# NISTIR 6191

# Demonstration Of Biodegradable, Environmentally Safe, Non-Toxic Fire Suppression Liquids

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manufacturers, fire fighters, researchers and special experts in the field of fire fighting with water based fire fighting agents.

The primary recommendations of the attendees are listed below:

1. Class A fire fighting effectiveness should be the focus of the project.
2. Utilize existing standardized tests to demonstrate the fire fighting effectiveness on Class B and D fires.
3. Experimental scenarios should include fire knockdown, “overhaul,” and exposure protection.
4. Experiments should be conducted at “real life scale” when possible.
5. Efforts characterizing the physical, environmental safety and toxicity attributes of liquid fire fighting agents should continue.

These recommendations were incorporated into the research program.

## TASK 2

The Alliance for Fire and Emergency Management compiled a list of names and addresses of manufacturers of “Alternative Liquid Fire Extinguishing Agents” that are marketed in the U.S. as being suitable for Class A fires, Class A and B fires and Class A, B and D fires. Information was found on twenty nine commercially available agents. The list includes agents which are described as wetting agents, emulsifiers, foams, and gels. According to the agent manufacturers', all of these agents are “environmentally safe” or “biodegradable”. Of the twenty nine agents, all are advertised as being effective on Class A fuels, twelve of the agents are also advertised as being effective on Class B. Three of the agents are advertised as being effective on Class A, B and D fuels.

While this list of agents is by no means a complete listing of liquid fire fighting agents, it does demonstrate that there are a wide range of fire suppression liquids commercially available. It also highlights the problem fire departments have, when choosing an agent for use. With no standardized test methods available to measure the fire fighting effectiveness of these agents, a fire chief, typically, has limited information on effectiveness when making a decision concerning use of a new agent.

## TASK 3

The Intermountain Fire Science Laboratory (IFSL) of the U.S. Forest Service, has been conducting a program to collect the environmental impact, human health safety, and physical property data, available through existing standardized tests on the water based fire fighting agents currently meeting Specification 5100. Utilizing the standardized tests, the IFSL has evaluated all of the agents with respect to biodegradability, mammalian acute oral and acute dermal toxicity, primary eye and skin irritation, and fish toxicity.

The physical properties of the liquid fire suppression agent are very important to determining "usability" of the agent in the field. The IFSL have characterized the following physical properties for each agent on the list; flash point, fire point, vapor pressure, pH, density, viscosity, pour point, miscibility, surface tension, conductivity, refractive index, stability, wetting and foaming ability, expansion and drain time and corrosion effects on materials in foam delivery systems. In order to make efficient use of project funds and to avoid redundant efforts, NIST contracted with the IFSL to develop a report on all of the standardized testing conducted under their direction for all of the agents currently on the Forest Service QPL. Their agent characterization can be found in Appendix C of this report.

## TASK 4

This broad-based study on fire-suppression effectiveness of water-based fire fighting agents utilized laboratory-scale experiments and large-scale fire suppression experiments. Four commercially available fire suppression agent solutions were selected. Water was used as the basis for developing performance data because of its well known physical characteristics and wide use in the fire fighting community. It was found that some of the test methods provide a basis for clear differentiation of fire fighting effectiveness between water and fire-fighting agents. Others demonstrated little capability to differentiate fire-fighting effectiveness. This does not mean that these properties do not effect fire fighting efficiency, rather that the measurement is not particularly sensitive to the application.

Based on the limited results of this study, the following test methods have the highest degree of differentiation between water and the fire-fighting agents: surface cooling and fuel penetration, agent retention on surfaces, ignition inhibition, tire fire suppression and Class B fire suppression.

Based on the limited results of this study, the following test methods have small or no discernable capability to differentiate between water and fire-fighting agents: specific heat, drop size, contact angle, wood crib fire suppression, smoke generation and Class D fire suppression.

### Summary

For demonstration purposes, tests examining the following properties and conducted in accordance with the methods identified in this report can be used to provide information on some important characteristics contributing to measures of the fire fighting effectiveness of liquid fire suppression agents relative to water.

- specific heat
- fuel cooling and penetration
- mass retention
- ignition inhibition
- tire fire suppression
- wood crib fire suppression
- heptane fire suppression
- magnesium fire suppression

The results presented here provide preliminary data upon which fire fighting effectiveness tests may be developed. Certain plausible scenarios can be constructed regarding the action of the agents in extinguishing fires. However, additional research efforts are necessary to develop a broader base for such development. Areas recommended for further study include:

- effectiveness of agent application technique (i.e. fog nozzle vs. compressed-air foam),
- fire suppression effectiveness test methods should be designed to reflect the training of fire fighter to include the complexities necessary to expeditiously extinguish a fire,
- investigation into a test to measure emulsification capability, and
- experiments involving structural-fire suppression.

The fuel cooling and penetration experiment should be developed further, since it incorporates the benefits of the surface tension and contact-angle tests as well as cooling and penetration aspects for a given fuel.

# ACKNOWLEDGEMENTS

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A wide variety of fire test facilities were required to accommodate the broad spectrum of experiments needed for this demonstration. Appreciation is extended to the staffs of the following facilities: University of Maryland, Maryland Fire and Rescue Institute Princess Anne Training Center; University of Maryland, Maryland Fire and Rescue Institute Western Regional Training Center; U.S. Naval Research Laboratory, Chesapeake Beach Detachment and Underwriter's Laboratories, Northbrook. John Hoglund of the University of Maryland, Maryland Fire and Rescue Institute; Tom Wilson of the University of Maryland, Maryland Fire and Rescue Institute Princess Anne Training Center; Ronald R. Bowser, Charles H. Wood, and Debbie Sklodowski of the University of Maryland, Maryland Fire and Rescue Institute Western Regional Training Center; and William Carey and Martin Pabich of Underwriters Laboratories, Inc. deserve special recognition for their support of this project.

The agent characterization found in Appendix C was prepared by Charles W. George and Cecilia W. Johnson of the U.S. Department of Agriculture, U.S. Forest Service, National Wildfire Suppression Technology (NWST) Program. Their efforts toward the success of this project are greatly appreciated.

The authors would also like to thank Dr. David D. Evans and Erik Johnsson of the Building and Fire Research Laboratory and Dr. James Whetstone and Dr. Wing Tsang of the Chemical Science and Technology Laboratory for their thorough reviews of this document.

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# Demonstration of Biodegradable, Environmentally Safe, Non-Toxic, Fire Suppression Liquids

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## ABSTRACT

The Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST), under the direction of and funding by the United States Fire Administration (USFA), has conducted a series of experiments to demonstrate the suppression effectiveness of water-based fire fighting agents. Accepted test procedures for suppression effectiveness do not currently exist. Therefore, the results of these experiments are a first step toward establishing standardized tests for evaluating the fire fighting effectiveness of water-based agents. Because issues of toxicity and environmental effects of commonly used agents are of paramount concern to the fire-fighting community, this report includes as an appendix, Wildland Fire Foam Characterization. This characterization study includes methods for demonstrating environmental safety and toxicity as developed by the United States Department of Agriculture (USDA). The work reported here addresses a broad range of tests in order to determine those parameters that most critically effect fire-fighting performance.

This project was a result of Public Law 103-327 which provided funding to the USFA, to demonstrate biodegradable, environmentally safe, nontoxic fire suppression liquids which are effective on Class A, B and many D fires. Since no standardized test methods or protocols were available to demonstrate the effectiveness of water-based fire suppression liquids, USFA tasked BFRL with developing a methodology for conducting a demonstration. This task is consistent with NIST's mission to advance measurement science and develop standard test methods and with BFRL's program to improve fire safety.

This study focused on fire-suppression effectiveness of water-based fire fighting agents utilized laboratory-scale experiments and large-scale fire suppression experiments. Four commercially available fire suppression agent solutions were selected. Water was used as the basis for developing performance data because of its well-known physical characteristics and wide use in the fire fighting community. It was found that some of the test methods provide a basis for clear differentiation of fire fighting effectiveness between water and fire-fighting agents. Others demonstrated little capability to differentiate fire-fighting effectiveness. This does not mean that these properties do not effect fire fighting efficiency, rather that the measurement is not particularly sensitive to the application.

Based on the limited results of this study, the following test methods have the highest degree of differentiation between water and the fire-fighting agents: surface cooling and fuel penetration, agent retention on surfaces, ignition inhibition, tire fire suppression and Class B fire suppression.

Based on the limited results of this study, the following test methods have small or no discernable capability to differentiate between water and fire-fighting agents: specific heat, drop size, contact angle, wood crib fire suppression, smoke generation and Class D fire suppression.

Key words: class A fires; class B fires; class D fires; compressed air foam; fire extinguishing agents; fire suppression; large scale fire tests

# CHAPTER 1

# INTRODUCTION

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# INTRODUCTION

The Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST), under the sponsorship of the United States Fire Administration (USFA), has conducted a series of experiments to demonstrate the suppression effectiveness of water-based fire fighting agents. Accepted test procedures for suppression effectiveness do not currently exist. Therefore, the results of these experiments are a first step toward establishing standardized tests for evaluating the fire fighting effectiveness of water-based agents. Because issues of toxicity and environmental effects of commonly used agents are of paramount concern to the fire fighting community, this report includes as an appendix, Wildland Fire Foam Characterization. This characterization study includes methods for demonstrating environmental safety and toxicity as developed by the United States Department of Agriculture (USDA).

The work reported here addresses a broad range of tests in order to determine those parameters that most critically effect fire-fighting performance.

This project was a result of Public Law 103-327 [1,2]* which provided funding to the USFA, to demonstrate biodegradable, environmentally safe, nontoxic fire suppression liquids which are effective on Class A, B and many D fires. Since no standardized test methods or protocols were available to demonstrate the effectiveness of water-based fire suppression liquids, USFA tasked BFRL with developing a methodology for conducting a demonstration. This task is consistent with NIST's mission to advance measurement science and develop standard test methods and with BFRL's program to improve fire safety.

## 1.1 Background

Water is the most widely used fire extinguishing agent because it is effective, environmentally friendly, nontoxic, inexpensive and in many cases, readily available. In addition, water has a very high heat of vaporization per unit mass, at least four times as high as that of any other nonflammable liquid [3]. However, water is not an ideal fire extinguishing agent for many materials such as liquid hydrocarbon spill fires and metal fires.

The latent heat of vaporization of water is 2254.8 kJ/kg (970.3 Btu/lb.) [4]. This means that 2254.8 kJ (2138.7 Btu) of energy is required to change 1 kg (2.2 lb.) of water into steam. When water is vaporized, its volume increases approximately 1,600 times. Because the energy absorbing capabilities of water are well quantified, they can be used as a basis to calculate the theoretical minimum delivery rate of water needed to extinguish a burning material with a known heat (energy) release rate. Unfortunately, experience has shown that water must be applied at 10 to 100 times the theoretical rate in practice to control and extinguish the fire [5]. As a result of this apparent inefficiency and the need to address fires containing a wide variety of materials, water-based fire fighting additives have been utilized for many years to enhance the fire fighting capabilities of

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* Numbers in brackets refer to the literature references at the end of each chapter.

ordinary water. As mentioned above, no quantifiable method to gauge the effective of these agents currently exists.

The most widely used of the water-based agents are the foams used on Class B (liquid hydrocarbon) fires. Agents designed primarily for Class A (ordinary combustible) fires have been used most extensively in conjunction with wildland fires. More recently these agents have been promoted for use on a wider range of Class A and in some cases Class B and D (combustible metal) fires. These agents are frequently claimed to be more effective than plain water while being environmentally safe. In some cases, they are also claimed to reduce the quantity and toxicity of smoke. To gain an understanding of how additives might enhance the fire suppression capabilities of water, it is important to examine the principles of fire suppression.

### 1.1.1 Overview of Fire Suppression

While there are many texts which provide detailed descriptions of the mechanisms of fire suppression [3,4,5,6] only a basic overview is provided here. A fire is a chemical reaction in which oxygen combines with a fuel and produces heat and light. The energy from the fire is transferred to the surroundings by two heat transfer mechanisms, convection and radiation. The transfer of heat by a medium, such as gas or liquid, is convection. The transfer of heat via electromagnetic waves, such as light, is radiation.

While a fuel source could be a solid, a liquid or a gas, only the gas can be directly involved in the fire. In the case of solid or liquid fuels, the temperature of the material must be high enough for it to gasify and then react with the oxygen in the air to burn. NFPA 10, Standard on Portable Fire Extinguishers [7], classifies fires based on fuel type. A Class A fire involves ordinary combustibles such as wood, textiles, rubber and plastics. A Class B fire involves liquid hydrocarbons, such as gasoline or oil. Class C fires may involve ordinary combustibles and /or liquid hydrocarbons, in conjunction with energized electrical equipment. The last category, Class D fires, involves combustible metals such as magnesium, titanium or zirconium.

There are four means to extinguish a fire: remove the fuel, remove the oxygen, cool the fuel, or chemically interfere with the reaction. It is important to understand that fires and the optimum means of suppressing them can depend on the fuel or the fuel geometry. If the fire is located in an open area, where there is no impediment to oxygen reaching the combustion zone of the fire, the fire is fuel limited (Figure 1). If the fire is located in a closed compartment, where the amount of oxygen available for combustion is limited, the fire is considered ventilation limited (Figure 2). The rate of heat release that can be supported by a given ventilation opening can be readily calculated [8].

Given water's excellent heat absorption characteristics, its primary means of suppressing a fire is by cooling the fuel. In order for the water to cool the fuel, it must make contact with the fuel surface. Water works well on many Class A fires. However, some fuels, such as rubber, naturally repel water. Since it is difficult for the water to remain on hot rubber, the ability to transfer the heat from the rubber is limited. The suppression effects of the water could be enhanced if the water were held in place on the hot fuel.

Other Class A fires are deep-seated, meaning the surface area involved in combustion is larger than the exterior surface area of the burning item and the pyrolyzing surfaces are shielded from direct water application. If the water could penetrate to the pyrolyzing surfaces it would cool them. Due to the relatively high surface tension of water, it typically beads up and rolls off of the fuel surface and does not penetrate it.

Water has a number of secondary suppression effects, such as cooling the combustion zone, reducing radiation feedback to the fuel surface and steam generation, which can displace the oxygen. Steam generation works especially well in ventilation limited situations.

### 1.1.2 Water-Based Fire Suppression Agents

The use of additives to enhance the performance of water is not new. Mechanical foams made from water additives were in use as early as 1904 [9]. Since that time, foam agents such as aqueous film forming foam, AFFF, developed by the U.S Naval Research Laboratory in the early 1960's, have gained widespread acceptance for use on many, Class B fires. There are a number of commercially available water-based fire suppression agents designed primarily for Class A fires. Generically, these agents can be classified as surfactants which reduce the surface tension of water, potentially modifying its fire fighting capabilities.

There are a number of standards [10-15] for assessing water-based fire suppression agents. However, most of the criteria do not address the fire fighting (protection/suppression) capabilities of the agent. This is particularly true for Class A and Class D fires. An evaluation protocol is needed to measure the fire fighting capability or effectiveness of these agents. By developing demonstration methods for relating the performance of each agent to plain water, the effectiveness of the agents in given situations could be evaluated. This would enable the fire protection community to select the most cost effective fire suppression agent(s) to fit their specific needs.

### 1.1.3 Agents Selected for Demonstration

Given the time constraints and the developmental nature of this program, only a limited number of agents could be used. These agents were chosen from a list of water-based fire suppression agents currently meeting the interim requirements of U.S. Forest Service Specification 5100 [16]. The agents on the 1995 qualified products list (QPL) are: Angus ForExpan S, Ansul Silv-Ex, Chemonics Fire-trol FireFoam 103 and 104, Monsanto Phos-Chek WD 881, Pyrocap B-136 and TCI Fire Quench*. All of these agents are recognized as meeting the U.S. Forest Service Specification 5100 Interim Requirements for environmental impact, human health safety, and physical properties.

Utilizing agents from the QPL provided products with an existing database of information that could not otherwise have been obtained within the time and funding constraints of this project. Four

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* Certain equipment or materials are identified in this report. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology or the U.S. Fire Administration, nor does it imply that the equipment or materials identified are necessarily the best available for the purpose.

agents, representative of a cross section of the agents on the QPL, were chosen based on differences in selected physical properties data and cost. The specific product names used for the fire protection/suppression demonstration will not be identified in this report.

The impact of the physical properties or characteristics of the water-based fire fighting agents on their effectiveness was examined through laboratory and large-scale fire suppression tests. The physical characteristic tests were used to determine which properties or characteristics, if any, of the agent are indicators of enhanced fire fighting capabilities. Examples of the parameters which were considered are surface tension, expansion ratio, thermal conductivity, and concentration ratio.

For products on the QPL, field use information was available in addition to the environmental impact, human health safety and physical properties. Water-based agents intended primarily for Class A fires are used on a regular basis by a limited number of fire departments around the country. A number of these departments were contacted to provide input on their experience using these water-based agents. The experience gained by these departments is useful in determining the situations in which water-based agents are most effective. This type of information was invaluable in developing the protocol for a demonstration of fire fighting effectiveness.

## 1.2 Objective and Tasks

The objective of this project was to develop methods for demonstrating biodegradable, environmentally safe, nontoxic fire suppression liquids which are effective on Class A, B and many D fires. The demonstration project was divided into four specific tasks:

1. Conduct a workshop with users, manufacturers and researchers interested in biodegradable, environmentally safe, nontoxic fire suppression liquids.

2. Collect information on fire suppression agents which are considered by their manufacturer to be biodegradable, environmentally safe, nontoxic fire suppression liquids which are effective on Class A, B and many D fires.

3. Develop methods as required and assess the biodegradability, environmental safety, toxicity and physical properties of a limited number of water-based fire fighting agents.

4. Develop methods as required and demonstrate the fire fighting effectiveness of a limited number of water-based fire fighting agents for Class A, B, and many D fires.

### 1.2.1 Workshop Summary

A workshop was held in Gaithersburg, MD on June 27, 1995. The workshop had three objectives:

1. to brief the attendees on the objectives, scope and approach of the demonstration project,
2. to solicit comments and suggestions on the demonstration project and obtain any available information on previous fire suppression effectiveness test results, and
3. collect field use experience from the fire service on water-based fire suppression agents.

The meeting was attended by fire fighting agent manufacturers, fire fighters, researchers and special experts in the field of fire fighting with water-based fire fighting agents. A list of invites/attendees can be found in Appendix A. The agent manufacturer's group was composed of representatives from Angus, Ansul, Chemonics, Monsanto, and Pyrocap. Each manufacturer has an agent on the U.S. Forest Service's Qualified Products List for Wildland Fire Chemicals. Each of the agents on the list has met the U.S. Forest Service Specification 5100 Interim Requirements for environmental impact, human health safety and physical properties.

Representatives from five geographically and service area diverse fire departments which use Class A agents attended as end users. The fire departments represented were: Fairfax County, VA; Harrisburg, PA; Los Angeles County, CA; Nashville, TN; and Travis County, TX.

The research group was composed of scientists and engineers from: Bureau of Land Management; Hughes Associates; U.S. Forest Service's Intermountain Fire Science Laboratory; Underwriters Laboratories; and NIST. Each member in this group has significant experience in developing and/or conducting tests with liquid fire fighting agents.

The special experts were individuals who had published papers on liquid fire suppression agents and their use by the fire service or had been involved in a liquid fire suppression agent research program as a participant or a sponsor.

Presentations were made on the proposed demonstration plan, the current status of the Forest Services' efforts to characterize the physical characteristics of wildland fire foam (Class A foam), the results of the National Fire Protection Research Foundation's fire suppression effectiveness studies and an end users perspective on the use of Class A foam by an urban fire department. After the presentations, the groups met separately to develop comments and recommendations on the proposed demonstration plan. Each group discussed the issues of concern or the issues of priority that they felt needed to be addressed by the project and developed prioritized lists of recommendations. The groups were reconvened and each group made a presentation to the collective attendees. All of the presentations then were discussed by the groups, and the results of the meeting were summarized.

The major recommendations were:

1. Class A fire fighting effectiveness should be the focus of the project.

2. Utilize existing standardized tests to demonstrate the fire fighting effectiveness on Class B and D fires.

3. Test scenarios should include fire knockdown, "overhaul", and exposure protection.

4. Testing should be conducted at "real-life scale" with 100 gpm flow rates when possible.

5. Efforts characterizing the physical, environmental safety and toxicity attributes of liquid fire fighting agents should continue.

These recommendations were incorporated into this research project.

### 1.2.2 Survey of Water-based Fire Suppression Agents

As part of this project, a list of names and addresses of manufacturers of Alternative Liquid Fire Extinguishing Agents that are marketed in the U.S. as being suitable for Class A fires, Class A and B fires and Class A, B and D fires was compiled and is included in this report as Appendix B. Information was found on twenty-nine commercially available agents. The list includes agents which are described as wetting agents, emulsifiers, foams, and gels. According to the agent manufacturers, all of these agents are environmentally safe or biodegradable. Of the twenty-nine agents, all are advertised as effective on Class A fuels, twelve of the agents are also advertised as effective on Class B. Three of the agents are advertised as effective on Class A, B and D fuels. The results of the survey are summarized in Table 1.

While this list of agents is by no means a complete listing of liquid fire fighting agents, it does demonstrate that there is a wide range of fire suppression liquids commercially available. The list also indicates the need for a standard method for evaluating the performance of these fire-fighting agents so that manufacturers and their customers in the fire service can have more information for decisions.

The environmental and health safety assessment methods called for in Task 3 are addressed in Appendix C. The following chapters of this report address the results of Task 4 outlined above. Finally, the results for this project are summarized and recommendations are made for the evaluation of water-based fire suppression agents.

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**Table 1. Sample of commercially available liquid fire fighting agents, their fire suppression capabilities according to fire class and environmental safety as listed in the manufacturer's literature.**

| Agent | Class A Fires | Class B Fires | Class D Fires | Comments |
|---|---|---|---|---|
| Angus Forexpan 'S' | X | | | "outstanding environmental characteristics" |
| Ansul Silv-Ex | X | | | "safeguarding environment" |
| Baum's Pyrocool | X | | X | "biodegradable" |
| Chemguard Class A Plus | X | | | "environmentally friendly, biodegradable" |
| Chemonic Fire-Trol Class A Firefoam | X | | | |
| Blackout Class A Foam | X | | | "biodegradable" |
| Drench | X | X | | "biodegradable, non-toxic" |
| Control A | X | | | "biodegradable, safe for environment" |
| ECO-Foam 2004 | X | X | | "environmentally friendly" |
| FireXPlus | X | X | | "enhances bioremediation" |
| Gem Enviro-skin | X | X | | "assuming Class B since agent is described as "film-forming foam" "not to be used on Class C and D fires" |
| Fine Water DP30 | X | | | "biodegradable" |
| Fine Water HS | X | | | "biodegradable" |
| Coldfire | X | X | X | "biodegradable, non-toxic" |
| Barricade | X | | | "safe, non-toxic" |
| Fuel Buster | X | X | | "environmentally safe" |
| Wetting Agent Class A Concentrate | X | | | |
| Monsanto Phos-Chek | X | | | "biodegradable" |
| Defense Class A Foam Concentrate | X | | | "non hazardous, biodegradable" |
| Water Stretcher Class A Foam | X | | | "biodegradable, no environmental hazard" |
| Nochar's E112 | X | | | "water soluble, non hazardous" |
| FireBlok | X | X | | "biodegradable" |
| Pyrocap B-136 | X | X | X | "environmentally safe" |
| Pentro-Wet | X | X | | "biodegradable" |

| Agent | Class A Fires | Class B Fires | Class D Fires | Comments |
|---|---|---|---|---|
| Fire Quencher | | | | |
| Water Plus | X | | | "biodegradable" |
| BioSolve PinkWater | X | X | | "biodegradable" |
| Wetter Water Water Extender | X | | | "biodegradable, non toxic, environmentally safe" |
| U.S. Class A Foam | X | | | "biodegradable" |
| AFFF ATC Fire Out 1 Fire Fighting Foam | X | X | | "biodegradable" |

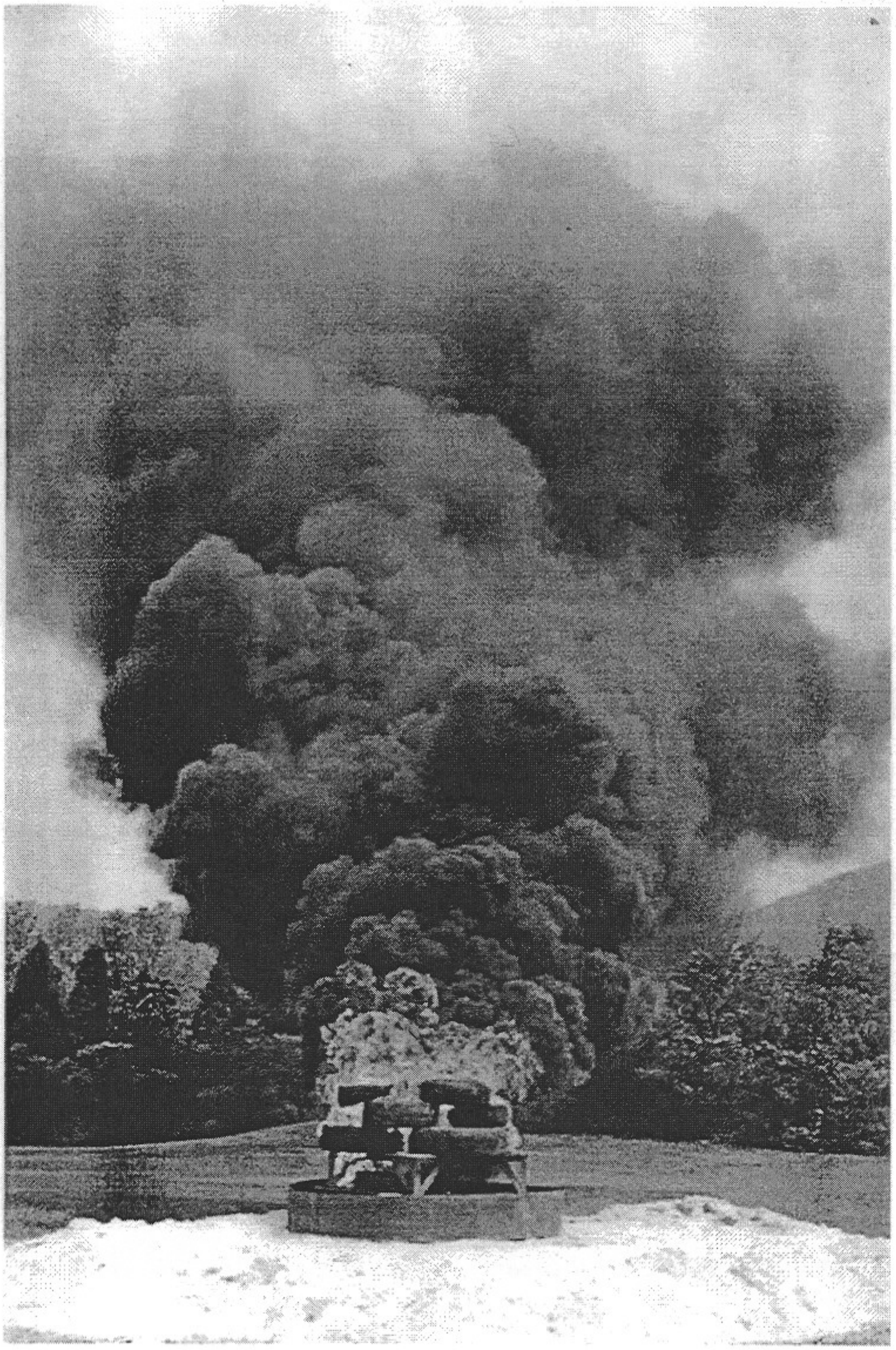

Figure 1. Fuel Limited Fire

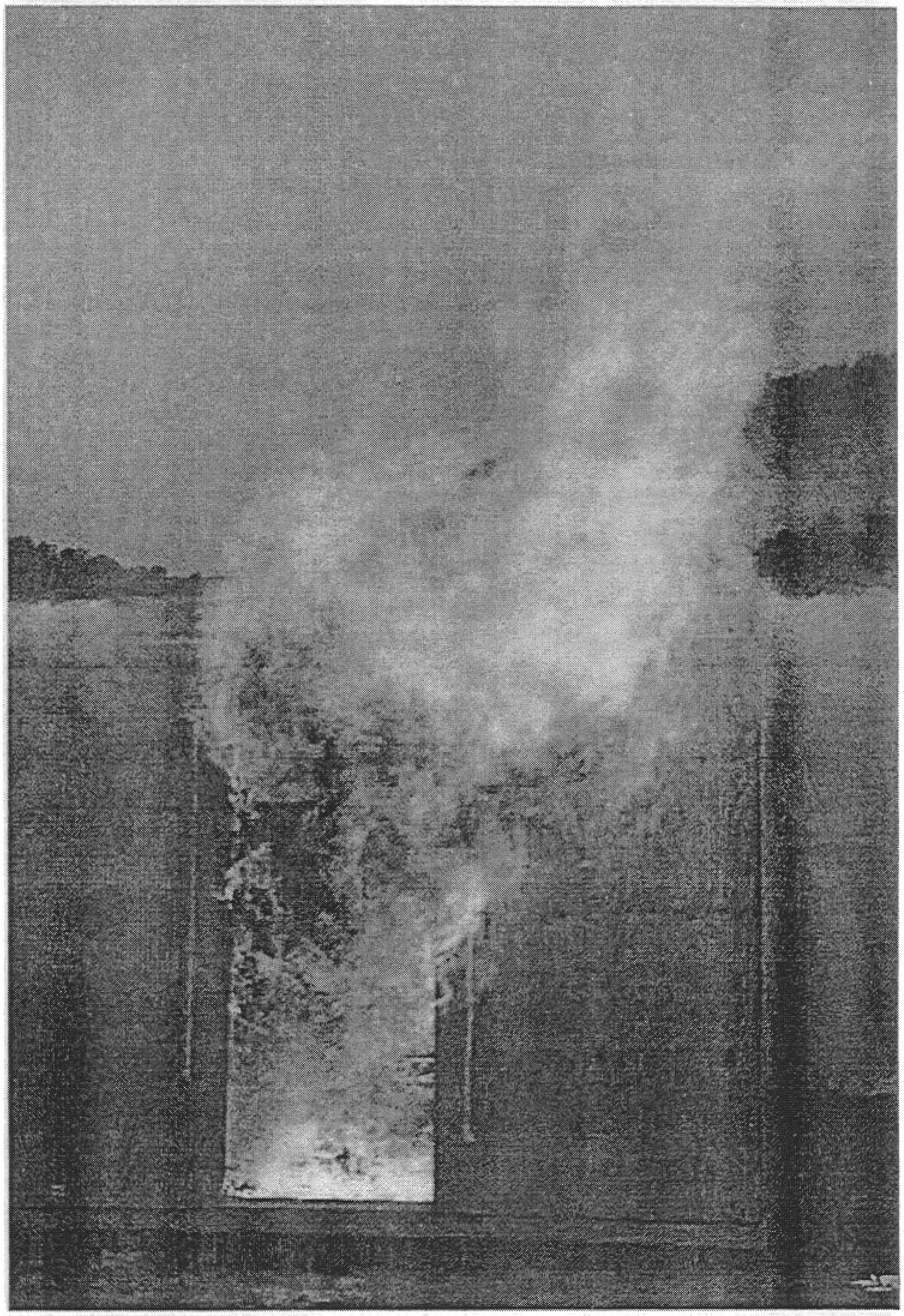

Figure 2. Ventilation Limited Fire

# CHAPTER 2

# FIRE FIGHTING PROPERTIES

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# FIRE FIGHTING PROPERTIES

## 2.1 Introduction

Water uses several different mechanisms to suppress and extinguish fires: fuel cooling, flame cooling, oxygen displacement and reduction of radiation feedback to the fuel. Laboratory experiments were conducted to determine which of these mechanisms play dominant roles in the suppression of Class A fires and which mechanisms are enhanced by addition of the agents. These laboratory-scale experiments have the advantage of being able to examine individual mechanisms one at a time. The sections in this chapter address experiments conducted to quantify specific heat, droplet size, fuel cooling and penetration, and fuel surface contact.

## 2.2 Specific Heat

Specific heat can be used as a means to examine the cooling capability or ability to absorb heat of fire suppression agents. As noted in Chapter 1, "water has a very high latent heat of vaporization per unit volume, at least four times as high as that of any other non-flammable liquid", 2254.8 kJ/kg (970.3 Btu/lb) [1]. The latent heat of vaporization of water is the amount of heat absorbed by 1 kg (2.2 lb) of water when changing from a liquid to a gas, at atmospheric pressure. Another measure of a material's ability to absorb heat is specific heat. Specific heat is the amount of heat required to raise the temperature of a unit mass of a material one degree at constant pressure. Typically, water has a specific heat of 4.186 kJ/kg/K or 1 Btu/lb/F. This is the amount of thermal energy required to raise the temperature of 1 kg (2.2 lb) of water 1 °C (1.8 °F) [2].

### 2.2.1 Experimental Procedure

The objective of these experiments was to develop data on the specific heat capacities at constant pressure, $c_p$, for various aqueous fire fighting agents near 298.15 K. A differential scanning calorimeter with an enthalpy-step procedure using hermetically sealable pans to prevent vapor loss was used for measurements of specific heat capacity. Temperature calibration of the instrument for a previous study of aqueous sodium chloride was performed with indium, water, mercury, and adamantane. New calibration verification tests with indium and water showed deviations from the previous calibration no larger than the estimated temperature uncertainty of 0.08 K.

The enthalpy step technique involved an initial isotherm at 294 K, followed by an 8 K increase in temperature to an isotherm at 302 K. The area of the peak for the step multiplied by the calibrated cell constant is equal to the change in enthalpy, $\Delta H$. The change in enthalpy was divided by the temperature change and assigned as the heat capacity at the average temperature. Calibration of the cell constant for the above method was performed using sapphire (NIST SRM 720) and distilled, deionized water with electrical resistivity of approximately 18MΩ•cm.

### 2.2.2 Results

The measurement of the heat capacities for these solutions was cumbersome due to a reaction process inconsistently occurring within the solutions. The reaction process possibly could be release of $CO_2$ for example. The solutions in their containers at ambient temperature showed a slight layer of foam on the surface. For different trials of each agent, different values of the heat capacity would be calculated, depending on whether the other reaction process did or did not occur. The enthalpy for the process would be added to the enthalpy from the temperature change making the heat capacity calculation invalid. For example, two trials of agent "B-1% solution" had $c_p$'s of 4.192 and 4.059 with uncertainties of 0.05. A third trial had a peak for the temperature change giving a heat capacity of 4.060. However, during the final isotherm at 302 K a second peak occurred from a chemical reaction process. This second peak area was added to the first with the invalid resulting heat capacity of 4.190. The above indicates the heat capacity value of 4.060 was correct. For all other trails, only one peak was seen so this reaction, when it occurred, proceeded during the temperature change. The magnitude of the enthalpy of the process appeared approximately identical for 1% concentrations of agents A and B and 3% concentrations of agent C but was larger for 3% concentrations of agent D. The above method was extended to include a temperature step from 302 K back to 294 K to check reversibility. The $\Delta H$ for the step-up and step-down were always identical within experimental uncertainty indicating the reaction process was reversible. Experimental results showed the above process did not occur for the concentrated agent samples. Results of the measurements of the solutions are shown in Table 1.

**Table 1 Specific Heat of Fire Suppression Agents at Constant Pressure**

| Sample | Temperature (K) | Specific Heat, $C_p$ (J/g K) | Uncertainty,d (J/g/K) |
|---|---|---|---|
| Tap Water | 298.39 | 4.18 | 0.03 |
| Agent A 1% solution | 298.41 | 4.17 | 0.04 |
| Agent B 1% solution | 298.37 | 4.06 | 0.05 |
| Agent C 3% solution | 298.42 | 4.12 | 0.05 |
| Agent D 3% solution | 298.41 | 3.84 | 0.06 |
| Agent A concentrate | 298.55 | 2.95 | 0.04 |
| Agent B concentrate | 298.58 | 3.09 | 0.04 |
| Agent C concentrate | 298.56 | 3.64 | 0.05 |
| Agent D concentrate | 298.60 | 3.81 | 0.06 |

### 2.2.3 Conclusions

The measurements in Table 1 show the specific heat of all the agent solutions to be equal or less than the specific heat of plain water. Given that the specific heat of the concentrates, are significantly less than the specific heat of water, adding more concentrate would continue to reduce the heat absorbing capability of the solution. From this set of experiments it has been demonstrated that these agents do not increase water's ability to absorb heat.

## 2.3 Fuel Cooling and Penetration

One of the advantages frequently cited for Class A agents is their ability to decrease the surface tension of water. Water has an inherently high surface tension. This characteristic causes water to bead and tend to roll off surfaces. It has been estimated that only 5 to 10 percent of the water applied during a fire attack contributes to the extinguishment [3]. The addition of a Class A concentrate reduces the surface tension of the water and improves its ability to cover and penetrate surfaces.

The combination of improved penetration capability and foaming serves to increase the quantity of water retained on the surface of the fuel. This can potentially significantly increase the effectiveness of water during fire department mop-up operations. As part of this project, an experimental procedure was developed to evaluate the change in water penetration capability obtained through addition of Class A foam concentrates. Experiments were conducted to determine relative rates of penetration, rates of cooling, and areas of coverage.

An infrared imaging radiometer was used to examine penetration rate and measure surface temperatures. Thermal imaging radiometers produce photographs or other two dimensional records of the apparent temperature of surfaces. All objects radiate energy; the amount of energy radiated increases with increasing temperature. Objects at or near room temperature have spectral energy distributions that peak in the middle infrared region, near 10 µm. A sufficient amount of energy is radiated to allow detection at great distances by a sensitive instrument. The consistency of the relationship between object temperature and radiated energy allows a calibrated instrument to make highly accurate non-contact temperature measurements [4].

The earth's atmosphere absorbs radiated energy in the infrared except for two wavelength regions called atmospheric windows. Typically, it is water vapor in the atmosphere that absorbs the majority of the infrared energy over much of the spectral band. The atmospheric windows allow radiometric measurements with minimal losses. The 8-14 µm region is exceptionally free of absorption except with very high water content. The 3-5 µm region has relatively high transmission, but usually requires compensation when high accuracy measurements are to be made at path lengths greater than one meter. In addition, sun glint is a far more serious problem in the 3-5 µm waveband than in the 8-14 µm waveband. Modern thermal imaging radiometers are available with 8-14 µm, 3-5 µm, or 3-14 µm spectral response. The system used in these experiments was of the third type [5].

The great advantage of thermal imaging radiometers is their ability to rapidly display changing conditions of a planar image. The device response time is on the order of nanoseconds while other typical non-contact thermometers require milliseconds to respond for a single point. A thermal imaging radiometer performs over 1 million measurements per second. With video recording and computer processing, tremendous amounts of thermal data can be archived, accessed, and analyzed. The major disadvantage of thermal imaging radiometers compared to other non-contact thermometers is their cost which is typically 20 to 30 times higher [6].

### 2.3.1 Experimental Procedure

To evaluate the relative penetration capability, droplets of water and foam solution were simultaneously placed on the top side of a substrate. The response of the substrate was examined by viewing the bottom side with the infrared imaging radiometer. The thermal image obtained from the radiometer was recorded on videotape and analyzed using computer software. A diagram of the apparatus is shown in Figure 1.

After some trail and error, the optimum combination of droplet size, solution temperature, and substrate material was identified. Plain water and foam solution were placed on the substrate using two hypodermic syringes each calibrated to deliver 100 µl. This quantity of liquid was sufficient to provide a measurable response within the radiometer's field of view. To improve response and minimize the influence of extraneous variables, the water and foam solutions were chilled using an ice bath. The liquid temperature was typically 2 °C when placed on the room temperature (22 °C) substrate.

A 0.2 m (7 in) square by 6.3 mm (1/4 in) thick hardboard was used as the test sample. Hardboard is one of several types of composition-boards, manufactured from wood elements ranging from veneers to fibers using one of several methods. The American Hardboard Association identifies hardboard as a board with a density of 480 kg/m$^3$ or greater. In the trade, however, a distinction is made between medium density fiberboard, often referred to as MDF, and higher-density fiberboard, called hardboard in the narrowest sense. The higher-density fiberboard typically has a density of 900 kg/m$^3$ or greater [7]. The hardboard used in these experiments had a density of approximately 960 kg/m$^3$. In addition to providing consistent material properties, the relatively smooth surface of this material provided a good visual indicator of the impact of the surfactant.

The temperature span covered by the radiometer during a typical test was 2 °C. This span was increased to 5 °C for a few tests when the surface temperature dropped to within 0.2 °C of the original lower limit. The underside of the sample was painted with a flat black paint to minimize reflection, and control the emissivity at a value near 1. The temperature data was determined from the infrared images using software provided by the manufacturer of the radiometer. As recommended by the manufacturer, the system was operated at an emissivity setting of 1, and variations in emissivity were accounted for using the analysis software.

Prior to the start of each test, the temperature of the surface of the sample was recorded using a 0.25 mm (0.01 in) diameter Type K thermocouple embedded in the material surface. The liquid temperatures were determined using a glass bulb thermometer with 1 °C graduations. At application, the typical temperature difference between the liquid and the solid was approximately 20 °C.

### 2.3.2 Analysis

A total of 17 tests were performed using four different Class A foam additives. The agents, identified as A, B, C, and D, were applied at their manufacturer's recommended concentrations. A 1% concentration was used for agents A and B while a 3% concentration was used for agents C and D. A test matrix indicating test number, foam concentrate used, and test duration is shown in Table 2.

Table 2. Test Matrix

| Test Number | Agent | Duration of Test (min) | Initial Thermal Penetration Time (s) | |
|---|---|---|---|---|
| | | | Water | Agent |
| 1 | A | 13 | 55 | 60 |
| 2 | A | 20 | 55 | 70 |
| 3 | B | 20 | 85 | 80 |
| 4 | C | 20 | 45 | 45 |
| 5 | D | 15 | 65 | 70 |
| 6 | A | 18 | 30 | 32 |
| 7 | B | 20 | 45 | 50 |
| 8 | C | 20 | 40 | 60 |
| 9 | D | 20 | 40 | 45 |
| 10 | A | 20 | 45 | 50 |
| 11 | B | 20 | 80 | 90 |
| 12 | C | 20 | 40 | 42 |
| 13 | D | 20 | 35 | 40 |
| 14 | A | 10 | 45 | 50 |
| 15 | B | 10 | 50 | 50 |
| 16 | C | 10 | 45 | 49 |
| 17 | D | 9 | 45 | 47 |

The rates at which the thermal effect of the agent solution and pure water penetrated the hardboard material were determined by measuring the time between placement of the liquids and appearance of initial cooling effect. Review of the infrared image videotapes indicates that the water and foam appear to penetrate hardboard at approximately the same rate. Typically, penetration rates were within 10 percent. The times for penetration of the water and agent are shown in Table 2. A significant portion of the variation in time is due to problems associated with simultaneously placing both drops on the hardboard. The average time required for initial penetration was about 50 s.

The relative rate at which each agent cooled the material was determined through analysis of the infrared images using the software provided by the radiometer manufacturer. The temperatures at points approximately in the center of the areas being impacted by the agent solution and the water were recorded as a function of time. To minimize the impact of emissivity, background temperature, and other variables, the temperature change was compared on a relative basis. Each data point was calculated by dividing the temperature change from ambient for the area cooled by the water into the temperature change for the area cooled by the agent. A value of 1 indicates the relative cooling rate was the same as water. Figures 2, 3, 4, and 5 present the results for Agents A, B, C, and D, respectively.

With the exception of Agent A, most of the data appears reasonably consistent between replicate tests. After about 3 minutes, the agent cooling rate begins to exceed that of the water. Over the course of a test utilizing a surfactant, the average cooling rate is about 1.5 times that of the water. The 3 minute delay would suggest that the primary reason for the improved cooling is the larger area covered by the agent solution. When placed on the hardboard material, all of the agent solutions would immediately spread across the surface. This is a direct result of the surfactant contained in the Class A foam additives. The water would remain as a single droplet on the surface. Typically, a significant quantity of water would remain beaded on the surface at the conclusion of a 20 minute test. In most cases, the agent solution would have disappeared from the surface as a result of absorption and evaporation.

The final piece of information obtained from the infrared data was relative area thermally effected by the agent solution versus the water. The ratio of agent on the bottom surface to that of water is summarized for the four agents in Table 3.

**Table 3. Relative Area of Coverage**

| Agent | Test Number | Relative Area of Thermal Impact |
|---|---|---|
| A | 1 | 3 |
| | 2 | 4 |
| | 6 | 3 |
| | 10 | 5 |
| | 14 | 3 |
| | Average | 3.6 |
| B | 3 | 6 |
| | 7 | 4 |
| | 11 | 4 |
| | 15 | 4 |
| | Average | 4.5 |
| C | 4 | 3 |
| | 8 | 5 |
| | 12 | 4 |
| | 16 | 4 |
| | Average | 4 |
| D | 5 | 4 |
| | 9 | 4 |
| | 13 | 2 |
| | 17 | 5 |
| | Average | 3.7 |

One of the features of the infrared analysis software is the ability to apply a direct measure scale to the area being viewed. The software uses the configuration of the experiment together with certain optical properties of the radiometer to determine appropriate length measurements. Using this feature and some of the other measurement tools, the ratio of area cooled by the agent solution to that cooled by the water was determined for each test. A higher number indicates that the agent solution had a greater area of impact. In all cases, the foam had an apparent area of impact at least twice that of the water with 4 times being typical.

### 2.3.3 Conclusions and Recommendations

Using infrared thermography techniques, it was possible to examine several of the properties potentially important in evaluating the fire fighting effectiveness of Class A foam additives. These properties dealt primarily with the surfactant contained in the agents and its impact on the surface tension of the water. The initial penetration time was the same for both the plain water and the water - Class A agent solution. The agents were shown to have measurably increased relative rates of cooling and areas of impact compared to water. The four agents investigated appear to have about the same impact on the wetting properties of water as determined through the infrared data.

A number of issues need further investigation and resolution before infrared thermography can be recommended as part of a standardized test for Class A agents. Changes in the measurements over the small temperature range, about 2 °C, can produce significant variations in the results. Methods need to be investigated to increase the temperature ranges without introducing additional variables such as cracking of the material surface and smoldering. Simultaneous placement of droplets on the surface is critical to conducting directly comparative measurements. An apparatus appropriate for this task must be developed. In addition, implications of and methods for placing multiple drops on surfaces must be examined.

## 2.4 Fuel Surface Contact

When an agent is in contact with the surface of a hot fuel, it is transferring heat by conduction. Heat transfer is only occurring at the interface of the fuel and the agent. If the agent has a high surface tension like water, 75 dynes/cm [8], most of the agent will be beaded up, limiting the surface area of contact. If the agent has a lower surface tension, the agent will spread on the fuel surface, increasing the contact area and the heat transfer (Figure 6).

Measuring the contact angle of a drop of liquid on a fuel surface can be used to quantify wettability and surface contact. The contact angle is the angle between the surface and the tangent line at the point of contact. If complete wetting occurs, i.e. maximum surface contact is approached, then the contact angle will approach 0°.

