal storage bin/bunker/silo scenarios. Validation tests might have to be performed to determine if real-scale storage height affects the findings from the moderate scale tests.

The combined 2D/3D fire test scenario was selected based on demonstrated scalability of the 2D fire, and demonstrated experience with the 3D fuel cascade mockup. The criteria derived from initial tests may have to be adjusted for the installation height of sprinklers.

Representative water additives will be selected for testing. Their performance will be compared directly with that of water, to quantify the performance improvement when additives are used. No attempt will be made at this time to define the physio-chemical properties of any particular agent, such as encapsulation. Rather, the comparison will be made directly on fire-cooling, suppression, and extinguishment performance.

10.0 REFERENCES

Frank, J.A., “Characteristics and Hazards of Water and Water Additive for Fire Suppression,” *National Fire Protection Handbook,* 20th Edition, 2008, Quincy, MA, pp. 17-31–17-43.

Back, G.G., Parker, A.J., Scheffey, J.L., Williams, F.W., Gott, S.E. and Tabet, R.J., “Effects of Water Sprinklers on the Low Level AFFF Aircraft Hangar Fire Suppression Systems,” Naval Research Laboratory Report NRL/MR/6180-00-8456, Washington, DC, May 22, 2000.

Madrzykowski, D., "Water Additives for Increased Efficiency of Fire Protection and Suppression." Fire Detection, Fire Extinguishment and Fire Safety Engineering pp. 6 Tokyo, Japan 1998.

Scheffey, J.L. and Wright, J.A., "Analysis of Test Criteria for Specifying Foam Firefighting Agents for Aircraft Rescue and Firefighting," FAA Technical Report, DOT/FAA/ CT-94/04, Atlantic City, NJ, August 1994.

Scheffey, J.L. and Williams, F.W., "The Extinguishment of Fires Using Low Flow Water Hose Streams -Part II," Fire Technology, 27 (4), November 1991.

Schultz, Harry E., III, and Richards, Robert C., "Suppression Methods for Deep Seated Coal Fires," Report Number CG-M-2-90, United States Coast Guard, Washington, D.C., March 1990.

Kim, A. and Crampton, G., " Compressed Air Foam (CAF) System for Fire Protection of Power Transformers." *Fire Suppression and Detection Research Application Symposium,* Fire Protection Research Foundation, Quincy, MA, pp. 8 2006

APPENDIX A – LITERATURE SEARCH

A.1 Bosley, Kirsty, “Water Additives for Fighting Class A Fires: Summary Report.” Fire Research and Development Group 1997

This report was meant to summarize tests conducted in 1995 and 1996 on Class A water additives. Both of the studies tested roughly 11 additives each against the control – water. Surprisingly, both of the studies found that there was no considerable improvement of extinguishment due to the use of the Class A additives. This study contradicts some other studies that found that Class A additives do, in fact, increase fire fighting performance; this may be because most of the positive studies used water misting nozzle along with the additive, while this series of tests used a hose reel to deliver the additive.

A.2 Bowes, P. and Skeet, G., "The Use of Wetting Agents for Firefighting II: The Extinction of Fires in Fibrous Materials." pp. 18 1955

This study looks at how effective “wet water” is against smoldering and more deep-seated fires. The wetting agent used was an aqueous solution of an alkyl-phenyl substituted polyethylene glycol and was used at a dilution containing 2% by volume. The investigation used various types of ignition on bundles of straw and applied the water or agent via stationary nozzles. The investigation found that the extinction of the fire depended on the penetration of the applied water into the bale. They found that the wet water was more effective than the plain water in more tightly packed bales of straw, while there was no difference in the loosely packed bales. The investigators attribute this increased wet water effect to the fact that plain water cannot easily penetrate the more tightly packed straw.

A.3 Boyd, C. F.; diMarzo, M., "Fire Protection Foam Behavior in a Radiative Environment." September 1995-September 1996. Maryland Univ., College Park, National Institute of Standards and Technology, Gaithersburg, MD, NIST GCR 96-702; 182 p. October 1996.

This study created experiments to predict the behavior of a protein based foam subjected to radiation. They found that the temperature gradient is not strongly affected by the applied heat flux and it decreases with an increasing foam expansion ratio.

A.4 Chang, W., Fu, P., Chen, C., and Shu, Y., "Evaluating the Performance of a Portable Water-Mist Fire Extinguishing System with Additives." Fire and Materials (Volume 32, Number 7) 2008 pp. 15

This study investigates how high-pressure water–mist system discharge methodologies influence the fire extinction performance for pan pool fires (heptanes, gasoline, or diesel) and the corresponding mechanisms of restraining fire. The fire source is a pool-fire burner. Fine water spray is injected using a portable device. The additive in the water–mist consists of 97% fire-retardant, 1.8% surfactant, 0.6% mint, and 0.6% camphor. The additive forms a thin layer of foamy film on the fuel source when sprayed from the nozzle. The study found that the nozzle discharge angle and additive solution volume played a significant role in fire extinction. It concluded that mist system with the additive was very effective in extinguishing Class A, Class B, and motorcycle and car fires.

A.5 Chien, Wendy S., Grosshandler, William L., King, Michelle D., Yang, Jiann C., “Evaporation of a Small Water Droplet Containing an Additive.” Proceedings of the ASME National Heat Transfer Conference Baltimore, Maryland 1997

This study evaluated the evaporation of a water droplet containing either potassium acetate and sodium iodide. The experiment used a stainless steel hot plate to generate temperatures between 50^{o}C and 100^{o}C in order to evaluate the evaporation rates of the droplets. Ultimately, the study found that the addition of the salts decreased the average evaporation rates (and as the concentration of the salt increases, the evaporation rate continues to decrease). As the study points out, this can be effective in fighting fire if the droplets fully penetrate the fire plume and reach the fire, but it can be counterproductive is the droplets fail to reach the fire and are deflected away.

A.6 Crampton, G., Kim, A., and Richardson, J., "A New Fire Suppression Technology Introducing Fixed-Pipe Compressed Air Foam Systems, an Important Innovation in Fire Suppression System Design." NFPA Journal 1999 pp. 6

The need for this study arose when the limitations of fixed-pipe foam systems were realized. In response, this study sought to examine how well CAF can be delivered through a fixed-pipe system and how effective Class A foam would be against pool fires. They found that the Class A foam performed well in both their open and closed space tests – even when the fire was shielded from direct CAF spray.

A.7 Dlugogorski, B. and Kim, A., "Multipurpose Overhead Compressed-Air Foam System and Its Fire Suppression Performance." Journal of Fire Protection Engineering 1997 pp. 133-150

This study looks at the efficacy of an overhead fixed-pipe CAF system. They created experiments to evaluate how well CAF systems suppressed Class A and Class B fires and then compared its performance to water mist and sprinkler installations. It found that the CAF system outperformed water mist and sprinkler systems when extinguishing wood crib fires, while it was as effective as the water mist system at extinguishing flammable liquid pool fires.

A.8 Huang, X., Wang, X., Jin, X., Liao, G., and Qin, J., "Fire Protection of Heritage Structures: Use of a Portable Water Mist System under High-Altitude Conditions." Journal of Fire Sciences 2007 pp. 23

In order to verify the application of water mist on fire protection of the Potala Palace in Tibet and deepen the knowledge of its suppression mechanisms under high-altitude conditions, a series of experiments were performed with a portable water mist fire protection system and with diesel oil, gasoline and, in Lhasa, ghee as fuels. All of the experimental tests were conducted with and without multicomposition (MC) additives. In all of the tests, the MC additive allowed for improved extinguishing times. Also, the higher altitude negatively affected extinguishment.

A.9 Ishida, H. and Watanabe, H., "Flame Suppression over Liquid Pool by W/O Emulsification." Combustion Science and Technology (Volume 71, Issues 1-3) 1990 pp. 10

This study examined the suppression of flame spread over an oil pool with a water-in-oil (2-10% water) type emulsification. The effects by the emulsification on flash point, the velocity of the flame spread over the pool, and on the development of preceding surface flow ahead of the flame's leading edge was investigated. It was found that the flash point of the oil emulsification rises 2-4^{o}C as a result of the increase in water content. Also, the flame spread velocity over the pool is 1/2~2/3 of the velocity with the original oil pool. It was concluded that the suppression of flame spread with the emulsification is a result of the rise in flash point and the increase in heat loss through the emulsion.

A.10 Jones, J., Hughes, K., and Wearing, H., "On the Action of Wetting Agents in the Extinction of Wood Fires." Journal of Fire Sciences (Volume 10, Issue 1) 1992 pp. 8

This investigation examined how well three different wetting agents could extinguish a wood fire. The parameter that was being tested was how fast the temperature of the fire could return to ambient temperature. This experiment utilized basket heating of 88 grams of wood shavings to a temperature of 555K. At this temperature, the water/wetting agent mix was admitted via a nozzle and peristaltic pump to the basket of wood. The three different agents used Nonyl Phenol Ethylene Oxide (A), Nonyl Phenol Ethylene Oxide and Dioctyl Sodium Sulphosuccinate (B), and Alcohol Alkoxylate (C). They found that Agent C allowed for the fastest cooling out of the three agents, followed by B and A. In fact, Agent C took almost half as long as plain water did to return to the fire to ambient temperature.

A.11 Jordan, K., Thorne, P. F., "Preliminary Experiments on the Use of Water Additives for Friction Reduction in Fire Hose." Fire Research Notes 959 Borehamwood, England 1973

This study investigated the use of polyethylene oxide (PEO) and its effects on the drag of water flowing through a fire hose. At first, the study examines the theory behind friction reducing additives via the Reynolds number and other fluid dynamics applications. The experimental aspect of the study found that a "rough" fire hose stands to benefit the most from an additive like PEO, as its friction factor reduces by about 46%. This additive does not help with the actual extinguishment of the fire itself, but it can help in the physical fire fighting aspect.

A.12 Kim, A.; Crampton, G., "Evaluation of the Fire Suppression Effectiveness of Manually Applied Compressed-Air Foam (CAF) System." National Research Council of Canada, Ottawa, Ontario, Suppression and Detection Research Application: A Technical Working Conference. SUPDET 2009. Proceedings. Fire Protection Research Foundation. February 24-27, 2009, Orlando, FL, 43-45 pp, 2009

The investigators aimed to systematically evaluate the effectiveness of a mobile CAF system versus an ordinary stream of water or foam from a hose. Full scale compartment (4.26 x 3.65 x 2.44 m) fires with adequate ventilation were created for this experiment. Tests revealed that the temperature measurements and the amount of water used were the most useful data for determining suppression effectiveness. They found that, using 200^{o}C as a benchmark critical temperature, the CAF system cooled the compartment the fastest, followed by the foam-water, followed by the water alone. Also, the CAF used much less water to control the fire – 6 gallons versus 30 gallons for water alone.

A.13 Kim, A., Dlugogorski, B., and Mawhinney, J., "The Effect of Foam Additives on the Fire Suppression Efficiency of Water Mist." Halon Options Technical Working Conference - HOTWC pp. 12 Albuquerque, New Mexico 1994

This study investigated the use of film-forming and foam-forming agents against crib fires, and heptane, and diesel pool fires. Against pool fires, a small quantity of Class A or B foam concentrates greatly improved the performance of the water mist system. For the crib fire, a small amount of foam additive to the water mist system did not affect the performance. It is postulated that a thick foam blanket on the crib surface is required to stop the burning and improve performance.

A.14 LeBlanc, D., "Localized Protection of Flammable Liquid Hazards Utilizing Water Mist Nozzles with an AFFF Additive." The Fire Protection Research Foundation 4th Fire Suppression and Detection Symposium pp. 11 Orlando, Florida 2000

The study tested different mist nozzles using 3% AFFF extinguishing capabilities against various spray and pool fires. It found that in all cases where a mist nozzle with AFFF was used, both the pool and spray fires were successfully extinguished, while no case of water alone was capable of extinguishing the fires.

A.15 Madrzykowski, D., "Water Additives for Increased Efficiency of Fire Protection and Suppression." Proceedings of the 14th Joint Panel Meeting of the UJNR Panel on Fire Research and Safety pp. 6 Tsukuba, Japan 1998

This study tested the performance of four separate water additives (mostly foam-forming). They investigated the characteristics of each of the additives on a laboratory scale including: specific heat, drop size, cooling and penetration, contact angle, mass retention, and ignition inhibition. Large scale wood crib and tire fire tests were also conducted. An important finding of this study was that the application of the additives did not affect the chemical composition or size distribution of the soot particles that were formed. Overall, the study concluded that the reduced surface tension and increased contact with the fuel provide for increased fuel cooling and wetting.

A.16 Manzello, Samuel L. and Yang, Jiann C., "On the Collision Dynamics of a Water Droplet Containing an Additive on a Heated Solid Surface." Proceedings of the Royal Society (Volume 458, Issue 2026) London 2002 pp. 2417-2444

This study examined water-droplet impingement containing 30% sodium acetate trihydrate upon a stainless-steel surface. The collision dynamics of the droplet on various temperature surfaces were examined using a high-speed digital camera and compared to the dynamics of a droplet without the additive. The study found that, for surface temperatures below 140^{o}C, the evaporation lifetime of the droplets with the additive were considerably longer than those without the additive. Also, they found that as the Weber number increased, the presence of the salt appeared to have less influence on the evaporation lifetime of the droplet. This is important because most fire suppression applications are expected to have a higher impact We.

A.17 Schlobohm, Paul, and Rochna, Ron. "Foam as a Fire Suppressant: An Evaluation." Wildland Fire 2000 1987 pp. 226

This study evaluated the effectiveness of various foaming systems and agents against Class A fires. It was found that the combination of synthetic foaming agents and the CAFS was the most powerful tool they tested. The “fine-bubbled mist” and long discharge distances that were unique to the CAFS made it especially effective.

A.18 Shou-Ping, Hsu, Kee-Chiang, Chung, “The Effect of Additive on the Fire Extinguishing Improvement of Water Mist Spray.” Journal of Applied Fire Science (Volume 14, Issue 1) 2005 pp. 1-11

This experiment tested the efficiency of a water mist additive at varying droplet sizes (500 µm and 200 µm) and concentrations (5% - 25%). The additive used is not explicitly named, only that it is an “environmentally friendly” one. A heptanes pool fire was used as the sole fire source for the investigation. The study found that the additive had a positive impact on the extinguishment times. Surprisingly, it also found that the larger droplet sized mist with the additive had the better extinguishment times than the smaller droplet sizes, which is something that was not evaluated by other studies.

A.19 Tafreshi, A. M.; diMarzo, M.; Floyd, R.; Wang, S. , "Fire Protection Foam Thermal Physical Properties."June 1996-July 1997. Maryland Univ., College Park, National Institute of Standards and Technology, Gaithersburg, MD, NIST GCR 98-742; 110 p. March 1998.

This study made an effort to establish a testing procedure to evaluate the relevant properties of fire protection foam. The investigators tested five different foams - four synthetic hydrocarbon based foams and one protein based foam. They aimed to study the physical characteristics of the foam (bubble structure and conditions) and the thermal properties of the foam (thermal expansion coefficient, thermal diffusivity, radiation absorption). Thermal expansion was evaluated by putting the foams in a convection oven; it was found that the high expansion foams have a lower thermal expansion than low expansion foams. The thermal diffusivity was found to be the same for all the foams. And, the radiative absorption coefficient was found by exposing the foam to a radiative heat source and measuring the transmitted radiation; they found that ultimate goal is not to have a foam the reflects and scatters the best, or absorbs the best, but one that has the best combination of the factors which will protect a structure the best.

A.20 Torero, J., Olenick, S., Garo, J., and Vantelon, J., "Determination of the Burning Characteristics of a Slick of Oil on Water." Spill Science and Technology Bulletin (Volume 8, Issue 4) 2003 pp. 23

In this study, they examined the burning rate of an oil slick on water. They also conducted experiments (closed cup test) to back up their theoretical claims – one with emulsified oil and one with weathered crude oil. They found that, for emulsified oils, water addition results in a linear decrease in the efficiency of the ignition.