### 2.4.1 Experimental Procedure

A contact angle meter with a range from 10° to 120° was used for these experiments. Substrate materials included glass, stainless steel, material from the sidewall of an automobile tire, unstained T1-11 plywood siding, stained T1-11 plywood siding and a high density hardboard. Similar volume droplets where placed on the substrate with a micro dispenser with 5 ml pipette tubes. Separate pipette tubes were used with each agent to avoid cross contamination. A contact angle reading was made within a few seconds of the droplet being placed on the surface.

The substrates were carefully handled and prepared to avoid fingerprints or other contaminates from contacting the surfaces. The glass microscope slide covers were taken from sealed packages and used without further cleaning. The stainless steel was polished with very fine crocus cloth, washed off with tap water and dried with a paper towel. Then the test surface was washed with acetone and blown dry with "dry" compressed air. The tire sidewall was washed off with water to remove grit and residue from cutting the sample from the tire. The unstained plywood siding was cut from a sheet of plywood as delivered from a lumber yard; the moisture content was less than 10%. The stained plywood sample had one coat of waterproofing stain applied with a roller. The amount of stain applied averaged 265 g/m$^2$ over the 1.22 m x 2.44 m panel from which the sample was cut. The sample cured for approximately 6 months. The stain meets federal specification TT-W-572B for water repellency on wood. The hardboard sample is medium density hardboard with a density of 960 kg/m$^2$. The hardboard was wiped with a clean, dry cloth prior to testing to remove any sawdust.

In addition to the tap water and agent samples, distilled and deionized water was also used for the contact angle experiments. All of the solutions were made from tap water. The agent solutions were mixed within 24 hours of use in the experiments.

### 2.4.2 Results and Discussion

Each combination of agent and substrate had a least three replicate experiments performed. The results shown in Table 4 are the averages of the replicate experiments. The uncertainty of the contact angle measurement device is ±0.5°.

**Table 4 Contact Angle Measurements**

| Agent | Substrate | | | | | |
|---|---|---|---|---|---|---|
| | Glass | Stainless Steel | Tire | Unstained Plywood | Stained Plywood | Hardboard |
| D/D Water | 42.4 | 88.0 | 80.0 | ~ | 98.7 | 100.4 |
| Tap Water | 50.4 | 86.8 | 81.6 | ~ | 106.7 | 99.6 |
| Agent A 1% | 25.3 | 14.0 | 18.8 | ~ | ◆ | X |
| Agent B 1% | 37.3 | 11.3 | 16.0 | ~ | ◆ | X |
| Agent C 1% | 29.0 | <10 | 16.4 | ~ | ◆ | X |
| Agent D 1% | 27.8 | <10 | 31.6 | ~ | ◆ | X |
| Agent C 3% | 32.2 | <10 | 19.2 | ~ | ◆ | X |
| Agent D 3% | 30.2 | <10 | 25.6 | ~ | ◆ | X |
| Agent C 6% | 31.1 | 10.7 | 22.8 | ~ | ◆ | X |
| Agent D 6% | 31.8 | <10 | 19.6 | ~ | ◆ | X |

~ Completely absorbed into unstained plywood within 5 seconds after application.
◆ Completely absorbed into stained plywood within 30 seconds after application.
X Completely absorbed into hardboard within 15 seconds after application.

With the exception of the unstained plywood, water in both distilled and tap form, beaded up on top of the substrate. In the case of the unstained plywood, the water and the agent solutions were absorbed or penetrated into the wood within seconds of application. All of the agents demonstrated significantly lower contact angles relative to water on the impenetrable surfaces and penetrated surfaces, stained plywood and hardboard, which water could not.

Stainless steel was used as benchmark to compare with a study on droplet evaporation by Qiao et. al.[9,10]. This study examined the effect of evaporation of drops placed on a hot stainless steel plate. Contact angles were used to characterize the droplets. The contact angles were varied by adding a surfactant, sodium dodecyl sulfate, to the water. The results state, "As the liquid layer becomes thinner, heat transfer from the solid to the liquid-vapor interface is enhanced. Spreading of the droplet also increases the heat transfer area. Both of these effects contribute to a faster evaporation rate: decreseasing the contact angle from 90° to 20° reduced the droplet evaporation time by approximately 50%"[10]. In other words, the water/surfactant solution provided twice the cooling as plain water. Table 4 shows the baseline water contact angles to be approximately 90° and the agents all have contact angles less than 20°. Therefore, based on these contact angle tests and Qiao's results, an increased cooling capability of a factor or two would be expected from these agents.

### 2.4.3 Conclusions

The surfactants in Agents A.B,C and D significantly reduce the contact angle of their solutions relative to plain water. This increases the surface area covered by a single droplet and based on previous studies should increase the rate of cooling.

## 2.5 Droplet Size

Heat transfer is very important in suppressing fires. Heat transfer is dependent on many mechanisms, such as: the ability of materials to absorb heat, the difference in temperature and the surface area. An example of a ventilation limited room fire is a sofa burning and flames starting to come out of the window. In this case, the agent's capability, based on specific heat, to absorb heat is similar to water and the temperature differences would be the same with an agent or water. The heat transfer will vary as a function of surface area. When a fire suppression agent is discharged into the room it can transfer heat from the hot gases or flames, the surfaces in the room, and the burning sofa.

When the agent is delivered as a straight steam, its surface area is small when it passes through the flames. Therefore almost all of the agent will hit a surface, break up and splash. If the surface is hot, the agent will start absorbing the heat. So the heat transfer is limited by the area of the hot surfaces in the room. If the water hits the burning item or the ceiling, steam will be generated to displace oxygen in the room and help knock down the fire.

If the agent is delivered as a spray, the surface area of the agent will increase dramatically. If the drops are small enough, significant amounts of heat can be transferred while the agent is passing through the flames and hot gas. This scenario can provide faster steam conversion and a very rapid fire knockdown compared to straight stream application.

Discharging agent into a room, in the form of a 51 mm (2.5 in) stream provides a surface area of $0.24 m^2$ ($370 in^2$) per gallon prior to the stream impacting on a surface. If the agent is discharged as a stream of large drops, 2 mm (0.078 in) in diameter, then surface area of the water per gallon increases almost 50 times to 11.4 $m^2$ (17,700 $in^2$). If the diameter of the drops were reduced to 1 mm, the surface area or the agent available for heat transfer would double over that for 2 mm drops. This illustrates the relationship between surface area available for heat transfer and droplet size.

Water has a relatively high surface tension of 75 dynes/cm [8]. A high surface tension means that water is cohesive, it likes to stick to itself. This high surface tension causes water to bead up into large drops.

One of the properties of water which the agents affect is surface tension. This means the agents are surface active agents or surfactants. The addition of a surfactant reduces the surface tension of water. This will potentially allow the solution, when sprayed through a fire fighting fog nozzle, to break into smaller droplets resulting in more surface area of the solution being exposed to the fire. The increased surface area provides greater heat transfer and heat loss from the fire. The greater the heat transfer/heat loss rate, the faster the fire will be extinguished. Due to their lower surface tension, droplets surviving beyond the flames, onto the fuel source, will be able to penetrate the fuel easier, extinguishing the fire more rapidly.

To investigate the impact of the agents on droplet size, droplet differences between water and water plus one of four surfactant agents (identified as agents A, B, C, and D) discharged from a hose were measured using a droplet analyzer. Droplet measurements were recorded at four different locations within a circular spray pattern. Droplet sizes, distribution and velocity were determined, averaged and compared. Finally, the percent differences were calculated.

### 2.5.1 Experimental Procedure

An optical array laser probe was used to record the droplet measurements. This laser probe uses a process called the shadowing principle to obtain droplet measurements. The beam of the probe laser is reflected between the area of the two appendages of the probe (known as the measurement volume) through which the droplets pass, Figures 7 and 8. As the beam passes through this volume, it is reflected onto a diode array. Droplets passing through the laser create a shadow on the diode array. The width and scan times are recorded to form the dimensions of the droplet. Data obtained from the probe was recorded on a personal computer using the image analysis software provided with the probe.

The probe's software and hardware contain functions for error correction and droplet verification. Images of multiple droplets and droplets that do not fall completely in the measuring area are rejected. Droplets sizes from 30 μm to 1860 μm in diameter can be measured and recorded by the probe. Droplet measurements are put into class groups of 30 μm.

A typical fire fighting fog nozzle, capable of flowing between 0.6 l/s (10 gpm) and 1.9 l/s (30 gpm), was used to produce the droplets. The nozzle was capable of being adjusted from a straight stream to a full fog pattern of approximately 90°. Foam solutions were either batch mixed and delivered through a portable centrifugal pump or proportioned using a bladder tank and the building standpipe system. Solutions were delivered to the nozzle through 30.5 m (100 ft) of 38 mm (1.5 in) diameter lined fire hose at a nozzle pressure of 690 kPa (100 psi).

The fog nozzle was secured above the ground at a height of 3 m (9.8 ft). It was oriented at a 90° angle to the floor, spraying downward. This produced a circular spray pattern parallel to the floor, Figure 7. The exact center of the spray pattern was located and marked on the floor. The spray pattern was adjusted to an approximate 15° degree angle with a radius of 0.3 m (1 ft) at a distance of 2.5 m (8 ft) from the nozzle. Throughout the remainder of the test series, the nozzle was not adjusted or moved in order to ensure identical results. However, a final test was conducted with the nozzle set to provide a full fog pattern.

The probe was mounted onto a movable platform with the laser sampling area 0.5 m (1.6 ft) above the floor and 2.5 m (8 ft) below the nozzle. The platform was positioned with the probe in the desired test location and measurements were recorded at positions 0 m, 0.1 m, 0.2 m, and 0.3 m radially from the centerline. Selected measurements were taken to ensure that a symmetrical pattern was obtained from the nozzle.

Tests were conducted using water and each of the four solutions for a minimum of 1200 seconds at each location within the spray pattern. Since the water was obtained directly from the building standpipe, the tests using plain water were completed in single, continuous 1200-second runs at each location . Agents A and B, mixed at 1%, were proportioned using the bladder tank. Because of the size of the bladder tank, the tests could only be run for a maximum of 600 seconds. Three 600-second tests were conducted for each location. Agents C and D, mixed at 3%, were batch-mixed in a tank and than pumped to the nozzle using a portable fire pump. The size of the tank allowed for tests that could run for a total of 1200 seconds. One 1200-second test was conducted at each location. One test using water with the nozzle set to the full fog pattern was conducted to examine the impact of the nozzle alone on droplet size. A flow rate of approximately 0.6 l/s (10 gpm) was used in all of the tests.

### 2.5.2 Analysis

Analysis of the data obtained from this test series was conducted using ASTM E 799-92, Standard Practice for Determining Data Criteria and Processing for Liquid Drop Size Analysis [11] as a guide. There are several values of interest in characterizing liquid drop size distributions. The volume median diameter or average droplet size is defined as the drop diameter such that 50% of the total liquid volume is in drops of smaller diameter, $D_{v0.5}$. The drop diameter such that 90% of the total liquid volume is in drops of smaller diameter is identified as the $D_{v0.9}$. The drop diameter such that 99% of the total liquid volume is in drops of smaller diameter is the $D_{v0.99}$. In addition, the average length/width ratios and velocities were calculated. For the final analysis, all values from the multiple tests were averaged. The $D_{v0.5}$, $D_{v0.9}$, and $D_{v0.99}$ for each solution at each location are shown in Tables 5, 6, and 7, respectively.

**Table 5. $D_{v50}$ (µm) Data for Water and Four Agents at Four Measurement Positions**

| Position | Water | Agent A | Agent B | Agent C | Agent D |
|---|---|---|---|---|---|
| Centerline | 309 | 297 | 325 | 287 | 252 |
| 0.1 m | 300 | 266 | 291 | 275 | 277 |
| 0.2 m | 260 | 296 | 300 | 278 | 278 |
| 0.3 m | 289 | 299 | 354 | 253 | 266 |

**Table 6. $D_{v90}$ (μm) Data for Water and Four Agents at Four Measurement Positions**

| Position | Water | Agent A | Agent B | Agent C | Agent D |
|---|---|---|---|---|---|
| Centerline | 573 | 626 | 663 | 516 | 464 |
| 0.1 m | 523 | 484 | 509 | 426 | 439 |
| 0.2 m | 421 | 517 | 453 | 464 | 445 |
| 0.3 m | 485 | 501 | 538 | 448 | 441 |

**Table 7. $D_{v99}$ (μm) Data for Water and Four Agents at Four Measurement Positions**

| Position | Water | Agent A | Agent B | Agent C | Agent D |
|---|---|---|---|---|---|
| Centerline | 906 | 805 | 1276 | 877 | 735 |
| 0.1 m | 824 | 806 | 864 | 575 | 602 |
| 0.2 m | 656 | 813 | 590 | 597 | 622 |
| 0.3 m | 638 | 683 | 802 | 639 | 639 |

In order to normalize the data for comparison with water, the $D_v$ values of water were divided into all the values. This gave water a value of one at every location. Agents that have a $D_v$ value larger than water are greater than one, agents with $D_v$ values less than water have are less than one. The normalized results are presented in Tables 8, 9, and 10. The average percent difference between water and each agent was calculated and shown in the last row in each Table. The estimated error was one size class of 30 μm. The error used for calculating percentage error was ±15 μm. The droplet size tests conducted on water gave a $D_{v0.99}$ value of 756 μm. The $D_{v0.99}$ values of agent A and B were both larger than water while the $D_{v0.99}$ values of agent C and D were smaller.

**Table 8. Normalized $D_{v50}$ (μm) Data for the Four Agents at Four Measurement Positions**

| Position | Agent A | Agent B | Agent C | Agent D |
|---|---|---|---|---|
| Centerline | 0.96 | 1.05 | 0.93 | 0.82 |
| 0.1 m | 0.89 | 0.97 | 0.92 | 0.92 |
| 0.2 m | 1.14 | 1.15 | 1.07 | 1.07 |
| 0.3 m | 1.03 | 1.22 | 0.88 | 0.92 |
| Percent Diff. | 0.52 | 10.01 | -5.25 | -6.79 |

**Table 9. Normalized $D_{v90}$ (μm) Data for the Four Agents at Four Measurement Positions**

| Position | Agent A | Agent B | Agent C | Agent D |
|---|---|---|---|---|
| Centerline | 1.09 | 1.16 | 0.90 | 0.81 |
| 0.1 m | 0.93 | 0.97 | 0.81 | 0.84 |
| 0.2 m | 1.23 | 1.08 | 1.10 | 1.06 |
| 0.3 m | 1.03 | 1.11 | 0.92 | 0.91 |
| Percent Diff. | 6.97 | 7.89 | -6.48 | -9.61 |

**Table 10. Normalized $D_{v99}$ (μm) Data for the Four Agents at Four Measurement Positions**

| Position | Agent A | Agent B | Agent C | Agent D |
|---|---|---|---|---|
| Centerline | 0.89 | 1.41 | 0.97 | 0.81 |
| 0.1 m | 0.98 | 1.05 | 0.70 | 0.73 |
| 0.2 m | 1.24 | 0.90 | 0.91 | 0.95 |
| 0.3 m | 1.07 | 1.26 | 1.00 | 1.00 |
| Percent Diff. | 4.41 | 15.33 | -10.56 | -12.71 |

Agent A created significant amounts of foam and appeared to be a foaming agent. The turbulence created as the solution passed through the fog nozzle appeared to induce a foaming action. The foams were thick and lasted for several hours before breaking down. The spray pattern was not altered by the solution and it flowed at a rate comparable to water. Agent B also created large amounts of foam similar to agent A. Agent C created very little foam when tested. It did not alter the spray pattern and flowed at a rate comparable to agents A and B. Agent D also did not foam and was unique in that it flowed at a much higher rate than the other three agents under identical conditions. It is possible that agent D lowered the viscosity, which decreased friction loss in the hose, but this can not be verified without additional testing. Agent D appeared to foam less than the other agents during these experiments.

Agent A had a $D_{v0.99}$ of 776 μm. This size difference of 20 μm turned out to be less than one class size (30 mm) larger than water. With a size difference so small, it would seem that the solution characteristics would be similar to water. However, Agent A had a velocity 1.17 m/s slower. The velocity data obtained for water and the four agents is summarized in Table 11. A comparison of Agent A to water indicates that Agent A produces larger, lighter, and slower moving droplets.

**Table 11. Velocity in m/s for Water and the Four Agents at Four Measurement Positions**

| Position | Water | Agent A | Agent B | Agent C | Agent D |
|---|---|---|---|---|---|
| Centerline | 5.00 | 5.90 | 5.80 | 4.50 | 3.60 |
| 0.1 m | 3.50 | 3.20 | 3.60 | 3.30 | 3.00 |
| 0.2 m | 3.20 | 0.97 | 1.70 | 2.60 | 3.60 |
| 0.3 m | 3.40 | 0.35 | 0.18 | 2.30 | 5.00 |
| Average | 3.78 | 2.61 | 2.82 | 3.18 | 3.80 |

Agent B had a $D_{v0.99}$ value of 883 μm. This represents a difference of 127 μm or over 4 size classes larger. It is the greatest difference of any of the agents tested. Agent B also changed the spray pattern into a much smaller angle and produced foam with a velocity approximately 1 m/s slower. When compared against water, agents A and B both performed about the same. Agent B produced droplets much larger than water with a low velocity.

The testing of Agent C resulted in a $D_{v0.99}$ of 672 μm with droplets 84 μm smaller and velocities 0.6 m/s slower than water. The loss in speed could be a result of energy loss from the forming of the smaller droplets. Additionally, the smaller droplets would have less mass and momentum and could be slowed more by the air. The smaller droplets of Agent C are unlike the droplets of agents A and B in that Agent C did not create foam or foam droplets. This translates into smaller water-like droplets. This decrease in droplet size can increase the surface area of solution exposed for heat transfer. The smaller droplets coupled with the slower speed may result in more steam and less penetration.

Agent D produced the smallest of all the droplets with a $D_{v0.99}$ of 649 μm. This represents a difference of 106 μm, which is more than 3 size classes. Agent D was unique in that it increased droplet velocity. Agent D flowed at a higher rate than the other surfactants, and produced a droplet velocity 0.02 m/s faster than water. Although the difference is small compared to water, it is an average of 1 m/s faster than the other three surfactants. The result is a smaller droplet at approximately the same velocity as water.

The comparison of the water at a 15° angle to a full fog pattern showed that solely using the nozzle, with no additive, the water droplet size could be decreased from a $D_{v0.99}$ of 756 μm to a $D_{v0.99}$ of 600 mm. The velocity of the smaller drops was lowered to 2 m/s; this is 1.78 m/s slower. In the comparison with water plus agents to water alone, droplet size was smallest when water alone was sprayed through the nozzle at a full fog pattern. The fog nozzle data is shown in Table 12.

**Table 12. Summary of Data for a Typical Fog Nozzle**

| Cone Angle | $D_{v50}$ | $D_{v90}$ | $D_{v99}$ | Velocity (m/s) |
|---|---|---|---|---|
| 15 | 289 | 501 | 756 | 3.78 |
| 90 | 353 | 479 | 600 | 2.00 |
| Percent Difference | 21.97 | -4.40 | -20.6 | ——— |

### 2.5.3 Conclusion

From the perspective of this experiment, which was to demonstrate the effect of surfactant agents on water, Agent D produced the smallest droplets. Its smaller droplets, with no loss in velocity, would theoretically prove more efficient in transferring heat in the hot gas layer. However, the effectiveness of these agents on different types of fires can only be determined through additional testing on actual fires.

Further research should be conducted with single droplet generators to eliminate the variability of the nozzle. An additional project should be conducted to examine the effect of surfactant agents on drop size, pattern, and throw when applied through adjustable fog nozzles at higher fire fighting flow rates 6 to 16 l/s (100 to 250 gpm).

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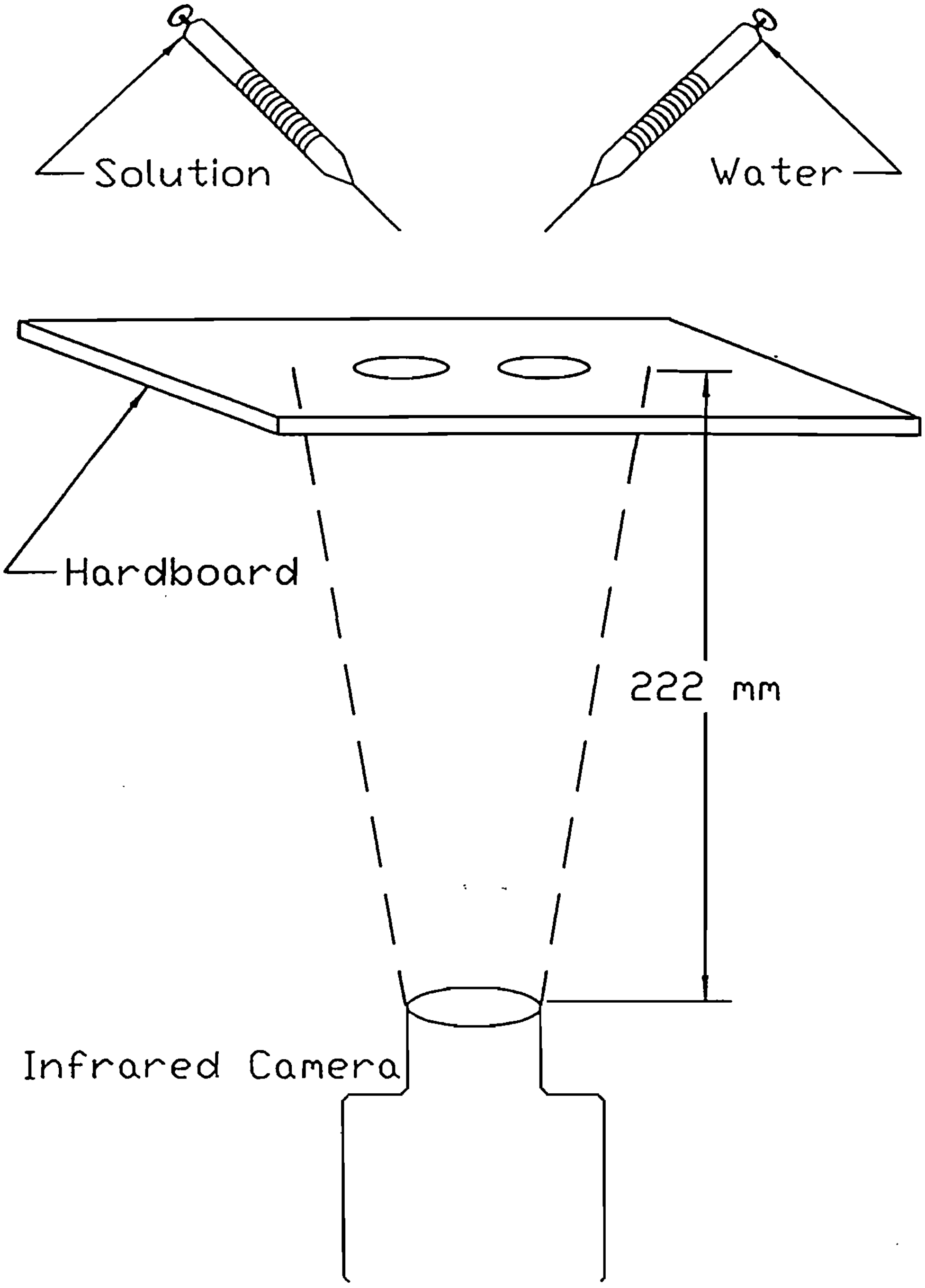


Figure 1. Diagram of Experimental Arrangement

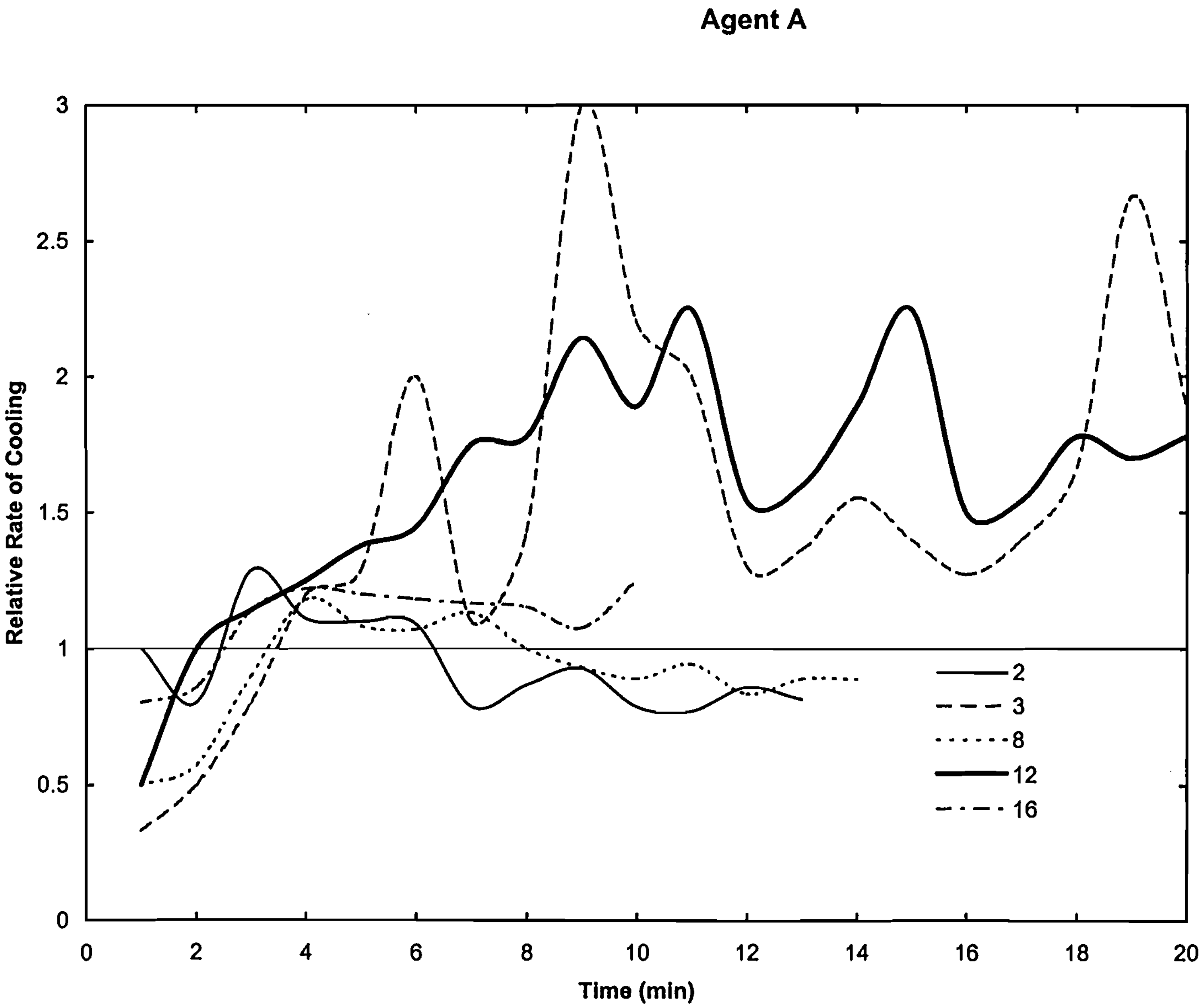


Figure 2. Rate of cooling relative to water, Agent A.

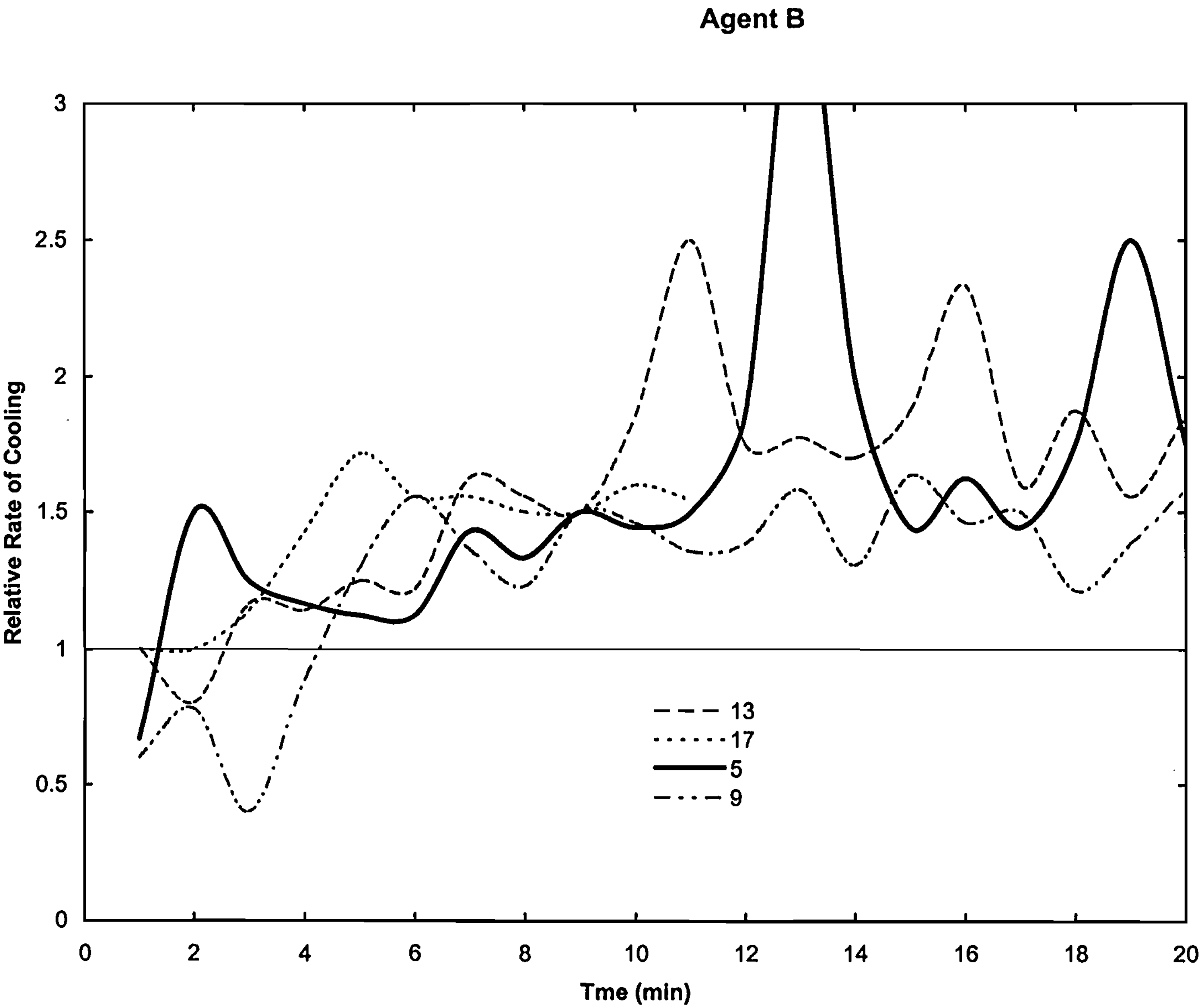


Figure 3. Rate of cooling relative to water, Agent B.

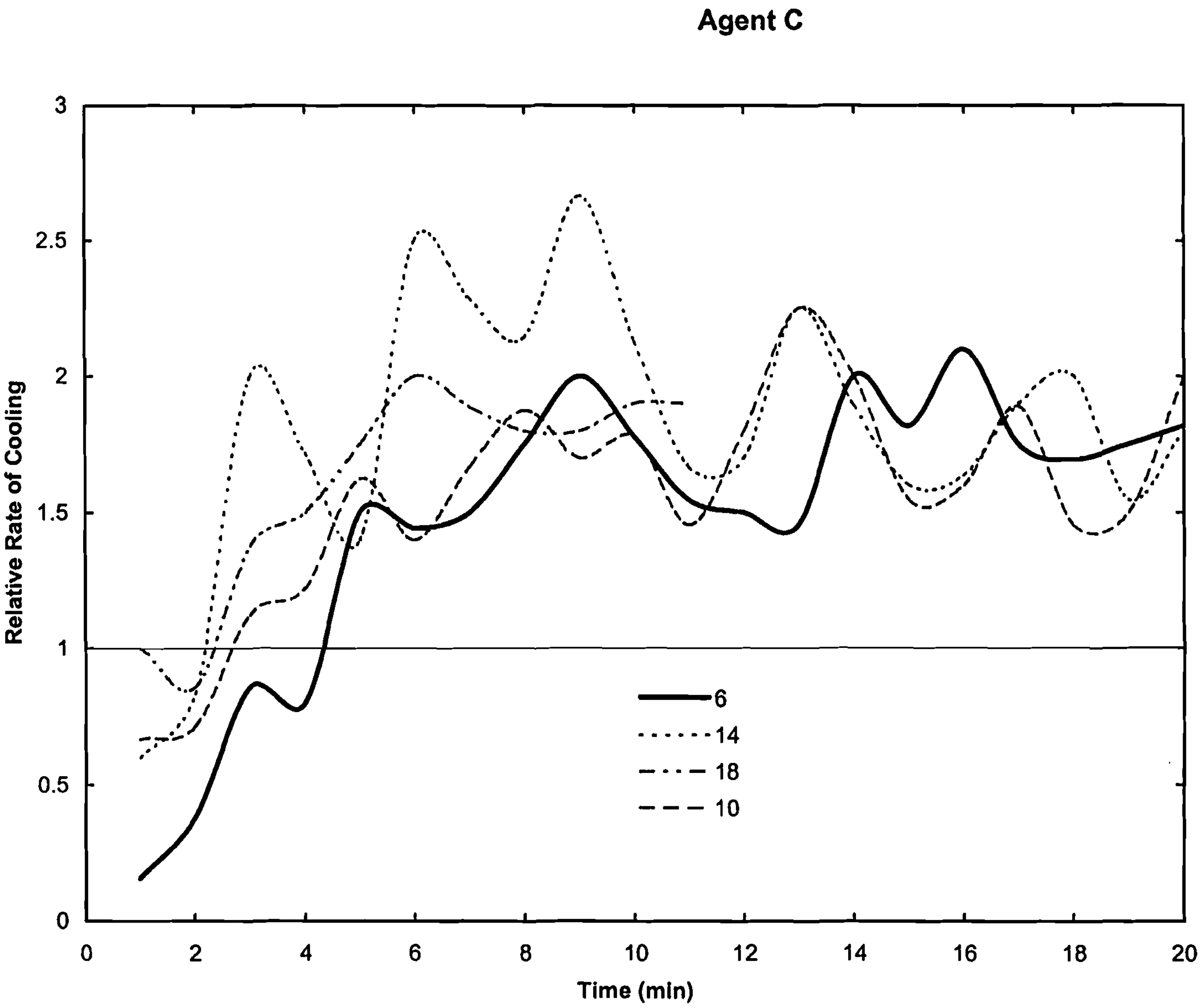


Figure 4. Rate of cooling relative to water, Agent C.

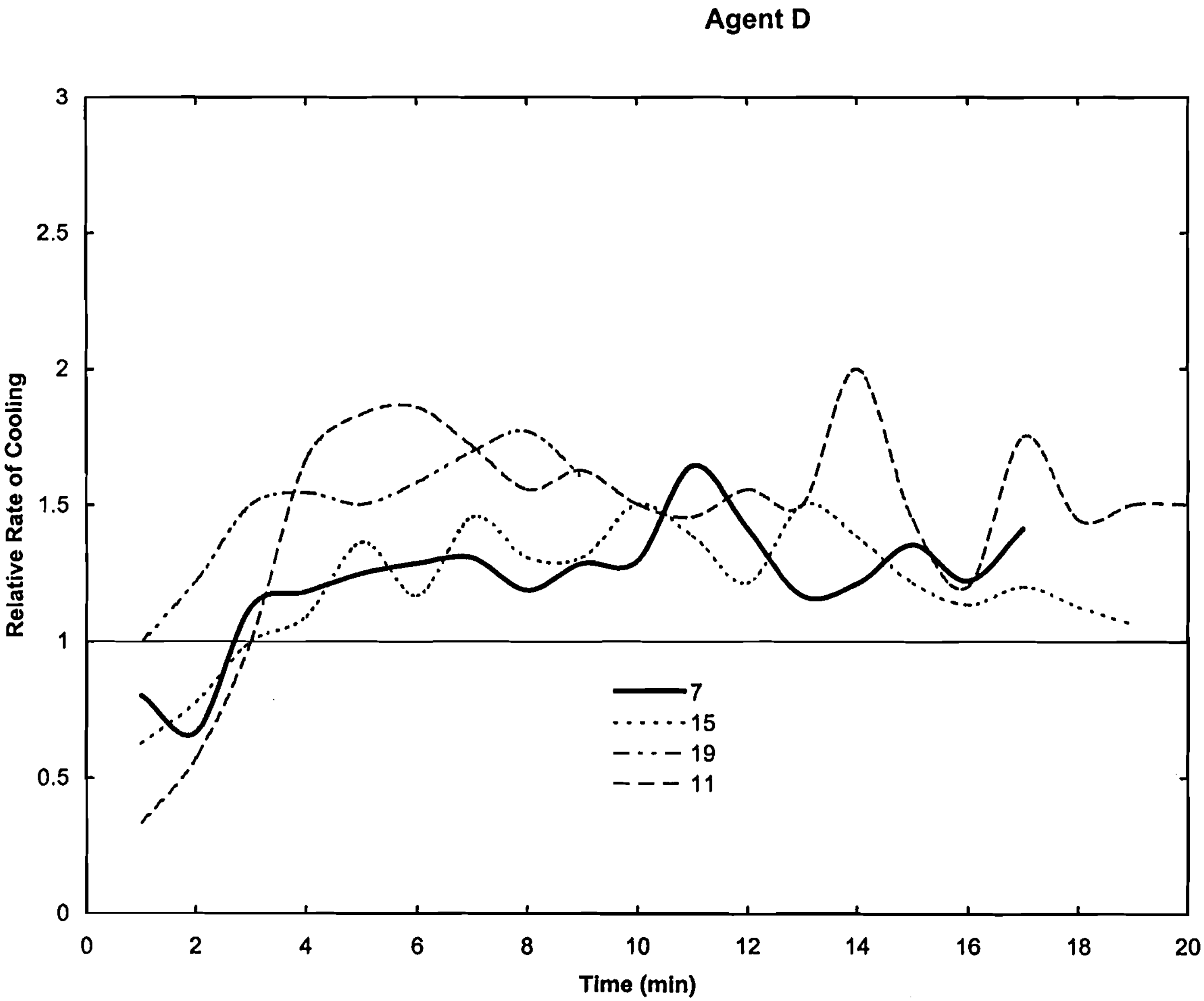


Figure 5. Rate of cooling relative to water, Agent D.

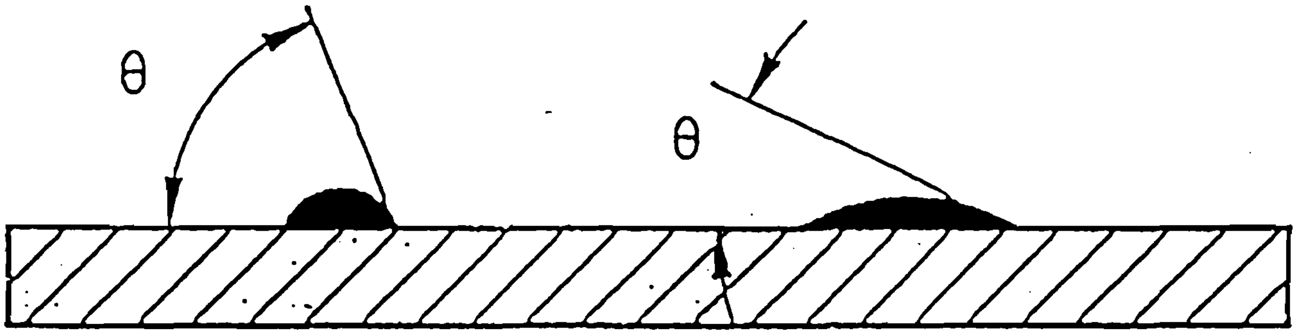
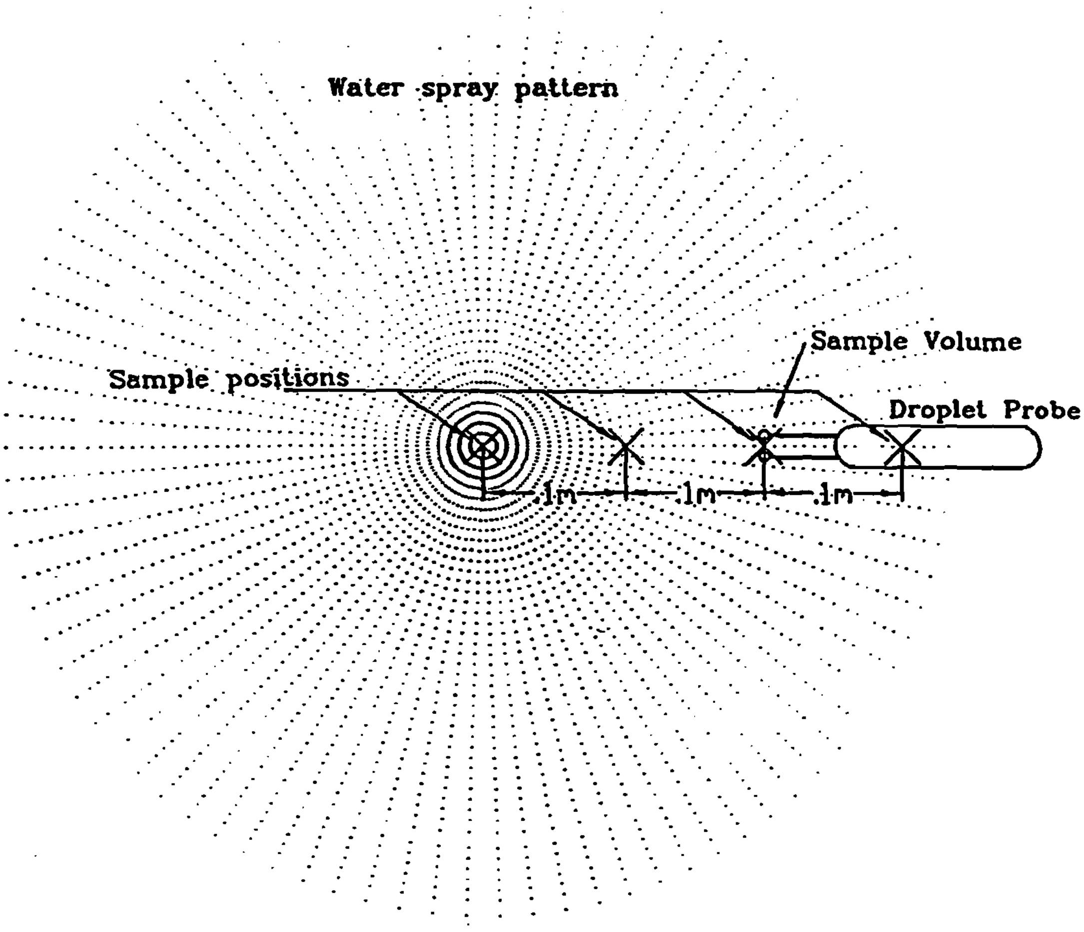


Figure 6. Diagrams of contact angle, θ

**Plan View Above Nozzle**



**Measurements were taken at the center, .1m, .2m, and .3m as shown.**

Figure 7. Plan view of droplet measurement arrangement.

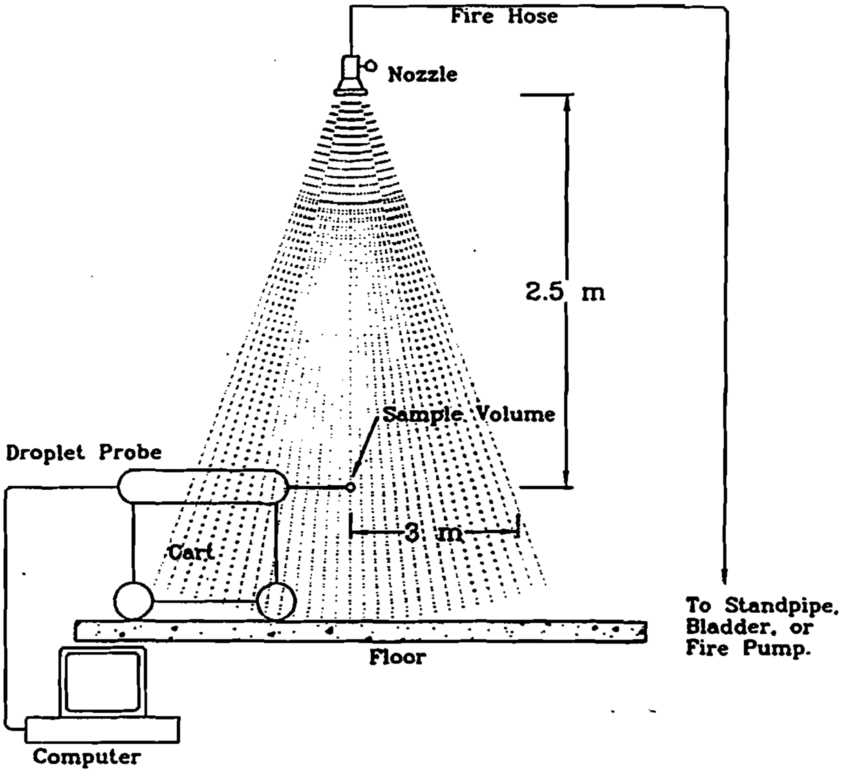


Figure 8. Elevation of droplet measurement arrangement.

# CHAPTER 3

# FIRE EXPOSURE PROTECTION

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# FIRE EXPOSURE PROTECTION

## 3.1 Introduction

Controlling the fire is second in priority only to search and rescue for fire departments first arriving on the scene. Exposure protection is an important defensive tactic used to limit fires to the property of origin. The main objective is preventing a large-loss fire in the community [1]. To provide exposure protection, fire department personnel may apply water, solution, or foam to the exterior of buildings at risk of becoming involved through radiation. Regardless of the agent being applied however, its effectiveness depends upon two characteristics. The first is its ability to stay on, or in, the material to which it is applied, and the second is how long it prevents or delays ignition.

All four water-based agents (hereinafter referred to as the agents) used during this demonstration are surfactants. One reported benefit of using surfactants for fire fighting is that they penetrate and wet the material to which they are applied better than plain water. Three more reported benefits are realized, which are particularly important to exposure protection, when these agents are applied in the form of compressed air foam (CAF): One, they can insulate the material to which they are applied. Two, they can cling to vertical and under horizontal surfaces. Three, they are easy to see, so they can be applied more efficiently than plain water [2].

## 3.2 Objective

There were two objectives of the exposure-protection experiments. The first was to determine how effective the agents are, relative to water, at remaining on or in exterior siding materials. This objective was met by the mass-retention experiments. The second was to determine if the additional mass of water remaining on or in the material, afforded by the agents, significantly increases the time to ignition. This objective was met by the ignition-inhibition experiments.

## 3.3 Mass Retention Experiments

To investigate the mass-retention effectiveness of the agents, large-scale experiments were conducted using three exterior building materials: unstained exterior textured plywood siding, stained exterior textured plywood siding, and vinyl siding. The materials represent some of those which may be found on residential dwelling units to which agents may be applied for exposure protection. In 1988, plywood was the most widely used exterior siding on single family homes, and vinyl was the most widely used non-wood siding material [3]. In addition to being practical material choices, it was expected that the three scenarios would provide varying degrees of difficulty for the agents to remain on or in the materials.