A.21 Wallace, Sean, “F-500 Encapsulator Technology: Sprinkler/Spray System Applications.” Dominion Corporate Risk Engineering, Virginia 2010

This study experimentally tested F-500 being discharged from a single sprinkler on a Class B fire against a control of plain water. The experimenters used two different sized pans for the diesel fires – a 4' x 4' pan and a 10' x 12' pan. To allow for equal measurements, the fires were allowed to preburn to a temperature around 1,200^{o}F for the small pan, and 1,500^{o}F for the large pan. The investigation found that the F-500 greatly reduced extinguishment times and the amount of water used to extinguish the fire. The greatest reduction occurred at a density of 0.20 gpm/ft^2, where the water required 113 seconds and 75.3 gallons, while the F-500 required only 13 seconds and 9 gallons of water to extinguish the fire; this is a great improvement in the efficiency of water.

A.22 Xiaomeng, Z., Guangxuan, L., and Bo, C., "Improvement Of Water Mist's Fire-extinguishing Efficiency With Mc Additive." Fire Safety Journal (Volume 41, Issue 1) 2006 pp. 39-45

In this study, experiments are conducted to test the effect of MC (multi-composition) additive to water mist's fire extinguishing efficiency of an ethanol fire, a diesel fire, and a wood crib fire. The MC additive consists of sodium acetate, a carbamide, and N-dimethylformamide. This additive allows a thin layer of film to form on the pool or wood surface. Ultimately, the study found that when the content of MC is 0.8 wt% for crib fires and 0.2 wt% for the pool fires, the fire extinguishing is at optimum efficiency. They found that the MC additive greatly improves the fire extinguishing efficiency of the mist system. At a concentration of 0.20% by weight, the MC additive extinguished the diesel pool fire and the ethanol pool fire in 1.75 and 4.8 seconds, respectively, while water extinguishing times were 10 and 27 seconds, respectively. In the case of the wood crib fire, the additive extinguished the fire in 5.7 seconds at a concentration of 0.8%, while water took 32 seconds.

A.23 Zhang, J., Delichatsios, M., and O'Neill, A., "Assessment of Gas Cooling Capabilities of Compressed Air Foam Systems in Fuel and Ventilation Controlled Compartment Fires." Journal of Fire Sciences (Volume 29, Issue 6) 2011 pp. 12
This study aimed to assess the cooling capabilities of CAFS compared to water mist suppression in fuel and ventilation-controlled compartment fires. For the tests, they used wooden pallets and clip boards to provide a realistic fire environment. They found that, for fuel-controlled environments, the CAFS was far superior to the water mist as it reduces the temperatures more substantially. For ventilation-controlled scenarios, little difference was observed in the suppression effectiveness between the CAFS and water mist.

A.24 Zhao, Dao-ling, Lian, Feng, Liu, Ying-xuel, "Experimental Research on Low Pressure Water Mist Extinguishing Systems in Cookroom with Micelle Encapsulator Additive." Journal of Safety Science and Technology Shanghai, China 2009

This study used a water mist system along with the F-500 additive. They found that, while the low pressure mist system can extinguish the cooking oil fire, re-ignition occurs frequently. However, with the F-500 additive, the extinguishment times were found to be three to ten times faster, without the possibility of re-ignition.

A.25 Coal Fire Fighting: From Bunker Fire Fighting Guidelines and PRB Coal Users Group (membership required for access)

- Names micelle-encapsulators as the agent of choice for Powder River Basin (PRB) coal fires because of its ability to reduce water's surface tension, micelle formation, and free radical interruption
- It's recommended that a concentration of 0.5-1.0% is used to extinguish a coal fire
- F-500 is somewhere in the middle between foam and a wetting agent.
- Experiments done by Clemson University found that F-500 was much more effective than foam in dissipating the heat
- The micelle mechanism in F-500 works as a result of being an amphipathic molecule

A.26 Teacoach, l., and Thomas, R., "Evaluation of Novel Fire Suppression Systems for Conveyor Belt Fires in Underground Coal Mines", *Proceedings of the Seventh International Seminar on Fire and Explosion Hazards,(ISFEH7),* pp453-462, Research Publishing, 2013

Tests were conducted by NIOSH on water gel additives applied through a standard sprinkler system used for conveyor belt protection. The fire scenario was a belt fire. Foam and water mist were also evaluated. The results were compared against baseline tests using water. The general conclusion was that the three novel fire suppression systems were no more efficient than water. Ventilation, water supply, and sprinkler nozzle placement were found to be key factors.

APPENDIX B – DEEP SEATED COAL FIRE SCENARIO DRAFT TEST PLAN

B1.0. DEEP SEATED COAL FIRE

The Class A coal fire represents a challenging deep seated fire with real life applications. Coal stored for use in power generation facilities are subject to self-heating and potential combustion. The encountered fires are deep seated and difficult to extinguish.

During these tests, water and representative additives would be applied from on top of a suspended drum containing the coal fire. The flow rate of the water or water plus additive would be varied over successive tests utilizing a bracketing technique to determine the minimum flow rate required to extinguish the fire within, say, 2 minutes of the start of the agent application.

B2.0. APPARATUS

This apparatus consists of a 208 L (55 gal) steel drum suspended 25 cm (10 in) above a water collection pan. The top and bottom of the drum will be removed with a screen supported with an angle iron cross brace installed on the bottom of the drum to support the coal. The 10 cm (4 in) gap between the elevation of the lip of the pan and the bottom of the drum will allow for the free flow air to supply the fuel combustion and to allow the water or water with additive to drain from the drum.

The drum would be filled with coal to a level 10 cm (4 in) from the top of the drum. The space at the top of the drum would prevent the overflow of the water or water with additive from the top of the drum. The coal to be utilized for these tests should come from the same source for all of the tests to be conducted to ensure that the variation in coal supply does not influence the evaluation. At least initially, a single coal size would be used; for example, a range of 0.8 to 1.4 cm (0.3 to 0.6 in) “Buck” size. The coal pile would be ignited with a tubular heater inserted 20 cm (8 in) from the bottom of the coal layer. Thermocouples would be inserted into the coal to monitor the coal combustion.

The water or water with additive would be discharged from a pressurized 75 L (20 gal) tank. A quarter turn ball valve on the tank outlet would control the flow of the agent. The agent would flow from the tank and discharge onto the top of the coal pile from a nozzle suspended 27 cm (11 in) above the top of the coal pile with a nozzle with a 90^{o} full cone pattern. If a nozzle with a different spray pattern is used, then the height of the nozzle will be adjusted to achieve full coverage over the top surface of the coal pile. The tank would be pressurized with nitrogen utilizing a commercial nitrogen cylinder with a pressure regulator installed on the outlet of the cylinder.

The square water collection pan would have nominal dimensions of 71 cm (28 in) on a side with a depth of 15 cm (6 in) designed to contain the maximum of 75 L (20 gal) of water to be discharged during a test.

The apparatus is shown in Figure B1.

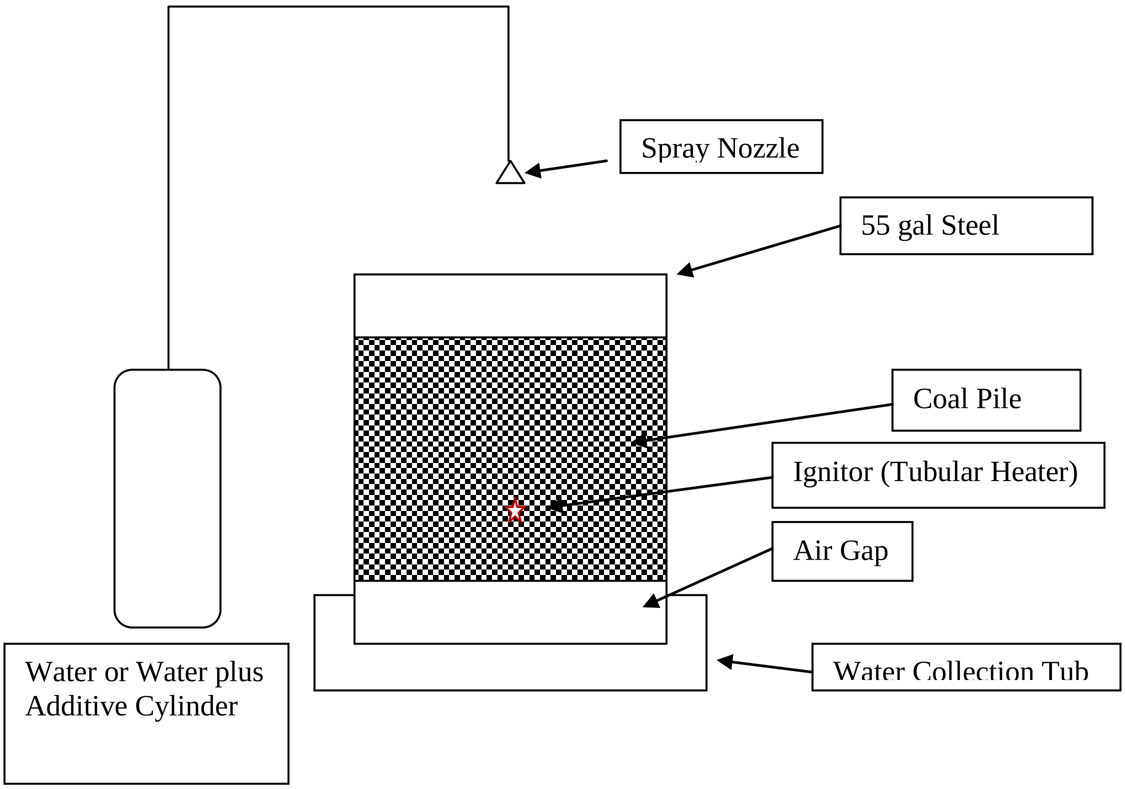

Figure B1 – Coal Fire Apparatus

B3.0. TEST PROCEDURE

The steel drum would be filled with coal to a level 10 cm (4 in) from the top of the drum and the tubular heater connected to the power supply.

The agent tank would be filled with water or water plus additive and pressurized with nitrogen. The outlet of the tank would be connected to the discharge piping leading to the desired nozzle. The water collection pan would be located below the steel drum

The tubular heater would be energized and the thermocouples monitored for signs of combustion. The application of the water or water with additive would be started 1 minute after the observation of visible smoke above the coal pile.

The water application would be stopped and the test concluded when there are no signs of continued combustion (smoke or raised temperatures).

The duration of the water application and the application rate would be recorded.

The steel drum and the water collection pan would then be emptied and dried in preparation for the next test.

B4.0. TEST RESULTS

The minimum application rate required to cause extinguishment would be determined utilizing a bracketing technique. The determined application rate requirements determined for the additives could then be compared to that required for water alone to illustrate the performance enhancement due to the use of the additive.

B5.0. TEST MATRIX

A total of 36-50 tests are estimated to be conducted with the coal fire apparatus. This is based on five tests to successfully bracket the minimum flow rate requirement for each of the additives to be tested and for water itself, with six tests to be used for confirmation of the determined requirements. Several tests will be needed to develop the fire scenario.

APPENDIX C – CLASS B FIRE SCENARIOS

C1.0 BACKGROUND

The Technical Panel and Sponsors desire a 3D Class B fire combined with a 2D pool fire to test fixed systems discharging water with additives. Preferably, a test article/protocol which establishes design parameters would be created. At this point of the study, performance differences between additives and plain water, e.g., for transformer or generator scenarios, has yet to be established. The goal of initial Class B tests is to identify these performance differences:

- Through reduced extinguishment time (where agent discharge rates relatively equal)
- Through reduced agent quantity (where extinguishment times relatively equal)

A range of three dimensional fire scenarios which could be used to test fixed systems were evaluated. Advantages and disadvantages of each approach are outlined in Table C1.

There are some basic assumptions and parameters affecting all potential test scenarios. A 2D pool fire of some size will be associated with the 3D fire. It is the intent to prevent the 2D fire from dominating the scenario; some size catch basin will be required. Each potential scenario must have a piping grid with maximum flexibility (for nozzle and/or nozzle spacing variation). An example grid is shown in Figure C1. At this point, none of the current configurations are set up with a variable grid.

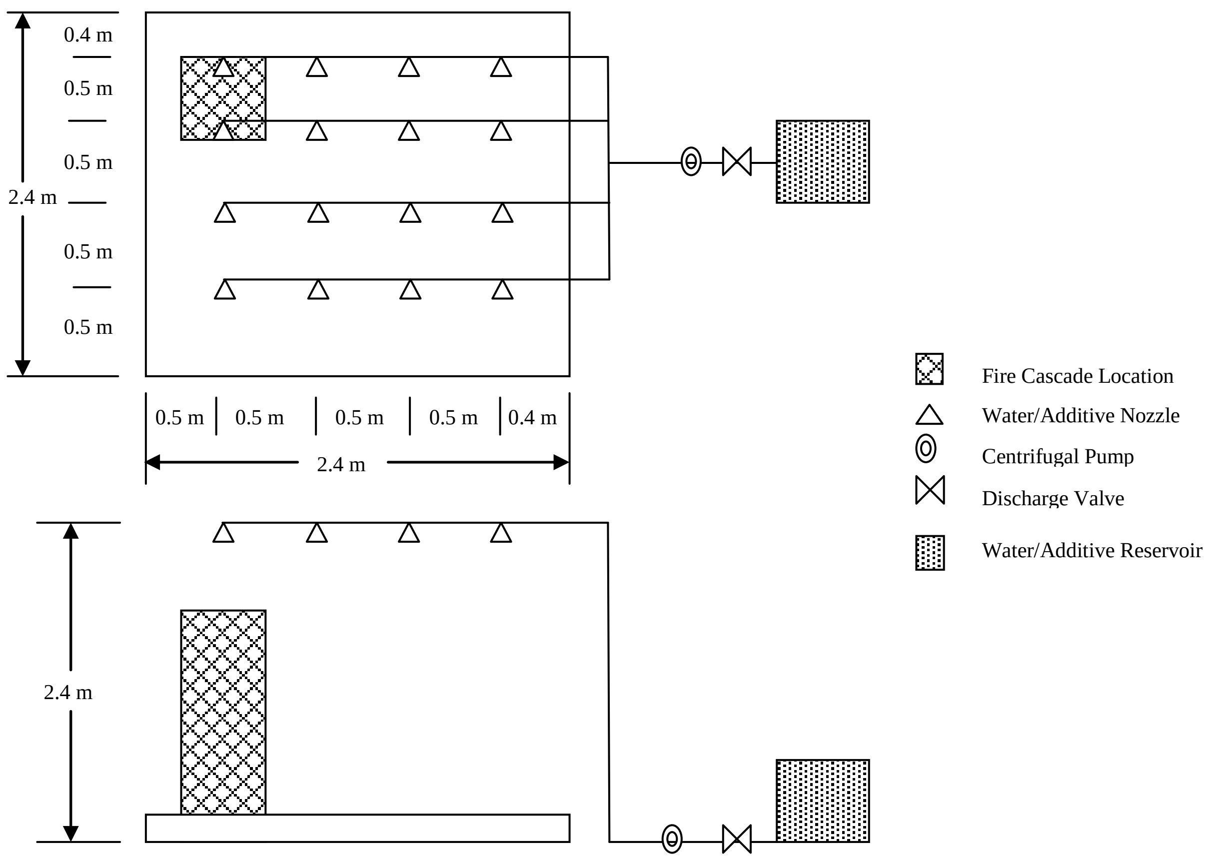

Figure C1 – Example nozzle array configuration

Table C1 – Test Scenario

Attributes	18A #1	DoD Cascade #2	NRCC Transformer #3	FM Turbine #4
Fuel flow rate (gpm)	3.5 gpm	2.5- 12 gpm	21 gpm	6-10 gpm
Availability of Apparatus	FAA?	NRL/Hughes	NRCC?	FM
Repeatability/Use	Proposed – no data reported in the public domain	Many Navy manual & fixed fire tests – good repeatability	6 tests described in reference	23 tests reported, only 2 with cascade scenario
Pro	Recognized in NFPA 18A Detail apparatus specs in Annex D of NFPA 18A Use of scenario already referenced in 18A	Has been successfully used to investigate 3D challenges; fairly cost effective	Simulates transformer at regional scale	Most challenging/realistic
Con	Vertical tower specified to be cooled	Does not directly simulate any particular scenario	Higher cost?	Water can't extinguish all scenarios (pool yes, 3D no) High water flow rates Very high cost

Each scenario could potentially use variable fuels. Testing should probably start with a higher flashpoint fuel (diesel, kerosene, transformer oil). Standard test fuels such as diesel or kerosene are likely less expensive than transformer or lube oils. Consideration should be given to testing a lower flashpoint fuel.