### 3.3.1 Experiment Setup

Water and four different agents were used during these experiments. The agents were applied to the siding as sprayed solution and as CAF. Water was applied as a spray, with the same nozzle used to apply solutions. The same mass of water, solution, or CAF was applied to each siding material during their respective experiments and the change in agent/water mass was measured over a six-hour period. The agents' mass-retention effectiveness, both relative to water and to each other, was then evaluated. Table 1 below shows the experiment matrix.

**Table 1.** Mass-Retention Experiment Matrix.

| Series | Experiments | Agent/Water | Application Method |
|---|---|---|---|
| 1 | 1-3 | Water | Spray |
| 2 | 4-6 | A | Spray Solution |
| 3 | 7-9 | B | Spray Solution |
| 4 | 10-12 | C | Spray Solution |
| 5 | 13-15 | D | Spray Solution |
| 6 | 16-18 | A | CAF |
| 7 | 19-21 | B | CAF |
| 8 | 22-24 | C | CAF |
| 9 | 25-27 | D | CAF |

Panels of exterior siding were suspended vertically from above by a load-cell. Wire was attached to the bottom corners of each panel and the wall behind each panel to prevented it from spinning about its vertical axis. Each panel was set upon a stand when the agents were applied. This provided stability and reduced the strain on the load-cell. A distance of approximately 0.3 m (12 in) was maintained between the bottom of the panel and the floor surface to provide room for agent drainage (Figure 1).

The three exterior siding materials used for this experiment were as follows:

- 1.22 m x 2.44 m x 13 mm (4 ft x 8 ft x ½ in) unstained, textured plywood siding (T1-11).
- 1.22 m x 2.44 m x 13 mm (4 ft x 8 ft x ½ in) textured plywood siding (T1-11), stained with one coat of house stain containing waterproofing and passing federal specification TT-W-572B for water repellency on wood. A roller was used to apply an average of 790 ± 50 g (28 ± 2 oz) of the stain to each panel. This is approximately 1/4 gallon of stain per T1-11 panel.
- 1.22 m x 2.44 m (4 ft x 8 ft) vinyl siding panel, mounted to a wood frame consisting of 38 mm x 38 mm (1-1/2 in x 1-1/2 in) members.

Two vinyl panels were constructed and used so that one panel could be pressure-washed and dried while the other was being used for an experiment.

A commercially available compressed air foam system (CAFS), with a double-diaphragm pump was used to apply water and agents (Figure 2). The water and solutions were pumped through a 15.24 m (50 ft) long, 1.6 cm (5/8 in) I.D. hose fitted with a 0.62 cm (1/4 in) I.D. reducer and 15° full cone spray nozzle rated 5.3 Lpm (1.4 gpm) at 276 kpa (40 psi). The CAFs were pumped through a 15.24 m (50 ft) long 3.18 cm (1-1/4 in) I.D. fabric hose, fitted with a 2.54 cm (1 in) quarter-turn ball valve.

The agents and water were kept in separate 126 L (33 gal) containers so that no mixing occurred between different agents. Also, after each experiment, the container, pump, and hose were rinsed with plain water to avoid obtaining solutions with higher concentrations over time and to avoid agent mixing. Solutions were batch mixed, using the agent manufacturer's recommended concentrate-to-water ratio, within one-half hour of application.

The target mass to apply to the panels was 2.7 ± 0.14 kg (6 ± 0.3 lbs) or 0.9 ± 0.05 $kg/m^2$ (0.1 ± 0.01 $lbs/ft^2$) of agent or water. This mass was determined from preliminary experiments using the CAFS during which mass flow rates and application times were considered. Mass flow rates of approximately 5 kg/min (1.3 gpm volumetric flow rate), for water and solutions, and 8 kg/min (2.1 gpm volumetric flow rate) for CAFs produced the reach and patterns appropriate for the laboratory environment in which the experiments were conducted. However, the expansion of the CAF was found to vary between agents for a given mass flow rate. In order to obtain expansions that were similar, the mass flow rate was adjusted for each agent. Also, it was found that at least 15 seconds were needed to apply the agents uniformly over the area of the panel. The combination of the needed mass flow rates and application times resulted in the target mass to apply to the panels.

### 3.3.2 Instrumentation and Measurements

A computer controlled data acquisition system recorded the following measurements every 60 s:

- Mass of the panels.
- Relative humidity and temperature, measured 1.2 m (4 ft) in front of the center panel, and 1.3 m (4.3 ft) up from the floor.

In addition to using the mass of the panels to determine the amount of agent in or on the panels, the initial moisture content of the unstained panels was measured with a drive-in electrode moisture meter using electrical resistance technology. Because the stained and unstained panels were stored in the same area and were subject to the same environmental conditions, the initial moisture content readings from the unstained panels should provide a reasonable estimate of the initial moisture content in the stained panels as well. These readings ensured each set of three panels contained approximately the same amount of moisture at the start of the respective test.

The moisture content was measured in three locations along the vertical centerline of the panels. Measured from the bottom of the panel, the locations are 0.61 m (2 ft), 1.22 m (4 ft), and 1.83 m (6 ft). Shown below, in Table 2, are the average initial moisture content readings of the unstained panels before each experiment. The plus/minus (±) indicates the farthest deviation from the average of the three readings.

**Table 2.** Moisture Content of Unstained Panels before each Experiment.

| Experiment Number | % Initial Moisture Content | Applied Agent | Agent Form |
|---|---|---|---|
| 1 | <6 | Water | NA |
| 2 | <6 | Water | NA |
| 3 | <6 | Water | NA |
| 4 | 6 ± 3 | A | Solution |
| 5 | 11 ± 1 | A | Solution |
| 6 | 7 ± 1 | A | Solution |
| 7 | 10 ± 3 | B | Solution |
| 8 | 10 ± 1 | B | Solution |
| 9 | 8 ± 2 | B | Solution |
| 10 | 8 ± 1 | C | Solution |
| 11 | 6 ± 3 | C | Solution |
| 12 | 7 ± 1 | C | Solution |
| 13 | 8 ± 2 | D | Solution |
| 14 | 9 ± 1 | D | Solution |
| 15 | 8 ± 2 | D | Solution |
| 16 | 11 ± 1 | A | CAF |
| 17 | 12 ± 2 | A | CAF |
| 18 | 6 ± 1 | A | CAF |
| 19 | <6 | B | CAF |
| 20 | 9 ± 0 | B | CAF |
| 21 | <6 | B | CAF |
| 22 | <6 | C | CAF |
| 23 | <6 | C | CAF |
| 24 | <6 | C | CAF |
| 25 | <6 | D | CAF |
| 26 | <6 | D | CAF |
| 27 | <6 | D | CAF |

Wood with moisture content values of 6% or less may not yield accurate moisture content readings with an electrical resistance moisture meter. Usually, the electrical resistance of the wood at or below this moisture content is too high ($\approx 10^{11}\ \Omega$) for the meter to measure [4]. For this reason, panels with an associated moisture content of 6% or less listed in Table 2 had an actual moisture content of between 0% and 6%, probably not the actual value shown.

Once agent has been applied to the panels, a moisture content meter using electrical resistance technology may not provide accurate results for two reasons:

1. The conductivity of the agents is much greater than that of water. Experiments performed for the Structure Fires portion of this demonstration resulted in an increase in conductivity of more than 400% over that of water for one of the agents. This should result in higher-than-normal measurements because the instrument uses electrical resistance, the inverse of conductance, to estimate the moisture content of the wood.

2. The accuracy of an electrical resistance moisture meter is unreliable when the wood is above the fiber saturation point (approximately 30% moisture content). This is mainly due to a decrease in the rate of change of resistance with moisture content, which reduces the sensitivity of the meter[4].

Solutions, by definition of expansion, should have an expansion of 1. However, the combination of forcing the solution through the spray nozzle and the impact of it striking the surface of the panel creates some foam. For this reason, the expansion of the solutions was measured using a foam slider board, shown in Figure 3, and 1600 ml plastic cylinder (100 mm (3.9 in) I.D., 200 mm (7.8 in) height with a 0.64 cm (1/4 in) drain and valve) as described in NFPA 11, Standard for Low-Expansion Foam [5], Appendix C section C-1. The expansion depended largely on how quickly the cylinder was pulled from its holder. Even a few seconds delay lowered the expansion value considerably as there was a high rate of solution flowing into the cylinder. Also, the resulting bubble structure tends to consist of large bubbles which burst quickly, making it difficult to determine when the cylinder is actually full.

The expansion of the CAFs could not be measured using the foam slider board and 1600 ml plastic cylinder because the foam tended to flow over and around, but not into, the small cylinder. It was found that the smaller cylinder would work only for foams with expansions of approximately 10 or less. Therefore a vertical surface instead of the foam slider board, and a 103.4 L plastic cylinder, with 450 mm (18 in) I.D. and 650 mm (25.6 in) height, were used. This cylinder was also fitted with a 0.64 cm (1/4 in) drain and valve to measure 25% drain times.

### 3.3.3 Experimental Procedure

New T1-11 panels and a pressure-washed and dried vinyl panel were suspended from the load cells. The moisture content of the unstained panels was measured less than 20 minutes prior to agent application. The agent container was filled with tap water, and if agent was being used it was batch-mixed in the container. Three mass flow trials were conducted, averaged, and recorded using a container, a balance accurate to 1 g, and a stopwatch. Then, the application time was determined from the average of the three mass flow rates. The data acquisition system was started, and five minutes of background data were recorded. The panels were put onto their stands, and the agent was applied at a uniform rate such that the 2.7 kg of agent was distributed evenly over the area of the panel. Application was made from approximately 1.2 m (4 ft) in front of the panel with the nozzle held approximately 1.5 m (5 ft) from the floor surface. The panels were released from their stands after the agent was applied. This serves as time zero for the mass-retention data. If CAF was applied, the expansion and 25% drain time tests were conducted within 20 minutes after application was made to the panels.

### 3.3.4 Results and Discussion

The results of the mass-retention experiments are presented in tables and figures. A list of those tables and figures follows, along with a brief explanation about why these particular results were included in this report. Following the list of results is a discussion, which follows the sequence of the results. Finally, the summary is presented in the form of four main points.

#### 3.3.4.1 Results

Table 3 lists the results of the mass flow rates, expansions, and 25% drain times for the nine series of experiments. This table is included to give the reader an indication of the variability of the Agents used in this demonstration. It also highlights some of the limitations of the available commercial CAFS.

Figures 4-12 show the mass-retention results of the nine series of experiments conducted. Figure 4 shows the results of sprayed water. Figures 5-8 show the results of sprayed solution for Agents A, B, C, and D respectively. Figures 9-12 show the results of the CAF for Agents A, B, C, and D respectively. These figures serve primarily to show the reader the repeatability of the experiments. But, they also illustrate another important aspect of the experiments: how the environment affects exposure protection.

Figures 13 & 14 show how effective the agents were, relative to each other and to water, at remaining in or on the siding. These two figures are essentially the summary of the mass-retention experiments.

In addition to these figures, the Appendix contains the full set of computer acquired data, shown as Figures F1-F54, for all twenty-seven experiments.

#### 3.3.4.2 Discussion

The values shown below in Table 3 are the average of the three readings taken during the three experiments in the series. The plus/minus (±) is the maximum deviation from the average of the readings. As evidenced by the over one-half hour difference in 25% drain times between Agents A & D, the characteristics of each agent were very different. These different characteristics illustrate the difficulty of developing a CAFS which will produce foam with similar characteristics regardless of agent.

The commercially available CAFS used during this demonstration was marketed as a portable, self contained unit which could be used by a homeowner for exposure protection. However, minor adjustments to the solution flow valve and the air mixing valve of this CAFS often produced foams with considerably varying expansions. If the foam expansion is a critical variable in exposure protection, then CAFS unit manufacturers will need to consider this factor in the design of units.

**Table 3.** Mass Flow Rate, Expansion, and 25% Drain Time Results.

| Agent | Solution/Water Mass Flow Rate (kg/min) | CAF Mass Flow Rate (kg/min) | Solution/Water Expansion | CAF Expansion | CAF 25% Drain Time (min) |
|---|---|---|---|---|---|
| Water | 5.4 ± 0.1 | na | na | na | na |
| A | 5.3 ± 0.2 | 8.9 ± 0.5 | 2 ± 1 | 32 ± 6 | 46 ± 5 |
| B | 5.6 ± 0.2 | 9.0 ± 0.1 | 2 ± 1 | 43 ± 1 | 42 ± 10 |
| C | 5.1 ± 0.3 | 6.3 ± 0.2 | 2 ± 1 | 55 ± 6 | 19 ± 4 |
| D | 5.5 ± 0.1 | 9.3 ± 1.2 | 2 ± 1 | 35 ± 12 | 9 ± 1 |

Figure 1 demonstrates how the environment, in particular relative humidity, can affect water (agent) retention. Even though essentially the same mass of water was initially retained by the unstained panel during all three experiments, by the end of the sixth hour the unstained panel used in experiment 3 contained approximately one-half the amount of water as the other two panels. This can be largely attributed to the relative humidity during the experiments which, during experiment 3, was approximately one-half the value it was during experiments 1 & 2. Because wood is a hygroscopic material, its moisture content is very sensitive to relative humidity, and future exposure protection research should include different climate conditions as part of the scope [6].

Because the effectiveness of the agents is discussed in relation to water, the mass-retention of water, as shown in Figure 4, is very important. Similar mass-retention experiments were conducted by Madrzykowski [7] on unstained T1-11 plywood, during which he found 0.039 g/cm$^2$ to be the approximate maximum amount of water which would initially be retained by a sample. This equates to 1.16 kg of water per siding panel. This is within 10% of the 1.05 kg of water per siding panel found during these experiments. Therefore, the unstained panels are initially at or near their maximum water-holding capacity, which is approximately 3 times more water than the other two panel types. Approximately the same amount of water is retained by the stained and vinyl panels, starting at approximately 0.4 kg and ending at 0.05 kg. In the following discussion on the effectiveness of the agents, it is important to remember the approximate amounts of retained water on the three panels.

### 3.3.4.2.1 Solution Effectiveness

The agents' retention effectiveness is defined as the ratio of the average mass of agent on the panel at time t, to the average mass of water on the panel measured during the water mass-retention experiment at time t.

The solutions' effectiveness is shown in Figure 13. All solutions performed similarly with respect to the three panels. The maximum effectiveness of approximately 4.25 ± 0.75 was realized on the stained panels. The unstained panels maximum effectiveness was approximately 2 ± 0.3, and the solutions were not as effective as water on the vinyl panels.

For the unstained panels, at the zero-hour mark the solutions' effectiveness is approximately 1 to 1.5, so there is little or no mass-retention advantage over water. From the zero-hour to four-hour mark, it increases nearly linearly until it reaches a maximum of 2 ± 0.25. The four-hour to six-hour mark is essentially a period of steady-state retention effectiveness because the evaporation rate of the solutions and water is similar.

For the stained panels, at the zero-hour mark the solutions' effectiveness is approximately 1 to 1.5, so, again, there is little or no mass-retention advantage over water. From the zero-hour to four-hour mark, however, the effectiveness increases non-linearly and at a greater rate than that of the unstained panels until it reaches a maximum of 3.5 to 5. The four-hour to six-hour mark is essentially a period of steady state retention effectiveness because the evaporation rate of the solutions and water is similar.

No dripping occurred from the stained and unstained panels after approximately fifteen minutes from initial application, so the effectiveness after this time is the result of evaporation rather than run-off. It is not fully understood why the stained panels retain more solution relative to water than the unstained panels. It may be that the solution, because of its lower surface tension, wets a greater area of the panel and can better penetrate the stain. Once the solution does penetrate the stain and diffuse into the wood cell walls and cavities, the stain may then impede evaporation [8]. Although the effects appear dramatic on the effectiveness chart, in all cases the unstained panels retain more water/solution than the stained panels. The solutions' effectiveness on the unstained panels is not as pronounced because water and solution both can easily penetrate the unstained panel. It appears, from the solution penetration experiments conducted as part of this demonstration, that the mass-retention advantage afforded by solution on the unstained panels is the result of a deeper, quicker penetration than water.

For the vinyl panels, at the zero-hour mark the solutions' effectiveness is approximately 0.5; the vinyl retained half as much solution as water, and it remained at that level or below for the remainder of the experiments. This reveals a negative consequence of using surfactants in solution form; if the material to which it is applied is not porous, such as vinyl or aluminum, then because of its lower surface tension, it may run off the material at a faster rate than water.

### 3.3.4.2.2 CAF Effectiveness

The CAFs' effectiveness is shown in Figure 14. All CAFs except Agent A performed similarly with respect to the three panels. Similar to the solution results, the maximum effectiveness of approximately 6 ± 2 was realized on the stained panels. The unstained panels maximum effectiveness was approximately 4 ± 1, and after fifteen minutes, the CAFs were not as effective as water on the vinyl panels.

For the unstained panels, at the zero-hour mark the CAFs' mass-retention effectiveness is between 2 and 2.75. From the zero-hour to four-hour mark, it increases nearly linearly until it reaches a maximum of 3.25 to almost 5. The four-hour to six-hour mark is essentially a period of steady state due to the CAFs (by then in solution form) and water evaporating at the same rate. The anomaly is Agent A; instead of reaching a steady state near the four-hour mark, it continues upwards to 4.75. The CAF-effectiveness curves are similar in shape to those for solutions but with a near doubling of effectiveness afforded by the CAFs.

For the stained panels, at the zero-hour mark the CAFs' mass-retention effectiveness is between 4 and 5.5. From the zero-hour to the one-tenth hour mark, the effectiveness increases slightly before decreasing to a minimum of approximately 3 ± 0.75. From this point it increases nearly linearly until reaching a maximum of 6 ± 2 at the three-hour to four-hour mark. The four-hour to six-hour mark is essentially a period of steady state due to the CAFs (by then in solution form) and water evaporating at a similar rate. Again, the anomaly is Agent A which attained a maximum effectiveness of approximately 3.5, about one-half as effective as the other three agents. Why Agent A exhibited this behavior is unclear. The effectiveness curves for Agent A on the unstained and stained panels cross at approximately the 20 minute mark, where it appears that the curve for the unstained panels starts to track the curves for the stained panel and the curve for the stained panels start to track the curves for the unstained panels. Since this behavior was not evident in Figure 4, the effectiveness curves for solution, it is possible that the behavior is the result of the agent being in CAF form. The two defining characteristics of Agent A, CAF form, are that it had the lowest average expansion and the highest average 25% drain time amongst all the CAFs. In comparison, Agent D, CAF form, had similar expansion characteristics but the lowest average 25% drain time amongst all the CAFs, one-fifth the 25% drain time of Agent A. Yet, Agent D was more than twice as effective as Agent A on the stained panels. A better understanding of the relationship between expansion, 25% drain time, and mass-retention is needed.

The curve is the result of the opposite behavior of the CAFs and water on the stained panels. For the first five minutes after application, the CAF remains on the panel because it has not yet begun to drain or slide. In contrast, the first five minutes after applying water to a stained panel is the period of most run-off. The result is an increase in effectiveness. After the five minute mark, the opposite occurs; the CAF starts to drain and slide from the panel at its fastest rate and the water run-off is at a slow rate compared to the first five minutes. The result is a decrease in effectiveness. By the one-hour mark, the CAF has stopped sliding from the panel and the curves are similar in shape to those for solutions but with a 50% increase in effectiveness afforded by the CAF.

For the vinyl panels, at the zero-hour mark the CAFs' effectiveness is greater than one, but within five to ten minutes it is approximately 0.5. It remained below 1 for the remainder of the experiment. The CAFs slide from the vinyl in sheets until only traces remain in some recesses of the panel.

In summary, there are four main points which resulted from using these agents in the form of solution or CAF during the mass-retention experiments:

- The material to which they are applied greatly affects the mass retention, and the mass retention may be better or worse than that of water for a given material. The agents are not effective on vinyl, and even though they were more effective on the wood, plywood absorbs much more moisture than boards or planks [4].

- The effectiveness of the four agents was similar, although some patterns developed. For example, Agent A in solution form was the third most effective on the stained panels, but it was the most effective on the unstained panels. Similarly, Agent A in CAF form was the fourth most effective on stained panels but, once again, the most effective on the unstained panels. Agent D, in both solution and CAF form was the most effective on the stained panels.

- The agent application method, solution vs. CAF, is an important mass-retention factor, especially within one-hour of application. The CAFs' effectiveness was approximately 1.5 times and 2 times greater than the solutions' effectiveness on the stained and unstained panels respectively.

- The large effectiveness values exhibited by the agents on the stained panels is mainly due to the ineffectiveness of water on those panels. The agents appear to evaporate at a near constant rate regardless of form, whereas water evaporates at a greater, non-constant rate.

## 3.4 Ignition-Inhibition Experiments

The mass-retention experiments demonstrated that, compared to water, the agents, both in solution and CAF form, were better able to remain in or on both stained and unstained T1-11 plywood siding. They also demonstrated that the agents, regardless of form, were ineffective on vinyl siding, so the vinyl panels were not included in the ignition-inhibition experiments. The NFPA Fire Protection Handbook indicates that when factors such as size, shape, and chemical make-up of the wood are the same, then an increase in moisture content will increase the time to ignition [1]. This is to be expected since the evaporation of moisture (up to 100 °C) is the first of the five phases of combustion for wood exposed to high temperatures [11]. The increase in time to ignition afforded by higher moisture content is likely to be the result of prolonging this phase. To determine how much of an increase in time to ignition may be realized by using the agents versus plain water on T1-11, the ignition-inhibition experiments were conducted as follows.

### 3.4.1 Experiment Setup

Water and the same four agents that were used during the mass-retention experiments were used during the ignition-inhibition experiments. Circular samples 9.8 cm (3-7/8 in) in diameter, were cut from the stained and unstained T1-11 and were placed in a conditioning room for not less than 72 hours before conducting an experiment. The temperature in the conditioning room was 23 ± 3 °C (73 ± 5 °F) and the relative humidity was 50 ± 5 %. Under these conditions the equilibrium moisture content of the wood was approximately 9 ± 1 %. The agents were applied as solution or as foam to the T1-11 samples. Water and solutions were applied as a spray, and a laboratory-scale foam generator was used to apply foam (Figure 6). The primary components of the foam generator are a solution container, needle valve, and glass-bead mixer. The solution container was maintained, via the air inlet, at a constant pressure of 97 ± 14 kPa (14 ± 2 psi).

The time to sustained flaming ignition was measured with an oxygen consumption calorimeter (cone calorimeter) [9]. The samples were held with a circular aluminum frame, mounted vertically in the cone calorimeter, and subjected to an irradiance of 30 kW/m$^2$ (Figure 7). To gain perspective on the effects of a 30 kW/m$^2$ heat flux, sunshine provides approximately 1 kW/m$^2$ at the earth's surface, when skin is exposed to 10.4 kW/m$^2$ pain is experienced after 3 seconds, and when skin is exposed to 16 kW/m$^2$ it blisters after 5 seconds. 12 kW/m$^2$ can be considered as a minimum for piloted ignition of most wood although 27 kW/m$^2$ is considered the minimum for hardboard, another commonly used exterior siding [12].

Many factors like wood type, grain orientation, period of heating, and wood geometry and arrangement influence the time to piloted ignition of wood. The following equation describes, using material properties, the time to piloted ignition of wood when exposed to a known heat flux [13].

$$\left[q_r - (q_r)_{\min}\right] t_{ig}^{2/3} = 0.6\left[\left(\sqrt{k\rho c}\right)^2 + 0.119\times10^6\right]$$

where, $q_r$ = the irradiance of the object (W/m$^2$).

$(q_r)_{\min}$ = the minimum irradiance at which ignition is possible (W/m$^2$).

$t_{ig}$ = the time to ignition (s).

$\sqrt{k\rho c}$ = the thermal absorptivity of wood (J/(m$^2$s$^{1/2}$K)).

The three variables inside the square root symbol, $k$, $\rho$, $c$, are collectively referred to as the thermal inertia. All three are material properties. The first, $k$, is the thermal conductivity which is a measure of how well the material conducts heat. Wood has a relatively low thermal conductivity, approximately 0.11-0.15 W/(mK) for plywood, but it increases with temperature, moisture content, and density [11]. The second, $\rho$, is the density of the wood. Wood with high density, such as hardboard (480 kg/m$^3$), is harder to ignite than wood with low density, say balsa (130 kg/m$^3$) [10,11]. The large range in wood density is the reason 12 kW/m$^2$ is considered as the minimum heat flux for piloted ignition of most wood but 27 kW/m$^2$ is considered the minimum for hardboard. The third, $c$, is the specific heat of the material. The specific heat is a measure of the amount of thermal energy needed to raise the temperature of a unit mass of material by 1 °C. The specific heat of wood is approximately 1.6 kJ/kg°C. The specific heat of wood is fairly independent of wood species and density but increases with temperature and moisture content [11]. By increasing the moisture content of wood, all three of these variables increase and, as a result, the time to ignition also increases.

**Table 4.** Ignition-Inhibition Experiment Matrix.

| Series | Experiments | Agent/Water | Unstained/Stained T1-11 | Application Method |
|---|---|---|---|---|
| 1 | 1-3 | none (Dry) | Unstained | na |
| 2 | 1-7 | Water | Unstained | Spray |
| 3 | 8-14 | A | Unstained | Spray Solution |
| 4 | 15-21 | B | Unstained | Spray Solution |
| 5 | 22-28 | C | Unstained | Spray Solution |
| 6 | 29-35 | D | Unstained | Spray Solution |
| 7 | 36-41 | A | Unstained | Foam |
| 8 | 42-47 | B | Unstained | Foam |
| 9 | 48-53 | C | Unstained | Foam |
| 10 | 54-59 | D | Unstained | Foam |
| 11 | 60-62 | none (Dry) | Stained | na |
| 12 | 63-69 | Water | Stained | Spray |
| 13 | 70-76 | A | Stained | Spray Solution |
| 14 | 77-83 | B | Stained | Spray Solution |
| 15 | 84-88 | C | Stained | Spray Solution |
| 16 | 89-93 | D | Stained | Spray Solution |
| 17 | 94-99 | A | Stained | Foam |
| 18 | 100-105 | B | Stained | Foam |
| 19 | 106-109 | C | Stained | Foam |
| 20 | 110-113 | D | Stained | Foam |

A total of 113 experiments were conducted in 20 series as listed in Table 4. A series, with the exception of 1 and 11, consists of experiments conducted in which the amount of solution or foam applied was determined by the results of the zero-hour, three-hour, and six-hour marks during the mass-retention experiments. For example, if 10 grams/unit-area of Agent B solution remained on the unstained panel at time zero during the mass-retention experiments, then 10 grams/unit-area of Agent B solution was applied to an unstained sample for the ignition-inhibition experiment. If the ignition-inhibition experiment was conducted immediately, then the corresponding time would be zero hours. Similarly, if 2 grams/unit-area of Agent A solution remained on the unstained panel at the three-hour mark during the mass-retention experiments, then the ignition-inhibition experiment was conducted when an unstained sample containing Agent A solution reached 2 grams/unit-area.

The corresponding time would be three hours, even if the sample reached 2 grams/unit-area in two hours. Series 1 and 11 consist of three experiments on dry samples. Series 2-6 and 12-14 consist of seven experiments: three of the zero-hour experiments and two each of the three-hour and six-hour experiments. Series 7-10 and 17, 18 consist of six experiments: two each of the zero-hour, three-hour, and six-hour experiments. Series 15, 16 consists of five experiments; three of the zero-hour experiment and two three-hour experiments. Series 19, 20 consist of four experiments: two each of the zero-hour and three-hour experiments. The number of repeated experiments was determined primarily by level of difficulty, but all experiments were repeated at least once.

### 3.4.2 Experimental Procedure

The average agent mass/unit-area of T1-11, determined from the large-scale mass-retention experiments at time zero, was applied to each sample. The ignition-inhibition experiment was either conducted immediately, or the sample was allowed to dry vertically. Ignition-inhibition experiments were conducted on the drying samples when their average agent mass/unit-area equaled the average agent mass/unit-area measured on the T1-11 during the mass-retention experiments at the three-hour or six-hour mark. The samples were placed vertically into the cone calorimeter 7.6 cm (3 in) from the face of the electric cone heater, and the spark ignitor was positioned 1.3 cm (½ in) above the aluminum frame of the sample. The sample was then exposed to an irradiance of 30 $kW/m^2$; this served as time zero for the experiment. Observations were made during the experiment and the time to sustained flaming ignition was recorded. The samples were allowed to burn until the peak heat release rate was observed on the data acquisition system.

### 3.4.3 Results

The results of the ignition-inhibition experiments are presented in Figures 8-11. Figures 8 and 9 show the time to ignition for solution on unstained and stained samples respectively. Figures 10 and 11 show the time to ignition for foam on unstained and stained samples respectively. An explanation of the results follows, starting with expansions and proceeding to solution on unstained and stained samples, and finally to foam on unstained and stained samples.

The mass flow rates from the foam generator were approximately 23% lower, on the order of 0.33 kg/min (0.09 gpm volumetric flow rate), than the mass flow rates from the CAFS used during the mass-retention experiments. This was both practical and necessary for use in a lab environment, however, the expansion and 25% drain times could not be measured using the foam slider board and cylinder set-up as was done in the mass-retention experiments. For this reason, and because it was easy to control the expansion with minor adjustments to the needle valve, all foam expansions were measured by using a 1 liter container and scale and were found to be 40 ± 5. The deviations from the average expansions found during the mass-retention experiments are +8, -3, -15, and +5 for agents A, B, C, and D, respectively.

Both water and solutions increased, by approximately 40%, the time to ignition of the unstained samples over the time to ignition of dry unstained samples at the zero-hour mark. The average dry sample time to ignition was approximately 101 s. As Figure 8 shows, however, during the zero-hour mark there was no advantage gained over water by using the solutions. At the three-hour mark, the solutions increased over water the time to ignition by as little as 14% for Agent A and up to 42% for Agent B. At the six-hour mark, the solutions increased over water the time to ignition by as little as 4% for Agent C and up to 35% for Agent D. Note, however, that by the six-hour mark the time to ignition of water sprayed samples is approaching 101 s, the time to ignition of dry samples.

Both water and solutions increased the time to ignition of the stained samples over the time to ignition of the dry stained samples at the zero-hour mark (Figure 9). The increases range from as little as 16% for Agents A and B and up to 35% for Agent D. Because of the stain, however, the dry stained sample time to ignition is approximately 25% less than the dry unstained sample time to ignition, dropping from an average of 101 s to 76 s. Similar to the results of the solution on the unstained samples, at the zero-hour mark there is little or no advantage gained over water by using the solutions. At the three-hour mark, the solutions increased over water the time to ignition by as little as 4% for Agent C and up to 56% for Agent A. Again, it should be noted that by the three-hour mark the time to ignition of the water sprayed samples is approaching the time to ignition of the dry samples. At the six-hour mark, the solutions increased over water the time to ignition by as little as 47% for Agent A and up to 57% for Agent B. Agents C and D were not included in experiments during the six-hour mark because there was no significant change in agent mass from the three-hour mark. Note that for unknown reasons, the time to ignition of water-sprayed stained samples after six hours is 11% less than the time to ignition for dry stained samples.

Both water and foams increased the time to ignition of the unstained samples over the time to ignition of the dry unstained samples at the zero-hour mark (Figure 10). The increases range from as little as 37% for Agent C and up to 88% for Agent D. The average time to ignition for all Agents except C was greater than or equal to water. Unlike the results of the solution on the unstained and stained samples, at the zero-hour mark there appears to be some advantage gained over water by using the foams. At the three-hour mark, the foams increased over water the time to ignition by as little as 24% for Agent A and up to 79% for Agent D. At the six-hour mark, the time to ignition increased by as little as 20% for Agent B and up to 82% for Agent D. Note, however, that by the six-hour mark the time to ignition of water-sprayed samples is approaching 101 s, the time to ignition of dry samples.

Both water and foams increased the time to ignition of the stained samples over the time to ignition of the dry stained samples at the zero-hour mark (Figure 11). The increases range from as little as 27% for water and up to 69% for Agent D. All agents increased over water the average time to ignition by approximately 27% at the zero-hour mark. At the three-hour mark, the foams increased over water the time to ignition by as little as 13% for Agents A and C and up to 100% for Agent D. At the six-hour mark, the time to ignition increased approximately 20% over water for Agents A and B. Agents C and D were not included in experiments during the six-hour mark because there was no significant change in agent mass from the three-hour mark. Note that as in Figure 9, the time to ignition of water-sprayed samples is 11% less than the time to ignition of dry stained samples.

### 3.4.4 Discussion

More ignition-inhibition research using agents is needed, especially in the zero-hour to three-hour range, to quantify the results. Because most experiments were repeated once, it can only be said that the agents performed as well as, or better, than water. However, for the purposes of this demonstration, the following qualitative observations may be made:

- With the exception of the zero-hour experiments, the average time to ignition for all samples to which agents were applied was equal to or greater than the average time to ignition of samples sprayed with water.

- The penetrating/wetting ability of the agents is probably the most significant ignition-inhibition factor. This is best illustrated by the zero-hour experiments in contrast to the three-hour and six-hour experiments. The zero-hour experiments show that in all but one case, foam on stained samples, water performed nearly as well as the agents. The separation between time to ignition of water-sprayed samples and time to ignition of samples to which agents were applied appears to be the greatest somewhere between the zero-hour and three-hour marks, after the agent has had time to penetrate the material.

- The dry stained sample time to ignition was approximately 25% less than the dry unstained sample time to ignition, from 101 s to 76 s. This may negate the penetrating/wetting benefits of the agents. Even though the agents' mass-retention effectiveness was greater on the stained panels than on the unstained panels, overall the times to ignition for the stained samples were equal to or less than the time to ignition of the unstained samples. Clearly the stained T1-11, rather than the unstained T1-11, is the more common case in practice.

When a foam is applied to a wood substrate and immediately exposed to a heat flux, the increase in time to ignition may only equal the time for the foam to dissipate. In this scenario the agent is on the sample rather than in the sample because presumably it has not yet had time to penetrate the wood to a significant degree. The agents in foam form remained on the sample for approximately 45 seconds after exposing the sample to the cone calorimeter heater during the zero-hour experiments. Figures 10 and 11 show that this is approximately the difference in time to ignition from a dry sample to a foamed sample at the zero-hour mark.

## 3.5 Conclusions

As expected, the time to ignition of water-sprayed samples is related to the mass of water in or on the sample; as water evaporates from the sample, the time to ignition decreases, and by the six-hour mark the ignition time is near or below the dry sample ignition time. The relationship between mass of agent in or on the samples and time to ignition may not be the same as it is for water, however.

All samples to which agents were applied lost agent mass over time, as expected. Eight of the ignition-inhibition experiments using agents resulted in curves which were similar to those of water, with decreasing time to ignition from the zero-hour to three-hour mark. However, eight other ignition-inhibition experiments using agents resulted in curves where the time to ignition at the three-hour mark increased from the time to ignition at the zero-hour mark. This may be partially the result of the penetrating/wetting ability of the agents. At the zero-hour mark there is the greatest mass of solution on the wood. However, the majority of solution is on the surface of the wood; it has not had time to penetrate the wood. By the three-hour mark the mass of solution has decreased from the zero-hour mark. By this time the solution has penetrated into the wood. The energy required to remove the penetrated solution may be greater than the energy required to remove the solution at the surface of the wood. Therefore, an increase in the time to ignition may occur from the zero-hour to three-hour mark, as eight of the experiments reflected.

In order to increase the time to ignition of wood which will be immediately subject to a radiant heat source the agent should be in CAF, rather than solution, form. The CAF will enable the user to apply much more agent mass/unit-area onto the wood. The increase in time to ignition, over the time to ignition of dry wood, will be approximately the time it takes for the foam to deteriorate to the surface of the wood from the impending radiant heat source. Usually, the increase in time to ignition afforded by the CAFs will be greater than the increase in time to ignition afforded by plain water.

Future ignition-inhibition research should be concentrated in the following areas:

1. The span between the zero-hour to three-hour mark. This would improve understanding of how the penetrating ability of the agents affects the time to ignition. An optimum agent application time for exposure protection might then be determined.

2. Dry climate conditions with wind. This would improve understanding of how the agents will react to environments which should significantly increase the mass-loss rate, both by evaporation and possibly physical removal. Environmental conditions such as this are not uncommon during wildland/urban interface fires.

3. Roofing materials such as cedar shingles and shakes. This would take full advantage of the wetting/penetrating ability of the agents. Agents in CAF form may be especially well suited for roofs for two reasons. First, roofs tend to be more horizontal than vertical; a 4 in 12 pitch is common. This will minimize the foam sliding and enable more mass/unit-area of foam to be applied. Second, usually roof shakes and shingles are not treated with water repellent so the agents might readily penetrate the wood.

## 3.6 References

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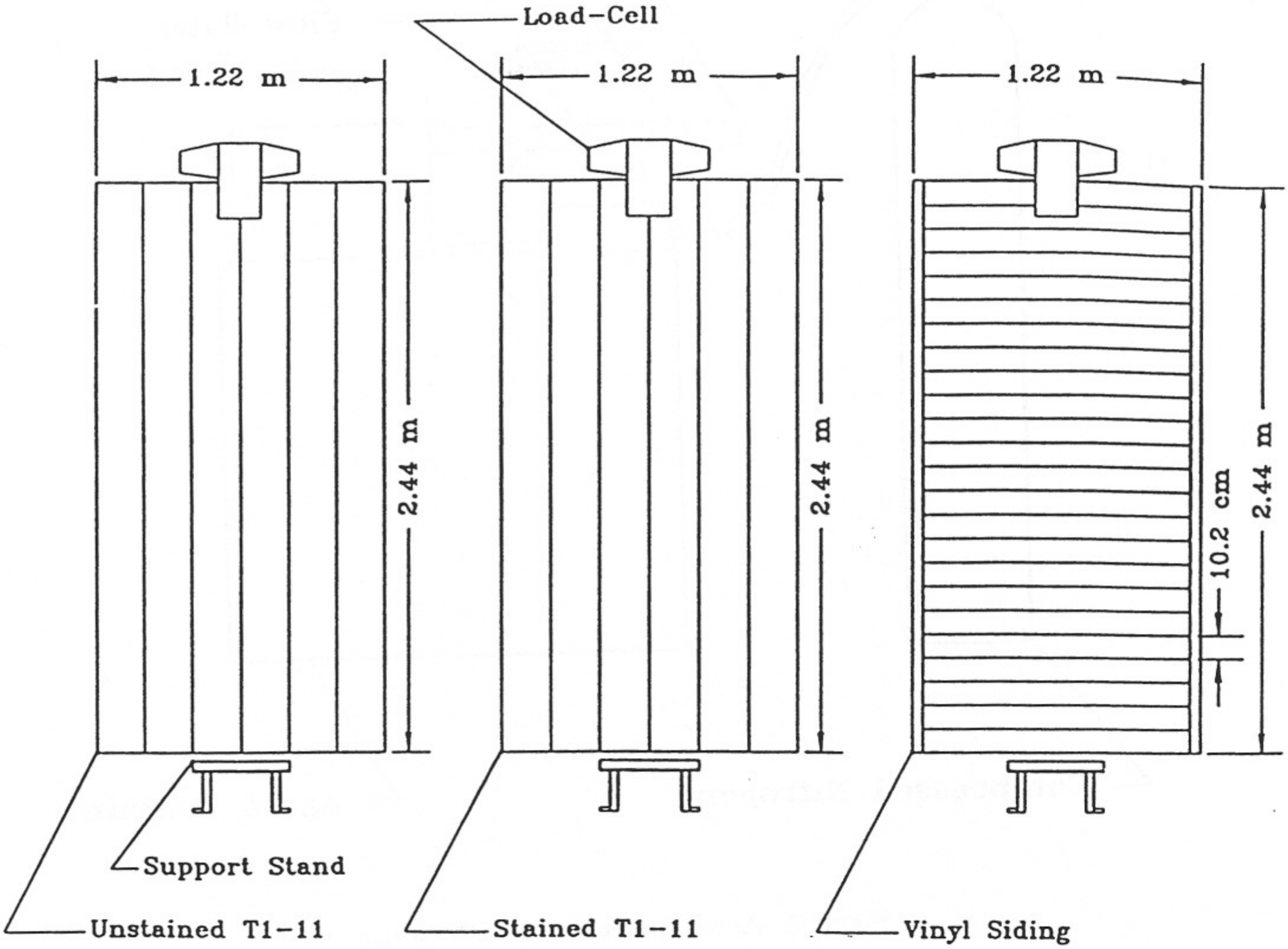

Figure 1. Exterior Siding Panels Set-up

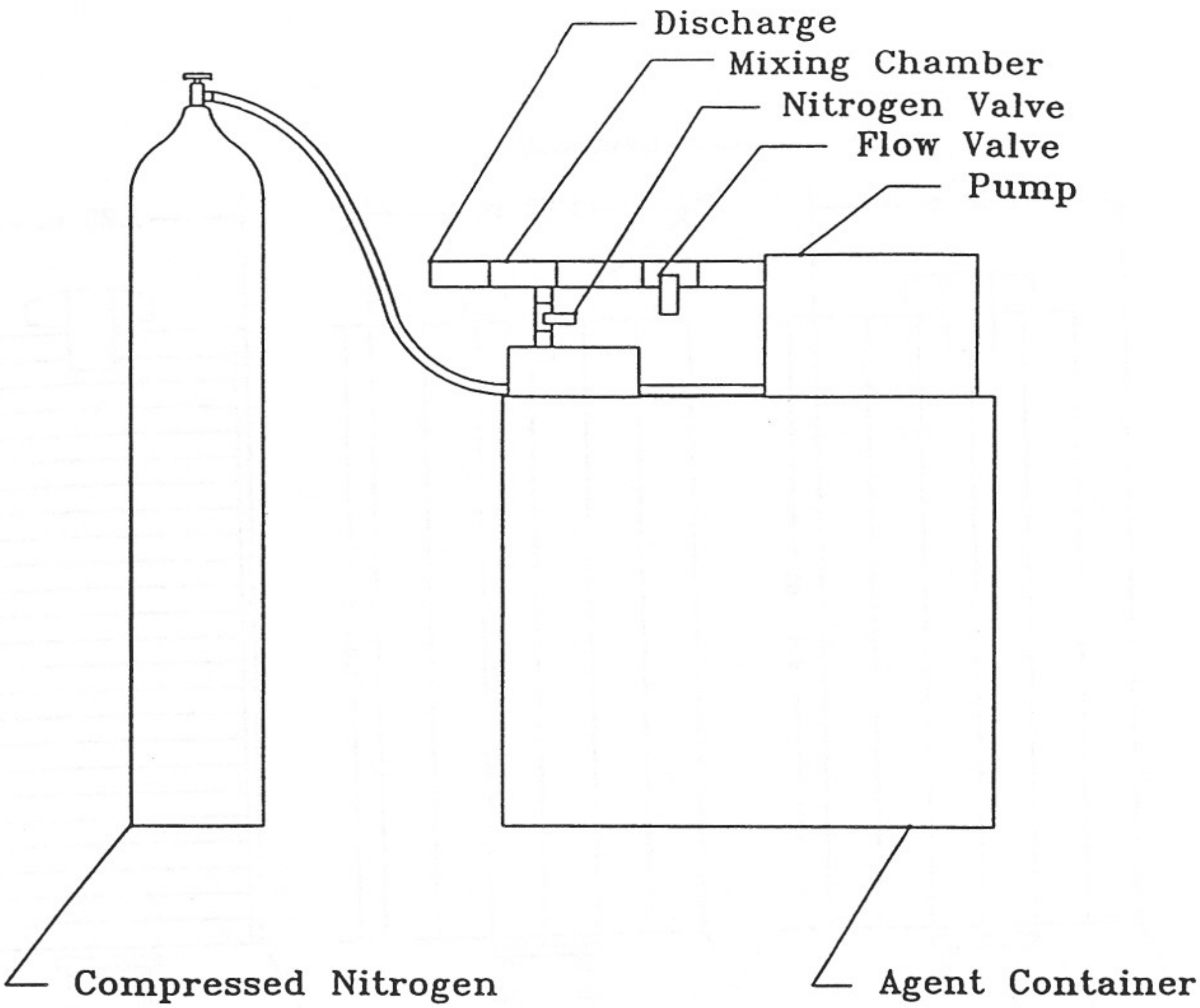

Figure 2. Agent Application (CAF) System

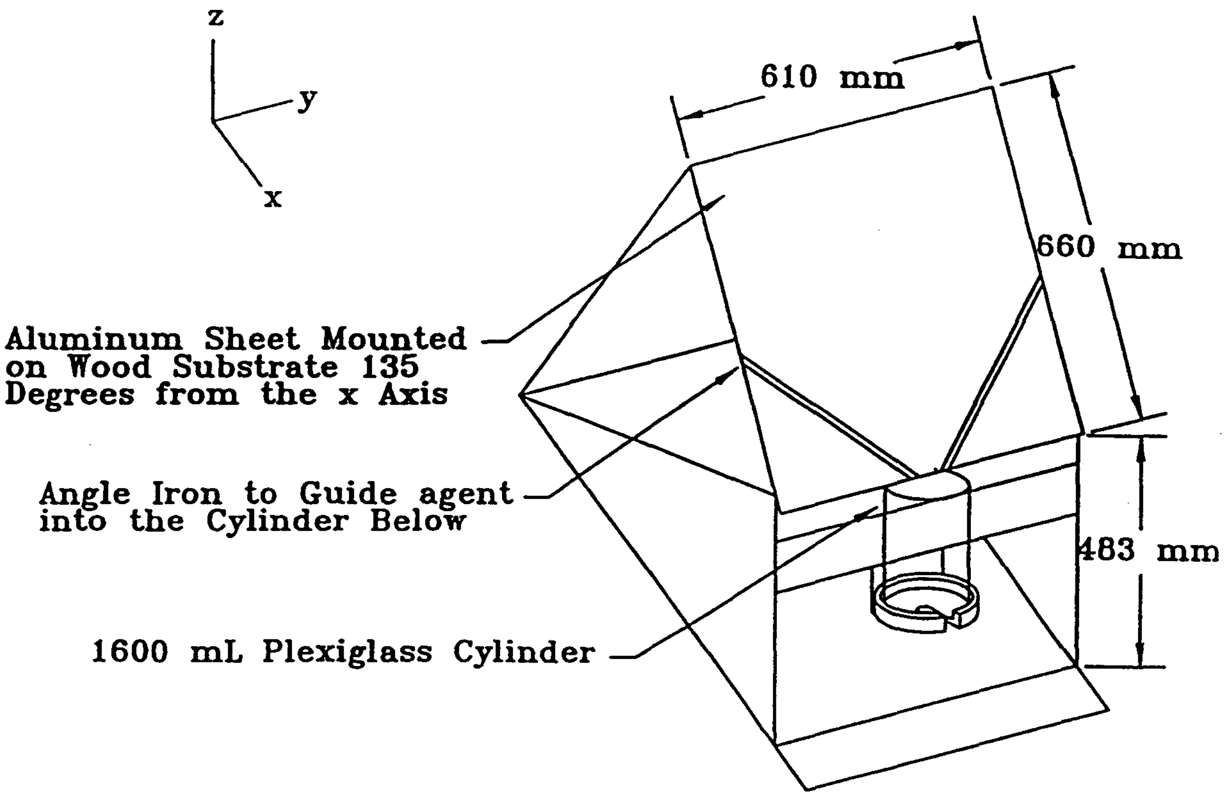

Figure 3. Foam Slider Board

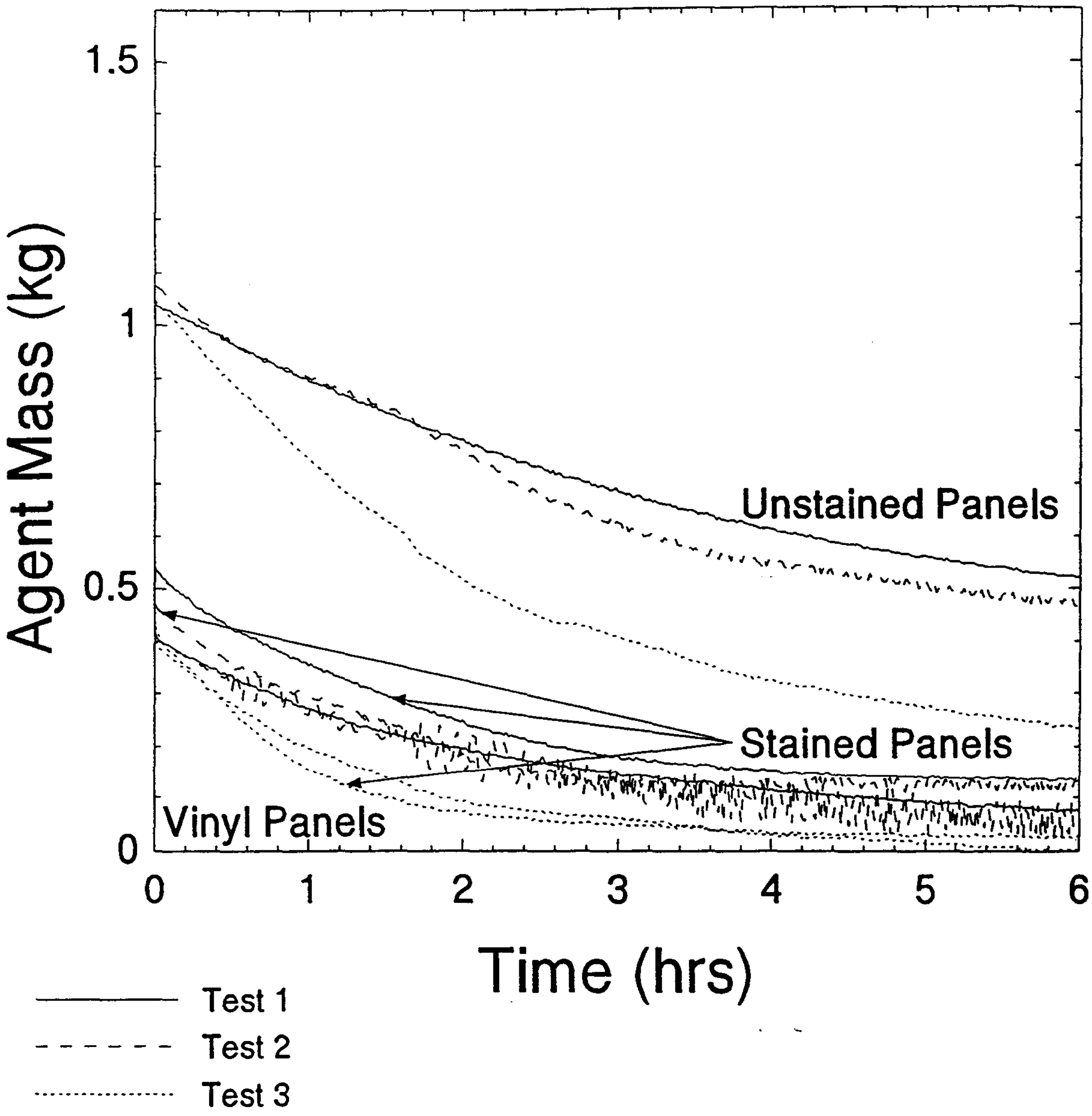

Figure 4. Mass-Retention of Water

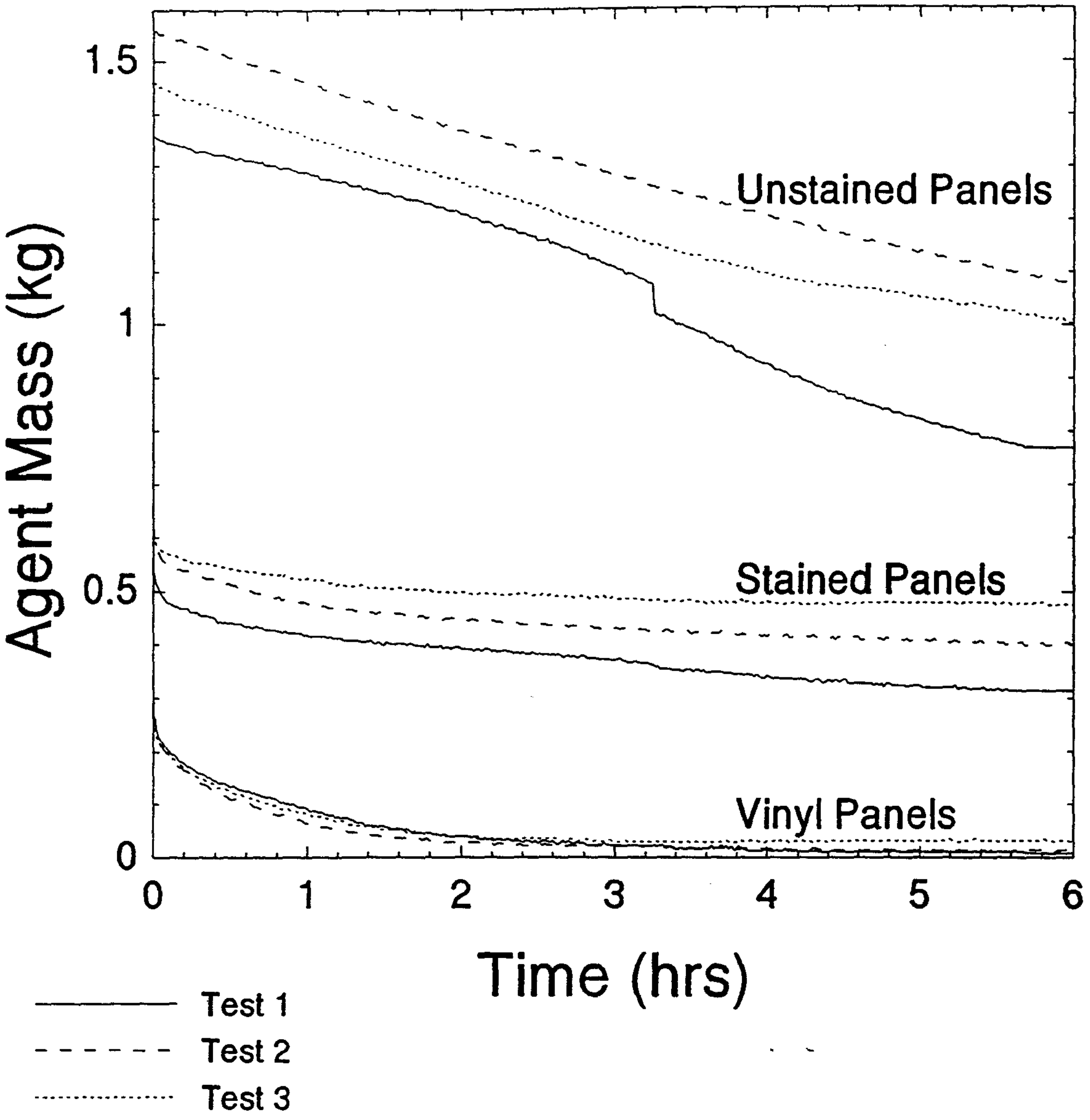

Figure 5. Mass-Retention of Solution A

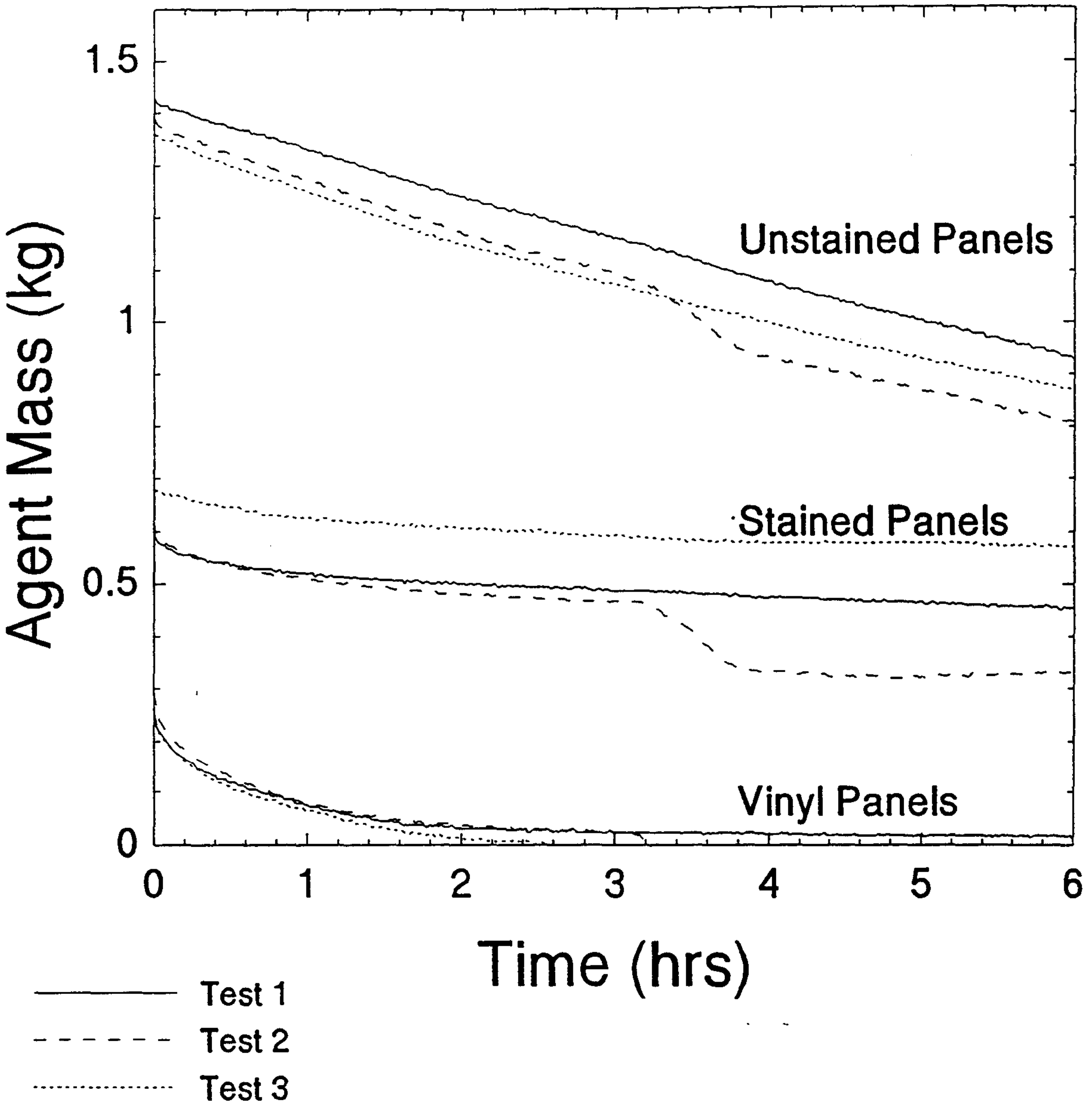

Figure 6. Mass-Retention of Solution B

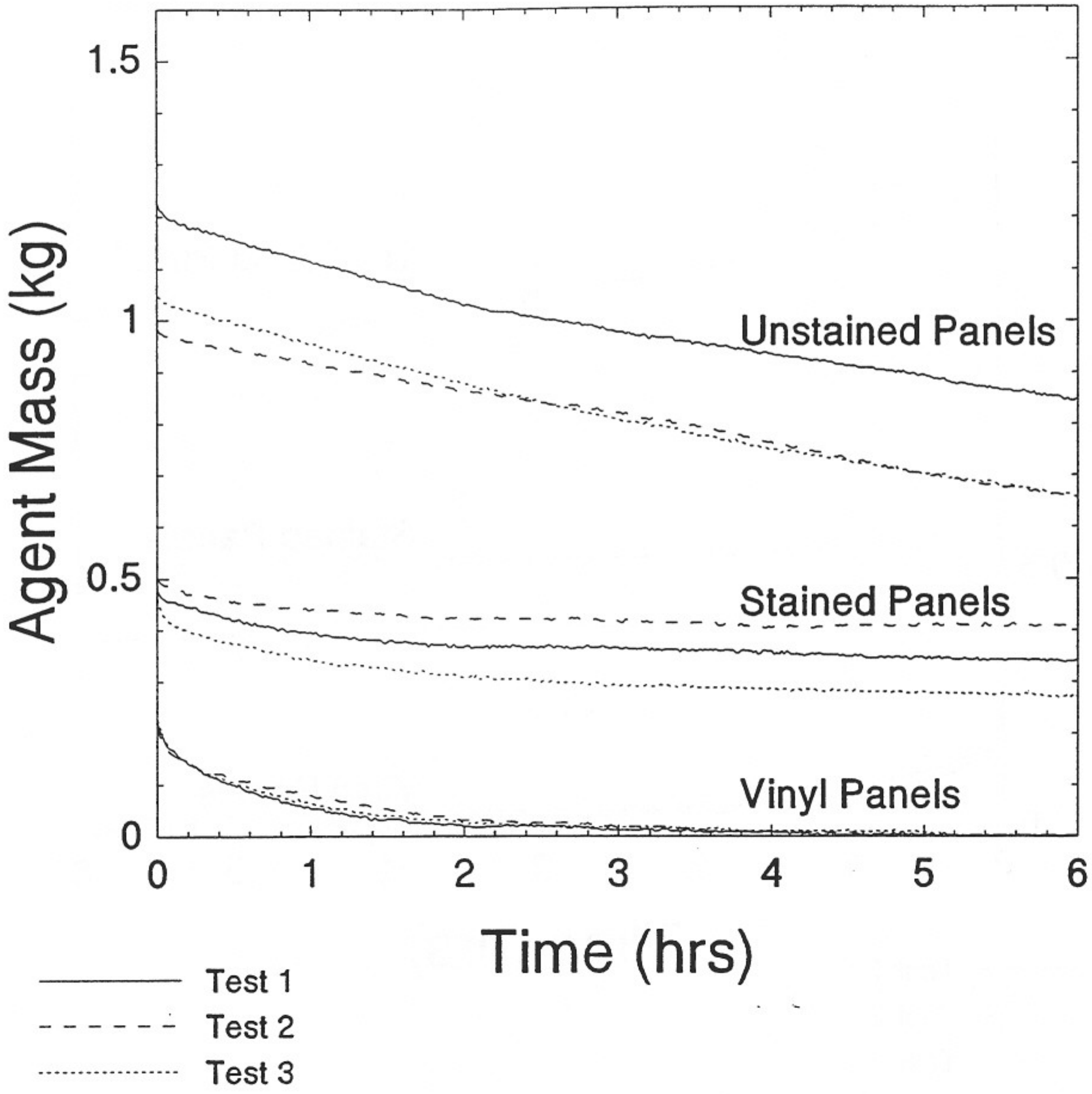

Figure 7. Mass-Retention of Solution C

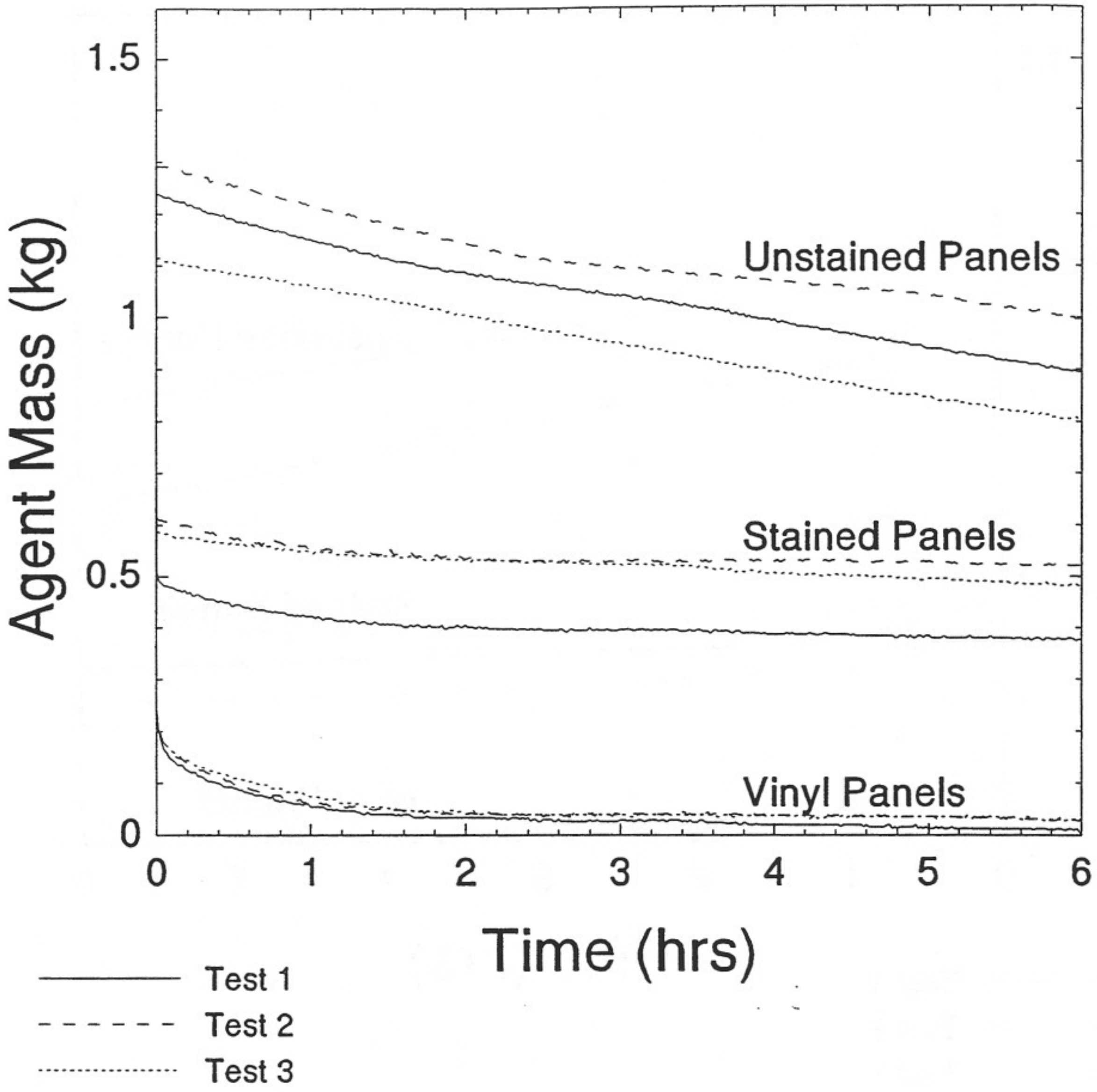

Figure 8. Mass-Retention of Solution D

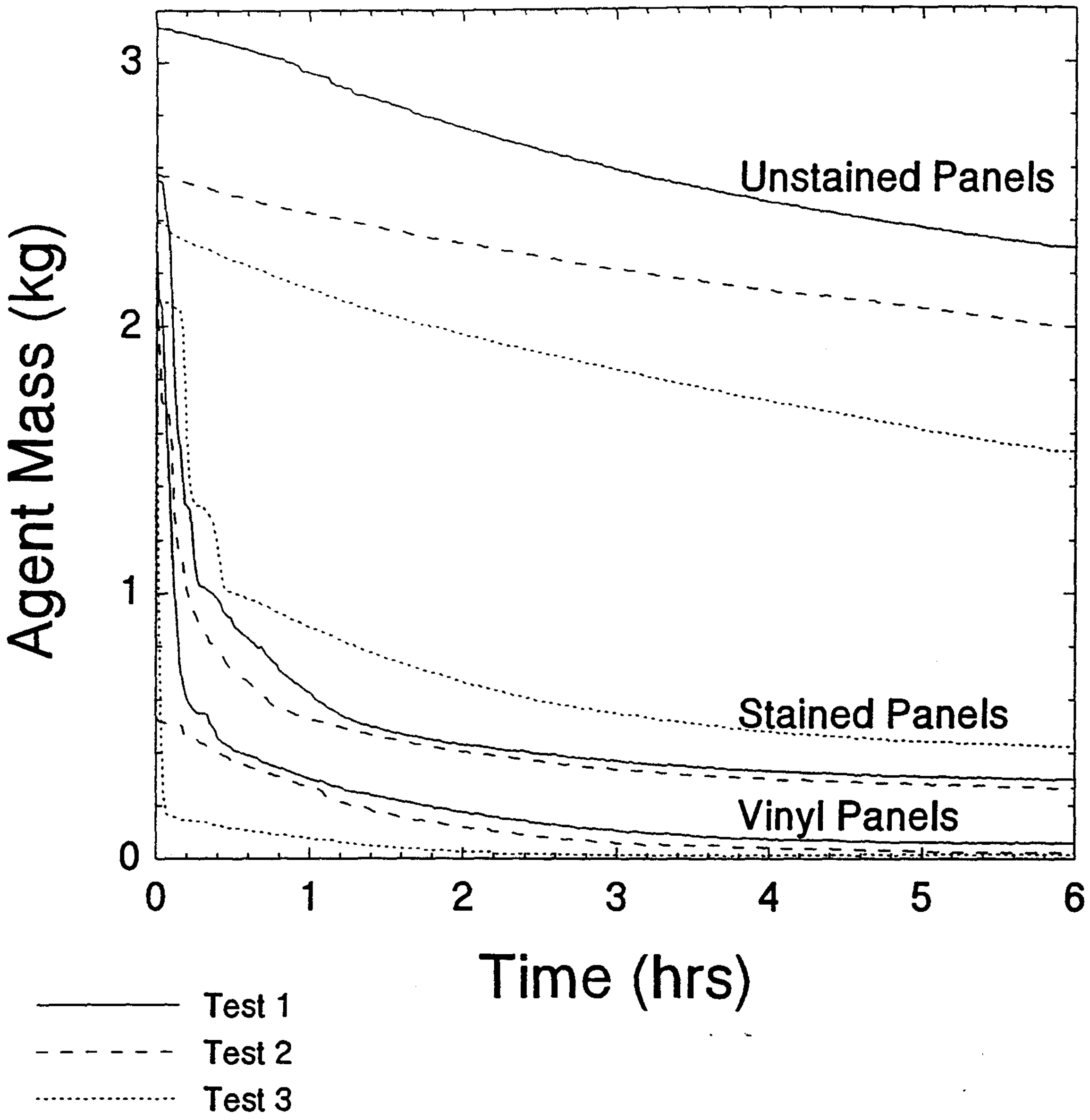

Figure 9. Mass-Retention of CAF A

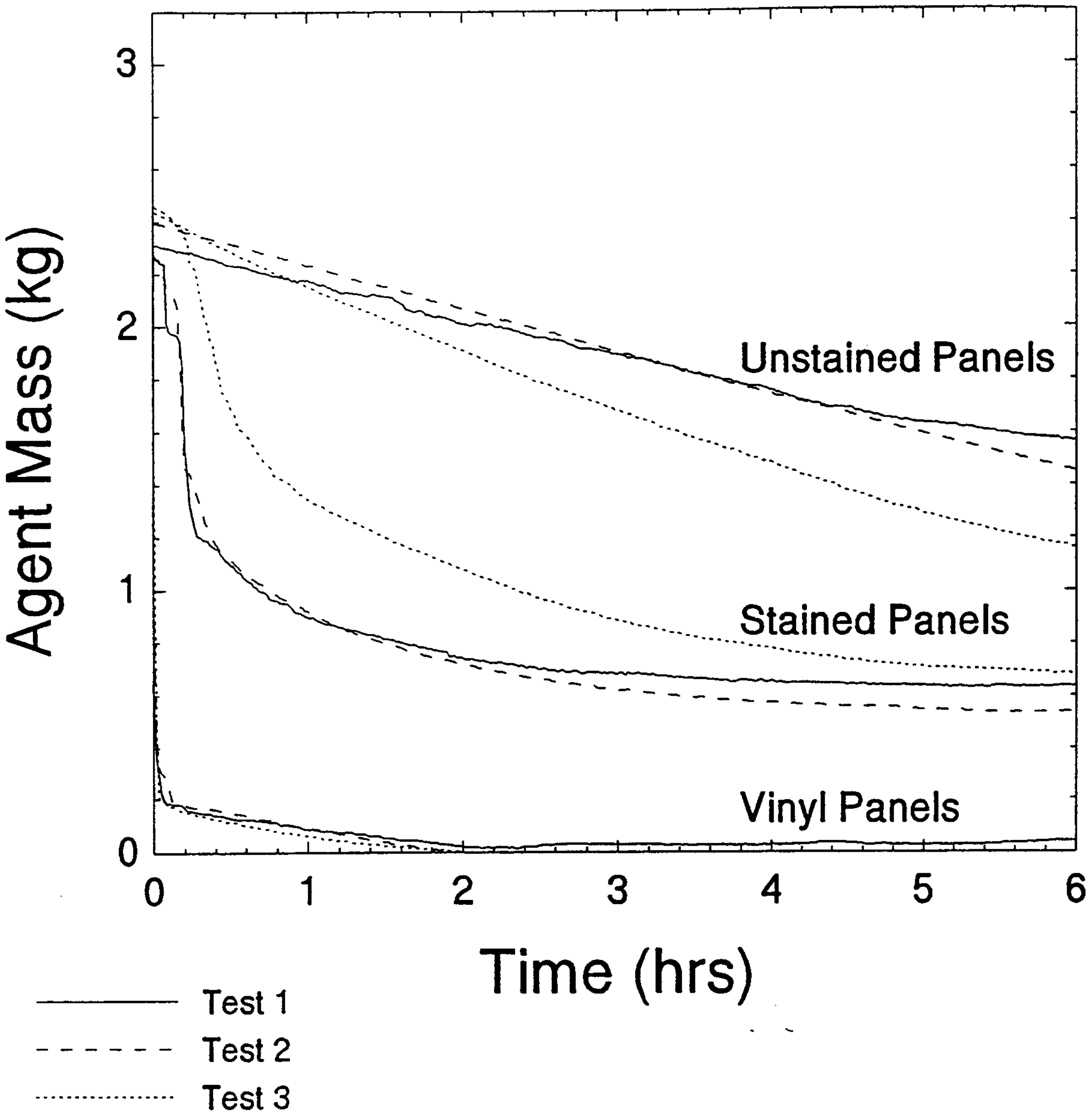

Figure 10. Mass-Retention of CAF B

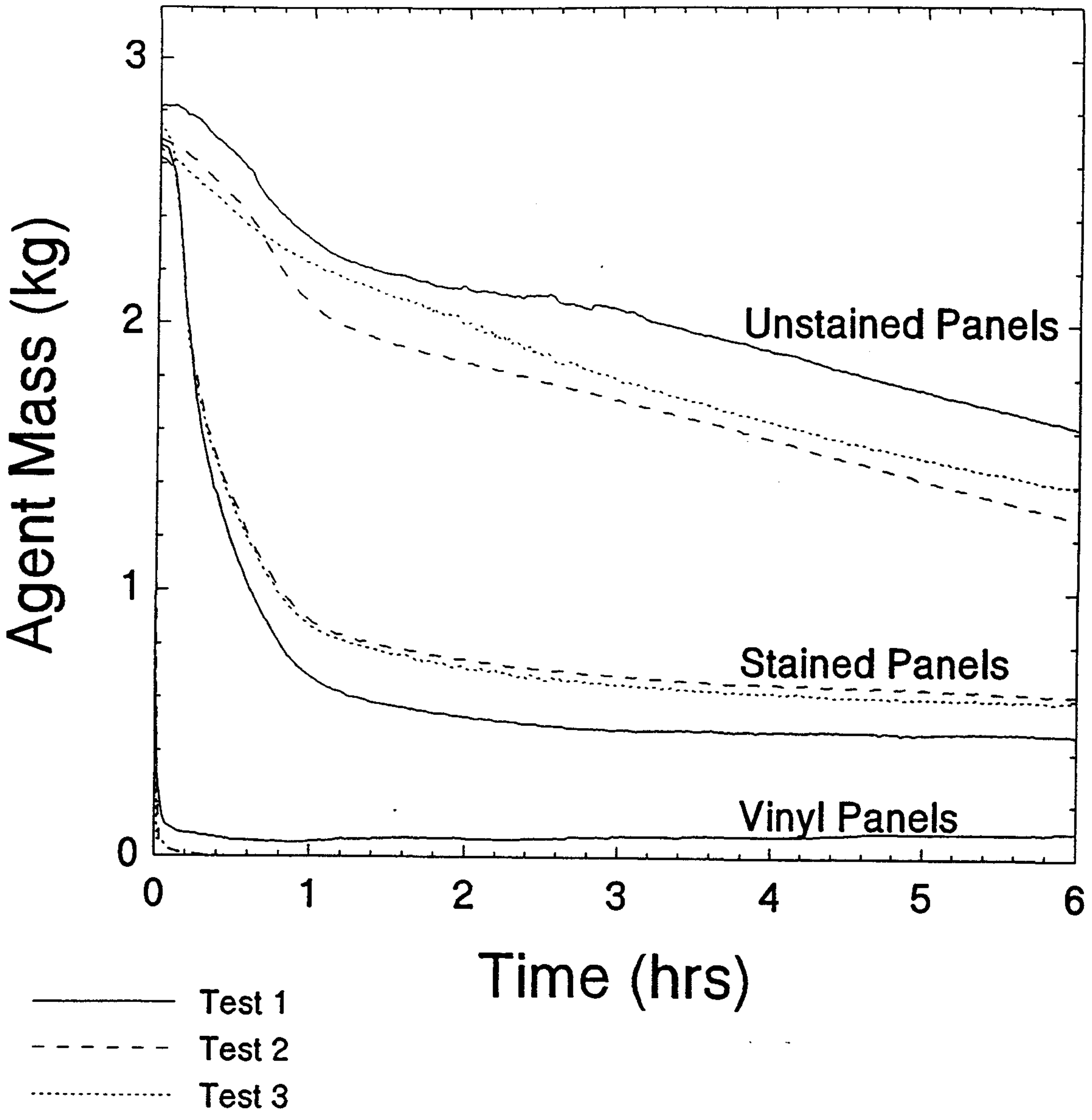

Figure 11. Mass-Retention of CAF C

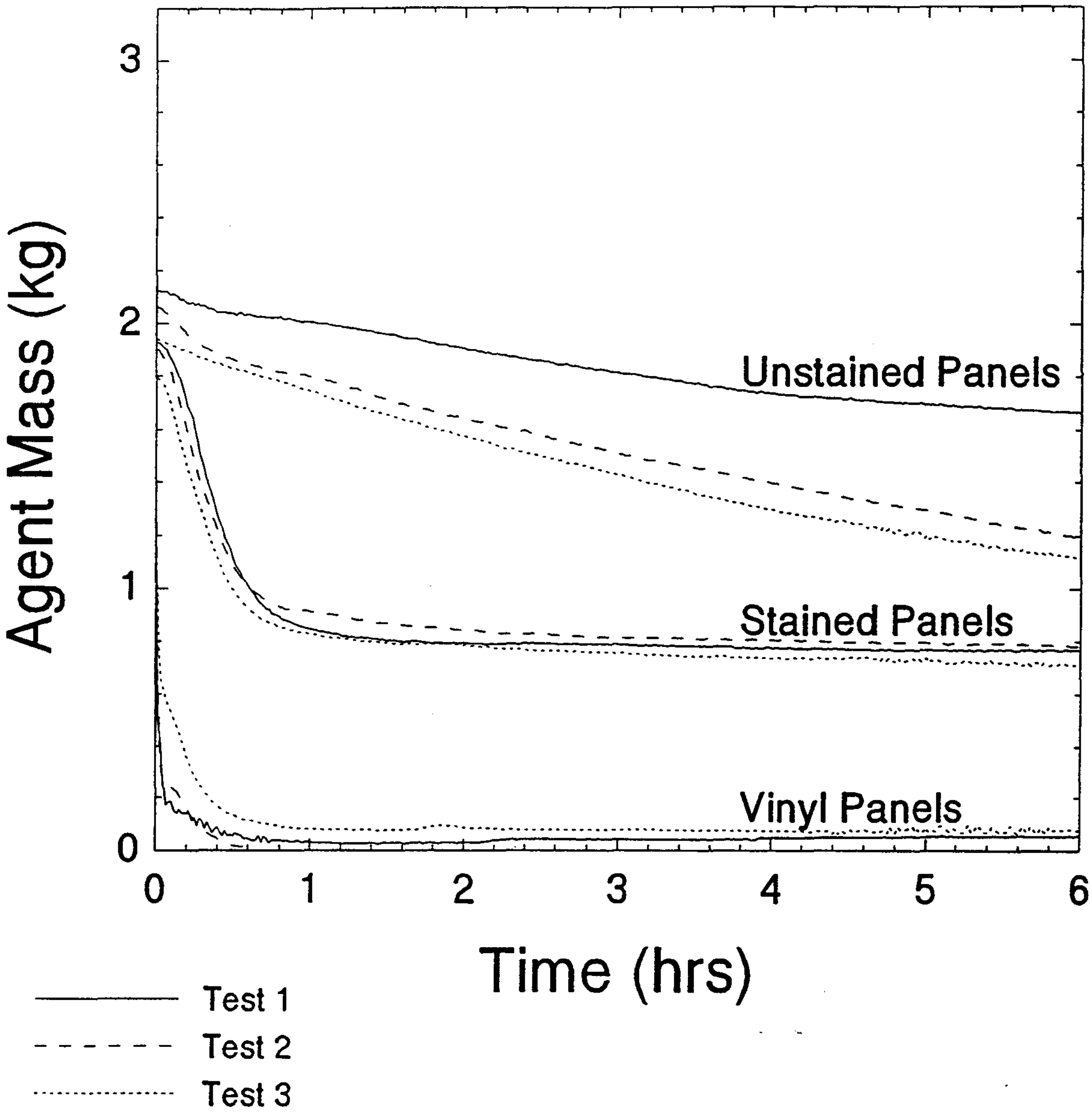

Figure 12. Mass-Retention of CAF D

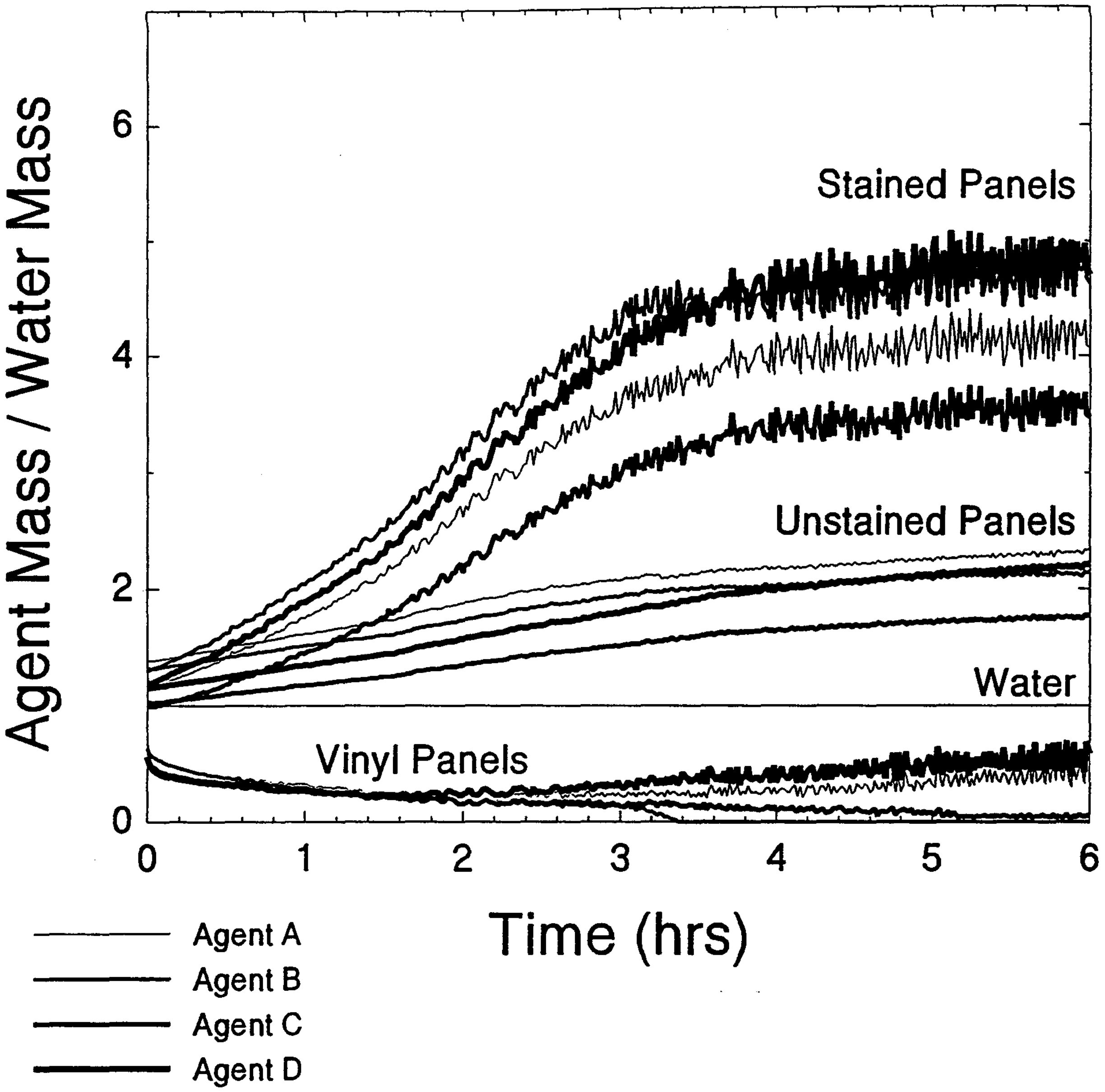

Figure 13. Solution Mass-Retention Effectiveness

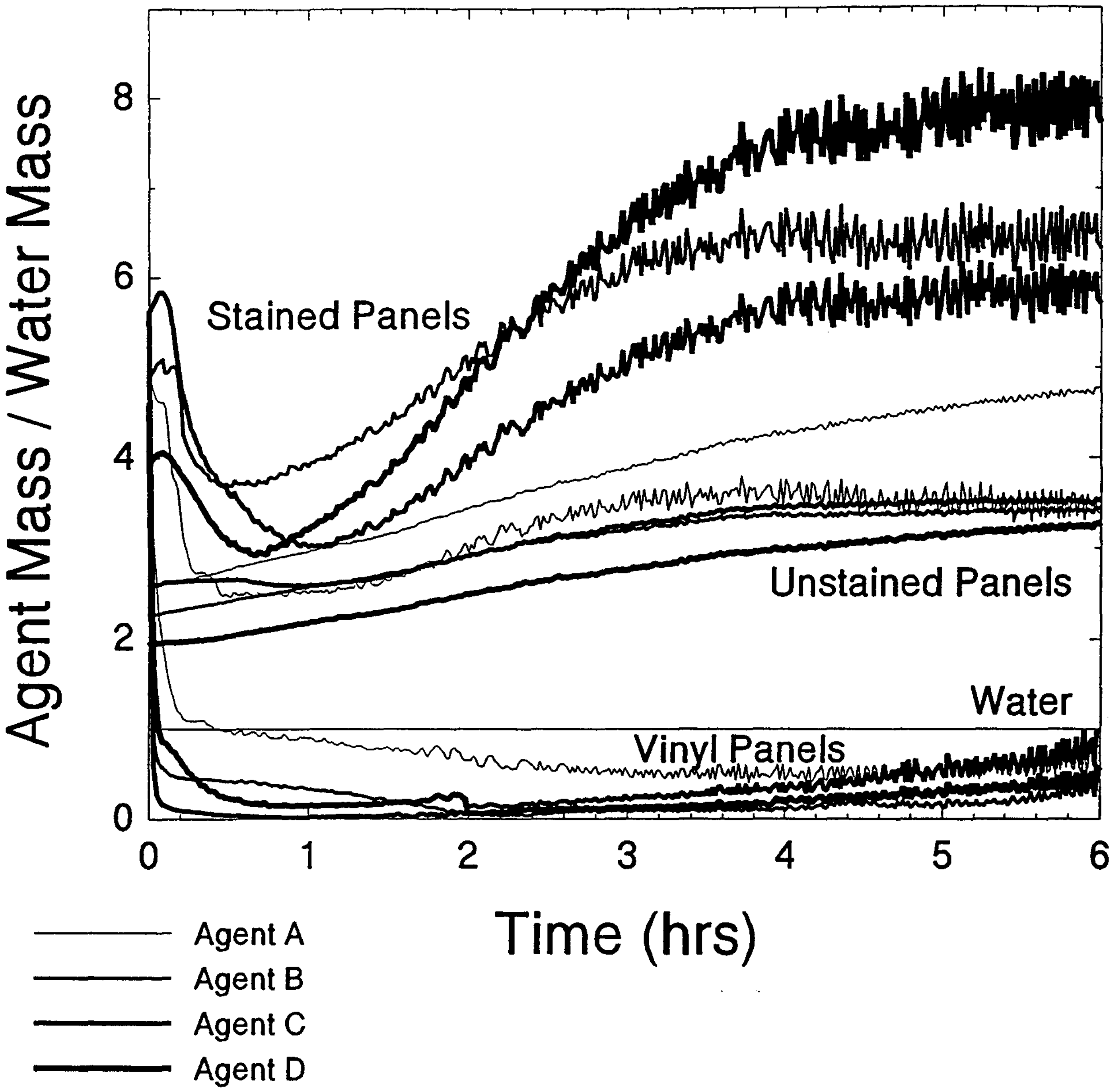

Figure 14. CAF Mass-Retention Effectiveness

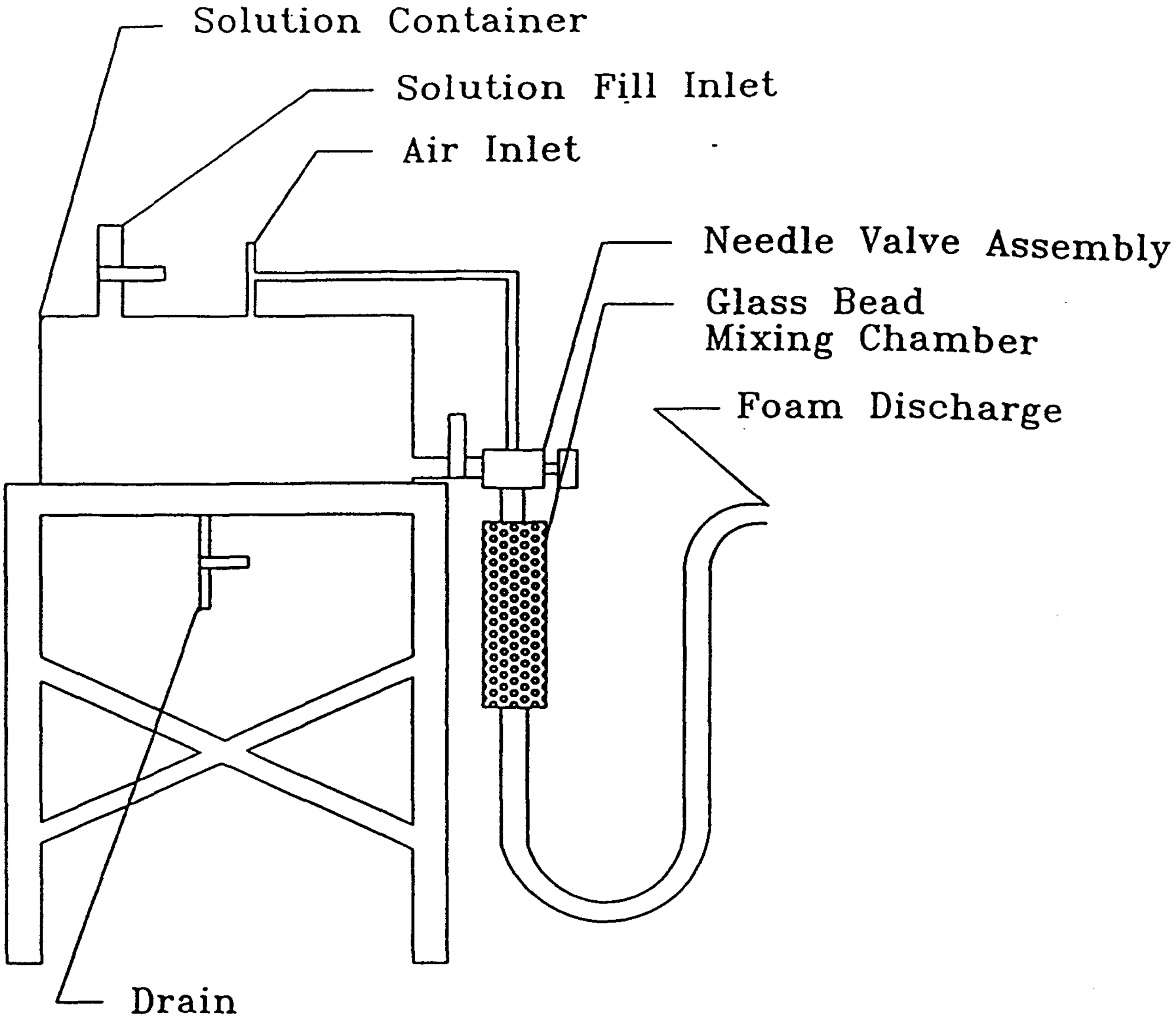

Figure 15. Foam Application System

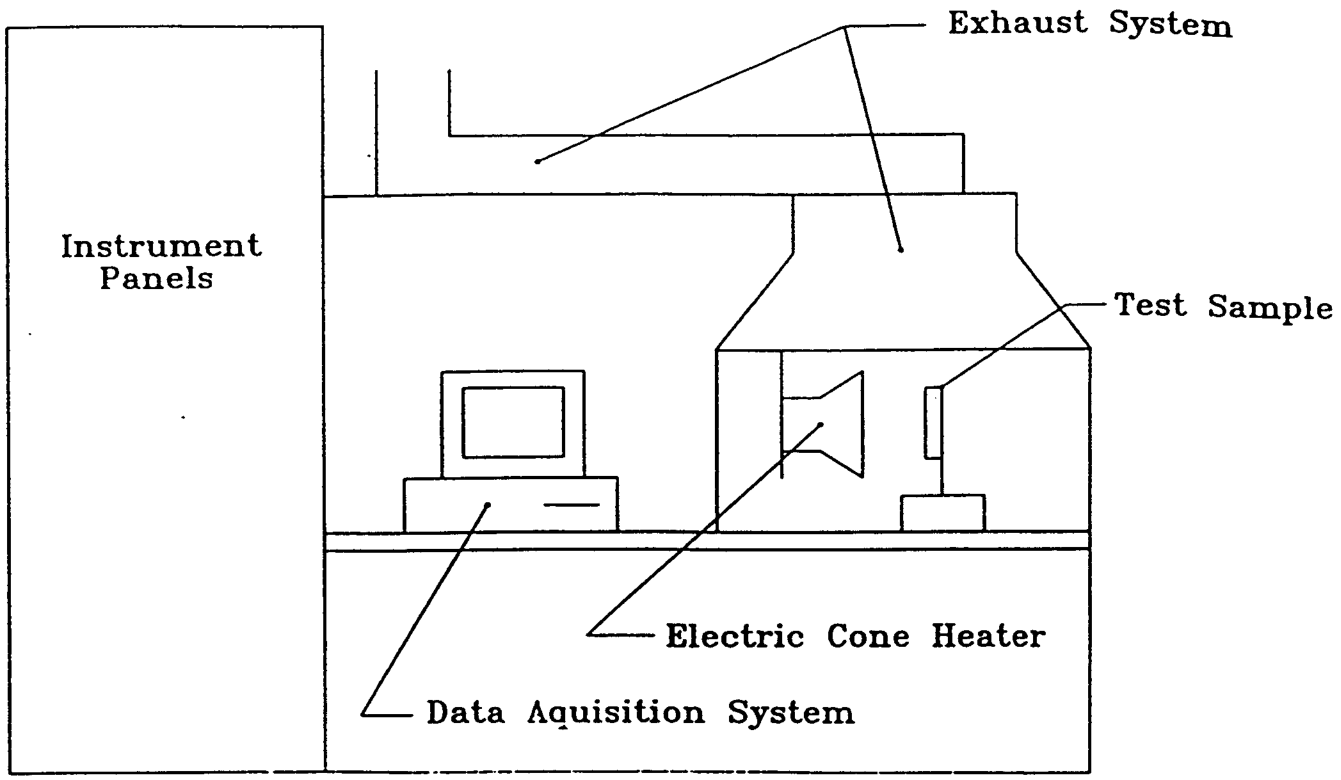

Figure 16. Cone Calorimeter Ignition-Inhibition Set-up

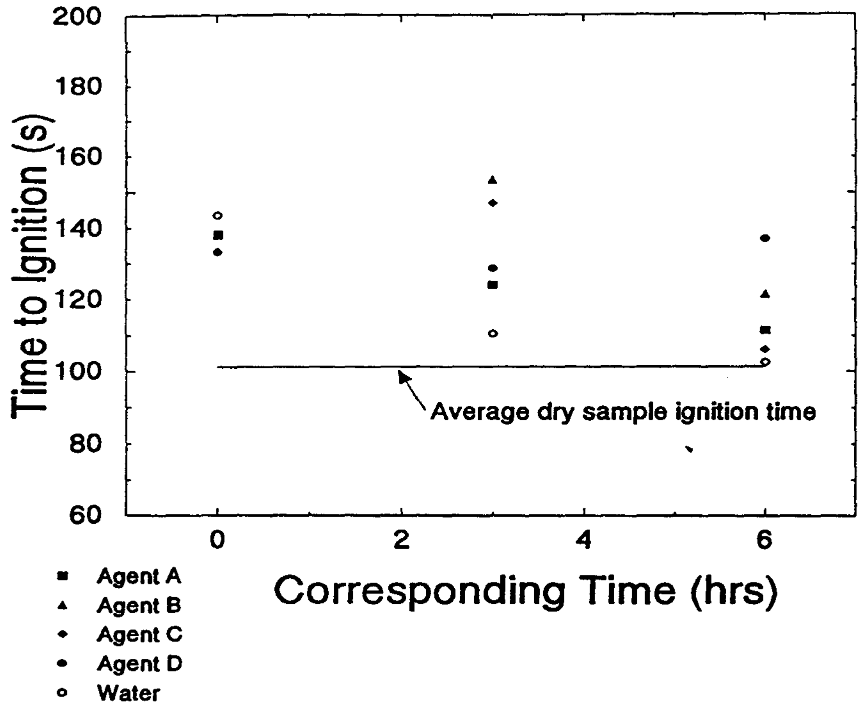

**Figure 17** - Ignition times for solution on unstained samples subject to 30 kW/m$^2$ heat flux

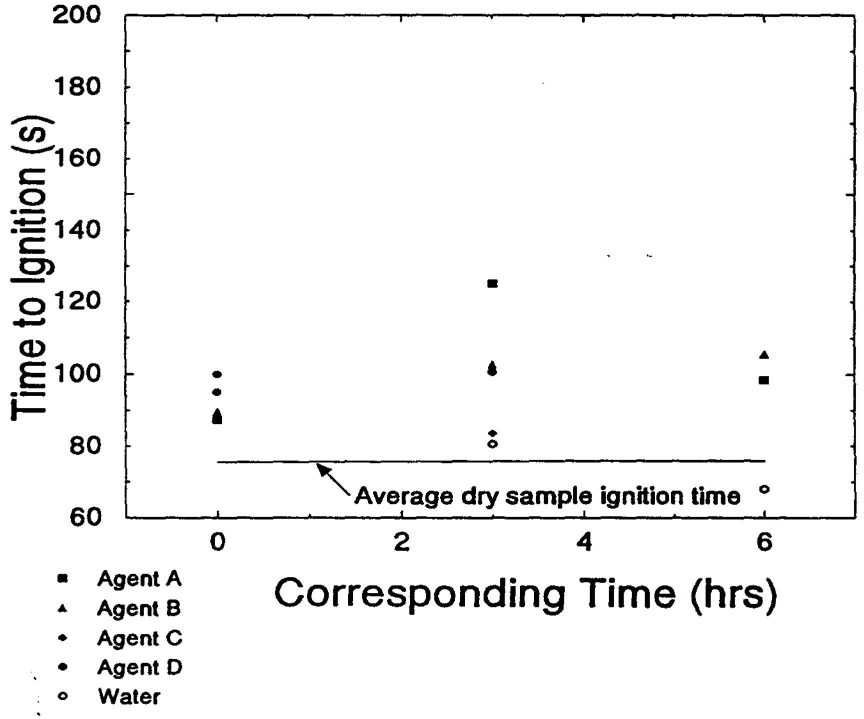

**Figure 18** - Ignition times for solution on stained samples subject to 30 kW/m$^2$ heat flux

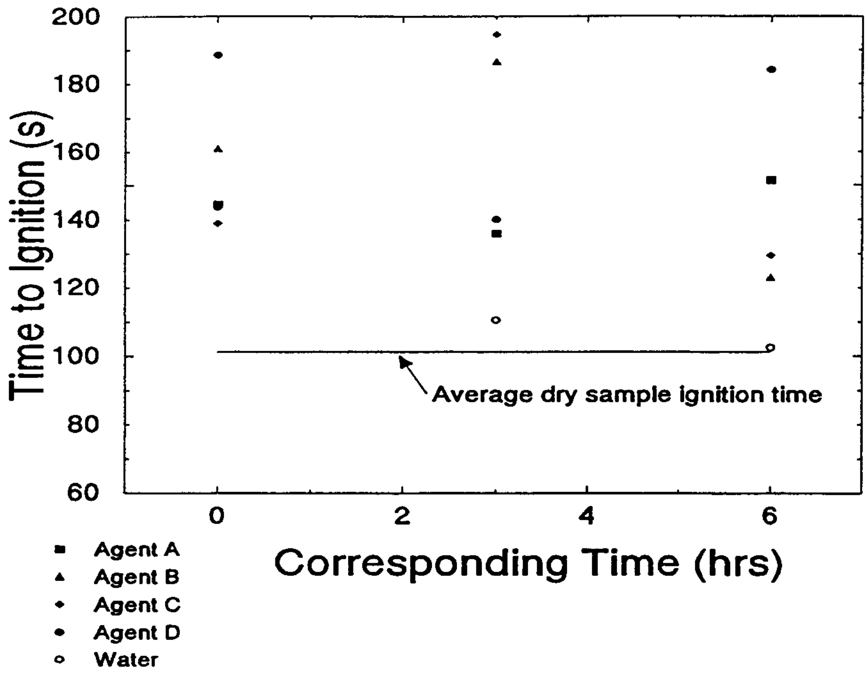

**Figure 19** - Ignition times for foam on unstained samples subject to 30 kW/m$^2$ heat flux.

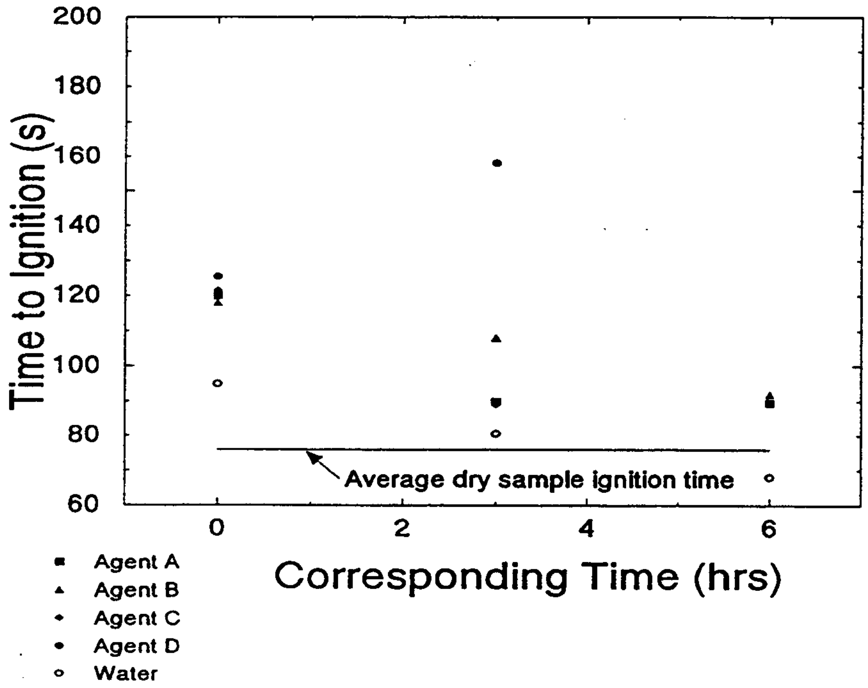

**Figure 20** - Ignition times for foam on stained samples subject to 30kW/m$^2$ heat flux

# CHAPTER 4

# SMOKE CHARACTERIZATION

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# SMOKE CHARACTERIZATION

## 4.1 Introduction

The impact of fire suppression agents on the quantity and composition of smoke generated during extinguishment has been investigated in two series of crib fires. Both series examined the physical and chemical properties of smoke from crib fires before, during and after extinguishment. Fire fighters have observed that a cloud of very bright "white smoke" is often generated as they extinguish a fire using a fire suppression agent (Figure 1). This "white smoke" is not usually observed when they use water to extinguish fires. Questions have arisen concerning what causes the generation of "white smoke" and whether or not it represents a significant new hazard for fire fighters.

In the first series of crib fires, seventeen identical wood cribs were ignited, one per test. Each crib fire was allowed to develop fully before being extinguished using water alone or water with a fire suppression agent. During the crib fires, smoke samples were collected before and after extinguishment for chemical analysis. This allowed determination of the concentration of polycyclic aromatic hydrocarbons, the ratio of elemental to organic carbon for pre-extinguishment (free burn) and post-extinguishment smoke. The inorganic and organic components of "white smoke" particulates were compared to smoke particulates collected from water extinguished fires in an attempt to identify a chemical "marker" which could be used to distinguish whether water or an agent solution was used to extinguish the fire.

The second series examined the physical and chemical properties of the smoke, both the particulate and gas phases. The concentrations of carbon monoxide, carbon dioxide, oxygen, nitrogen oxides, hydrogen chloride, and hydrogen cyanide, as well as the mass concentration and size distribution of soot particulates were measured before and after extinguishment with water alone and with agent solutions.

The objective of this effort was to characterize how fire suppression agents impact the physical and chemical properties of smoke. Specifically, the production of "white smoke" as a physical or chemical phenomenon was examined. Using this information, the hazard of the smoke exposure for fire fighters from the use of fire suppression agents of this type could be assessed.

## 4.2 Fabrication of the Cribs

Cribs for the first series were assembled completely out of Southern pine lumber, while for the second series, acrylonitrile butadiene styrene (ABS) and polyvinyl chloride (PVC) plastic sticks were included in each crib. Each square base crib consisted of 10 layers, with each square layer containing seven 55.9 cm (1.8 ft) long sticks of 3.8 cm (1.5 in) x 3.8 cm (1.5 in) cross section and each successive layer laid crosswise to the previous layer (Figure 2). These cribs are similar in design to the cribs burned by Gross [1], Block [2], and Bryner et al. [3]. Southern pine was selected to represent the framing lumber found in typical residential structures. For the second series, six pine sticks per crib were replaced with three ABS and three PVC sticks. The ABS sticks were selected to represent the asphaltic roofing, carpeting, and polyurethane furnishings while the PVC sticks were added to simulate the vinyl tile and PVC plumbing components within a house. All the cribs were assembled approximately one month before the first scheduled fire test. This allowed all the cribs to reach about the same moisture content before the first crib was burned. The moisture content of each crib ranged from 6 to 8% as measured using both Delm Horst and Lignomat moisture meters*. For the series of burns, the crib weights ranged from 24 to 27 kg (52.8 to 59.4 lb). For the second series of cribs with the additional mass of ABS and PVC sticks, each crib weighed between 29 and 34 kg (63.8 and 74.8 lb) of which approximately 3.2 kg (7 lb) was PVC and 2.6 kg (5.8 lb) was ABS.

### 4.3 Furniture Calorimeter Test Facility

After allowing the cribs to dry, the cribs were burned under a 2.4 x 2.4 m (7.9 x 7.9 ft) collection hood (Figure 3) with an exhaust rate of about 2 $m^3/s$ (70.6 $ft^3/s$). Each crib was ignited using 500 mL (0.13 gal) of heptane poured into a round steel pan (40.6 cm (16 in) diameter and 2.54 cm (1 in) deep) which was positioned 3.8 cm (1.5 in) below the bottom layer of the crib. The heptane averaged about 1.5% of the initial mass of the crib. The instrumentation associated with this facility measured the mass loss rate of the crib, the heat release rate, and gas concentrations of carbon monoxide, carbon dioxide and oxygen. The mass loss rate of the burning crib was monitored with a water-cooled load cell with a sensitivity of about 3 g. The heat release rate was determined via oxygen consumption calorimetry [4,5], which involves measuring the oxygen concentrations, the flow velocity, and the temperature in the exhaust duct. After drying the sample gases via a cold trap to remove water, the concentrations of carbon monoxide and carbon dioxide were measured using non-dispersive infrared gas analyzers. The oxygen concentration was monitored via paramagnetic analyzer.

### 4.4 Sample Collection and Analysis - First Series of Cribs

In the first series of crib burns, after the heptane burned out (typically 2.5 to 3 minutes after ignition) the fire was allowed to grow, involve the entire crib, and burn in a steady fashion before being extinguished 8 minutes after ignition. The mass burning rate of the cribs during the steady phase was approximately 30 g/s (0.07 lb/s) which resulted in a peak heat release rate of approximately 400 kW (378 Btu/s). Each crib was extinguished using either water, a solution of water and agent, or foamed water/agent solution. A single agent solution was applied without air as a liquid spray and with air injection as a compressed air foam. Above the collection hood, smoke was withdrawn from the exhaust duct via a heated, glass sample probe. The sample smoke was immediately diluted using dry nitrogen and then pulled through a filter manifold which held four 47 mm diameter filters. Prior to each crib burn, each of the four filter holders attached to the manifold was loaded with either a quartz fiber filter, a Nucleopore filter with 0.8 mm (0.03 in) diameter pores, or an Anapore ($Al_2O_3$) ceramic filter, each filter had been weighed prior to the test. Each filter holder was connected to a separate mass flow controller and vacuum pump to allow samples to be collected

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* Certain equipment or materials are identified in this report. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology or the U.S. Fire Administration, nor does it imply that the equipment or materials identified are necessarily the best available for the purpose.

serially or simultaneously. Each filter could be used to sample during the free burn stage, prior to extinguishment, or after the extinguishing agent had been applied to the crib. Sample flow rates and collection times were monitored for each filter. After each fire, the filters were weighed and placed in a dessicator for 24 hours. After reaching a constant weight, each sample was placed in a Petri dish lined with baked-out aluminum, sealed with Teflon tape and then stored in a refrigerator (< 2 °C).

The Nucleopore and Anapore filters were examined in an attempt to identify inorganic particles unique to either agent solution or water extinguishment. Samples of the Nucleopore filters, approximately 1 $cm^2$ each, were cut from the filters. These samples were then carbon coated with approximately 10 nanometers of carbon for conductivity. Individual particles from the samples were analyzed using conventional and environmental scanning electron microscopes and energy dispersive x-ray analysis.

Quartz fiber filters were cut in half and one half was analyzed for polycyclic aromatic hydrocarbons (PAHs) [6]. Most of the filter samples were sufficiently loaded with emissions to allow for the measurements of PAHs from 3.7 mm diameter circles punched from the original 47 mm filters. Filter samples were examined using on-line Supercritical Fluid Extraction - Gas Chromatography/Mass Spectrometry [7,8,9] in an attempt to identify polycyclic aromatic hydrocarbons unique to either water or foam extinguishment. The other half of the quartz fiber filters was analyzed for the ratio of elemental carbon to organic carbon using optical-thermal decomposition analysis [10].

### 4.5 Sample Collection and Analysis - Second Series of Cribs

In the second series of crib burns, after the heptane burned out (typically 2.5 to 3 minutes after ignition) the fire was allowed to grow, involve the entire crib, and burn in a steady fashion before being extinguished at 8 minutes after ignition. The mass burning rate of the cribs during the steady phase was approximately 30 g/s (0.07 lb/s) which resulted in a peak heat release rate of approximately 400 kW (378 Btu/s). Each crib was extinguished using either water or an agent solution. Four different agents were utilized and are referred to as Agents A, B, C, and D. The extinguishing agent, whether it was foam solution or water, was applied from a specific number of nozzles, at a specific flow rate and delivery pressure. The specific location of the nozzles, flow rates and delivery pressures are described in section 6.1 of this report.

Above the collection hood, smoke was withdrawn from the exhaust duct via a tapered, heated, glass sample probe. Attached to the end of the sample probe were two 47 mm filters, an Anderson Cascade Impactor, two gas impingers, and a chemiluminescent nitrogen oxides analyzer. Prior to each crib burn, each of the two filter holders was loaded with a quartz fiber filter, which had been pre-weighed. Each filter holder was connected to a separate mass flow controller and vacuum pump to allow samples to be collected in a serial or parallel fashion. Each filter could be used to sample during the free burn stage, prior to extinguishment, or after the extinguishing agent had been applied to the crib. Sample flow rates and collection times were monitored for each filter. After each fire, the filters were reweighed and placed in a desiccator for 24 hours. After obtaining a constant weight, each sample was placed in a Petri dish and stored in a desiccator. Each of the eight stages in the cascade impactor contained a sample collection substrate, which was also pre-weighted before each burn. The impactor had its own dedicated pump and regulator to pull 28.32 L/min of sample through the impactor. After each run the collection substrates were reweighed, desiccated for 24 hours and rechecked.

The hydrogen chloride and hydrogen cyanide were collected in preweighed 250 mL glass impinger bottles containing approximately 100 mL of 10 or 15 millimolar solutions of potassium hydroxide. To maximize the collection efficiency, two impingers were used in series, separated by a 45 mm diameter polytetraflouroethylene filter to collect the sample from the exhaust stream. The second impinger served to trap any gases that might break through the first impinger. Each sample was analyzed for hydrogen chloride or hydrogen cyanide via ion chromatography. A commercially available ion chromatograph equipped with a total conductivity detector was used to analyze for $Cl^{-1}$ and $CN^{-1}$. An anion column preceded by a precolumn module was used. All chemicals were of reagent grade quality. The water used was conditioned to 18.3 MΩ-cm and passed through a 0.45 mm nominal porosity filter. The eluent for the ion chromatograph was 5 mM KOH. Stock solutions of $Cl^-$ and $CN^-$, nominally 1000 ppm, were prepared by dissolving 0.2100 g of dried KCl and 0.2511 g of dried KCN, respectively, in 100 mL of 18.3 MΩ-cm water. Calibration solutions of 2.0 ppm $Cl^-$ and 1.0 ppm $CN^-$ were prepared by dilution of the stock solutions with the eluent. The eluent flow rate through the system was 1.2 mL/min. The sample loop had a volume of 100 mL. Unknowns were diluted 1:10 with eluent. Standards and unknowns were loaded into the loop using a 1 mL syringe and a 0.45 mm syringe filter. The sample loop was rinsed with approximately 1 mL of the analyte solution before the sample was injected onto the column.

A portion of the sample gas was dried and then pulled through the chemiluminescent nitrogen oxide analyzer. This analyzer also had its own dedicated vacuum pump. Before each series of crib tests, the analyzer was calibrated with span gas of a known concentration and zeroed with nitrogen. During the pre-test check for the fourteenth crib burn, the ozone generator malfunctioned and caused the reaction chamber to implode. The analyzer was not utilized for the last six crib burns.

## 4.6 Results

### 4.6.1 First Series of Crib Burns

The analysis of Nucleopore and Anopore filters demonstrate that although the filters were lightly loaded, large numbers of small particles aggregates were present (Figure 4). The size and structure of these aggregates are consistent with carbon containing particles originating from areas of incomplete combustion. These particles are found in samples from fires extinguished by water only and by the fire suppression agent solution. This analysis also demonstrated a second group of particles (Figures 5 and 6) which appear to be residual from liquid evaporation. Qualitatively, the particles from both water and water/agent contain major amounts of calcium with minor trace amounts of manganese, chlorine, and magnesium (Figures 7 and 8). The particles from the water/agent extinguishment also contain minor to trace amounts of phosphorous, sulfur, copper, and sodium (Figure 9).

The polycyclic aromatic hydrocarbon analysis demonstrates some differences between the free-burn and extinguished samples (Figures 10-13). The PAH profiles of the surfactant-extinguished samples demonstrate that although the relative levels of the different peaks may be similar, the overall magnitudes of the responses can vary significantly from sample to sample. Most notably, the emissions from the foam as well as the solution spray-extinguished fires were depleted in the PAHs with molecular weights greater than 228, compared to the water-extinguished burn, which showed relatively high levels of the range of PAHs measured. The suppression of the formation of higher molecular weight PAHs by the foam and surfactant during extinguishing of the crib fires may be due to the greater efficiency of the cooling by the two extinguishing agents compared with water. By their nature, the agent solution and foam might better coat or penetrate, and possibly cool, the combusting surfaces of the burning cribs.

One additional observation is that there was a general lack of the two softwood combustion species, retene and methyldehydroabietate, in the emission from all of the pre-extinguishment samples. The rate of combustion during all the free burns was quite high, suggesting that the two softwood-related species are not formed or do not survive the rapid (oxygen-rich) combustion phase of a fire, but are present in the smoldering, fuel-rich combustion of the extinguishing fire, regardless of the extinguishing agent.

### 4.6.2 Second Series of Crib Burns

For each of the extinguishment configurations, oxygen concentration, carbon dioxide concentration, carbon monoxide concentration, nitrogen oxides concentration, and heat release rate are plotted as a function of time (Figures 14-27). For all three configurations, the oxygen concentration (Figures 14-16) for water as well as the four agents all decrease to about 19.3% just before extinguishing agent is applied. In the two higher flow rate configurations, the oxygen concentrations return quickly to pre-ignition values. There does not appear to be significant differences between the four agents and water. For the lowest flow rate, 2 nozzles and 0.09 l/s (1.4 gpm), the oxygen values do not return as uniformly to pre-ignition concentrations. The lower flow rate may be less efficient at extinguishing the fire and slight differences in how the crib was burning or how the extinguishing agent is applied could be expected to have greater impact than in the higher flow rate cases where there may be excess extinguishing agent.

The ability of the higher flow rate configurations to extinguish the crib more completely than the lower flow rate is also demonstrated in the carbon dioxide (Figures 17-19) and carbon monoxide plots (Figures 20-22). The carbon dioxide concentrations increase to about 2.5 % just before the extinguishing agent is applied. $CO_2$ and CO concentrations obtained for the lowest flow rate configurations do not decrease as quickly as the higher flow rate configurations.

The impact of the higher flow rate configurations is also seen in the nitrogen oxides concentration plots (Figures 23 and 24). The higher flow rate configuration plots are much more uniform across the different agents than the lower flow rate configuration. The production of nitrogen oxides requires high temperatures, and three of the five fires (A, B, and C) (Figure 24) demonstrate different delays until the nitrogen oxides begin to appear. The range of delays observed are not well understood. Differences in fire development could account for the spread in the time before the appearance of nitrogen oxides. As the fire grows, the concentration of nitrogen oxides continues to increase until extinguishment. All the fires appear to have about the same slope after the appearance of the oxides. However, the similarity in slope after nitrogen oxides begin to appear suggests that if the crib fires had been allowed to burn for some additional time period, all of the crib fires would have been generating between 5 and 6 ppm of nitrogen oxides. It is interesting that this delay only appears in the pre-extinguishment generation of the nitrogen oxides. After extinguishment, the concentrations of nitrogen oxides drop uniformly to less than 0.5 ppm without any observable delay. These delays in generation were only observed in concentrations of nitrogen oxides, not the oxygen, carbon monoxide, or carbon dioxide.

Heat release rate versus time for three configurations demonstrates the reproducibility of the crib fires (Figures 25-27). Peak heat release rates ranged from 300 to 400 kW. Total heat released from the cribs ranged from 90 to 120 MJ.