These tests could be conducted indoors or outdoors. Wind is the primary limitation for outdoor testing. Indoor testing would likely incur greater facility costs, but be more controllable. The larger the scale of the testing, the greater the facility cost (and the smaller the number of facilities which could actually perform the experiment).

The potential scenarios include:

1. NFPA 18A 3D Cascade
    a. Reference: NFPA 18A
    b. Attributes:
        i. 6ft tall cascade within 6 ft x 6 ft x 12 in. pan
        ii. 3.5 gpm running fuel fire; fuel is a variable (Jet A for aviation; heptane for industrial; any fuel could be used)
        iii. Outdoors permitted; max. 8 kph
        iv. Vertical tower specified to be water cooled; < 38°C before test
        v. 5 gal pool; 45 second preburn;
        vi. Designed for manual agent application but could be adapted with overhead grid
    c. Fire extinguishing performance – unknown, no public domain literature (or limited); presumably large portable dry chemical extinguishers can extinguish this fire
2. DoD 3D Cascade
    a. Reference: Back, G.G, Parker, A.J., Scheffey, J.L., Williams, F.W., Gott, J.E., and Tabet, R.J. "Effects of Water Sprinklers on the Performance of Low Level AFFF Aircraft Hangar Fire Suppression Systems," NRL/MR/6180--00-8456, Naval Research Laboratory, Washington, DC, May 22, 2000.
    b. Attributes:
        i. Several variations have been used
        ii. Example - 6ft high with 3 ft x 3 ft igniter pan underneath
        iii. 2.5 – 12 gpm fuel flow typically used; marine diesel, JP-5 or JP-8 typically used; heptane can be used;
        iv. Containment pan can be variable size.
    c. Fire extinguishment – large (~100 gpm) handlines can extinguish; overhead AFFF sprinklers cannot extinguish 3D fire, even at high rates.
3. NRCC Transformer
    a. Reference: Kim, A. and Crampton, G., “Compressed-Air Foam (CAF) System for Fire Protection of Power Transformers, SUPDET, 2006
    b. Attributes:
        i. Transformer mockup 3.9 m x 1.2 m x 3 m high, with simulated oil reservoir on top

ii. Transformer oil fed from 205 l (55 gal) heated drum to pan on top of mock-up, which then apparently spills over the side
iii. Placed within 2.44 x ~5 m collection pan
iv. Initiating fire pan on top of transformer
v. 21 gpm electrical insulating oil heated to 74°C used to create 3D cascading fire
vi. Nozzle grid used to create water spray and CAFS protection system (details of grid unavailable)
vii. 1.5 min preburn
viii. Conducted indoors at NRC

c. Fire performance – CAFS at 17.5 – 48.8 gpm total flow provided more rapid suppression (generally < 1.5 min control time) compared to water spray at 240 gpm total flow (2 min control time)

4. FM Turbine
   a. Reference: Lebranc, J., and Wieczorck, C., "Large Scale Fire Tests of Oil Systems in Power Generation Facilities," NFPA World Safety Conference, June 6, 2006.
   b. Attributes:
      i. Lube oil tank (10 x 7 x 12 ft) within containment area (24 ft x 12 ft X 3 ft)
      ii. Two-story turbine and pedestal (20 ft x 15 ft x 18 ft) with grated walkway
      iii. Conducted indoors – 60 ft ceiling
      iv. 20 gpm/90 psi spray fire, 6-10 gpm two-dimensional spill, and 136 gal or 62 pool fires conducted
      v. Water sprinkler systems tested
   c. Fire performance – Using very high flow water sprinklers/spray, pool fires can be extinguished; 3D fires might be controlled but not extinguished.

C2.0 TEST PLAN OUTLINE

C2.1 NFPA 18A Fuel Cascade

Fuel cascades represent a significant challenge to water and water with additives. The disturbance of the fuel surface and continuous addition of burning fuel provide re-ignition sources that challenge any additive build-up on the fuel surface.

During these tests, water and the five representative additives would be applied from a four by four nozzle array located above and in front of the fuel cascade. The minimum flow rate required to cause extinguishment would be determined utilizing a bracketing technique with the flow rate varied between successive tests. The performance enhancement associated with the additives would be evaluated by comparison of the determined flow rate requirements with the requirements determined for water alone.

This evaluation would be initially conducted with a higher flash point fuel, e.g., No. 2 diesel.

C2.1.1 Apparatus

The NFPA 18A fuel cascade consists of a 0.61 m (2 ft) fuel pan on top of a 1.8 m (6 ft) tower. Ten holes on the two forward sides of pan allow for the fuel to flow down the front of the apparatus through a series of seven trays, each one extending 2.8 cm (1.12 in) further out than the tray above it, until reaching a 2.4 m (8 ft) square pan at the base of the tower. This apparatus is shown in Figure C2. It may be decided to center the cascade in the middle of the pan.

Figure C2 – NFPA18A fuel cascade.

Fuel is added to the pan at the top of the tower at a nominal rate of 13.25 LPM (3.5 gpm) resulting in a fire size of approximately 6.6 MW with n-heptane. The fuel would be drawn from a pressurized tank. The tank would be pressurized with nitrogen utilizing a commercial nitrogen cylinder with a pressure regulator installed on the outlet of the cylinder.

The tower itself is filled with water below the fuel pan with a small water flow during the conduction of the test.

C2.1.2 Water and Water with Additive System

The water or water with additives will be applied from an overhead grid of nozzles. The nominal 4 x 4 array of would be centered in front of the cascade apparatus over the collection pan. The water or water with additive would be pumped from a 1040 L (275 gal) reservoir to feed the nozzle array. This corresponds to a maximum total flow rate of 208 LPM (55 gpm) of water or water with additive over a 5 minute application time period. The nozzle array is shown schematically in Figure C3.