Size distributions of aerodynamic mass mean diameters for all smoke samples are tabulated in tables 1, 2 and 3. Each table contains the series of cribs, which was extinguished using a specific set of nozzles, flow rate and pressure. As compared to the free burn or pre-extinguishment sample, the mean diameter either remains unchanged or decreases slightly for cribs extinguished with water. The diameter decreases more significantly with each of the extinguishing agents. Since the impactor which was used to collect this data was designed to simulate the human respiratory system, the smaller mass mean diameter particles from the foam extinguished fires would penetrate further into the respiratory system (see Figure 28) [11,12].

The concentrations of hydrogen chloride for all smoke samples are summarized in tables 4, 5 and 6. Pre-extinguishment values range from 270 to 550 mg/m$^3$. With the application of extinguishing agent, the concentration of hydrogen chloride decreases at least 30% and sometimes as much as 80%. The Occupational Safety and Health Administration (OSHA) sets the prolonged exposure limit (PEL) at 5 ppm (approximately 5 mg/m3) [14]. The foam agents do not appear to be more or less efficient than water in decreasing the hydrogen chloride concentration.

Tables 7, 8, and 9 show the concentrations of hydrogen cyanide for all smoke samples. Pre-extinguishment values range from 6 to 31 mg/m$^3$. Application of extinguishing agent rapidly reduced the values to near zero in all but two fires. OSHA sets the prolonged exposure limit at 10 ppm TWA (time weighted average) (approximately 10 mg/m$^3$) [15]. The agents do not appear to be more or less efficient than water in decreasing the hydrogen cyanide concentrations.

While the impactor data provides insight into the size distribution, the gravimetric filter samples demonstrate the overall mass concentration of smoke particulates, before and after extinguishment (tables 10, 11, and 12). During the free-burn portion of the crib fire, the mass concentrations range between 650 and 950 mg/m$^3$. With the application of extinguishing agent the mass concentrations drop to a range between 100 and 260 mg/m$^3$. While the water extinguishment values are the lowest for each configuration, the difference may not be great enough to be significant when compared to the other agents. All the extinguishing agents reduce the mass concentration by 60 to 90%. As the fire is extinguished, fewer smoke particulates are generated. The lowest flow configuration is the least efficient at extinguishing the fire and this is reflected in a 60 - 80% reduction in mass concentrations. The agents do not appear to be more or less efficient than water in decreasing smoke mass concentrations.

## 4.7 Discussion

These two series of crib burns help to characterize how extinguishment affects the chemical and physical properties of smoke. Extinguishment by any of the fire suppressant combinations, water alone, agent solution, agent solution foam, caused the smoke to undergo significant changes in chemical composition and physical attributes. These changes were observed with all the agents and were not specific to any one agent or agent/water combination. For the post-extinguishment smoke, only small differences in the chemical properties were observed between specific extinguishing agents, water alone, agent solution, or foam. The specific extinguishing agent also did not appear to affect the physical properties of the smoke with the exception of the size distribution of the particulates. These changes in the distribution of smoke particulate sizes appear consistent with the appearance of "white smoke" after extinguishment (see section 4.7.2).

### 4.7.1 Chemical Properties

Extinguishing the crib fires causes a dramatic decrease in the concentrations of carbon dioxide, carbon monoxide, and nitrogen oxides. The oxygen concentrations also rapidly approach original levels as each fire was extinguished. This is not surprising since the burning fuel is producing the combustion gases and consuming the oxygen. Within the scatter of the different agents (water and agents A, B, C, and D), there does not appear to be any significant consistent difference in these gas concentrations that can be traced to a specific agent.

The different configurations (2 or 4 nozzle and 0.09, 0.1, or 0.13 l/s (1.4, 1.6, or 2.1 gpm) flow rate) do affect how quickly the gas concentrations return to their pre-burn levels. The lowest flow rate, 0.09 l/s (1.4 gpm), is not as effective in extinguishing the fire as the highest, 0.13 l/s (2.1 gpm), flow rate. Gas concentrations return to pre-burn values more slowly for the lowest flow rate as compared to the highest flow rate. This is not unexpected since fire continues to produce combustion gases until it is extinguished. The differences are a function of the ability of the given flow rate to extinguish the fire and do not appear related specifically to any one water/foam agent.

The pre-extinguishment concentrations of hydrogen cyanide dropped to essentially zero for most of the burns as the cribs were extinguished. The hydrogen cyanide resulted from the combustion of the ABS plastic sticks placed within the crib. The integrated nature of the sample, one sample collected over some period before or after extinguishment, precludes identification of any trends such as slowly decreasing concentrations as was observed in the other gas data. The specific flow rate and configuration did appear to affect the decrease in concentration of hydrogen cyanide. The lowest flow rate of water alone sprayed from the 2 nozzle configuration did not show as much of a decrease as the water was applied. This again appears to reflect the effect of configuration on the extinguishment process rather than being related to a specific extinguishing agent. The two nozzle configuration was less effective than the four nozzle set-up in extinguishing the crib fire. The fire continued to generate hydrogen cyanide until the fire was completely extinguished.

Extinguishment decreased the free burn concentrations of hydrogen chloride, but not quite as thoroughly as was observed with hydrogen cyanide. The hydrogen chloride resulted mainly from the combustion of the PVC plastic sticks placed within the crib. The integrated nature of the sample, one sample collected over some period before or after extinguishment, precludes identification of any trends such as slowly decreasing concentrations as was observed in the other gas data. The specific flow rate and configuration did not appear to affect the decrease in concentration of hydrogen chloride. There did not appear to be any consistent differences between the specific agents in terms of reducing the hydrogen chloride concentrations.

The application of extinguishing agents to the crib fires reduced the mass concentration of the smoke from each of the crib burns. Qualitatively, the reduction appeared somewhat less for the 2 nozzle/0.09 l/s (1.4 gpm) configuration. This again reflected the inability of the lower flow rate to extinguish the fire as quickly as the higher flow rates/4 nozzle combinations. There were no apparent differences between the water alone and the agent solutions.

The agent solutions did appear to affect the size distribution of the smoke particulates. Extinguishment via water alone appeared to cause minor shifts in the aerodynamic mass mean diameter. But the agents consistently shifted the mean diameter toward smaller values. As the smoke cools, the water condenses on the smoke particulates. As the water collects on the smoke particulates and later evaporates through mixing with dry air, the loose aggregate structure observed in the electron microscopy work may collapse to form a more compact particulate. The surfactant found in the agents would allow the spray to wet the particulates better than water alone. This could result in slightly more compact particulates emerging from a fire extinguished using an agent. However, this does not reduce the hazard presented by the smoke particulates. The smaller particulates represent an increased hazard because the smaller smoke particles can penetrate further into the lungs than the larger particulates [11,12]. Therefore based on limited data, the most significant change in the physical properties of the smoke, the smaller mean diameter, may actually be a negative or undesirable effect.

The inorganic analysis via scanning electron microscopy and environmental scanning electron microscopy was not successful in identifying a "chemical marker" which could be used to differentiate between water and agent generated smoke. There were slight differences noted in several inorganic metals, but metals such as sodium, magnesium, or manganese could result from the water used to deliver the foam agent. It was not possible to differentiate between inorganic compounds originating in the agents and compounds originating in the water used to deliver the agents. The low concentrations of agent, typically 1 to 6% in the water and the dilution of the volatilized agent as it is entrained by the fire plume also makes it more difficult to isolate a compound unique to water or agent extinguished smoke.

The PAH analysis confirms the presence of organic "chemical markers" identifying the source or fuel as softwood. The PAH concentrations also indicate that the foam agents may reduce the formation of heavier polycyclic aromatic hydrocarbons. This is probably related to the ability of the agents to reduce surface tension and increase vaporization of water, which absorbs more energy from the region over the fire. Lower temperatures are less conducive to the formation of heavier PAHs. If additional water were used in the extinguishment process, then it is possible the formation of heavier PAHs would also be impeded as in the foam case.

### 4.7.2 "White Smoke"

During the extinguishment process, the fire suppressant is injected or sprayed into or around the burning fuel. The fire suppressant may be water or a combination of fire suppression agent (1 - 6%) in water (94 - 99%). The energy released by the combustion of the fuel is absorbed by the water, and it undergoes a change in its physical state from liquid to vapor. The water vapor may be entrained by the fire plume and mixed with other combustion gases and smoke particulates. As the gases cool through radiation losses and mixing, the water vapor may condense on small particulates or condensation nuclei. As additional vapor condenses to form increasing numbers of small droplets, a cloud may appear. This cloud formation process requires that the gases be saturated in terms of water and that there be sufficient condensation nuclei present.

The agents could promote the formation of clouds by increasing the water content of the gases and by providing additional condensation nuclei. Surfactants and foam agents are designed to reduce the surface tension of the solution and encourage the formation of bubbles. The thin film of solution around a small volume of air or combustion gases can effectively increase the surface area of the solution. Increased surface area then translates into increased evaporation. As the water content increases, the air and/or combustion gases can become saturated with water vapor. The higher the degree of saturation or supersaturation, the quicker the water will condense to form droplets if condensation nuclei are present.

Additional condensation nuclei are provided by the salts, which are included in many surfactants and foam agents as water conditioners or softeners. As the agent is applied to the burning fuel, many small droplets of water/agent are sprayed on the fire. In the hotter regions of the fire, water evaporates from each droplet and the droplet collapses to form a small residue particle. The particles are the salts and other water conditioners added by the surfactant or foam agent as well as any impurities found in the water. These small particulates may provide additional condensation nuclei, which could promote the condensation of additional droplets.

## 4.8 Conclusions

The application of fire suppressant agents to crib fires did effect the chemical composition and size distribution of the smoke above the burning fuel. Most of the changes from pre- to post-extinguishment smoke were the result of the fire being extinguished. Extinguishment caused a significant reduction in the concentrations of carbon monoxide, carbon dioxide, hydrogen chloride, hydrogen cyanide, nitrogen oxides, and soot particulates in the post-extinguishment smoke. These reductions were observed for each of the fire suppressant agents, water alone, agent solution, and foam. With the exception of small shifts in smoke particulate size in the post-extinguishment smoke which was only observed with the foam, there did not appear to be significant differences in the post-extinguishment smoke between using water, agent solution, foam.

The agents, which reduce the surface tension of water and increase the surface area of a given mass of water, appear to expedite evaporation of the water. The agents also provide additional particulates, which may serve as condensation sites. Under the proper conditions, the additional water and particulates would promote the condensation of water into droplets, which may develop into a cloud of "white smoke".

## 4.9 References

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**Table 1. Size Distribution for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 2 nozzle/1.3 gpm/40 psi**

| | | Aerodynamic Mass Mean Diameter, µm |
|---|---|---|
| Pre- Extinguishment | | 1.6*<br>1.4 |
| | | |
| Post-Extinguishment | | |
| | Water | 1.4 |
| | Agent A | 0.9 |
| | Agent A (Repeat) | 1.0 |
| | Agent B | 1.3 |
| | Agent C | 1.2 |
| | Agent D | - |

Notes:

Reported values for aerodynamic mass mean diameter are estimated to be +/- 0.2 µm (Combined Standard Uncertainty - 2σ or 95% confidence level)

*The same pre-extinguishment samples are reported for all three extinguishment configurations.

**Table 2. Size Distribution for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 4 nozzle/2.1 gpm/26 psi**

| | | Aerodynamic Mass Mean Diameter, µm |
|---|---|---|
| Pre- Extinguishment | | 1.6*<br>1.4 |
| | | |
| Post-Extinguishment | | |
| | Water | 1.8 |
| | Agent A | 1.2 |
| | Agent B | 0.8 |
| | Agent C | 0.6 |
| | Agent D | 1.0 |

Notes:

Reported values for aerodynamic mass mean diameter are estimated to be +/- 0.2 µm (Combined Standard Uncertainty - 2σ or 95% confidence level)

*The same pre-extinguishment samples are reported for all three extinguishment configurations.

**Table 3. Size Distribution for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 4 nozzle/1.6 gpm/14 psi**

| | | Aerodynamic Mass Mean Diameter, µm |
|---|---|---|
| Pre- Extinguishment | | 1.6*<br>1.4 |
| | | |
| Post-Extinguishment | | |
| | Water | 1.0 |
| | Agent A | - |
| | Agent B | 0.8 |
| | Agent C | 0.6 |
| | Agent C | 0.8 |
| | Agent D | 0.7 |

Notes:

Reported values for aerodynamic mass mean diameter are estimated to be +/- 0.2 µm (Combined Standard Uncertainty - 2σ or 95% confidence level)

*The same pre-extinguishment samples are reported for all three extinguishment configurations.

**Table 4. Hydrogen Chloride Concentrations for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 2 nozzle/1.3 gpm/40 psi**

| | Pre-Extinguishment $mg/m^3$ | Post-Extinguishment $Mg/m^3$ | Reduction (Pre-Ext. - Post-Ext.) / Pre |
|---|---|---|---|
| Water | 520 | 300 | 0.4 |
| Agent A | 500 | 240 | 0.5 |
| Agent A (Repeat) | 520 | - | |
| Agent B | 550 | 100 | 0.8 |
| Agent C | 540 | 360 | 0.3 |
| Agent D | 440 | 100 | 0.8 |

Notes:

Reported values for hydrogen chloride concentrations are estimated to be +/- 100 $mg/m^3$ (Combined Standard Uncertainty - $2\sigma$ or 95% confidence level)

**Table 5 Hydrogen Chloride Concentration for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 4 nozzle/2.1 gpm/26 psi**

| | Pre-Extinguishment mg/m$^3$ | Post-Extinguishment Mg/m$^3$ | Reduction $\frac{\text{Pre-Ext. - Post-Ext.}}{\text{Pre}}$ |
|---|---|---|---|
| Water | 440 | 160 | 0.6 |
| Agent A | 270 | 120 | 0.6 |
| Agent B | 540 | 320 | 0.4 |
| Agent C | 550 | 410 | 0.3 |
| Agent D | 470 | 350 | 0.3 |

Notes:

Reported values for hydrogen chloride concentrations are estimated to be +/- 100 mg/m$^3$ (Combined Standard Uncertainty - 2$\sigma$ or 95% confidence level)

**Table 6. Hydrogen Chloride for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 4 nozzle/1.6 gpm/14 psi**

| | Pre-Extinguishment mg/m$^3$ | Post-Extinguishment Mg/m$^3$ | Reduction $\frac{\text{(Pre-Ext. - Post-Ext.)}}{\text{Pre}}$ |
|---|---|---|---|
| Water | 290 | 195 | 0.3 |
| Agent A | 450 | 150 | 0.7 |
| Agent B | 390 | 70 | 0.8 |
| Agent C | 490 | 210 | 0.6 |
| Agent C (Repeat) | 460 | 170 | 0.6 |
| Agent D | 520 | 290 | 0.4 |

Notes:

Reported values for hydrogen chloride concentrations are estimated to be +/- 100 mg/m$^3$ (Combined Standard Uncertainty - $2\sigma$ or 95% confidence level)

**Table 7. Hydrogen Cyanide Concentrations for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 2 nozzle/1.3 gpm/40 psi**

| | Pre-Extinguishment mg/m$^3$ | Post-Extinguishment mg/m$^3$ | Reduction $\frac{\text{(Pre-Ext. - Post-Ext.)}}{\text{Pre}}$ |
|---|---|---|---|
| Water | 23 | 11 | 0.4 |
| Agent A | 13 | 3 | 0.8 |
| Agent A (Repeat) | 15 | 0 | 1.0 |
| Agent B | 12 | 3 | 0.8 |
| Agent C | 12 | 0 | 1.0 |
| Agent D | 21 | 0 | 1.0 |

Notes:

Reported values for hydrogen cyanide concentrations are estimated to be +/- 6 mg/m$^3$ (Combined Standard Uncertainty - 2$\sigma$ or 95% confidence level)

**Table 8. Hydrogen Cyanide Concentration for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 4 nozzle/2.1 gpm/26 psi**

|  | Pre-Extinguishment mg/m$^3$ | Post-Extinguishment Mg/m$^3$ | Reduction $\frac{\text{Pre-Ext. - Post-Ext.}}{\text{Pre}}$ |
|---|---|---|---|
| Water | 6 | 0 | 1.0 |
| Agent A | 25 | 0 | 1.0 |
| Agent B | 31 | 0 | 1.0 |
| Agent C | 24 | 0 | 1.0 |
| Agent D | 21 | 0 | 1.0 |

Notes:

Reported values for hydrogen cyanide concentrations are estimated to be +/- 6 mg/m$^3$ (Combined Standard Uncertainty - 2$\sigma$ or 95% confidence level)

**Table 9. Hydrogen Cyanide for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 4 nozzle/1.6 gpm/14 psi**

| | Pre-Extinguishment mg/m$^3$ | Post-Extinguishment Mg/m$^3$ | Reduction $\frac{\text{(Pre-Ext. - Post-Ext.)}}{\text{Pre}}$ |
|---|---|---|---|
| Water | 15 | 0 | 1.0 |
| Agent A | 17 | 0 | 1.0 |
| Agent B | 19 | 0 | 1.0 |
| Agent C | 31 | 0 | 1.0 |
| Agent C (Repeat) | 24 | 0 | 1.0 |
| Agent D | 17 | 0 | 1.0 |

Notes:

Reported values for hydrogen cyanide concentrations are estimated to be +/- 6 mg/m$^3$ (Combined Standard Uncertainty - 2$\sigma$ or 95% confidence level)

## Table 10. Mass Concentrations for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 2 nozzle/1.3 gpm/40 psi

| | Pre-Extinguishment $mg/m^3$ | Post-Extinguishment $mg/m^3$ | Reduction $\frac{\text{Pre-Ext. - Post-Ext.}}{\text{Pre}}$ |
|---|---|---|---|
| Water | 910 | 170 | 0.8 |
| Agent A | 850 | 230 | 0.7 |
| Agent A (Repeat) | 810 | 220 | 0.7 |
| Agent A (Repeat) | 840 | - | - |
| Agent B | 650 | 230 | 0.6 |
| Agent C | 670 | 260 | 0.6 |
| Agent D | 860 | 211 | 0.8 |

Notes:

Reported values for mass concentrations are estimated to be +/- 150 $mg/m^3$ (Combined Standard Uncertainty - $2\sigma$ or 95% confidence level)

**Table 11. Mass Concentration for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 4 nozzle/2.1 gpm/26 psi**

| | Pre-Extinguishment $mg/m^3$ | Post-Extinguishment $mg/m^3$ | Reduction $\frac{\text{(Pre-Ext. - Post-Ext.)}}{\text{Pre}}$ |
|---|---|---|---|
| Water | 850 | 30 | 1.0 |
| Agent A | 860 | 120 | 0.9 |
| Agent B | 911 | 90 | 0.9 |
| Agent C | 910 | 160 | 0.8 |
| Agent D | 951 | 140 | 0.9 |

Notes:

Reported values for mass concentrations are estimated to be +/- 150 $mg/m^3$ (Combined Standard Uncertainty - $2\sigma$ or 95% confidence level)

**Table 12. Mass Concentration for Smoke from Fire Suppressant Foam Agents Extinguishment Configuration - 4 nozzle/1.6 gpm/14 psi**

| | Pre-Extinguishment mg/m$^3$ | Post-Extinguishment mg/m$^3$ | Reduction (Pre-Ext. - Post-Ext.) / Pre |
|---|---|---|---|
| Water | 890 | 100 | 0.9 |
| Agent A | 850 | 120 | 0.9 |
| Agent B | 830 | 120 | 0.9 |
| Agent C | 770 | 140 | 0.8 |
| Agent C (Repeat) | 720 | - | - |
| Agent D | 770 | 105 | 0.9 |

Notes:

Reported values for mass concentrations are estimated to be +/- 150 mg/m$^3$ (Combined Standard Uncertainty - 2$\sigma$ or 95% confidence level)

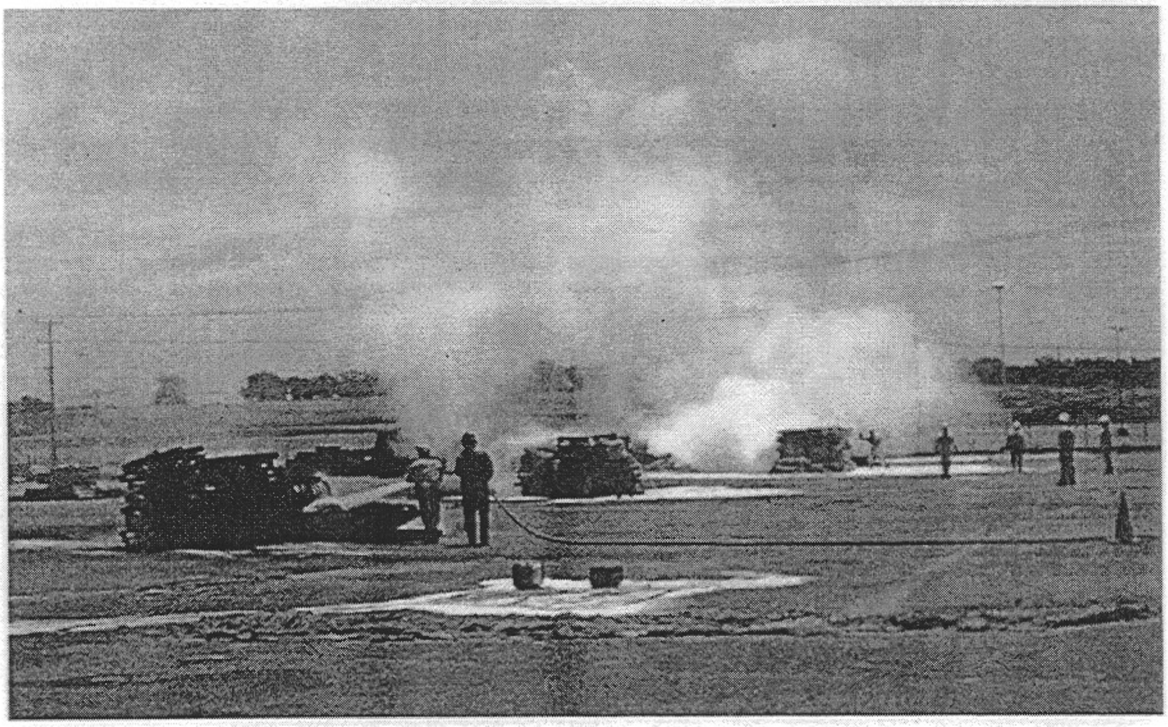


Figure 1. Wood pallet fire suppression demonstration with water (foreground), foam solution (center) and compressed air foam (background).

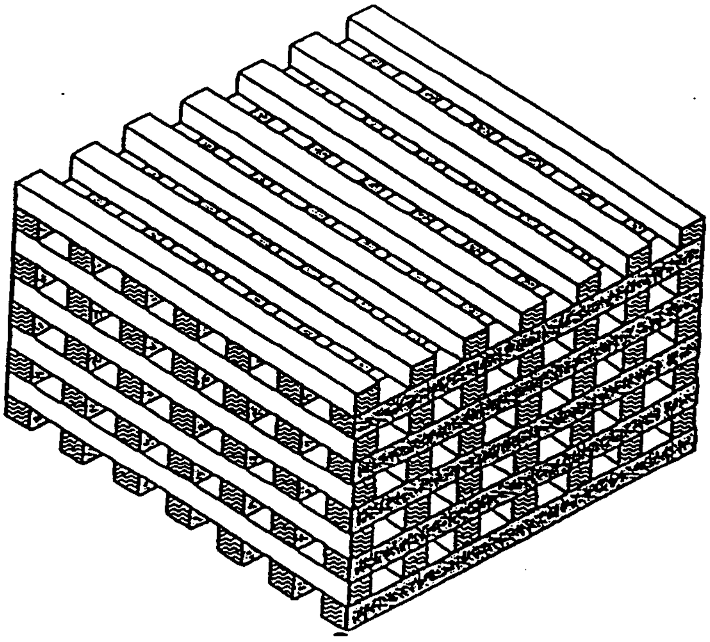


Figure 2. Diagram of crib (55.9 cm X 55.9 cm X 38 cm high) used for suppression experiments.

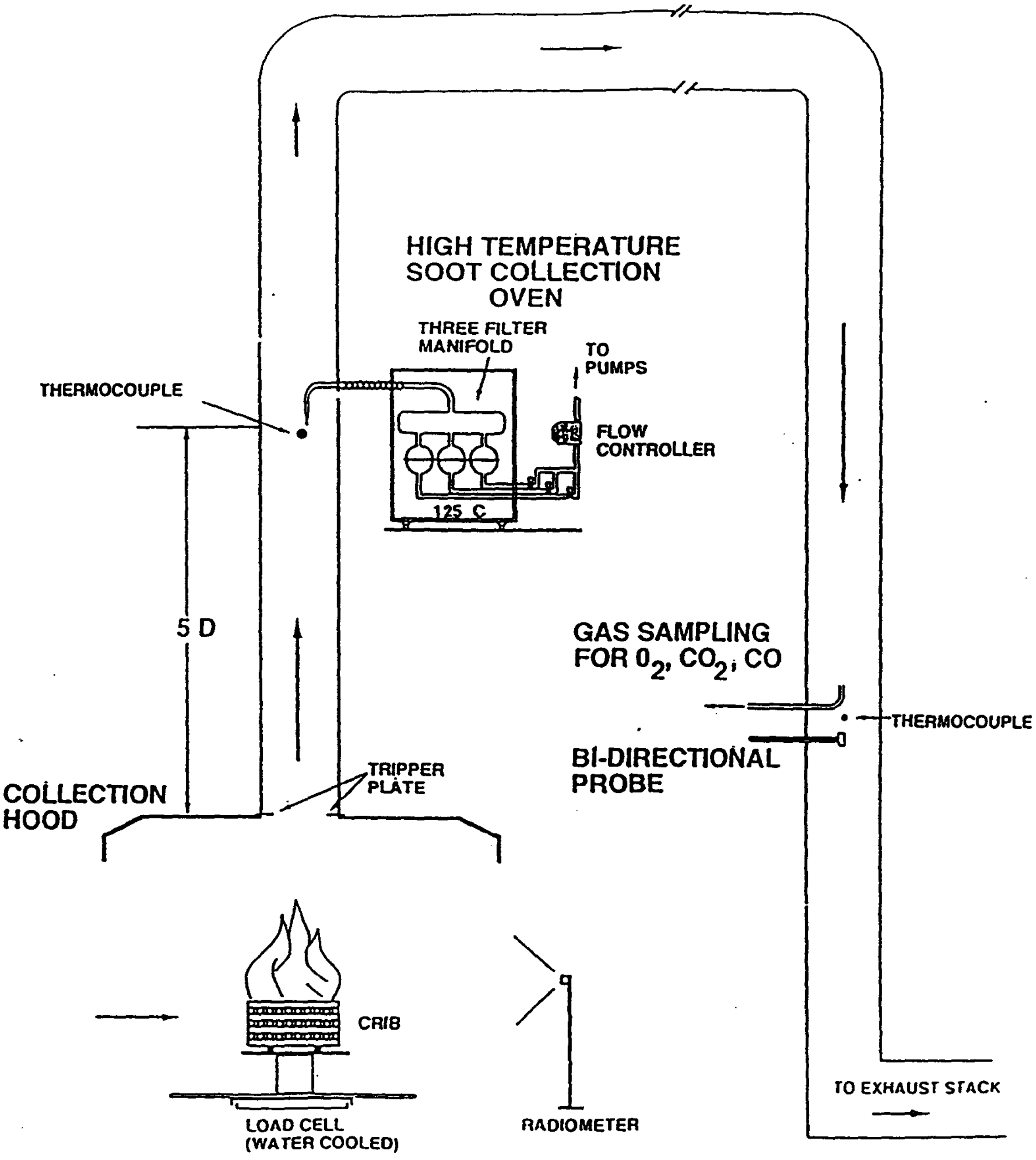


Figure 3. Diagram of furniture calorimeter and smoke sampling arrangement.

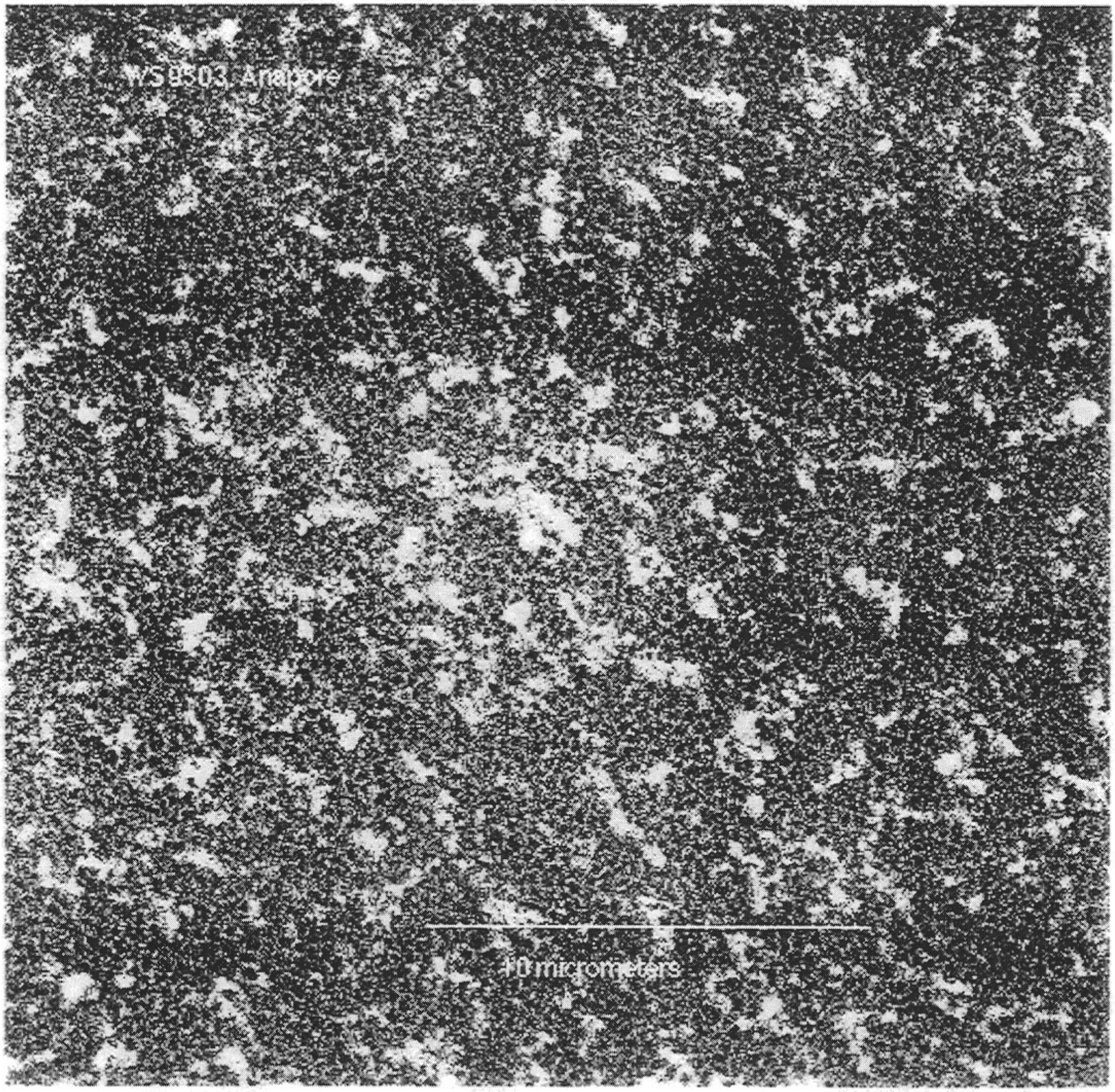


Figure 4. Electron micrograph of small aggregates on Anapore filter. Sample collected during extinguishment with foam.

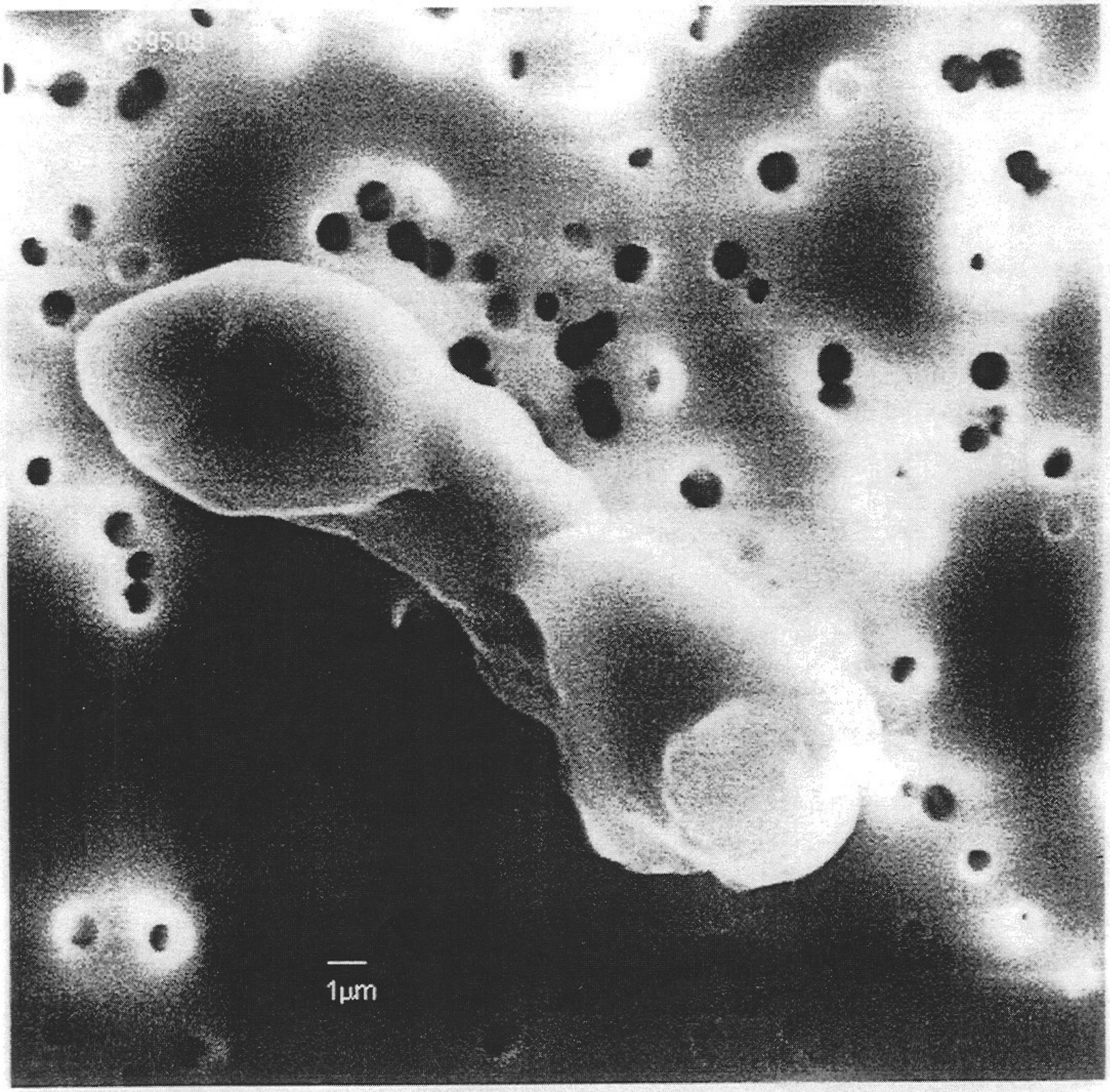


Figure 5. Electron micrograph of single aggregate on Nucleopore filter. Sample collected during extinguishment with foam.

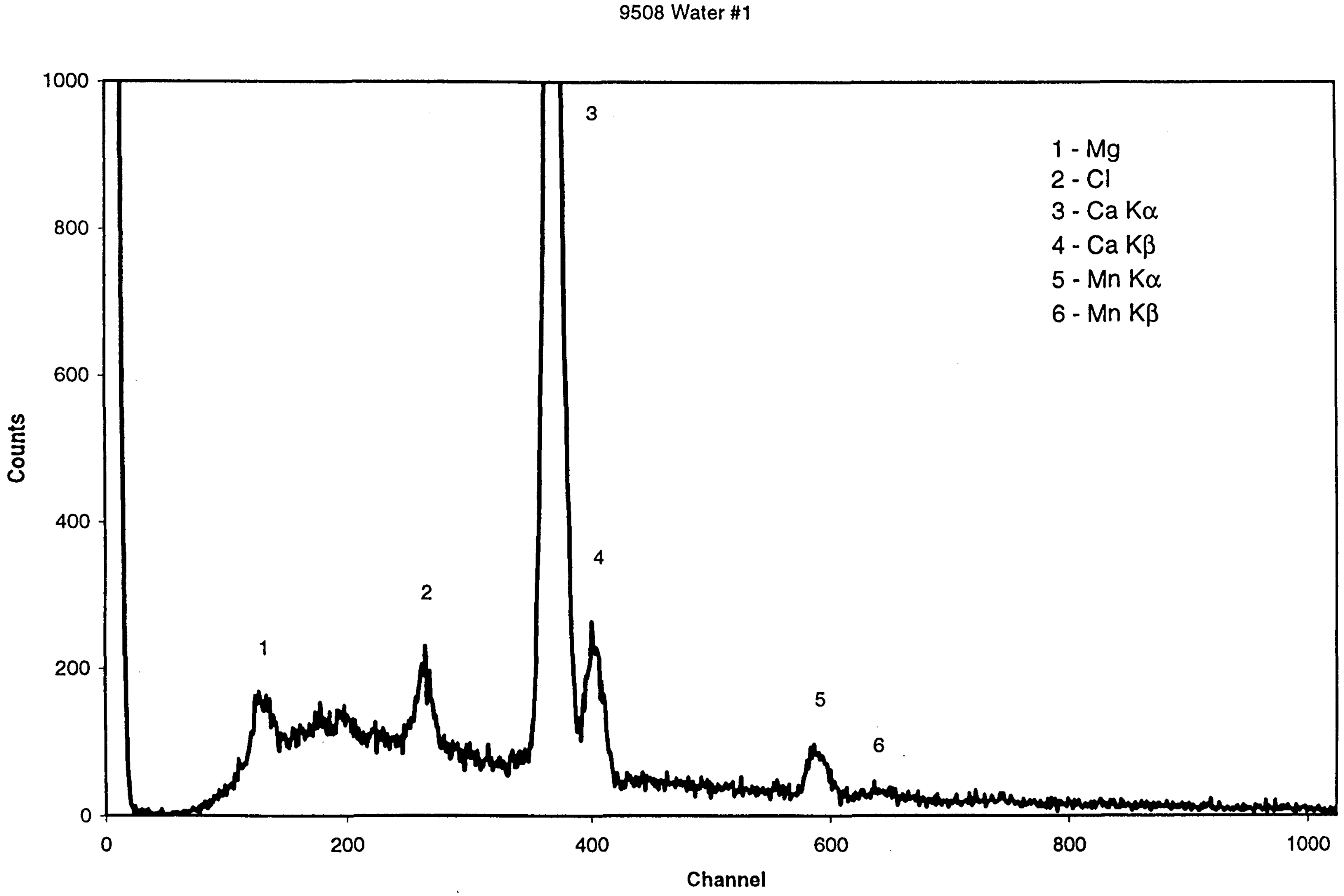


Figure 6. Spectrum from energy dispersive x-ray analysis of sample from Nucleopore filter collected during extinguishment with water. Peaks identified are magnesium, chlorine, calcium and manganese.

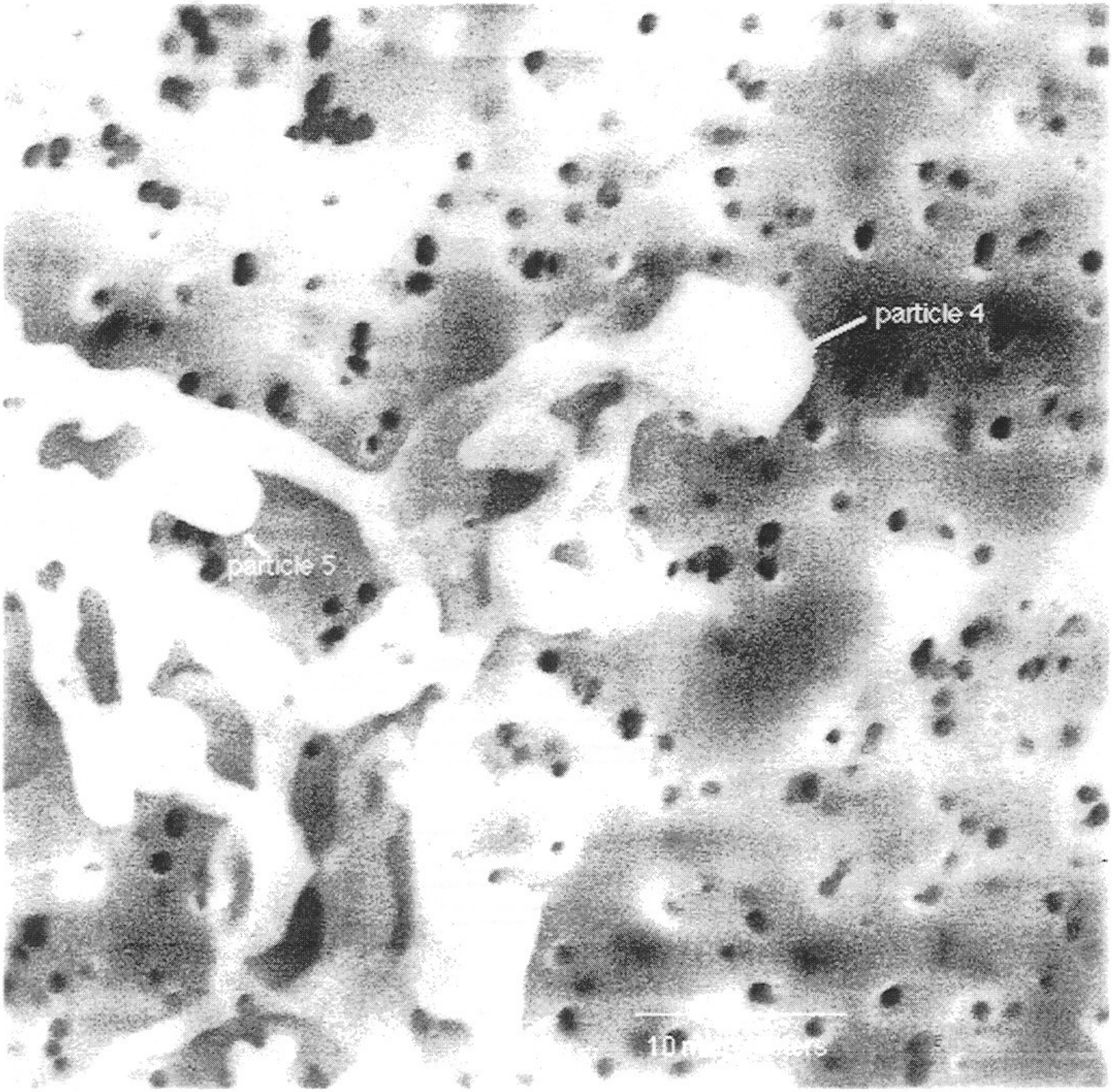


Figure 7. Electron micrograph of two aggregates (identified as particle 4 and 5) on Nucleopore filter. Sample collected during extinguishment with foam.

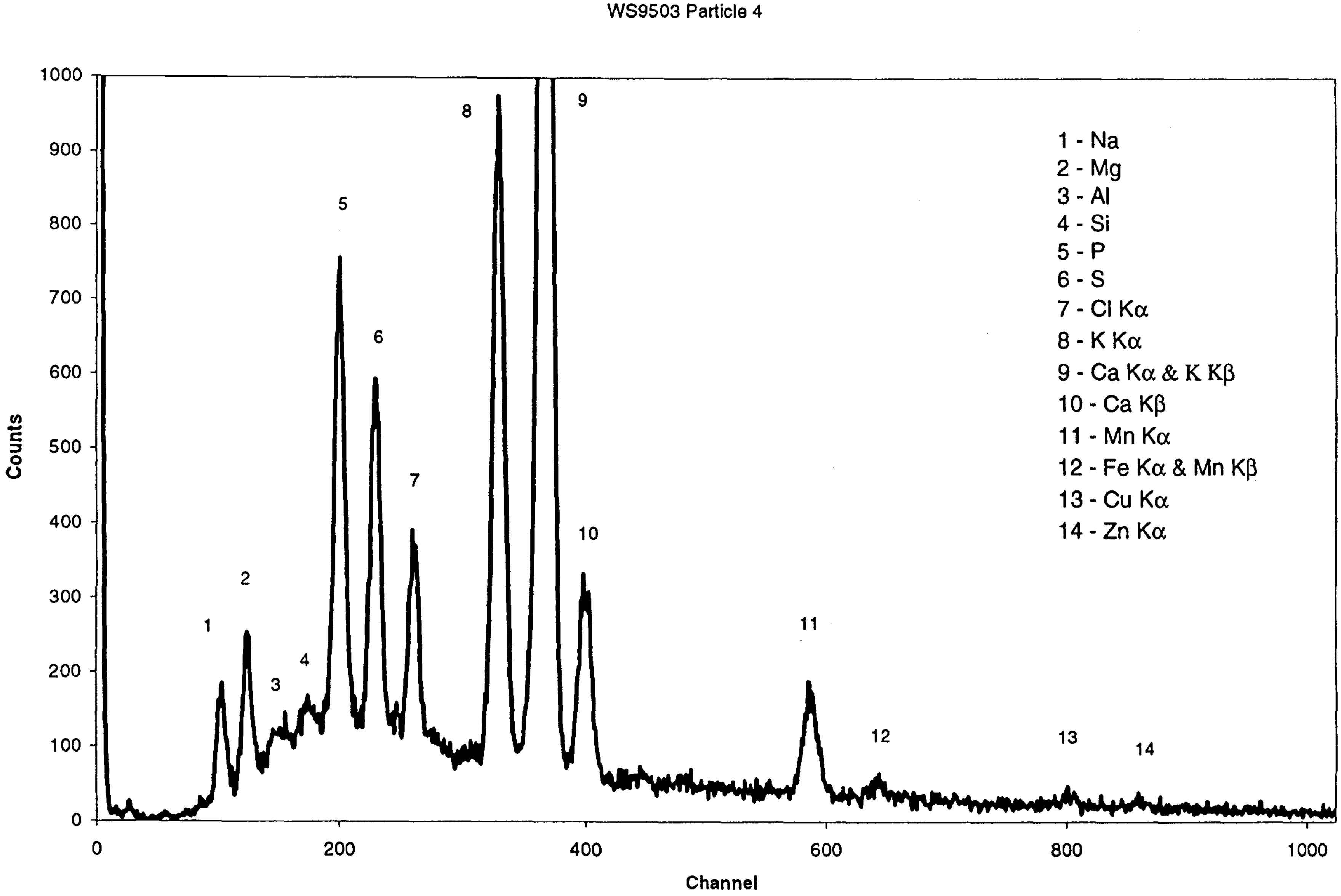


Figure 8. Spectrum from energy dispersive x-ray analysis of particle 4 from Nucleopore filter collected during extinguishment with foam. Peaks identified are sodium, magnesium, aluminum, silicon, phosphorous, sulfur, chlorine, potassium, calcium, iron, manganese copper and zinc.

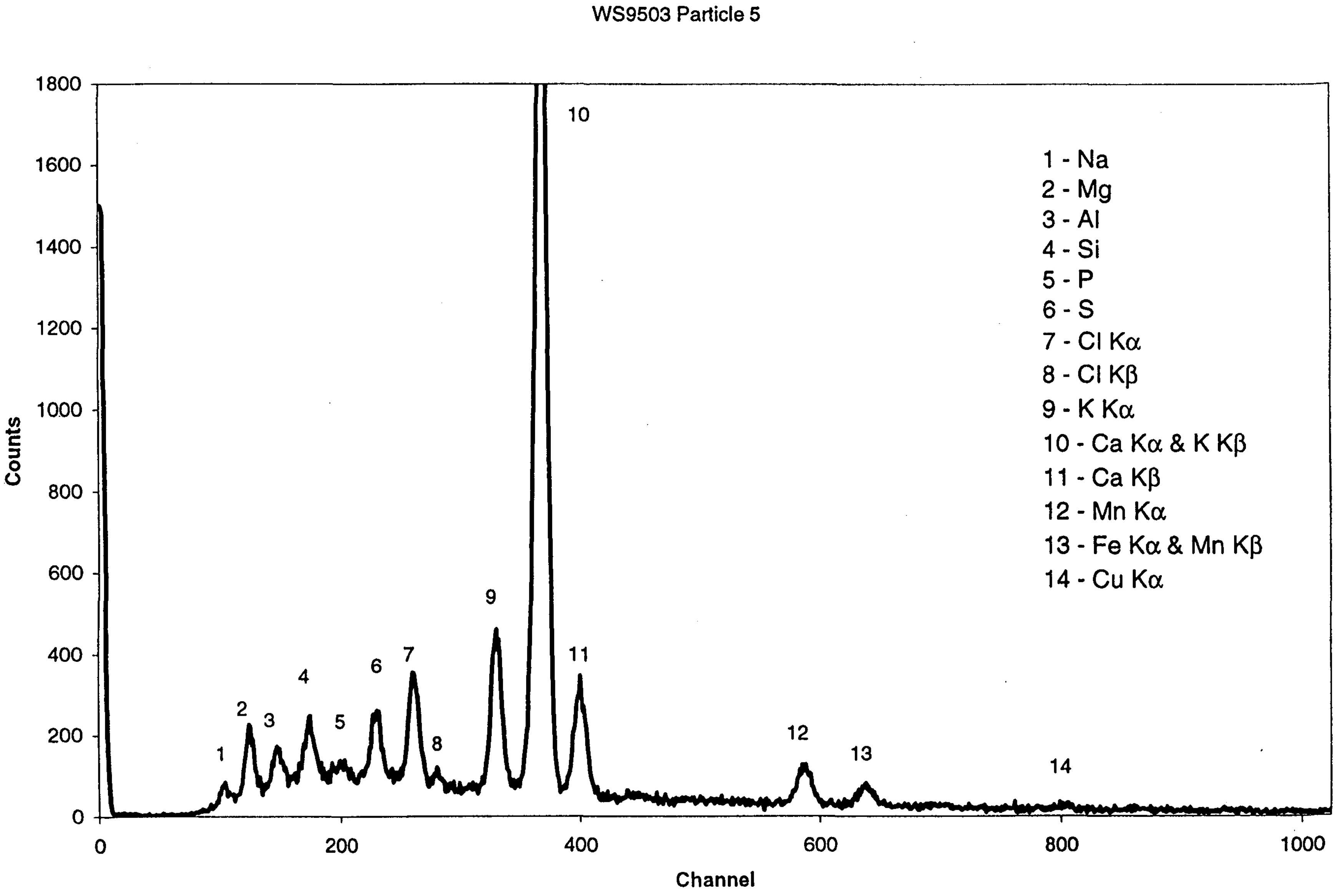


Figure 9. Spectrum from energy dispersive x-ray analysis of particle 5 from Nucleopore filter collected during extinguishment with foam. Peaks identified are sodium, magnesium, aluminum, silicon, phosphorous, sulfur, chlorine, potassium, calcium, manganese, iron, and copper.

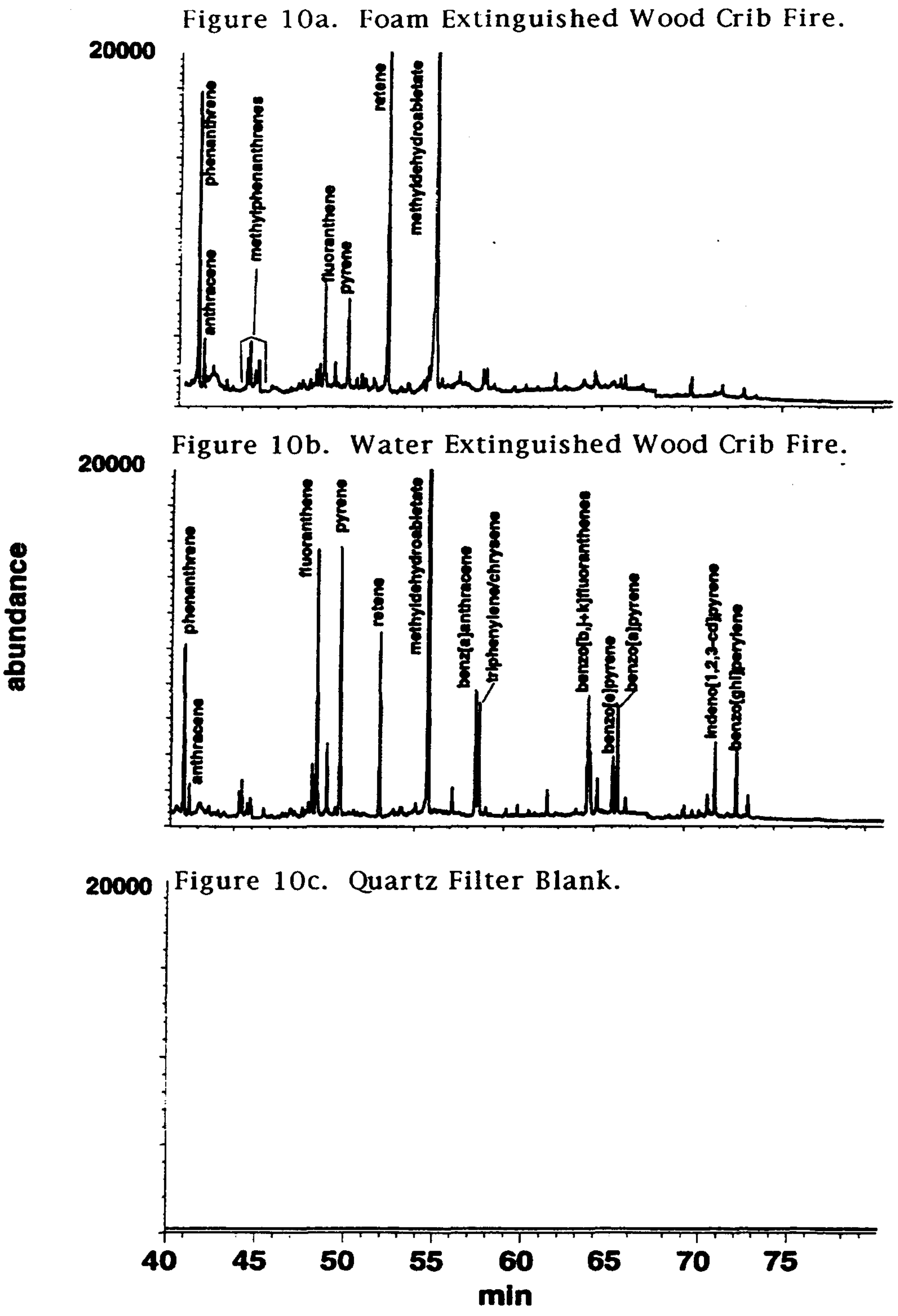


Figure 10a. Foam Extinguished Wood Crib Fire.

Figure 10b. Water Extinguished Wood Crib Fire.

Figure 10c. Quartz Filter Blank.

Figures 10a-c. Gas chromatograms for combustion smoke.

Figure 11a. Before Extinguishment with Agent Solution.

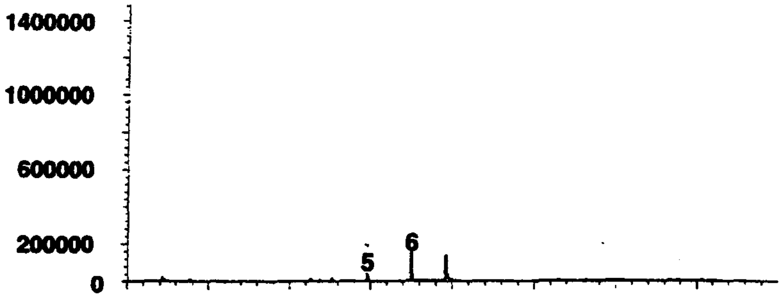


Figure 11b. After Extinguishment with Agent Solution.

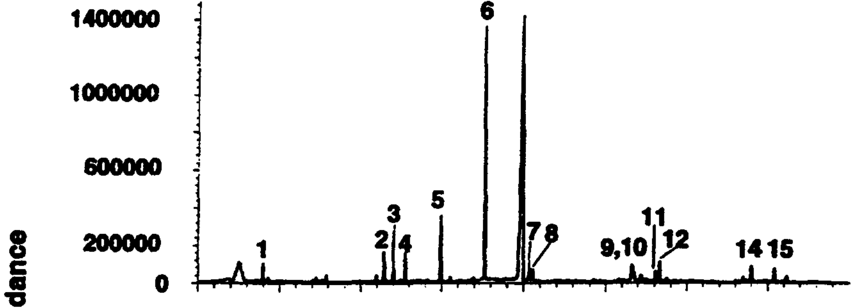


Figure 11c. Before Extinguishment with Agent Solution.

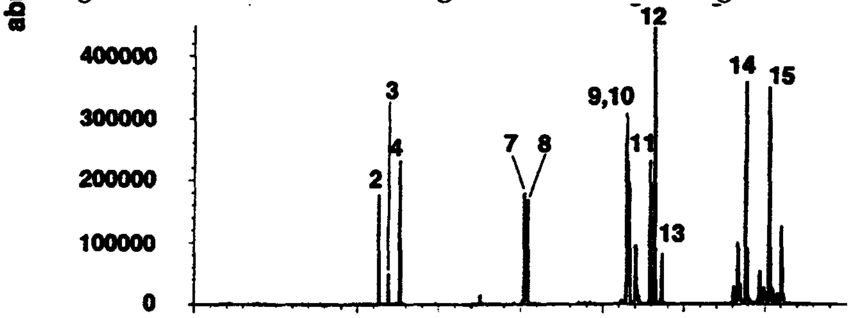
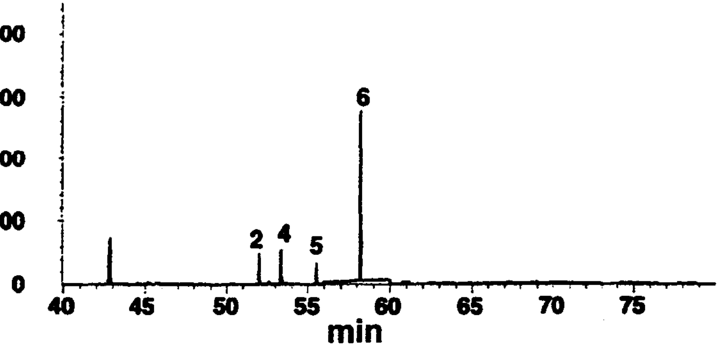


Figure 11d. After Extinguishment with Agent Solution.



Figures 11 a-d. Gas chromatograms for combustion smoke (each represents a different smoke sample).

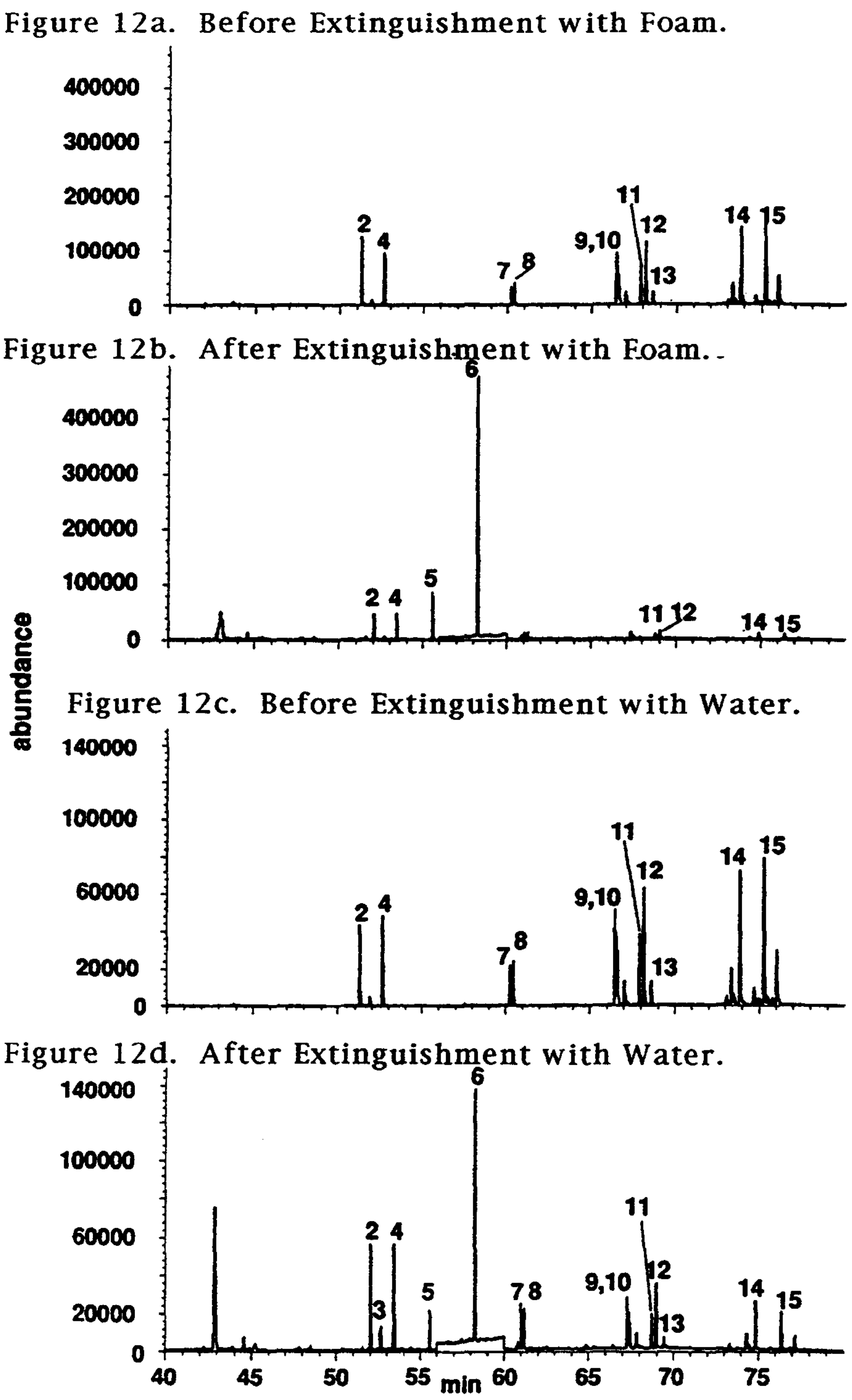


Figure 12a. Before Extinguishment with Foam.

Figure 12b. After Extinguishment with Foam.

Figure 12c. Before Extinguishment with Water.

Figure 12d. After Extinguishment with Water.

Figures 12 a-d. Gas chromatograms for combustion smoke (each represents a different smoke sample).

Figure 13a. Before Extinguishment with Foam.

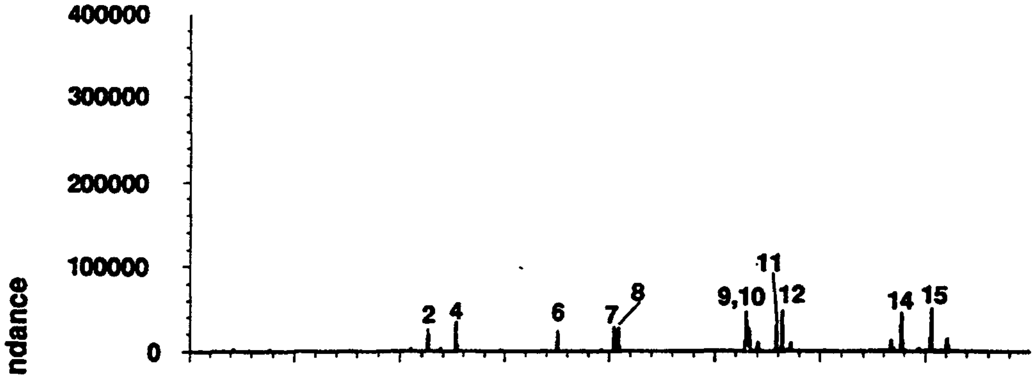
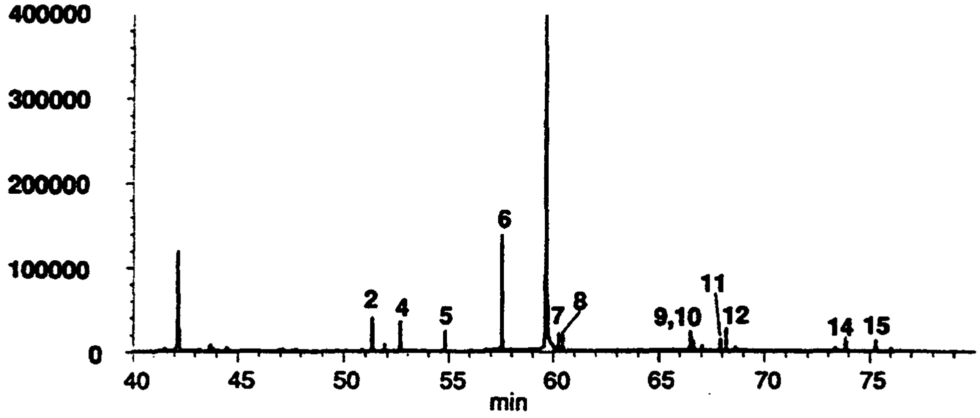


Figure 13b. After Extinguishment with Foam.



Figures 13 a-b. Gas chromatograms for combustion smoke (each represents a different smoke sample).

| Peak No.[1] | Identification |
|---|---|
| 1. | phenanthrene |
| 2. | fluoranthene |
| 3. | acephenanthrylene |
| 4. | pyrene |
| 5. | retene |
| 6. | methyldehydroabietate |
| 7. | benz[a]anthracene |
| 8. | triphenylene/chrysene |
| 9. | benzo[b]fluoranthene |
| 10. | benzo[j] and benzo[k]fluoranthene |
| 11. | benzo[e]pyrene |
| 12. | benzo[a]pyrene |
| 13. | perylene |
| 14. | indeno[1,2,3-cd]pyrene |
| 15. | benzo[ghi]perylene |

Figure 13c. Key to polycyclic aromatic hydrocarbons identified in figures 10 –13.

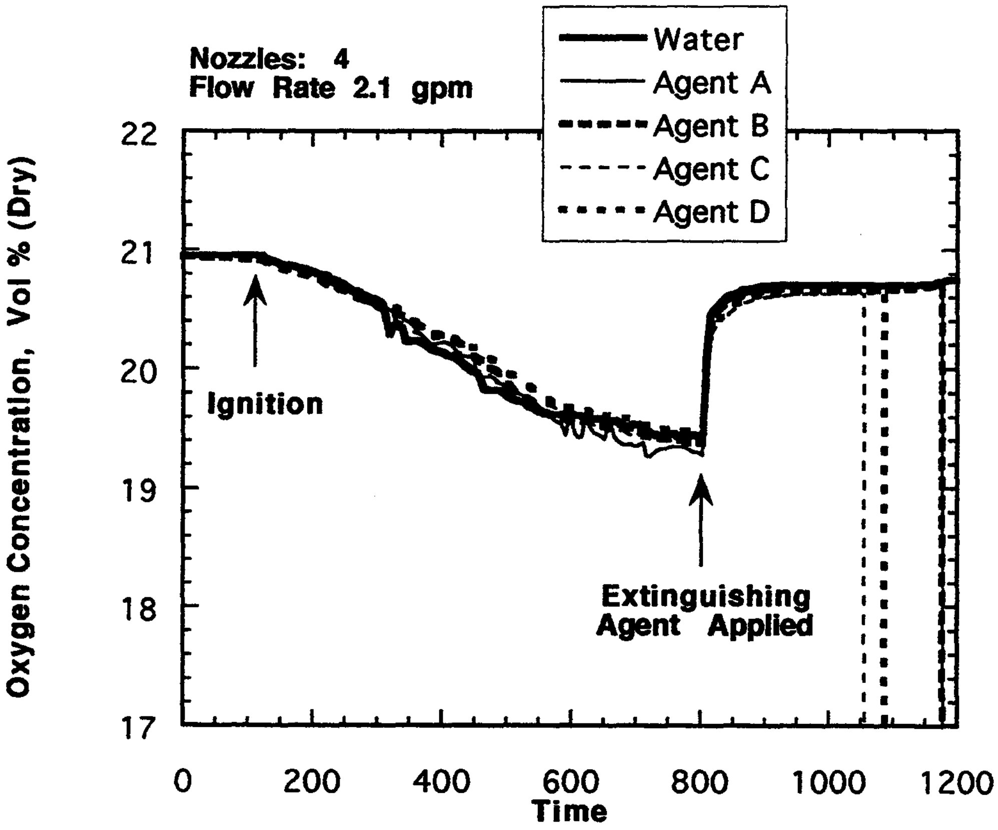


Figure 14. Oxygen concentration time history with four nozzles at 7.8 Lpm (2.1 gpm).