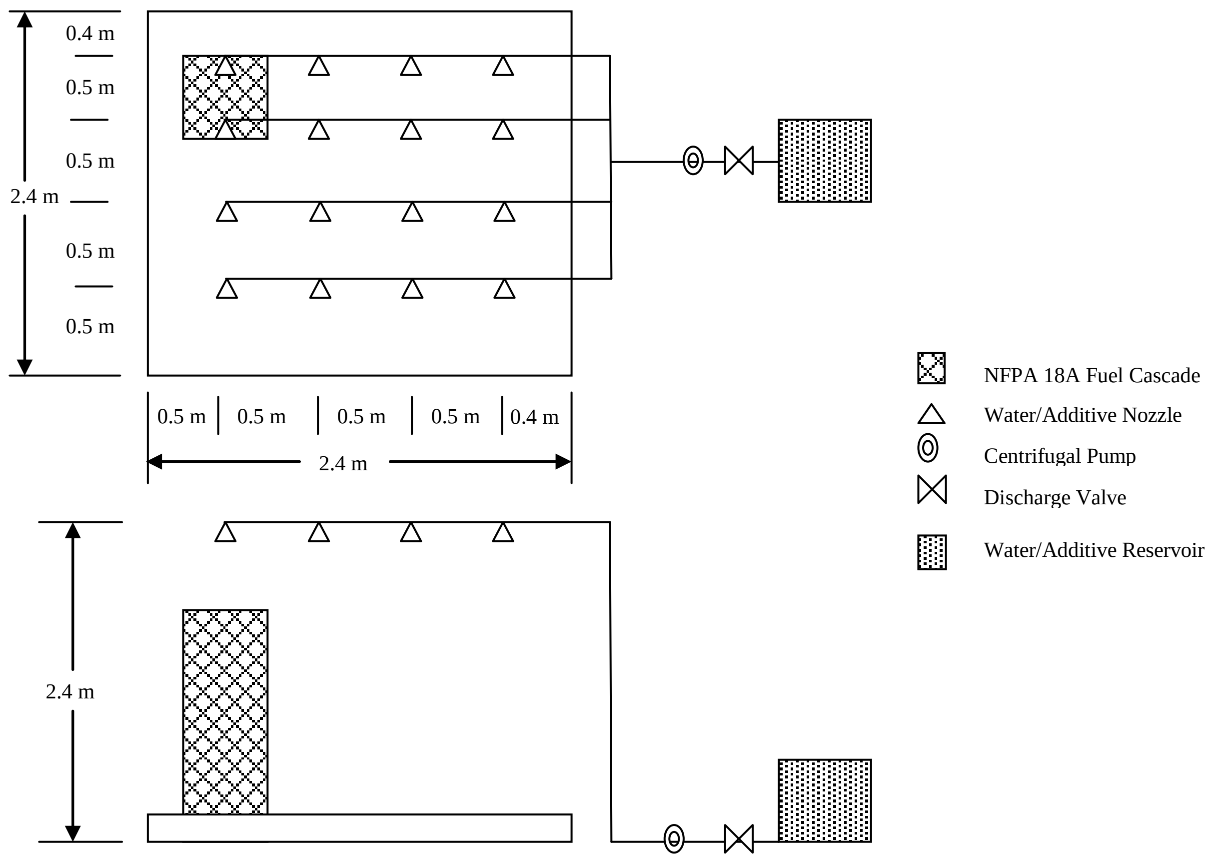

Figure C3 – Water and water with additive nozzle array schematic.

C2.1.3 Test Procedure

The nozzles in the discharge array would be checked and the desired nozzles installed. The agent tank would be filled with water or water plus additive. The outlet of the tank would be connected to the discharge piping.

The fuel line connections to the cascade setup would be checked. The fuel reservoir would be filled with the desired fuel. The fuel reservoir would then be pressurized with nitrogen. The tower would be filled with cooling water.

The cooling water flow in the tower would be started.

The n-heptane ignition fuel, 2L (0.5 gal), is added to the pan at the top of the NFPA 18A tower. The ignition fuel would then be ignited and the fuel flow started.

The application of the water or water with additive would be started after the completion of the 45 second pre-burn time.

The water application would be stopped and the test concluded when the fire has been extinguished or the five minute application period has been completed (test failure).

The duration of the water application and the application rate would be recorded.

The containment pan would then be emptied in preparation for the next test.

C2.1.4 Test Results

The minimum application rate required to cause extinguishment would be determined utilizing a bracketing technique. The determined application rate requirements determined for the additives could then be compared to that required for water alone to illustrate the performance enhancement due to the use of the additive.

C2.1.5 Test Matrix

A total of 36 tests are estimated to be conducted with the cascade apparatus, plus shakedown tests to establish basic test parameters. This is based on five tests for each fuel to successfully bracket the minimum flow rate requirement for each of the additives to be tested and for water itself.

C2.2 Test Plan Outline – DOD Fuel Cascade

Fuel cascades represent a significant challenge to water and water with additives. The disturbance of the fuel surface and continuous addition of burning fuel provide re-ignition sources that challenge any additive build-up on the fuel surface.

During these tests, water and the five representative additives would be applied from a four by four nozzle array located above and in front of the fuel cascade. The minimum flow rate required to cause extinguishment would be determined utilizing a bracketing technique with the flow rate varied between successive tests. The performance enhancement associated with the additives would be evaluated by comparison of the determined flow rate requirements with the requirements determined for water alone.

This evaluation would be initially conducted with a higher flash point fuel, e.g., No. 2 diesel.

C2.2.1 Apparatus

The DOD debris pile consists of five inclined trays mounted above a 0.9 m (3 ft) square pan. The fuel is discharged onto the top tray and flows down that tray to the tray below it inclined in the opposite direction. The fuel flows successively down each of the inclined trays prior to reaching the bottom pan. The bottom pan itself has a notch cut in the front of the pan to facilitate the flow of the fuel to a larger containment pan. This apparatus has been used with fuel flows ranging from 9.5 to 40 LPM (2.5 to 12 gpm) with the containment pan sized to prevent an excess build up of fuel in the pan. This apparatus is illustrated in Figure C4. It may be decided to center the apparatus in the pan.

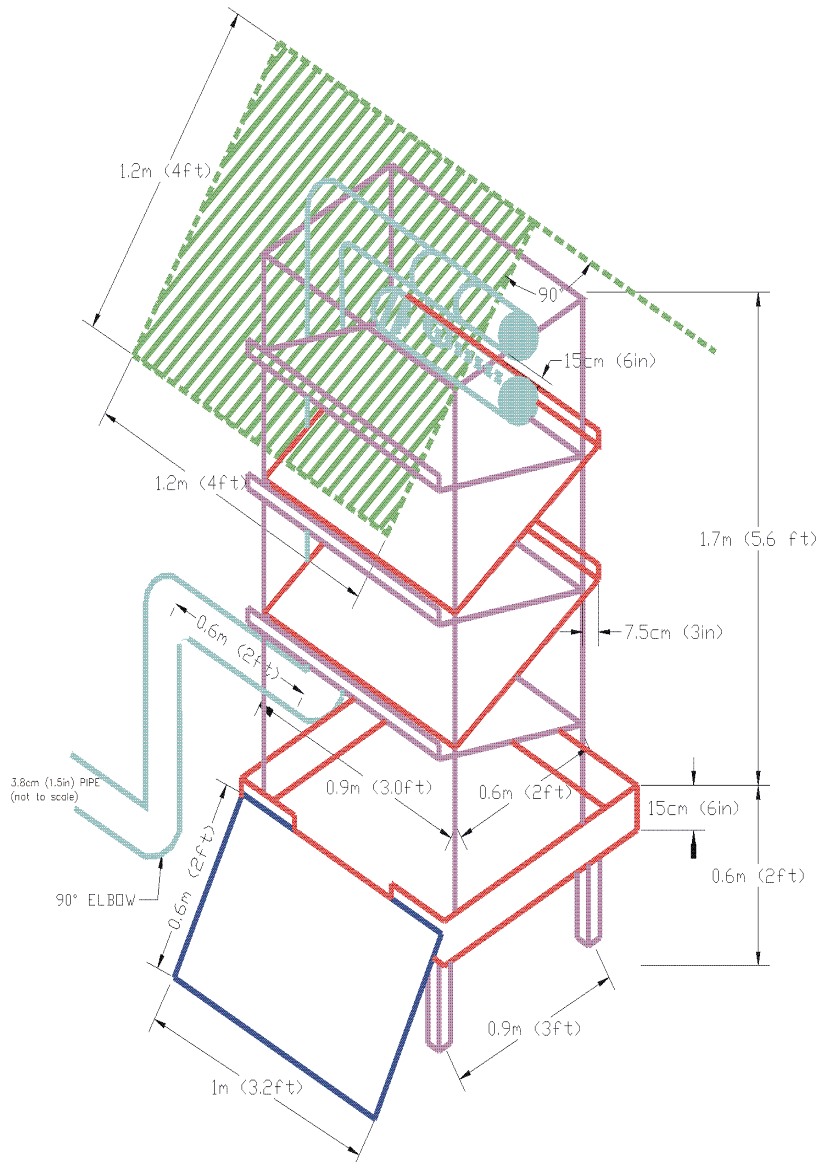

Figure C4 – DOD fuel cascade.

For these tests, the fuel flow rate would be limited to 15 LPM (4 gpm) with a square containment pan of 2.4 m (8 ft) on a side.

C2.2.2 Water and Water with Additive System

The water or water with additives will be applied from an overhead grid of nozzles. The nominal 4 x 4 array of would be centered in front of the cascade apparatus over the collection pan. The water or water with additive would be pumped from a 1040 L (275 gal) reservoir to feed the nozzle array. This corresponds to a maximum total flow rate of 208 LPM (55 gpm) of water or water with additive over a 5 minute application time period. The nozzle array is shown schematically in Figure C5.