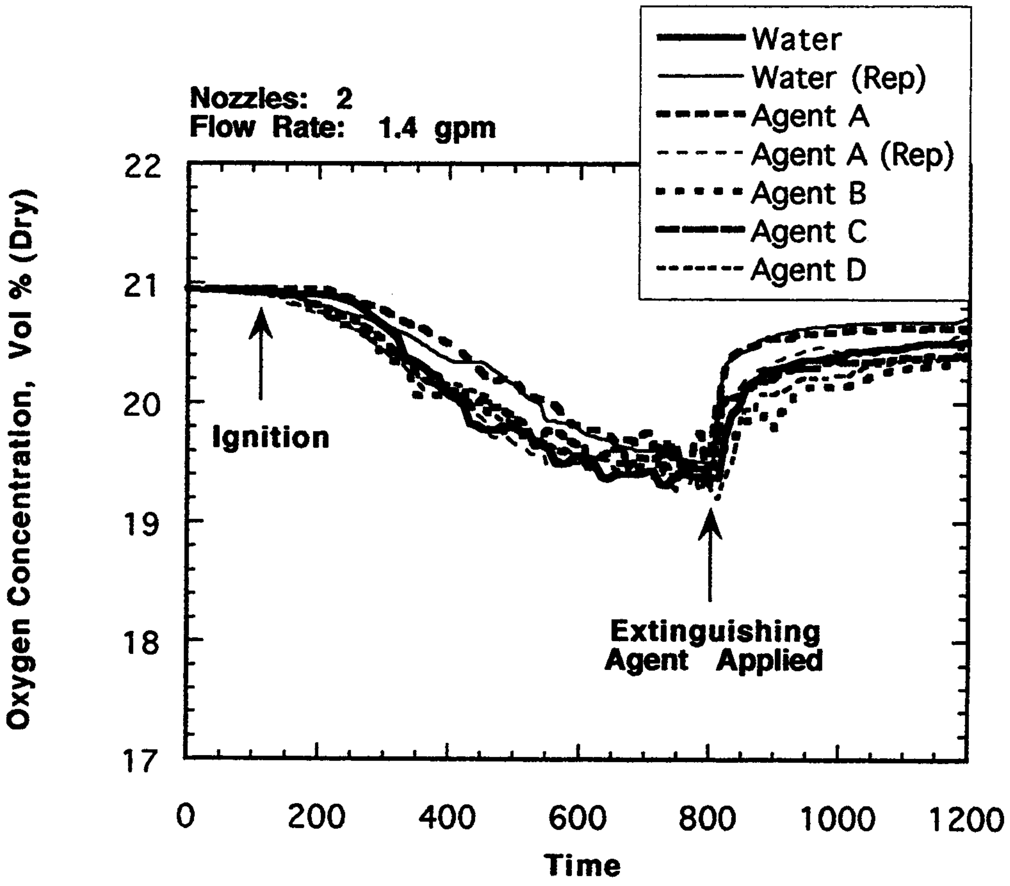


Figure 15. Oxygen concentration time history with two nozzles at 5.4 Lpm (1.4 gpm).

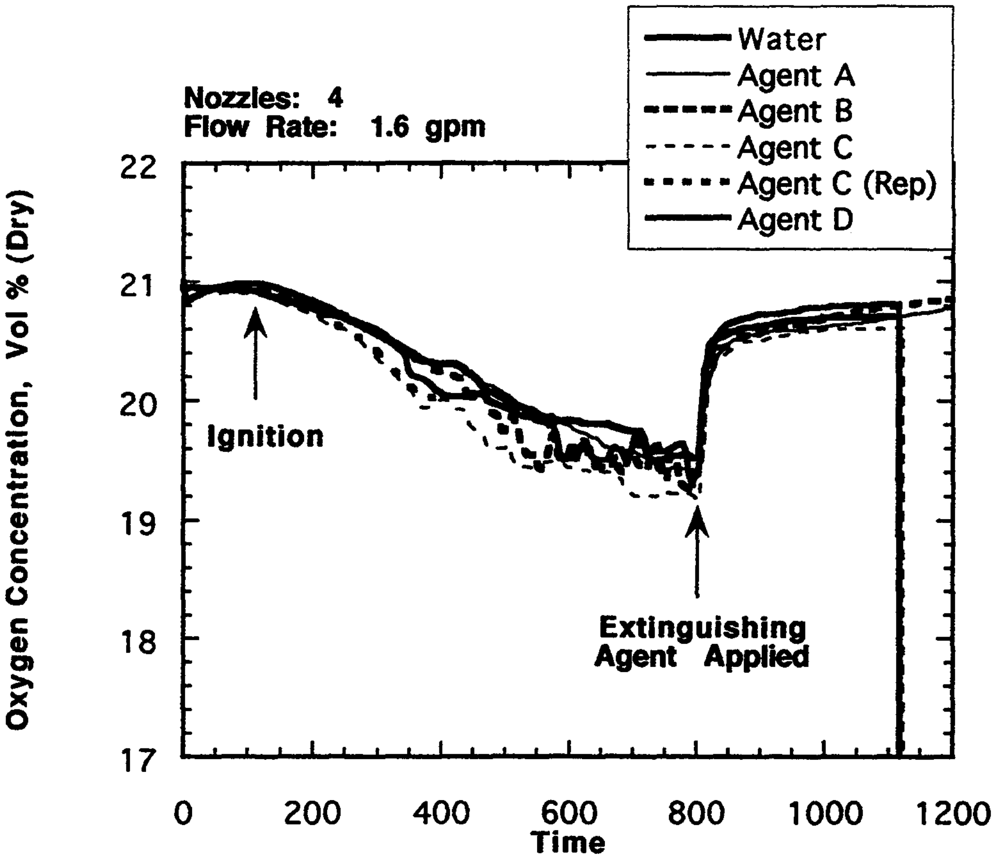


Figure 16. Oxygen concentration time history with four nozzles at 6 Lpm (1.6 gpm).

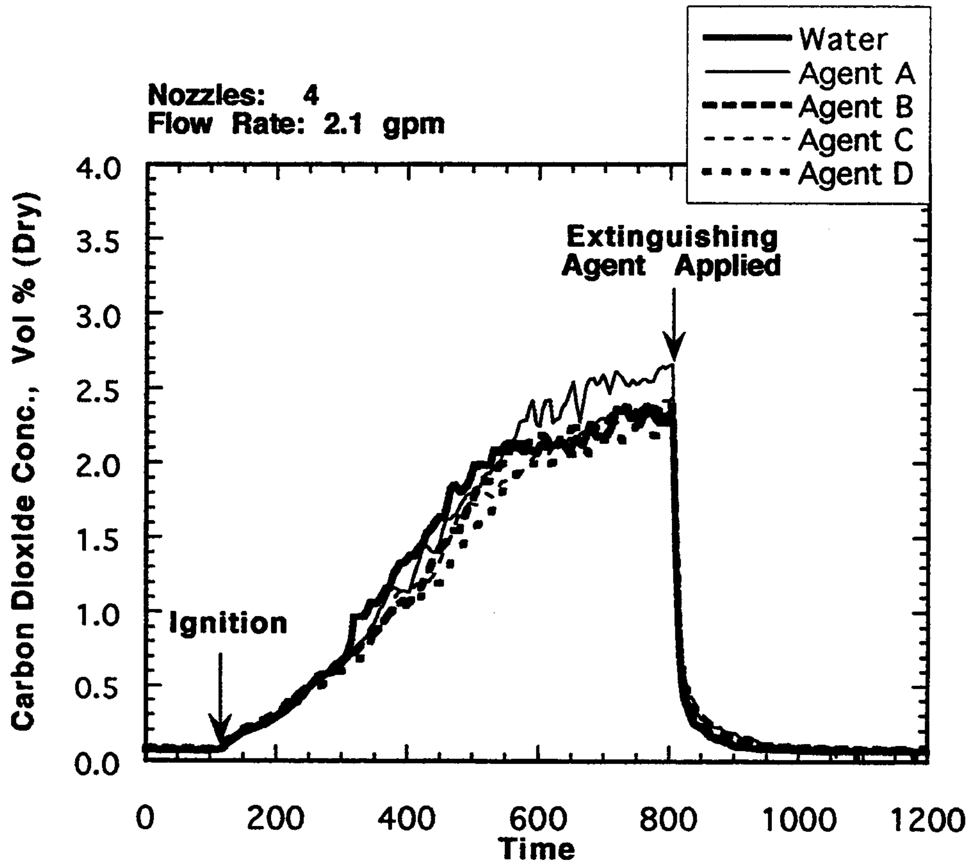


Figure 17. Carbon dioxide concentration time history with four nozzles at 7.8 Lpm (2.1 gpm).

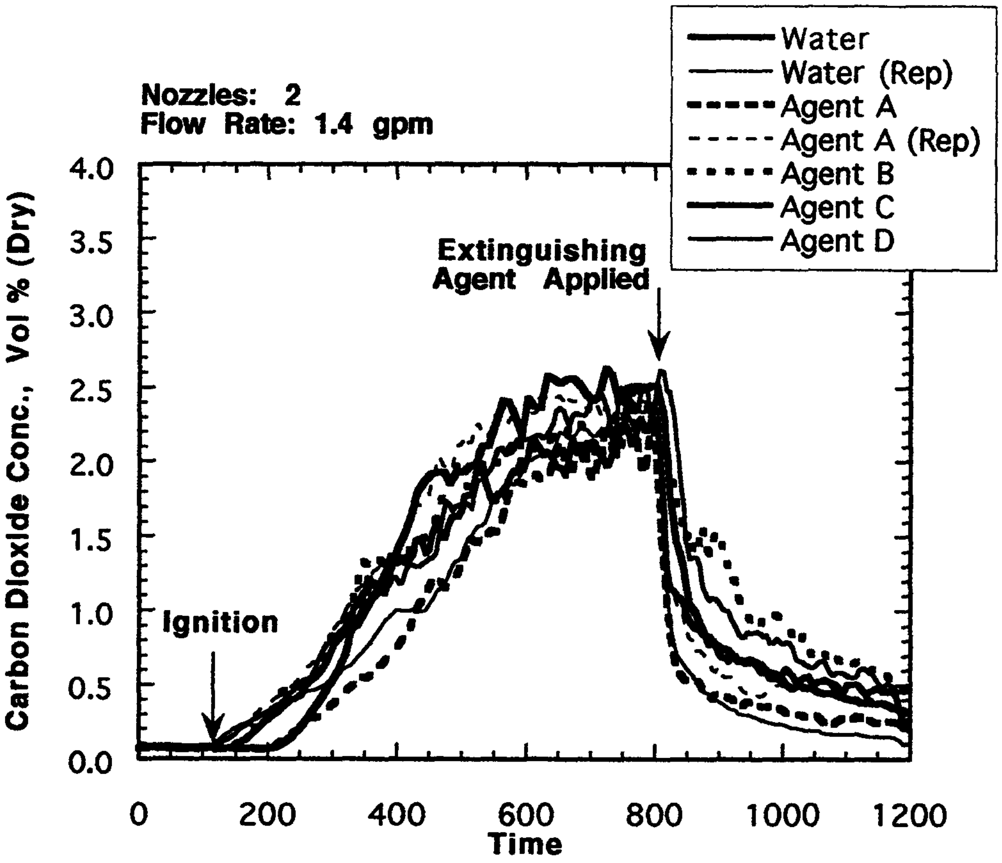


Figure 18. Carbon dioxide concentration time history with two nozzles at 5.4 Lpm (1.4 gpm).

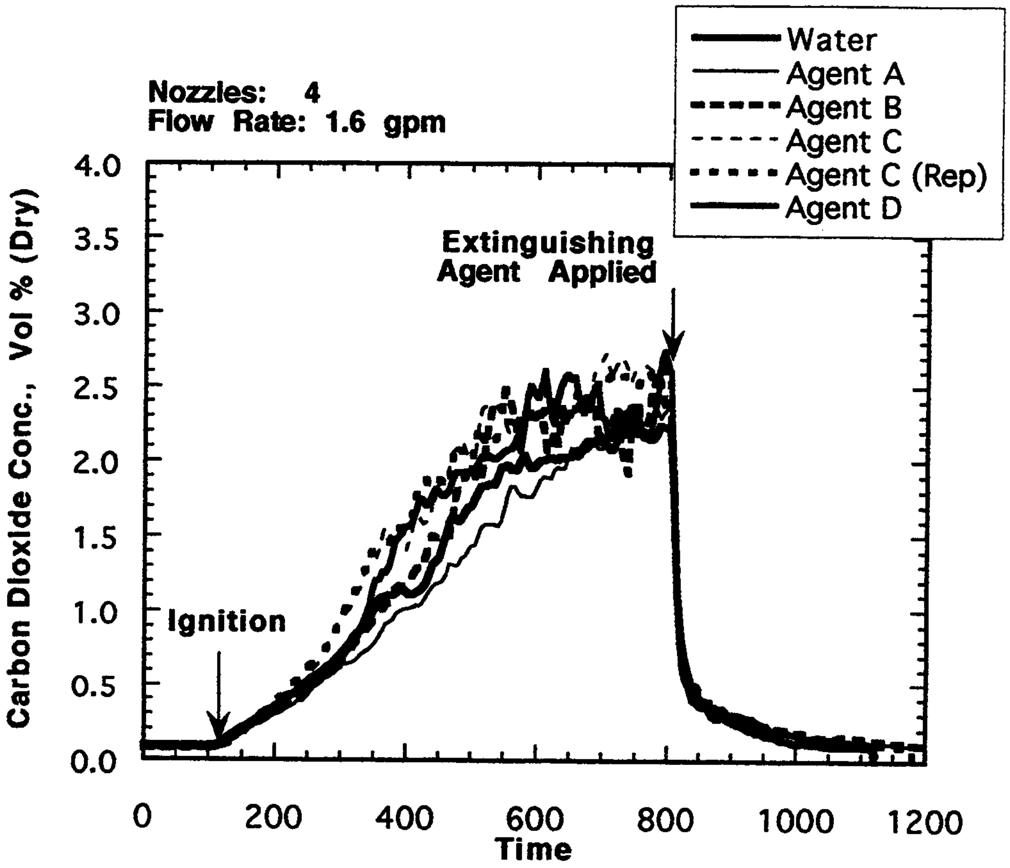


Figure 19. Carbon dioxide concentration time history with four nozzles at 6 Lpm (1.6 gpm).

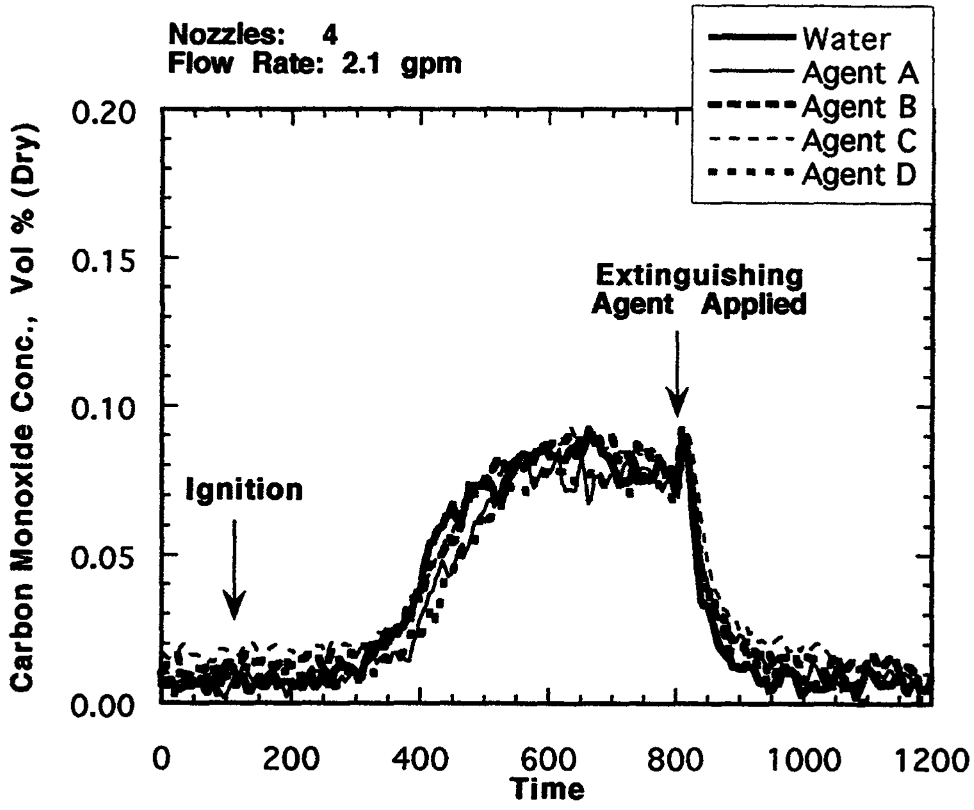


Figure 20. Carbon monoxide concentration time history with four nozzles at 7.8 Lpm (2.1 gpm).

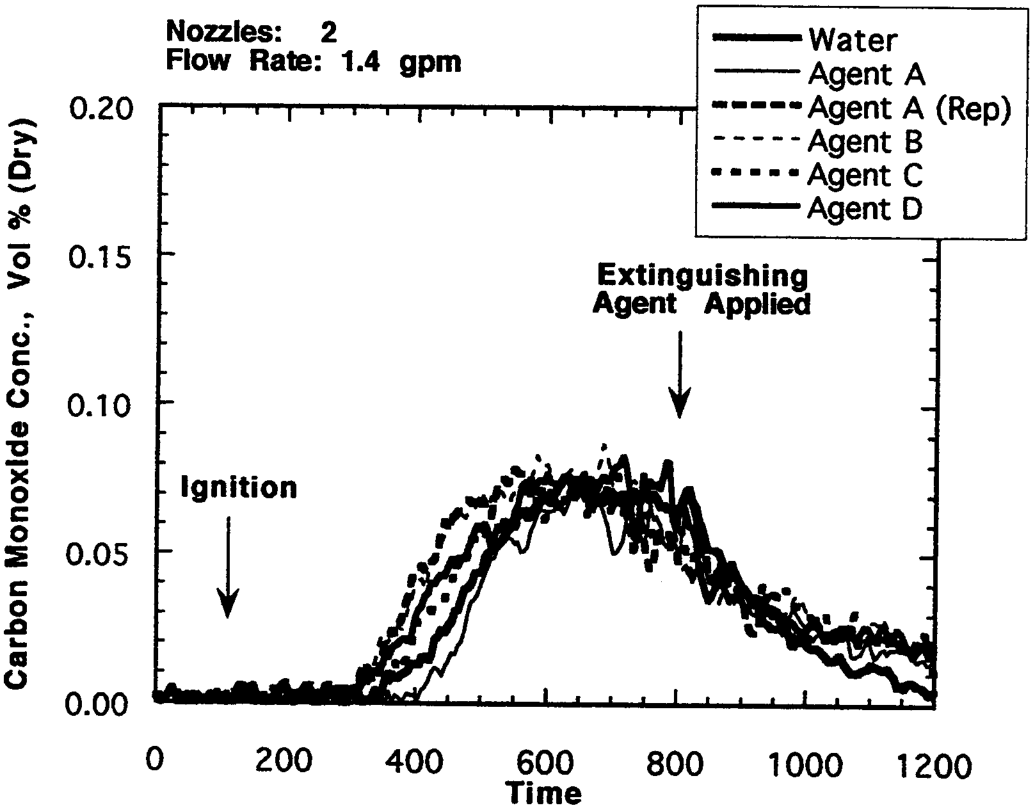


Figure 21. Carbon monoxide concentration time history with two nozzles at 5.4 Lpm (1.4 gpm).

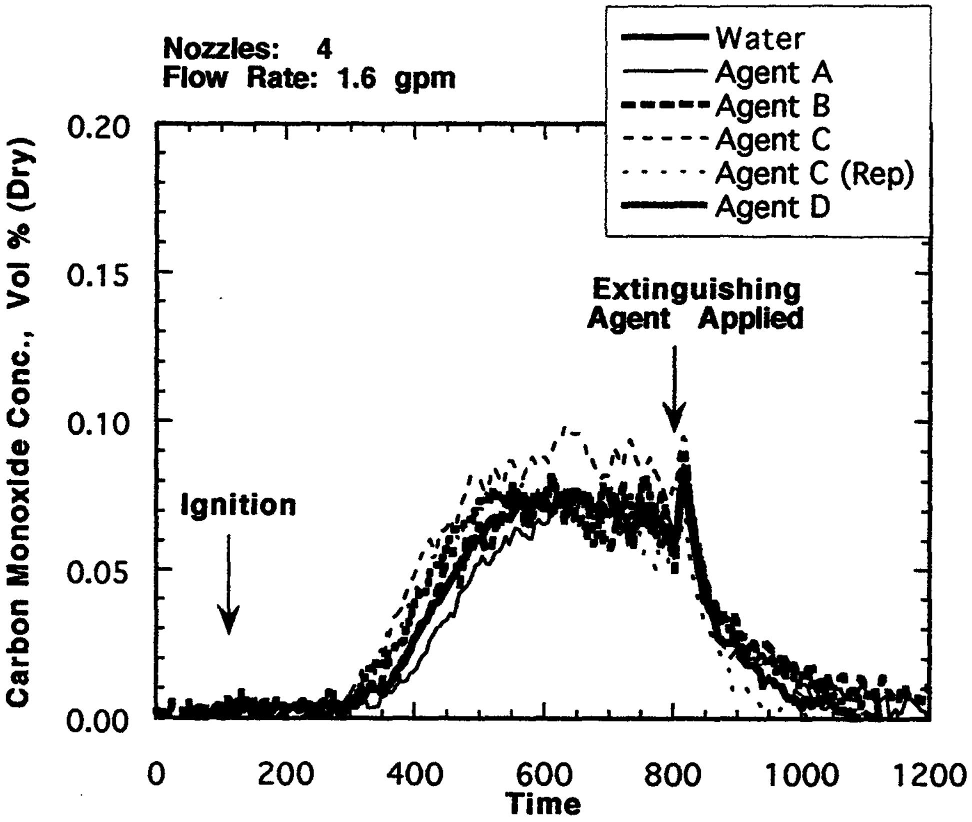


Figure 22. Carbon monoxide concentration time history with four nozzles at 6 Lpm (1.6 gpm).

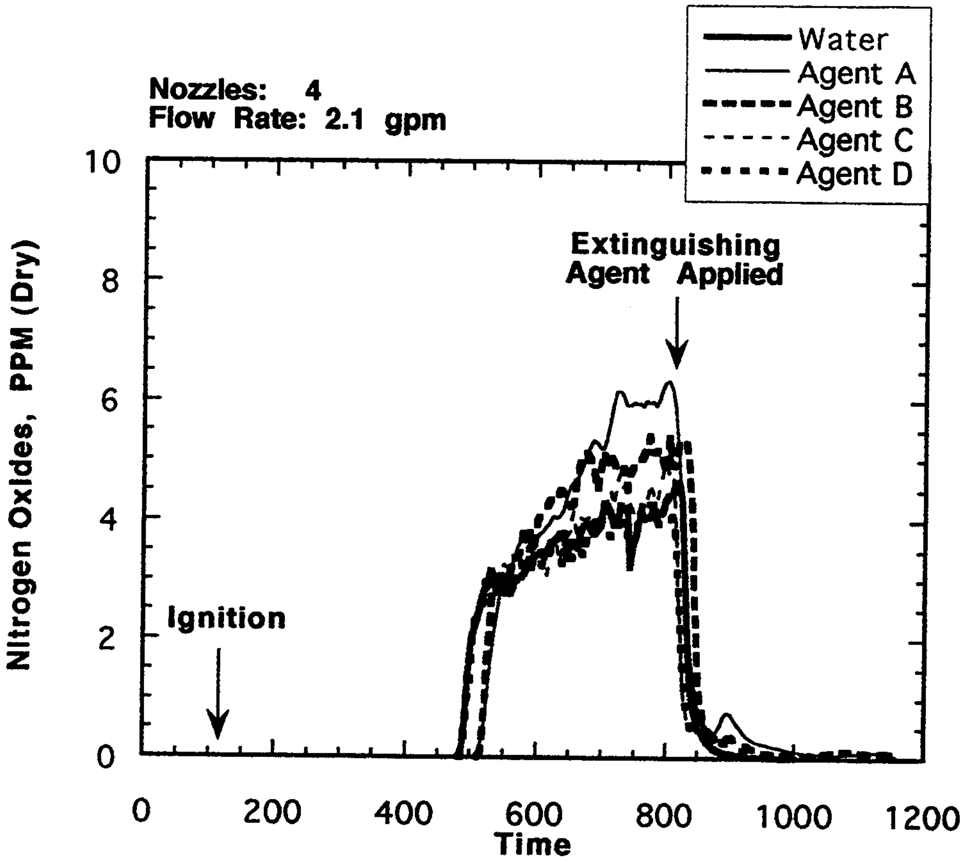


Figure 23. Nitrogen oxides concentration time history with four nozzles at 7.8 Lpm (2.1 gpm).

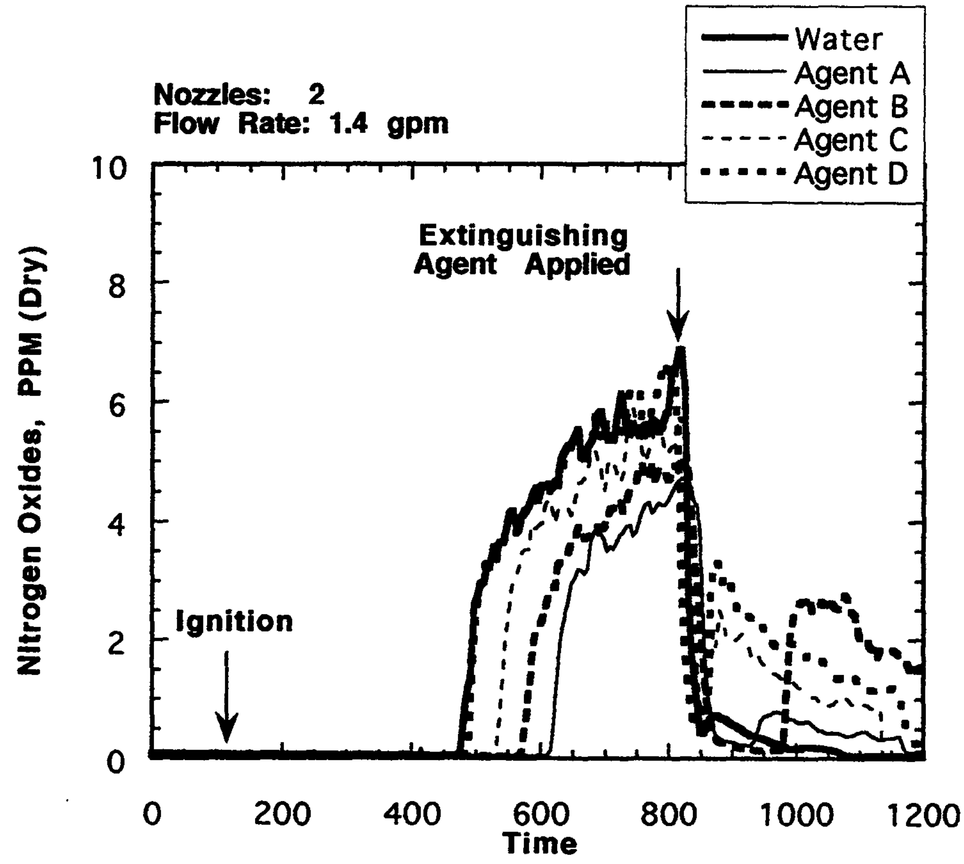


Figure 24. Nitrogen oxides concentration time history with two nozzles at 5.4 Lpm (1.4 gpm).

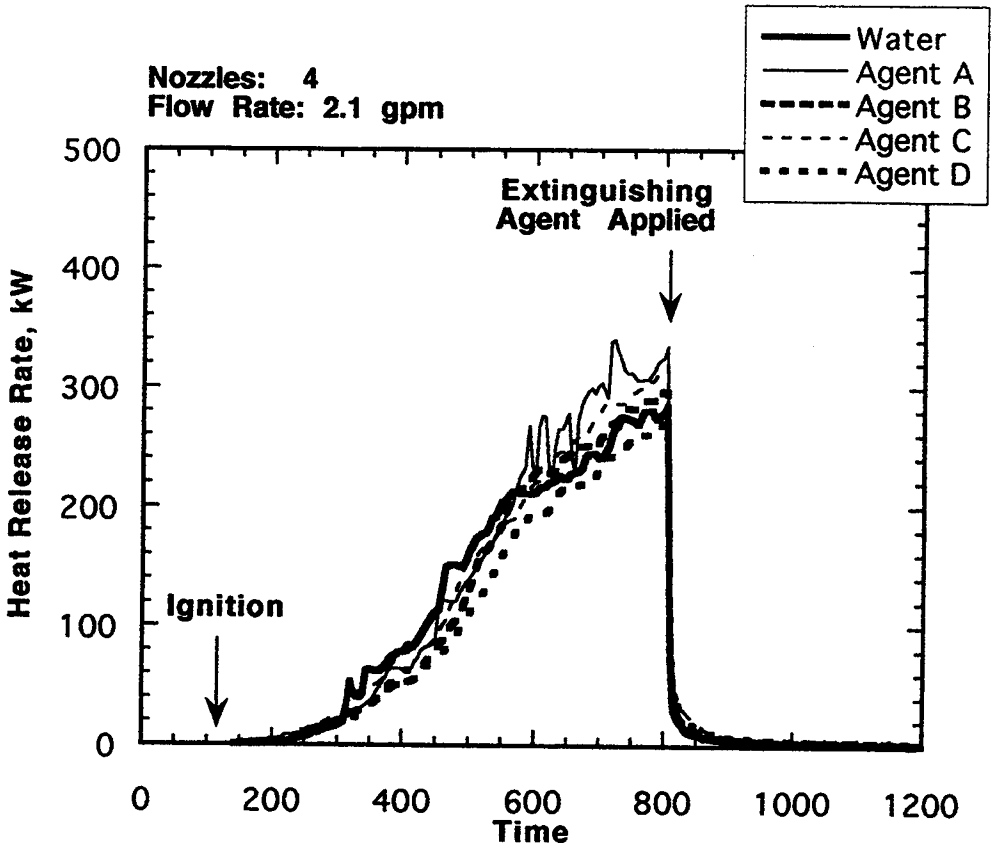


Figure 25. Heat release rate with four nozzles at 7.8 Lpm (2.1 gpm).

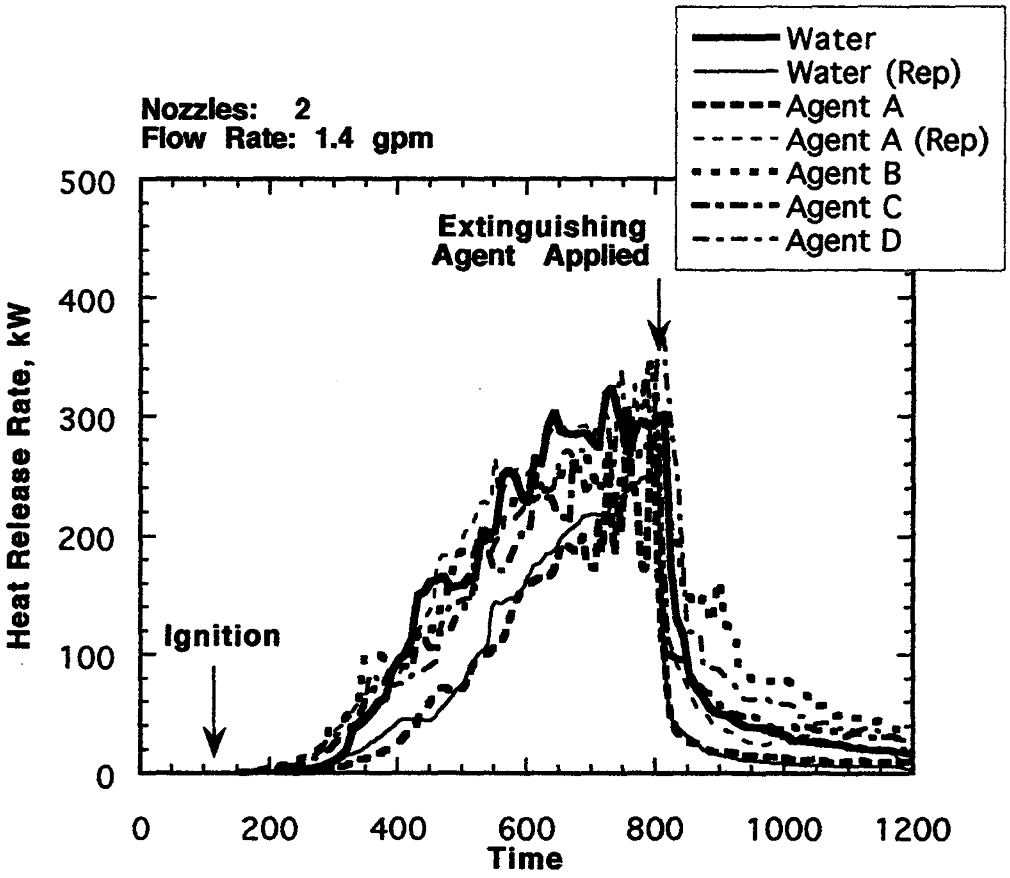


Figure 26. Heat release rate with two nozzles at 5.4 Lpm (1.4 gpm).

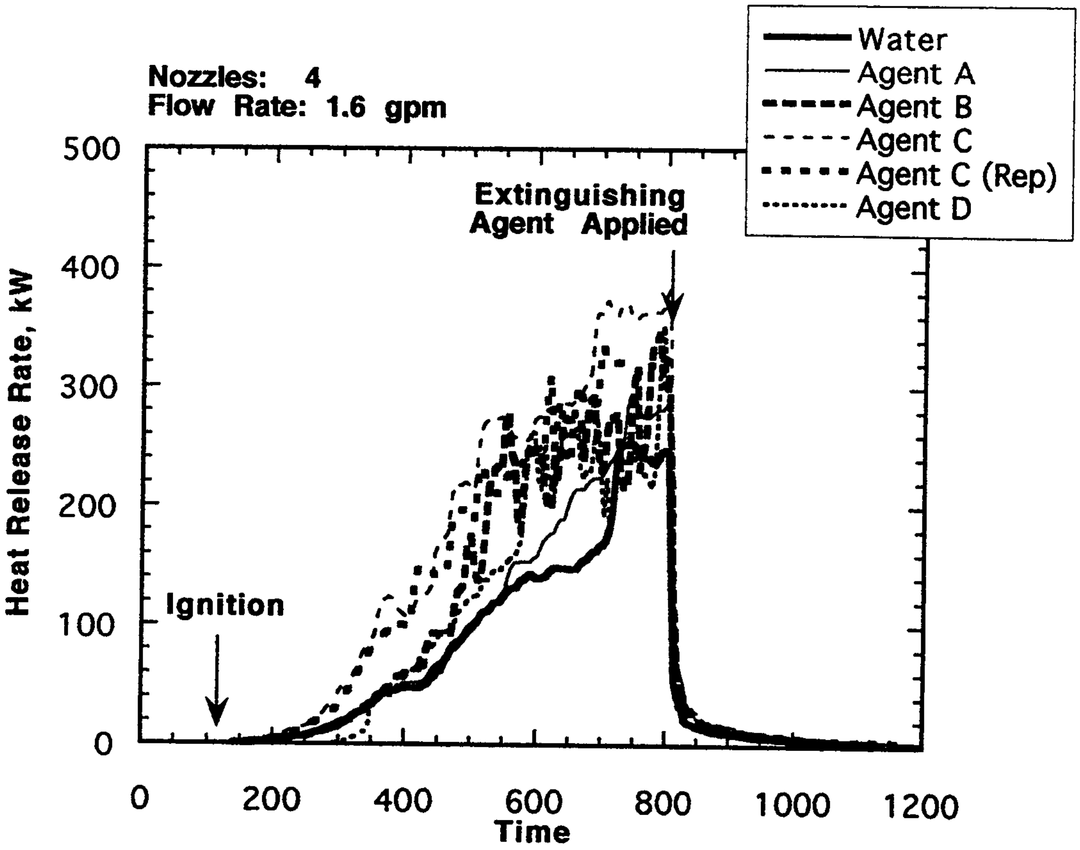


Figure 27. Heat release rate with four nozzles at 6 Lpm (1.6 gpm).

# CHAPTER 5

# CLASS A FIRE SUPPRESSION EXPERIMENTS

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# CLASS A FIRE SUPPRESSION EXPERIMENTS

## 5.1 Wood Crib Fire Suppression Experiments

This section reports on two studies conducted at NIST on the suppression of wood crib fires and tire fires. An overview of previous research on the use of water based fire suppression agents on wood cribs and tires is provided. A burning pile of rubble or a burning pile of tires, these are examples of fuel limited fires. If a fire has an adequate supply of oxygen, the size of the fire is limited by the fuel. The primary means of suppressing a fuel limited, deep seated fire is cooling.

### 5.1.1 Background

Wood cribs are a widely used fuel source for fuel limited fire suppression experiments. Underwriters' Laboratories (UL) has utilized wood cribs as a standard fire for rating fire extinguisher tests for many years [1]. Research conducted by Tamanini indicates that rapid knockdown can be obtained with flows greater than 0.0065 kg/s/m$^2$ [2].

In 1993, the National Fire Protection Research Foundation (NFPRF) sponsored a study [3] to examine the fire suppression effectiveness of a Class A foaming agent. The type of crib used in that study was a Class 20-A, as defined in [1]. The crib is constructed of nominal 50 mm x 200 mm (2 in x 4 in) fir sticks. Each stick is 1.58 m (62.25 in) long. The crib has 10 layers each with 15 sticks evenly spaced. The cribs are ignited with 17 l (4.5 gal) of heptane in a 1.85 m$^2$ (20 ft$^2$) pan. In accordance with ANSI/UL 711, a crib of this design can be extinguished with a 125 lpm (33 gpm) straight stream of water within 60 seconds. For this test series, 57 lpm (15 gpm) flows of water and agent solution were used. Manual applications of the single agent used for the tests included a straight stream nozzle, an aspirated nozzle and compressed air foam. Three different agent solutions were used during the test series: 0.1%, 0.3%, 0.5%. Given the test design, if the agent was successful at completely extinguishing the fire it would have demonstrated twice the level of performance relative to water.

In all cases, the agent outperformed plain water by suppressing the flames within 60 seconds. Unfortunately, none of the agent applications completely extinguished the fire. In all cases the crib, reignited. Therefore this test series demonstrated an increased efficiency, less than a factor 2.

In 1994, under the sponsorship of the U.S. Army, UL conducted another series of crib tests to examine the fire suppression effectiveness of seven different Class A agents [4]. A straight stream, self aspirating nozzle was used with a 57 lpm (15 gpm) flow rate for all of the tests. The fuel load consisted of a 20 A crib, as in the previous test series. In 21 of the 24 agent tests, the agent outperformed water by knocking down the flames, but all reignited after agent application stopped. In 7 of the 21 tests, reignition occurred within 20 seconds or less. Similar to the previous UL tests, the agents demonstrated an increased efficiency less than a factor of two.

### 5.1.2 Experimental Procedure

A series of crib fire tests were conducted to examine the impact of the selected agents on heat release rate. Cribs for the test series were assembled from a combination of Southern pine lumber, acrylonitrile butadiene styrene (ABS) and polyvinyl chloride (PVC) sticks. Each crib consisted of 10 layers, with each layer containing seven 55.88 cm (1.8 ft) long sticks of 3.81 cm (1.5 in) x 3.81 cm (1.5 in) cross section and each successive layer laid crosswise to the previous layer (Figure 1). These cribs are similar in design to the cribs burned by Gross [5], Block [6], and Bryner et al [7]. Southern pine was selected to represent the framing lumber found in typical residential structures. The ABS sticks were selected to represent the asphaltic roofing, carpeting, and polyurethane furnishings while the PVC sticks were added to simulate the vinyl tile and PVC plumbing components from a house fire. All the cribs were assembled approximately one month before the first scheduled fire test. This allowed all the cribs to reach about the same moisture content before the first crib was burned. The moisture content of each crib ranged from 6 to 8% as measured using two different types of conductivity moisture meters. Each crib weighed between 29 and 34 kg (63.8 and 74.8 lb) of which approximately 3.2 kg (7 lb) was PVC and 2.6 kg (5.8 lb) was ABS.

An isometric view of the suppression apparatus is shown in Figure 2. As shown in the figure, nozzles were located adjacent to each of the four sides of the crib. Each nozzle was positioned approximately in the middle of the side and at a level equal to the height of the crib. The typical nozzle spray angle was between 20° and 30° for the pressures used in the test series. The nozzles were angled to provide a spray pattern covering about two-thirds of the top and three-fourths of the side facing the nozzle. Data regarding agent, number of nozzles, nozzle pressure, and total flow rate are shown in Table 1. Either two nozzles on opposite sides of the crib or four nozzles adjacent to each side were used for the tests.

### 5.1.3 Analysis

Heat release rate versus time for three configurations demonstrate the reproducibility of the crib fires (Figures 3 - 5). Peak heat release rates ranged from 300 to 400 kW. Total heat released from the cribs ranged from 90 to 120 MJ.

As shown by the sharp heat release rate decreases in Figures 3 and 5 after "Extinguishing Agent Applied", the four nozzle configurations using flow rates of 7.8 lpm (2.1 gpm) and 6 lpm (1.6 gpm) easily extinguished the crib fires. There was not any discernable difference between the agents or plain water. The two nozzle configuration with a flow rate of 5.4 lpm (1.4 gpm) did not extinguish the fire. Some variation in heat release rate is evident in Figure 4 after application of the extinguishing agents. From visual observations of the tests, incomplete extinguishment appeared to be due primarily to inability of the nozzles to reach all parts of the burning crib and not to any differences agent extinguishment capability.

### 5.1.4 Conclusions and Recommendations

The various agents used in this series of experiments did not significantly alter the performance of water in reducing the heat release rate from a wood crib fire. When the water or agent could reach the burning surface, the fire was readily extinguished. The heat release rate data does not provide any useful information for identifying any differences in the extinguishing capabilities. More research work would be required to develop these experiments into an appropriate test procedure.

## 5.2 Tire Fire Suppression Experiments

In the United States, more than 240 million tires are discarded each year. The national inventory of scrap tires is estimated at 3 to 4 billion [8]. Piles of burning tires are extremely difficult to extinguish. The tires shed water, the shape of the tire provides shielded areas for burning, the synthetic rubber in tires can have an auto ignition temperature as low as 200 °C [9] and tires contain steel which is heated and then is insulated by the synthetic rubber. Therefore cooling and extinguishing a pile of burning tires can be difficult.

The difficulty of fighting a tire fire has been demonstrated in the field many times. A fire in Winchester, VA consumed between 6 and 9 million tires and burned for 9 months [8]. Three million tires burned outside of Hudson, CO in 1987 [10]. In Hagersville, Ontario a fire consumed several million tires during a seventeen day period [11].

In 1990, tests were conducted at Lawrence Livermore National Laboratory to evaluate the effectiveness of liquid fire suppression agents on stacks of burning tires [12]. Twelve tires were stacked three to a layer and allowed to become fully involved in the fire. Agents were discharged from a fixed spray nozzle at 57 lpm (15 gpm). Applications were made for 1 minute and stopped. If the tires were still burning, a two minute period was allowed for fire redevelopment and another 1 minute application was made. This sequence was repeated for a third application if necessary. Plain water could not extinguish the fire. Eleven agents were tested, four of the agents including a "wetting agent" and an AFFF performed similar to water. Seven of the agents were able to suppress the fire, therefore demonstrating an effectiveness greater than water. Three of the agents used in the study, are on the 1995 U.S. Forest Service QPL [13]. These Class A agents did extinguish the fire after three applications. No replicate tests were conducted.

Another series of tire fire suppression experiments were conducted in England in 1991 [9]. The fire scenario consisted of dual mounted tires, positioned and shielded as if they were mounted on a tractor-trailer. A wide variety of water-based agents were used in the tests: flouroprotein -3%, film-forming fluoroprotein-3%, alcohol resistant film-forming flouroprotein-3%; aqueous film-forming foam-3%, alcohol resistant film-forming foam-3%, a synthetic-3%, a wetting agent-1%, and two other products identified by their trademark only. The results showed that the fire could be put out with water at approximately 50 lpm (13 gpm) in 20 seconds or less, if the firefighter was in close proximity to the fire. If the firefighter's access was limited due to safety concerns, the attack would be made from a distance. For this test series a distance of 4.1 m (13.5 ft) was chosen. From that distance, firefighters using a narrow water spray (approximately 15°) and a flowrate of 100 lpm (26.5 gpm) had an average suppression time of 152 seconds. The average was taken from four tests with results ranging from 142 s to 163 s. Since the limited access case was more challenging the remainder of the tests fires were conducted with this scenario.

Of the agents tested, the synthetic foam, applied with an aspirating nozzle, had the shortest suppression time, extinguishing the fire in 48 s or approximately three times faster than water. The synthetic foam applied with a non-aspirating nozzle, had a time to suppression of 106 s. Three replicate tests were conducted with non-aspirated and aspirated AFFF. The average time to suppression for both types of application was 93 s. The results ranged from 72 to 111 s. The wetting agent had the longest suppression time, relative to the other agents, with a time of 146 seconds. This result is similar to the results from the tests using plain water.

### 5.2.1 Experimental Procedure

The objective of these experiments was to demonstrate the fire suppression effectiveness of liquid supression agents on tire fires relative to plain water. The matrix of agent and application combinations used in the tire suppression experiments is shown in Table 2. The National Institute of Standards and Technology prepared a test area at the University of Maryland, Maryland Fire and Rescue Institute, Western Regional Training Center near Cumberland, MD. The area had a sand bed over a plastic liner to prevent run-off of suppression agents and tire residue (Figure 6). Nine tires, arranged as three layers of three were stacked on an expanded metal deck for each test. The average mass of tires used in each test was 74.7 kg (165 lbs). The standard deviation of the mass of the tires was ±4.6 kg (10 lb) or 6%. The tires were ignited with a diesel fuel fire contained in a 0.5 m (20 in) diameter pan 0.18 m (7 in) deep (Figure 7). 750 ml (0.2 gal) of diesel was used for each experiment. Suppression was not started until the diesel fuel had burned itself out and the tire pile was fully involved with flames. This resulted in pre-burn times ranging from 255 s to 420 s. Photographs of the tire experiments during preburn and at the start of suppression are shown in Figures 8 and 9, respectively.

The agents were all batch mixed in separate containers, pumped with a diaphragm pump and delivered via a 25 mm (1 in) internal diameter, 15.2 m (50 ft) long hoseline. The spray nozzle was an commercially available, adjustible spray nozzle set to a narrow fog pattern of approximately 15° and a flow rate of 30 lpm (8 gpm) ±0.5 lpm (0.14 gpm) of plain water. The aspirating nozzle (AN) was a commerically available, "tube type" nozzle with an internal bore of 20 mm (0.8 in). For the compressed air foam (CAF) applications, a commercially available, residential scale, compressed air foam generator was used. A 25 mm (1 in) quarter turn, ball valve was served as the nozzle.

The agents were applied manually. The same firefighter was used for all of the experiments. A few trials were conducted to determine the best test procedure, flow rate and to acclimate the firefighter to the test procedure. Based on previous tire fire studies [9], suppression was attempted from a fixed position away from the tire pile. Suppression could not be achieved using this technique due to the amount of self-shielding provided by the shape of the tire and configuration of the tire pile. As a result, the method used for experiments allows the firefighter to have unrestricted access to the tire pile during suppression.