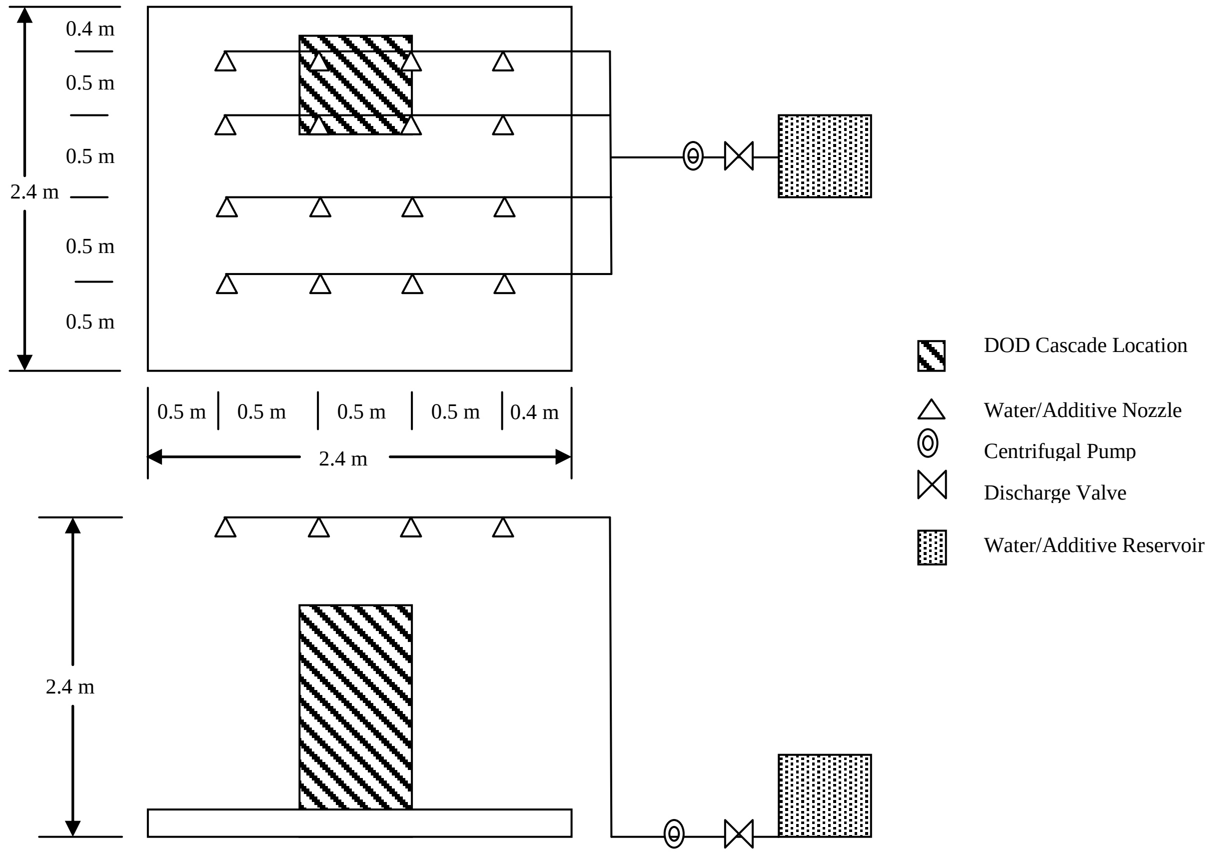

Figure C5 – Water and water with additive nozzle array schematic.

C2.2.3 Test Procedure

The nozzles in the discharge array would be checked and the desired nozzles installed. The agent tank would be filled with water or water plus additive. The outlet of the tank would be connected to the discharge piping.

The fuel line connections to the cascade setup The fuel reservoir would be filled with the desired fuel. The fuel reservoir would then be pressurized with nitrogen.

The n-heptane ignition fuel, 2L (0.5 gal), is added to the pan at the base of the DOD cascade. The ignition fuel would then be ignited and the fuel flow started.

The application of the water or water with additive would be started after the completion of the 1 minute pre-burn time.

The water application would be stopped and the test concluded when the fire has been extinguished or the five minute application period has been completed (test failure).

The duration of the water application and the application rate would be recorded.

The containment pan would then be emptied in preparation for the next test.

C2.2.4 Test Results

The minimum application rate required to cause extinguishment would be determined utilizing a bracketing technique. The determined application rate requirements determined for the additives could then be compared to that required for water alone to illustrate the performance enhancement due to the use of the additive.

C2.2.5 Test Matrix

A total of 36 tests are estimated to be conducted with the cascade apparatus, plus shakedown tests to establish basic test parameters. This is based on five tests for each fuel to successfully bracket the minimum flow rate requirement for each of the additives to be tested and for water itself.

C2.3 Test Plan Outline – NRCC Transformer Oil Fuel Cascade

Fuel cascades represent a significant challenge to water and water with additives. The disturbance of the fuel surface and continuous addition of burning fuel provide re-ignition sources that challenge any additive build-up on the fuel surface.

During these tests, water and the five representative additives would be applied from a four by four nozzle array located above and in front of the fuel cascade. The minimum flow rate required to cause extinguishment would be determined utilizing a bracketing technique with the flow rate varied between successive tests. The performance enhancement associated with the additives would be evaluated by comparison of the determined flow rate requirements with the requirements determined for water alone.

This evaluation would be initially conducted with a higher flash point fuel, e.g., No. 2 diesel.

C2.3.1 Apparatus

The NRCC transformer oil fire apparatus consists of a 1.2x3.9 m (4x12.8 ft) placed on top of a 1.2x3.9x3 m (4x12.8x10 ft) steel mock-up. The pan had a 1.8 m (6 ft) wide notch on the front face to allow the fuel to flow down the front face of the steel mock-up. A 1.2m (4 ft) diameter duct section 2.1 m (7 ft) long was suspended above and in front of the mock-up to represent an oil reservoir on a transformer. Steel sheets were hung in front of the mock-up to represent the cooling fins of the transformer. The entire mock-up was set inside a collection pan. This apparatus is illustrated in Figure C6.

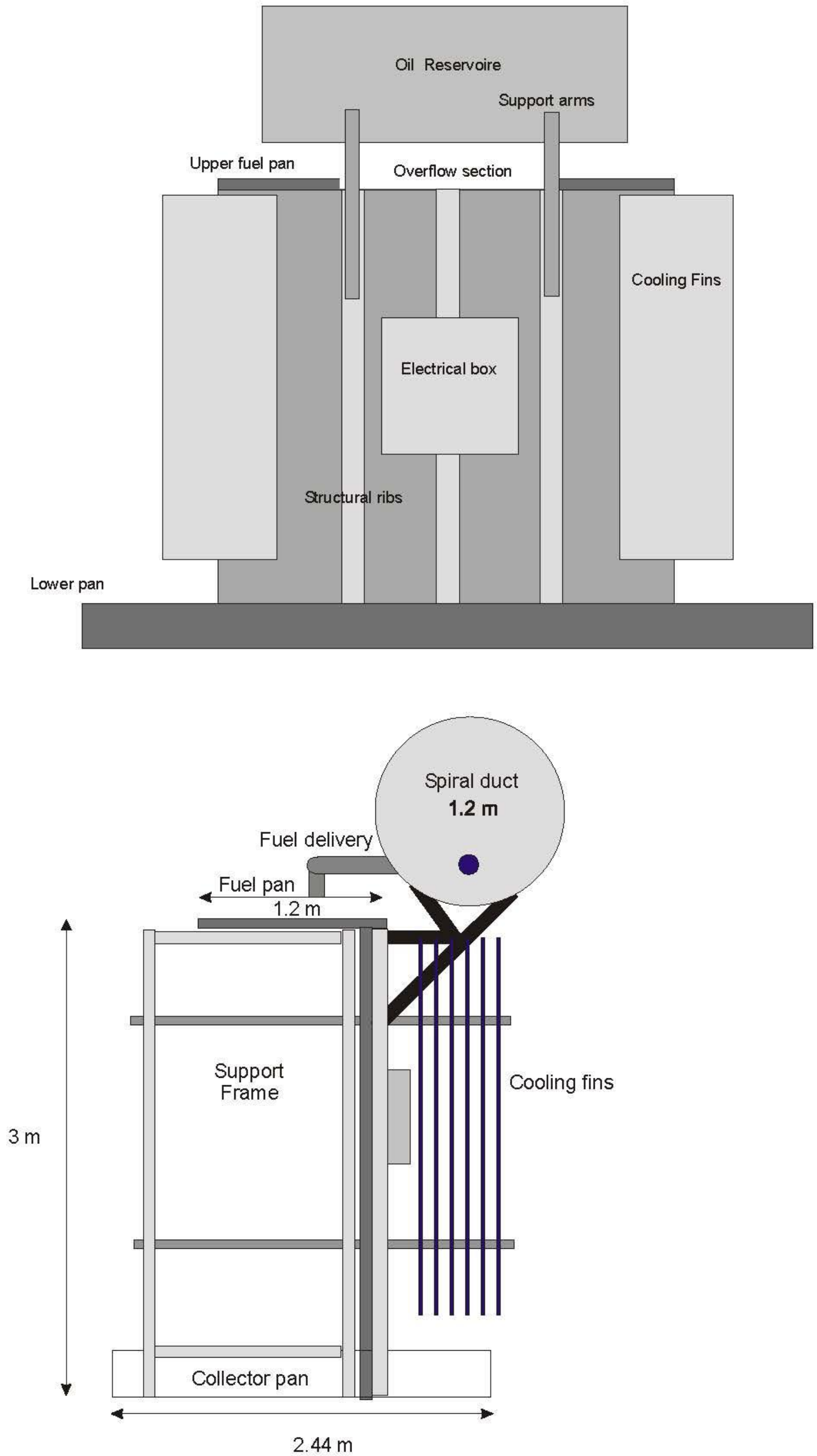

Figure C6 – NRCC Transformer oil fire apparatus.

The heated transformer oil was added to the pan at the top of the mock-up at a flow rate of 80 LPM (21 gpm). The transformer oil was heated in a separate 208 L (55 gal) reservoir which provides a flow duration of 2.5 minutes.

The size of the pan on top of the mock-up and the fuel flow rate would both be reduced to ensure cascade flow duration of at least 10 minutes. The pan on top of the mock-up would be resized to a 0.9 m (3 ft) square pan and the fuel flow rate reduced to 15 LPM (4 gpm). This would result in a fire size of approximately 7.6 MW with the n-heptane fuel.

C2.3.2 Water and Water with Additive System

The water or water with additives will be applied from an overhead grid of nozzles. The nominal 4 x 6 array of would be centered in front of the cascade apparatus over the collection pan. The water or water with additive would be pumped from a 1040 L (275 gal) reservoir to feed the nozzle array. This corresponds to a maximum total flow rate of 208 LPM (55 gpm) of water or water with additive over a 5 minute application time period. The nozzle array is shown schematically in Figure C7.

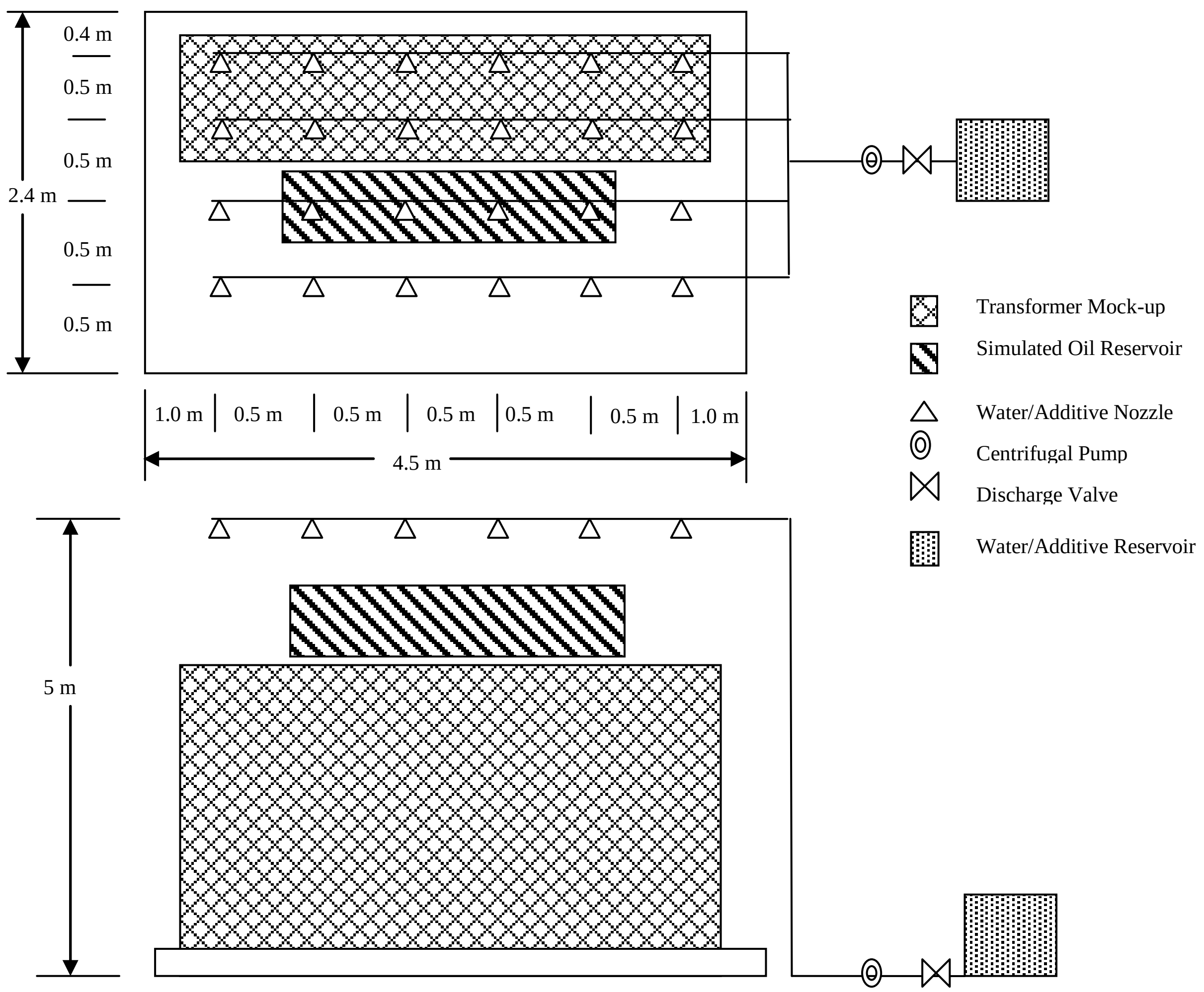

Figure C7 – Water and water with additive nozzle array schematic.

C2.3.3 Test Procedure

The nozzles in the discharge array would be checked and the desired nozzles installed. The agent tank would be filled with water or water plus additive. The outlet of the tank would be connected to the discharge piping.

The fuel line connections to the cascade setup would be checked. The fuel reservoir would be filled with the desired fuel. The fuel reservoir would then be pressurized with nitrogen.

The n-heptane ignition fuel, 2L (0.5 gal), is added to the pan at the top of the mock-up of NRCC transformer mock-up. The ignition fuel would then be ignited and the fuel flow started.

The application of the water or water with additive would be started after the completion of the 1.5 minute pre-burn time.

The water application would be stopped and the test concluded when the fire has been extinguished or the five minute application period has been completed (test failure).

The duration of the water application and the application rate would be recorded.

The containment pan would then be emptied in preparation for the next test.

C2.3.4 Test Results

The minimum application rate required to cause extinguishment would be determined utilizing a bracketing technique. The determined application rate requirements determined for the additives could then be compared to that required for water alone to illustrate the performance enhancement due to the use of the additive.

C2.3.5 Test Matrix

A total of 36 tests are estimated to be conducted with the cascade apparatus, plus shakedown tests to establish basic test parameters. This is based on five tests for each fuel to successfully bracket the minimum flow rate requirement for each of the additives to be tested and for water itself.