The flow rate used for the tire fire suppression experiments was 30 lpm (8 gpm) with a variance of less than 10 %. Depending on the agent and the application, the flow rates varied from lows of 28 lpm (7.4 gpm) to highs of 31.4 lpm (8.3 gpm). Before each experiment, the flow rate was measured. This procedure involved flowing the suppression system into a 113.5 l (30 gal) container for two minutes and determining the flow rate based on mass. If a foaming agent was used, then the expansion and drainage would also be checked at this time. The expansion and drainage were measured following the procedures given in NFPA 11, Standard for Low-Expansion Foam, Appendix C [14].

The experimental procedure is as follows, after the preburn the firefighter would open the nozzle to start the flow of firefighting agent as he approached the burning tire pile. The timer recording time to suppression starts as soon as the firefighter applies agent to the tires. The firefighter aggressively knocks down the fire and begins moving around the tire pile suppressing the shielded fires inside and under the tires. When no more fire is visible, suppression is stopped and the time to suppression recorded. The tire pile remained under observation to determine if a reignition of the tire pile would occur. The period of observation was 30 minutes or 1800 seconds.

### 5.2.2 Results and Discussion

A total of 31 suppression experiments were conducted. Five baseline water experiments were conducted. The average time to suppression was 286 seconds with an average reignition time of 365 seconds after suppression was stopped. The results from the water spray experiments are given in Table 3. Even though the experiments are designed to be reproducible, notice that the suppression times range from 125 to 390 seconds. This could be due to slight variations in the fuel configuration as the tires burn and melt or due to variations in the firefighter's attack. These results emphasize the importance of conducting multiple experiments for a given scenario.

The results for the tire fire experiments utilizing suppression agents other than water are provided in Tables 4, 5, and 6. The results are grouped by means of application: fog nozzle or spray, air aspirating nozzle, and compressed air foam. Given the limited number of experiments with each agent for each type of application, it is difficult to determine any relative difference between the agents.

Table 4 shows the results of eight suppression experiments, two with each agent, using the spray nozzle. The foam produced by the spray nozzle was extremely wet and runny. This is indicated by the very low expansion ratios and the very fast drain times. The suppression times are reasonably consistent with an average of 88.6 s within a range of values from 70 to 115 s. There do not appear to be any discernable correlations between time to suppression or application time and the time to reignition. Applying a two-sided normal test [15] to the time to suppression results from the water and the solution spray experiments demonstrates that the mean of the solution results are statistically significantly different (less) than the mean of the plain water spray results with 95% certainty. Based on the mean values, the tests have shown that for the given flow rate of 30 lpm (8 gpm), approximately one third the amount of solution produces the same results as water, with similar rekindle times.

Table 5 shows the results of eight suppression experiments, two with each agent, using the air aspirated nozzle. The foam produced by the nozzle was still wet and runny. Again as indicated by the low expansion ratios and fast drain times. With the exception of one data point, the time to suppression results have an average of 91.6 seconds within a range very similar to the spray application experiments, 75 s to 111s. The one exception of 153 s increases the average to 99.3 s, as well as the upper limit of the range.

The compressed air foam application, fire suppression results are given in Table 6. The larger expansion ratios and the longer drain times are representative of a moderately wet foam. Four of the experiments, out a set of ten, yielded suppression times approximately 50% faster than the average for the spray and self aspirated nozzle applications. The remaining six were in a range similar to that of the previous applications. As a result the average time to suppression is only slightly lower. However, 5 of the 10 of the experiments did not reignite within the half hour observation period. More foam remained visible in and on the tires after the CAF applications than it did with the two previous applications. This may account for the increase in time to reignition.

Based on the average times between the application types and by reviewing a graph (Figure 10)of the times to suppression, it appears that for this type of fire and intimate firefighting approach, the application technique had minimal if any impact on the time to suppression. Averaging the results of all 26 experiments utilizing a foaming agent produces a mean of 87.1 s. This average time to suppression is 30% of the average time to suppression using water.

Comparing these results to the previous studies provides some insight into what properties may be important to increasing the effectiveness of liquid fire suppression agents. In the tests conducted by Johnson [9] and Hasegawa [12], the agents identified as "wetting agents" performed similar to water. The reports do not provide any details on the agents. One of the principle characteristics or advantages is the reduction of the surface tension of water to which the agent is added. This is the same advantage the synthetic-hydrocarbon based agents used in this study have. The synthetic agents in this study performed better than water, which is in agreement with the results of the two previous studies. Perhaps the detergents or emulsifiers in the synthetic agents enhance water over and above the advantage due to surface tension reduction by having a high affinity for carbon. This advantage would demonstrate itself best on a fuel such as tires which contain a high fraction of carbon.

## 5.3 References

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**Table 1. Summary of Agent Used, Nozzle Pressures, and Total Flow Rate for Test Series**

| Test No. | Agent | Pressure (kPa) | | | | Total Flow Rate (lpm) |
|---|---|---|---|---|---|---|
| | | Nozzle 1 | Nozzle 2 | Nozzle 3 | Nozzle 4 | |
| 1 | A – 1% | 248 | 248 | Not Used | Not Used | 4.8 |
| 2 | B – 1% | 265 | 265 | Not Used | Not Used | 5.4 |
| 3 | C – 3% | 290 | 276 | Not Used | Not Used | 5.4 |
| 4 | D – 3% | 321 | 321 | Not Used | Not Used | 5.4 |
| 5 | Water | 179 | 179 | 172 | 172 | 7.8 |
| 6 | A – 1% | 193 | 165 | 165 | 172 | 7.8 |
| 7 | B – 1% | 193 | 159 | 159 | 172 | 7.8 |
| 8 | C – 3% | 186 | 186 | 186 | 186 | 7.8 |
| 9 | D – 3% | 193 | 193 | 193 | 193 | 8.4 |
| 10 | Water | 221 | 221 | Not Used | Not Used | 4.8 |
| 11 | A – 1% | 103 | 103 | 103 | 103 | 6 |
| 12 | Water | 97 | 97 | 97 | 97 | 6 |
| 13 | B – 1% | 103 | 103 | 97 | 97 | 6 |
| 14 | C – 3% | 103 | 103 | 97 | 97 | 6 |
| 15 | D – 3% | 103 | 103 | 103 | 103 | 6 |
| 16 | C – 3% | 110 | 110 | 110 | 110 | 6 |
| 17 | A – 1% | 276 | 276 | Not Used | Not Used | 5.4 |

### Table 2. Test Matrix

| Suppression Agent | Application Method |
|---|---|
| Water | Spray Nozzle |
| Agent A 1% Solution | Spray Nozzle |
| Agent A 1% Solution | Aspirating Nozzle |
| Agent A 1% Solution | Compressed Air Foam |
| Agent B 1% Solution | Spray Nozzle |
| Agent B 1% Solution | Aspirating Nozzle |
| Agent B 1% Solution | Compressed Air Foam |
| Agent C 3% Solution | Spray Nozzle |
| Agent C 3% Solution | Aspirating Nozzle |
| Agent C 3% Solution | Compressed Air Foam |
| Agent D 3% Solution | Spray Nozzle |
| Agent D 3% Solution | Aspirating Nozzle |
| Agent D 3% Solution | Compressed Air Foam |

### Table 3. Tire Fire Suppression Results - Water Spray

| Flowrate (lpm (gpm)) | Time to Suppression (s) | Time to Reignition (s) |
|---|---|---|
| 31.0 (8.2) | 305 | 390 |
| 30.7 (8.1) | 235 | 280 |
| 29.9 (7.9) | 125 | 445 |
| 29.9 (7.9) | 390 | 300 |
| 29.9 (7.9) | 375 | 405 |
| Average Times | 286 | 364 |

### Table 4. Tire Fire Suppression Results – Solution Spray Application

| Agent | Flowrate (lpm (gpm)) | Expansion Ratio | 25% Drain Time (s) | 50% Drain Time (s) | Time to Suppression (s) | Time To Reignition (s) |
|---|---|---|---|---|---|---|
| A | 28.0 (7.4) | 1.5 | <60 | <60 | 72 | 125 |
| A | 28.0 (7.4) | 3.5 | <60 | <60 | 95 | 255 |
| B | 28.8 (7.6) | 1.6 | <60 | <60 | 70 | 230 |
| B | 28.8 (7.6) | 1.6 | <60 | <60 | 75 | 105 |
| C | 30.7 (8.1) | 1.6 | <60 | <60 | 87 | 138 |
| C | 30.7 (8.1) | 1.6 | <60 | <60 | 90 | 440 |
| D | 30.7 (8.1) | 1.5 | <60 | <60 | 115 | 560 |
| D | 30.7 (8.1) | 1.5 | <60 | <60 | 105 | 1175 |
| Average Times | | | | | 88.6 | 378.5 |

### Table 5. Tire Fire Suppression Results - Aspirated Nozzle Application

| Agent | Flowrate (lpm (gpm)) | Expansion Ratio | 25% Drain Time (s) | 50% Drain Time (s) | Time to Suppression (s) | Time To Reignition (s) |
|---|---|---|---|---|---|---|
| A | 31.1 (8.3) | 4.6 | <60 | 120 | 75 | 85 |
| A | 31.1 (8.3) | 4.6 | <60 | 124 | 110 | 70 |
| B | 31.1 (8.3) | 5.4 | <60 | 65 | 85 | 185 |
| B | 31.1 (8.3) | 5.4 | <60 | <60 | 111 | None |
| C | 29.9 (7.9) | 6.6 | <60 | 80 | 153 | None |
| C | 29.9 (7.9) | 5.5 | <60 | <60 | 80 | None |
| D | 29.5 (7.8) | 4.2 | <60 | <60 | 85 | 130 |
| D | 29.5 (7.8) | 4.4 | <60 | <60 | 95 | 175 |
| Average Times | | | | | 99.3 | 550 |

Note: Values of 1800 s were used in place of "None" for purposes of calculating the Time to Reignition average.

## Table 6. Tire Fire Suppression Results - Compressed Air Foam Application

| Agent | Flow Rate lpm (gpm) | Expansion Ratio | 25% Drain Time s | 50% Drain Time s | Time to Suppression s | Time To Reignition s |
|---|---|---|---|---|---|---|
| A | 30.7 (8.1) | 8.0 | 260 | 540 | 55 | None |
| A | 30.7 (8.1) | 8.0 | 275 | 570 | 53 | 97 |
| B | 30.7 (8.1) | 12.9 | 186 | 306 | 20 | 165 |
| B | 30.7 (8.1) | 12.1 | 126 | 214 | 93 | None |
| B | 30.3 (8.0) | 13.9 | 191 | 325 | 105 | None |
| C | 30.3 (8.0) | 10.9 | 161 | 254 | 45 | None |
| C | 30.7 (8.1) | 10.9 | 163 | 256 | 85 | 360 |
| C | 30.3 (8.0) | 8.3 | 236 | 346 | 87 | 810 |
| D | 30.3 (8.0) | 10.3 | 137 | 351 | 112 | 973 |
| D | 30.3 (8.0) | 11.4 | 110 | 198 | 80 | None |
| Average Times | | | | | 73.5 | 1140.5 |

Note: Values of 1800 s were used in place of "None" for purposes of calculating the Time to Reignition average.

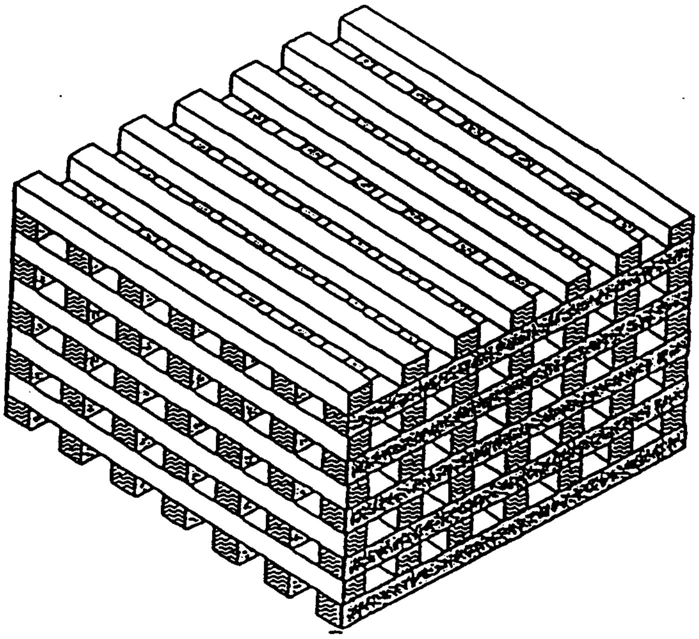

Figure 1. Diagram of crib (55.9cm X 55.9cm X 38cm high) used for suppression experiments

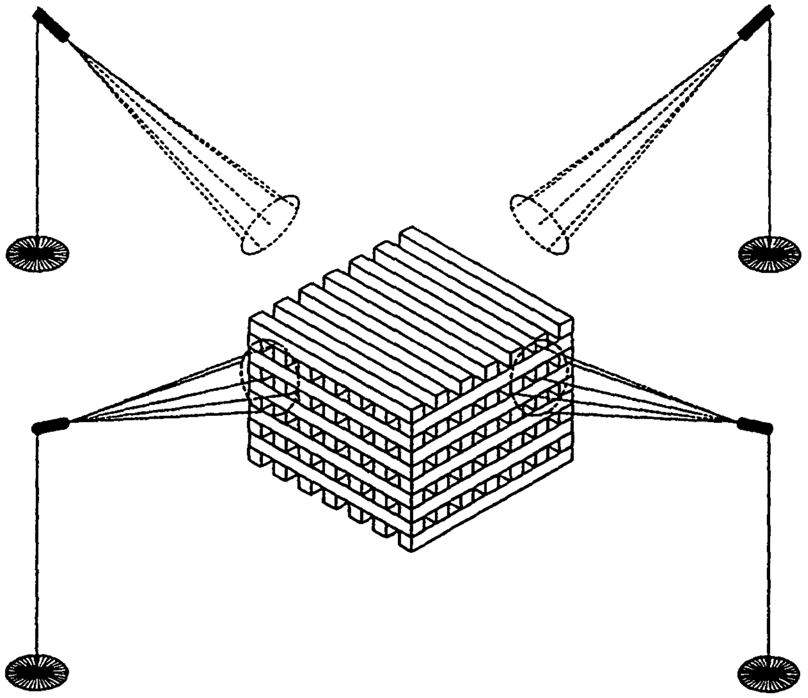

Figure 2. An Isometric view of the suppression apparatus

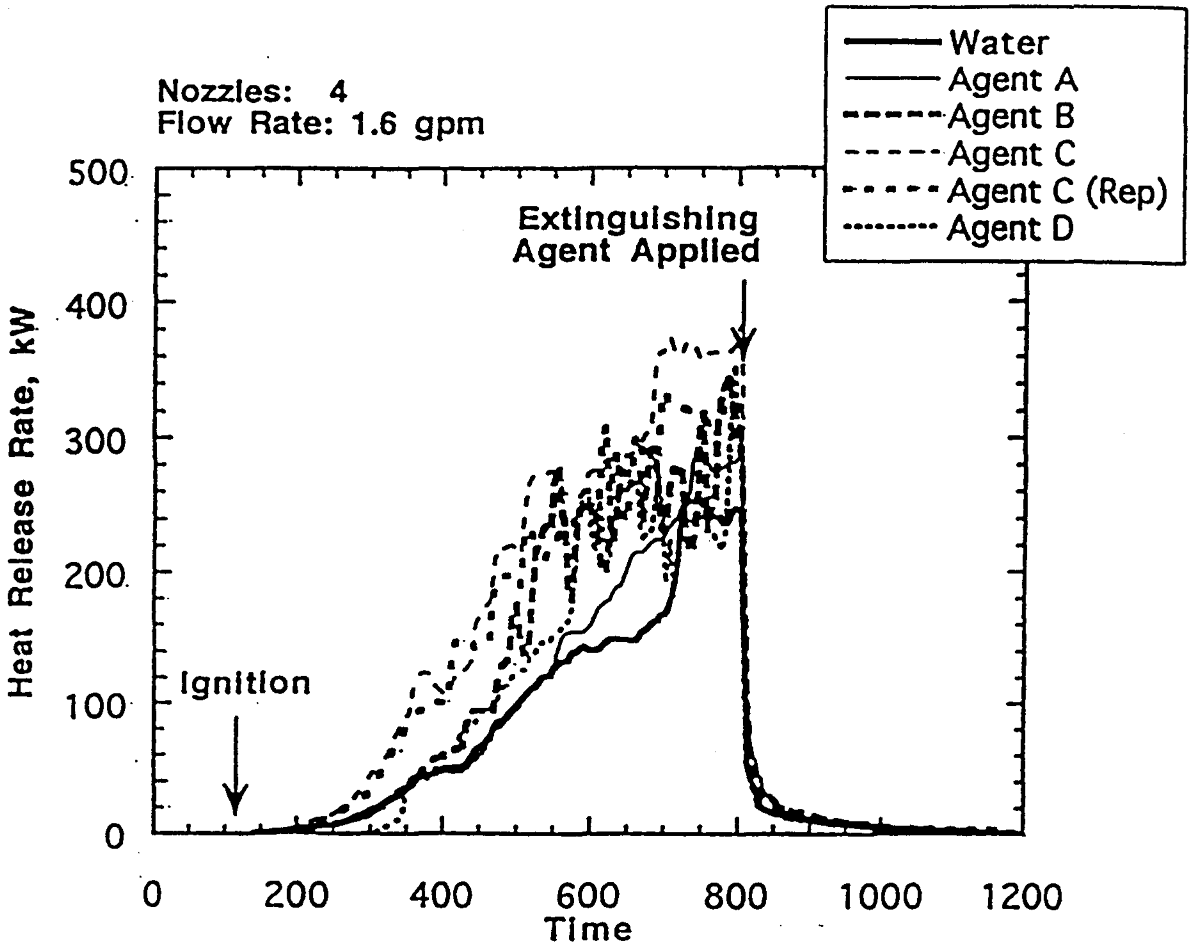

Figure 3. Heat release rate with four nozzles at 6 L/min (1.6 gpm)

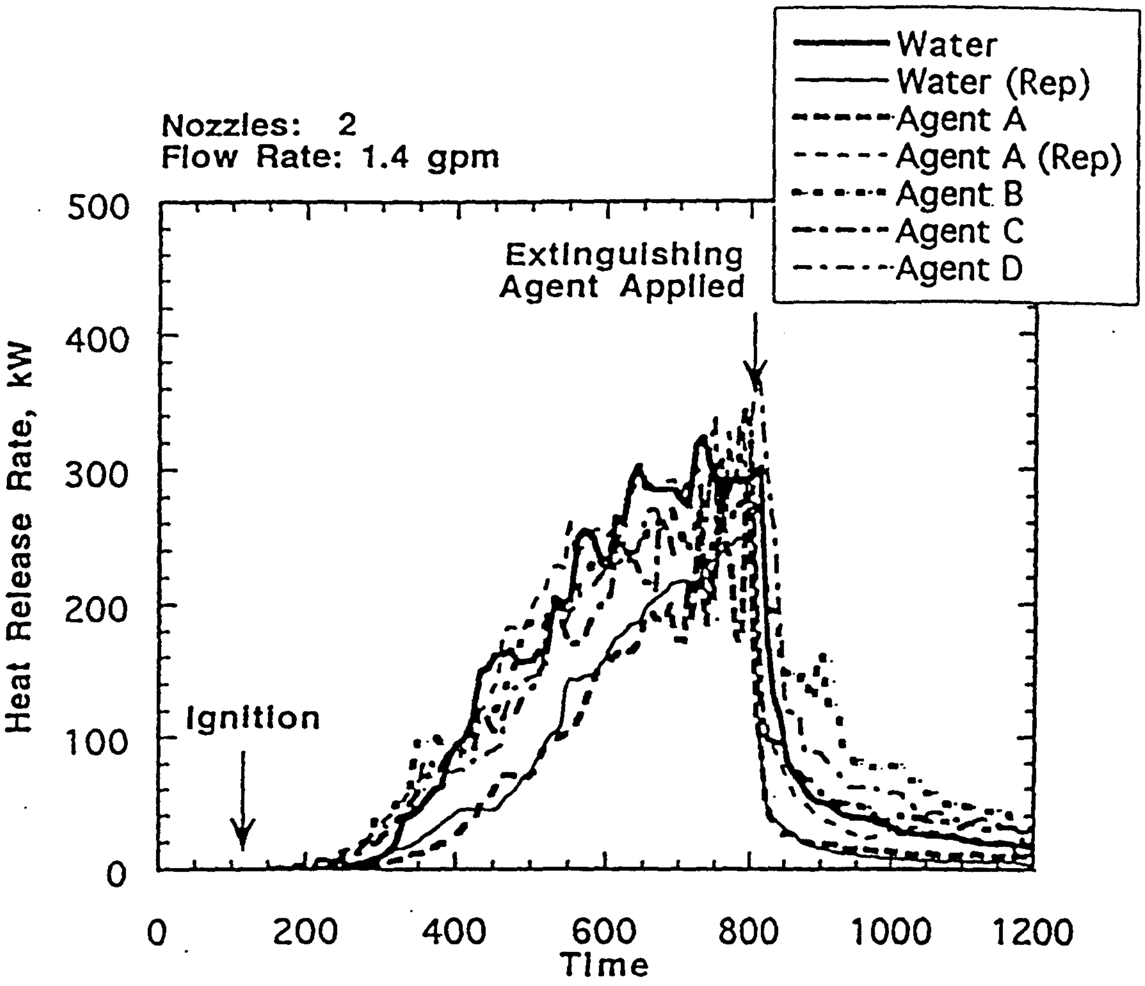

Figure 4. Heat release rate with 2 nozzles at 5.4 L/min (1.4 gpm)

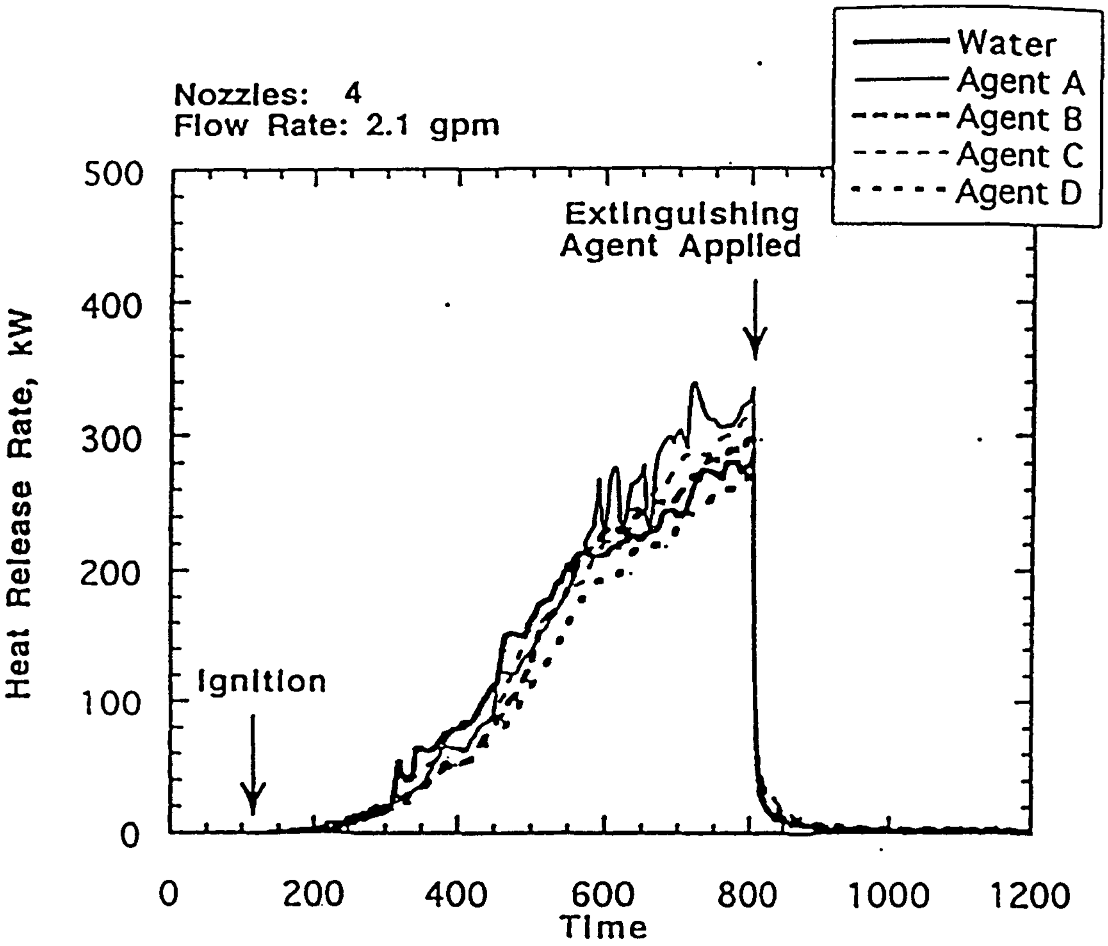

Figure 5. Heat release rate with four nozzles at 7.8 L/min (2.1 gpm)

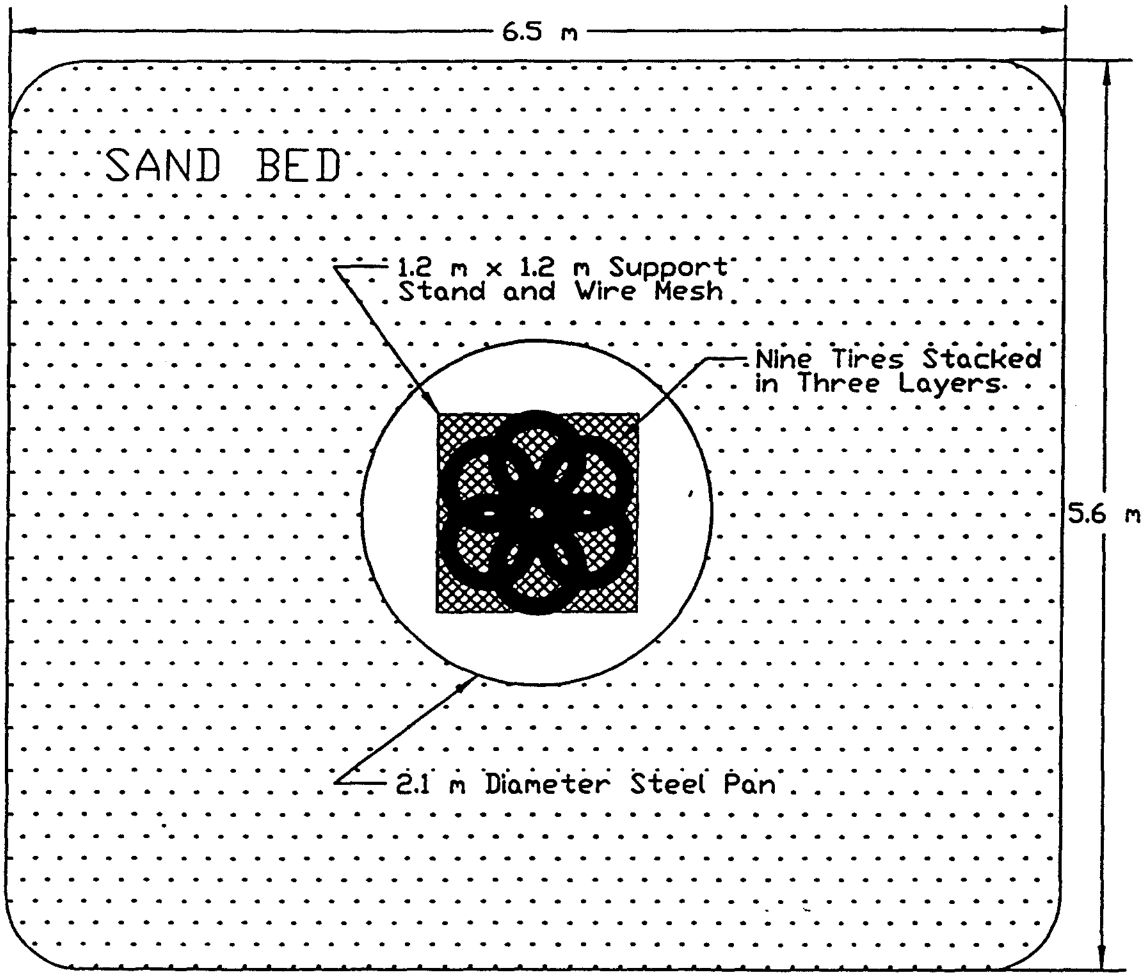

Figure 6. Plan view of tire fire suppression arrangment

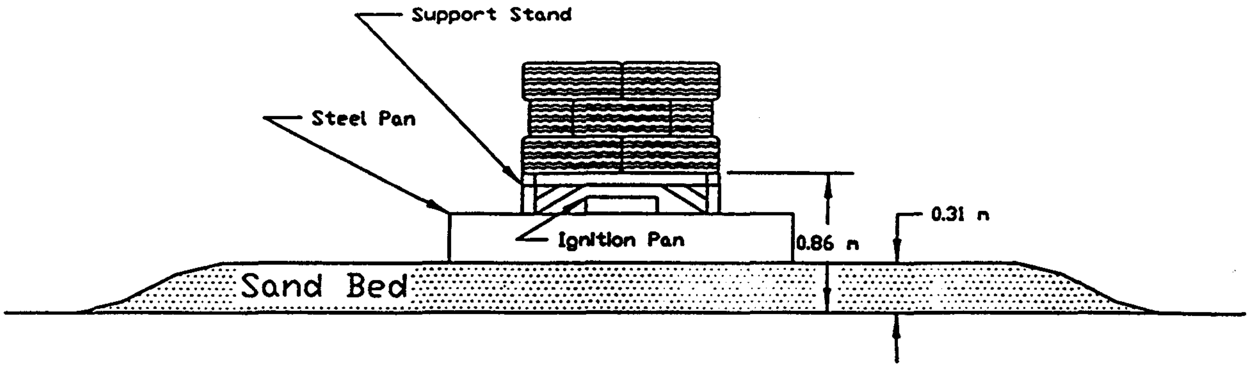

Figure 7. Elevation view of tire fire suppression experiment arrangment

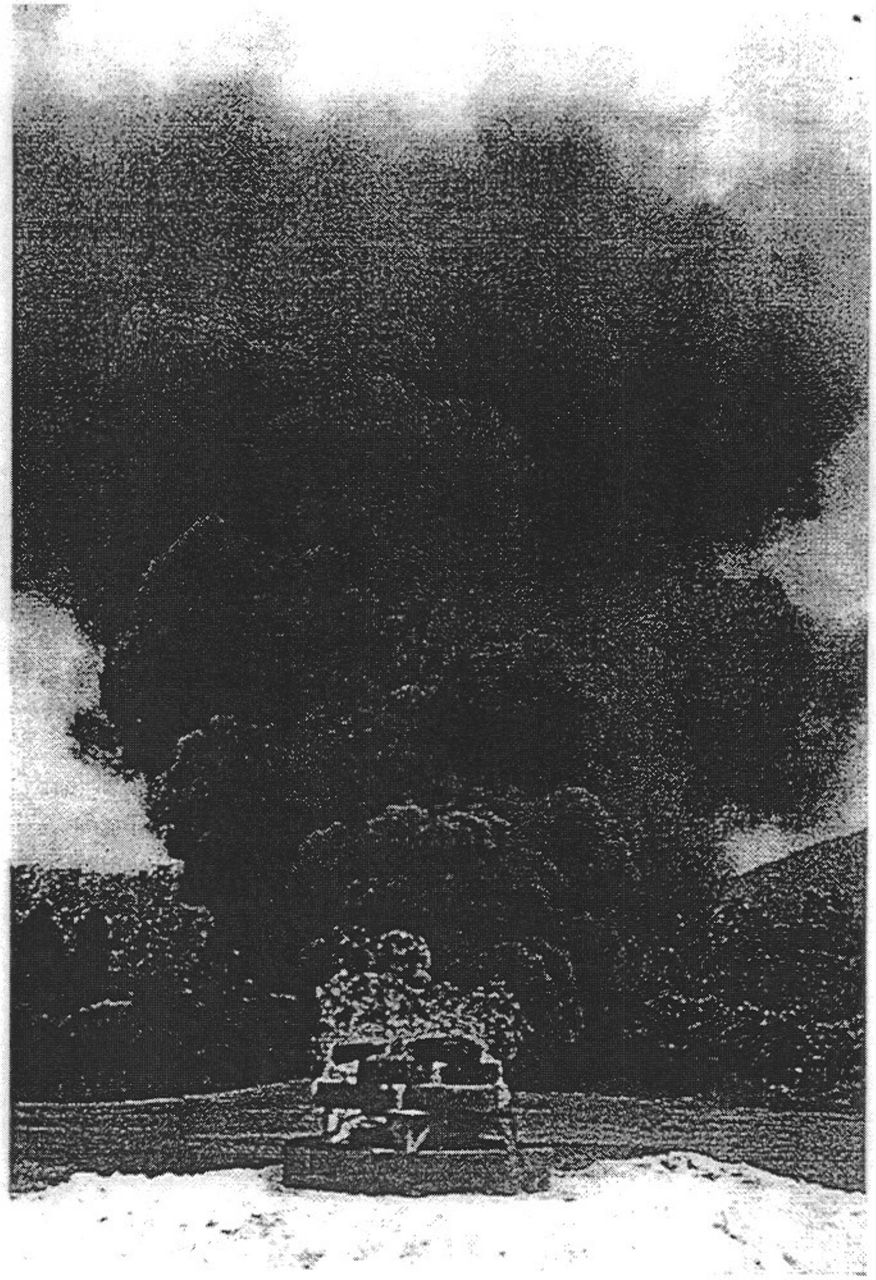

Figure 8. Tire fire before start of suppression

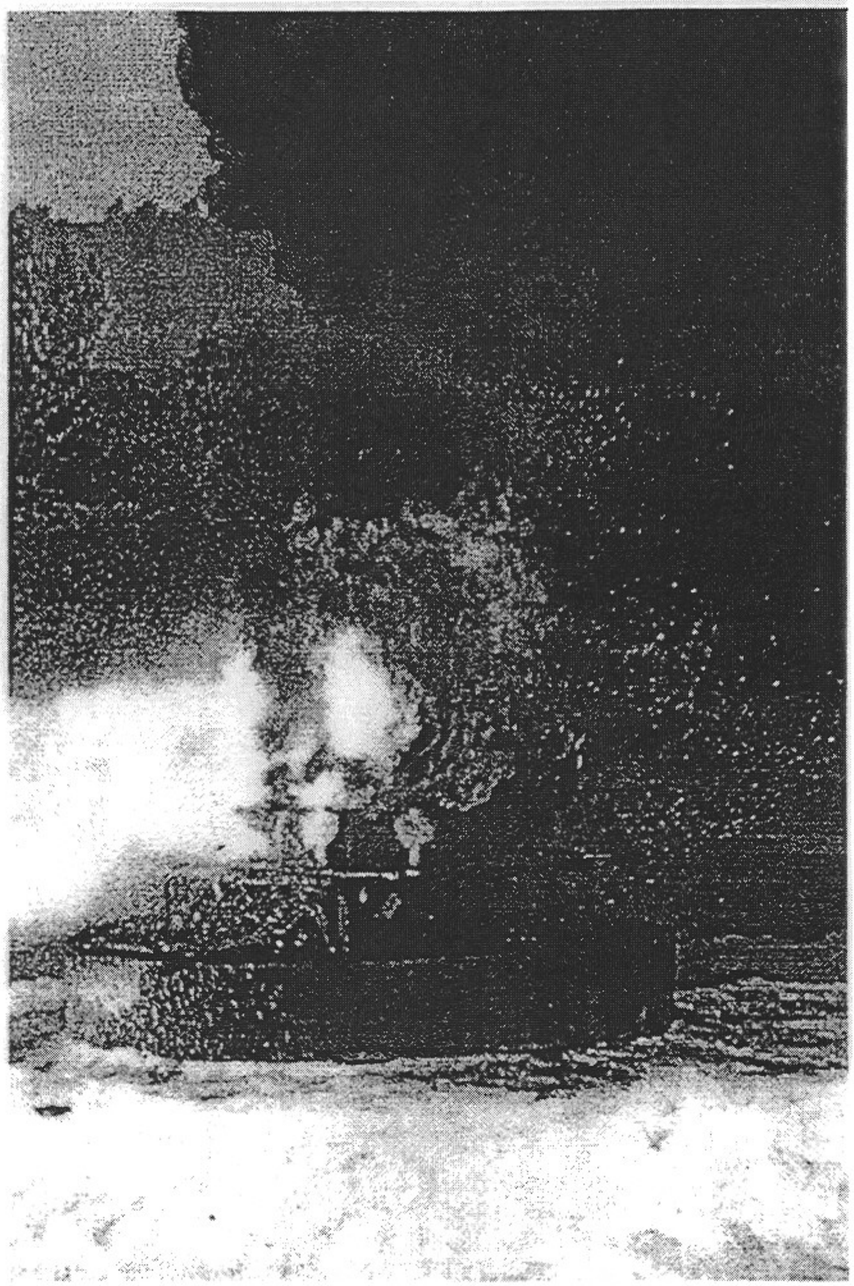

Figure 9. Tire fire at start of suppression

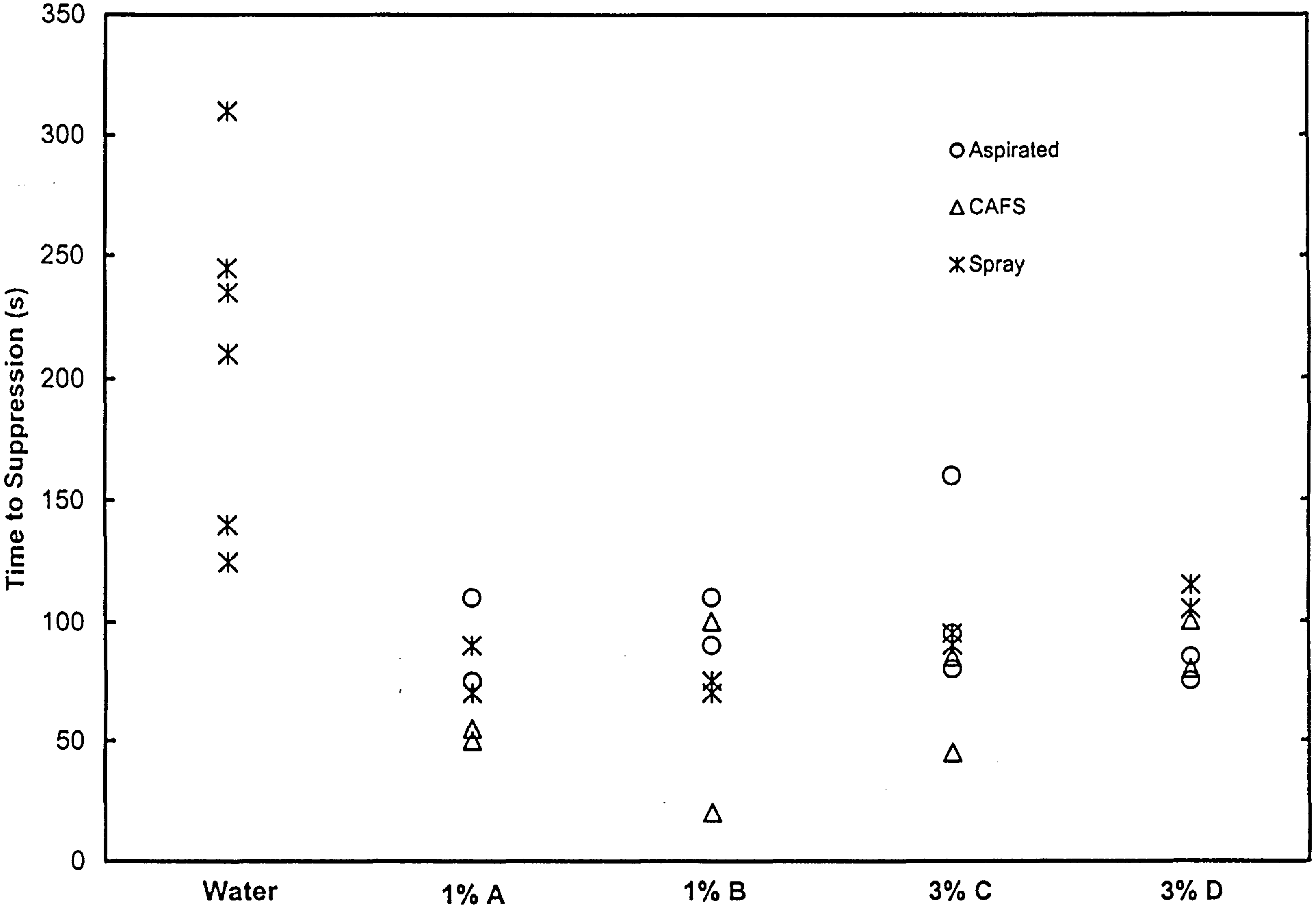

Figure 10. Fire suppression times for water and agents A, B, C, and D

# CHAPTER 6

# CLASS B FIRE SUPPRESSION EXPERIMENTS

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# CLASS B FIRE SUPPRESSION EXPERIMENTS

## 6.1 Introduction

Under the sponsorship of the United States Fire Administration (USFA), the National Institute of Standards and Technology (NIST) is developing methods for demonstrating biodegradable, environmentally safe, nontoxic fire suppression liquids which are effective on Class A, B, and many D fires. As part of this project, the Naval Research Laboratory (NRL) was tasked with conducting a series of standardized Class B fire tests. In addition, a series of large-scale Class B fire experiments was conducted in order to evaluate the standardized fire tests.

The objective of this Class B fire study was to develop test data and investigate test methods for evaluating the fire extinguishment and burnback resistance capabilities of selected Biodegradable, Environmentally friendly, Nontoxic (BEN) liquid firefighting agents on Class B hydrocarbon pool fires. Agent selection was limited to products currently on the U.S. Forest Service's list of approved agents [1]. Four agents were selected by NIST, none of which was listed as Class B fire fighting foams by either Underwriters Laboratories Inc. (UL) or the U.S. Military.

## 6.2 Approach

Testing was performed in three phases: foam expansion and drainage characterization, standard small-scale fire extinguishment and burnback testing, and large-scale pool fire testing. The first phase of testing evaluated expansion and drainage characteristics using both a full-scale, constant flow, air-aspirating nozzle and a small-scale, variable flow, air-aspirating nozzle. The flow from the small-scale nozzle was adjusted by exchanging a removable orifice, which allowed a desired flow to be obtained at various operating pressures. Tests were conducted with the small-scale nozzle first, using a number of different orifices to obtain results at a range of flow/pressure combinations. Testing was then conducted with the large-scale nozzle. Based on the results of these tests, a set of three orifices was selected that gave expansion and drainage characteristics from the small-scale nozzle which most closely replicated the large-scale nozzle results. Expansion and drainage characteristics tests conducted in conjunction with the fire test provided additional data for both small- and large-scale air-aspirating nozzles as well as data for a non-aspirating nozzle.

After selecting the appropriate orifices for the small-scale nozzle, a series of 4.6 $m^2$ (50 $ft^2$) fire tests were conducted. The tests were performed in accordance with UL 162 [2], Type III application method. Tests were conducted at flow rates of 7.6 lpm (2.0 gpm), 11.4 lpm (3.0 gpm), and 22.7 lpm (6.0 gpm). This resulted in application rates of 1.67 lpm/$m^2$ (0.04 gpm/$ft^2$), 2.44 lpm/$m^2$ (0.06 gpm/$ft^2$), and 4.88 lpm/$m^2$ (0.12 gpm/$ft^2$), respectively. Because the extinguishment characteristics of the BEN agents were marginal at the 11.4 lpm (3.0 gpm) flow rate, testing at the 7.6 lpm (2.0 gpm) flow rate was conducted with the AFFF agent only.

The final phase of testing was a series of large-scale 92.9 $m^2$ (1000 $ft^2$) fire tests. These tests were conducted with both an air-aspirating nozzle and a non-aspirating nozzle. Both nozzles were operated at a nominal flow rate of 454 lpm (120 gpm), resulting in an application rate of 4.88 lpm/m$^2$ (0.12 gpm/ft$^2$).

## 6.3 Agents Tested

The agents used for these tests included four (4) different biodegradable, environmentally friendly, non-toxic agents selected from the U.S. Forest Service's List of Approved Products [1]. These agents are referred to in this report as Agent A, B, C, or D. All testing was performed with premixed fresh water solutions, which were prepared in 1514 l (400 gal) batches for the large-scale tests and 150 l (40 gal) batches for the small-scale tests. All agents were initially mixed at the manufacturer's recommended concentrations. For Agents A and B, this was 1 percent (e.g., 99 parts water, 1 part concentrate), for Agent C, 6 percent and for agent D, 3 percent. In an effort to obtain more complete results, 4.6 m$^2$ (50 ft$^2$) fire tests were also conducted with Agent C at a 3 percent concentration and Agent D at a 6 percent concentration.

To provide a baseline and a measure of comparison, testing was conducted with an AFFF agent. This 3 percent concentrate agent is both UL Listed®[3] and is on the U.S. Military's Qualified Products List (QPL) [4]. To provide an additional baseline, a single large-scale fire test was also conducted with water only.

## 6.4 Expansion and Drainage Characteristics Tests

### 6.4.1 Test Setup

The expansion and drainage characteristics tests were conducted using the equipment described in Section 8.2 of UL 162 [2]. The foam expansion value is the ratio of the volume of foam produced over the volume of solution used in its production. The 25 percent drainage time is the time required for 25 percent of the total liquid contained in the foam sample to drain out of the foam. The backboard and 1600 ml collection cylinder used for these tests are described in the UL standard. A quarter-turn valve installed on the bottom outlet of the collection cylinder was used to control flow of the solution which had drained off of the expanded foam. As this solution was drained off, it was collected and measured in a 1000 ml graduated cylinder at 30-second intervals.

Expansion and drainage tests were conducted using three different nozzles. Two of these nozzles were of the air-aspirating type, and the third was a non-aspirating nozzle. The first nozzle, referred to as the large-scale air-aspirating nozzle was designed to flow 227 lpm (60 gpm) at an operating pressure of 552 kPa (80 psi). The initial expansion and drainage tests were conducted using the "factory" configuration. For the large-scale fire tests, this nozzle was modified (the orifice was enlarged) so that it could flow 454 lpm (120 gpm) at 690 kPa (100 psi).

The second nozzle, referred to as the small-scale test nozzle, was a modified version of the 7.6 lpm (2 gpm) nozzle described in the AFFF Military Specification (MIL-SPEC), MIL-F-24385F [5]. This nozzle is also an air-aspirating nozzle. The basic MIL SPEC test nozzle was modified by drilling and tapping the metering orifice so that it would accept any one of a set of metering orifice inserts.

These inserts in turn had various sized orifices which allowed an unlimited number of flow and pressure combinations at which the nozzle could be operated. This nozzle apparatus is used for Standard UL 162 fire testing. Tests were conducted at several different flow/pressure combinations with this nozzle.

The final nozzle, the large-scale, non air-aspirating nozzle, was a non air-aspirating, constant flow, variable stream nozzle that discharged 473 Lpm (125 gpm) at 690 kPa (100 psi). This nozzle is typical of those used by fire departments to discharge water on Class A fires. It is also used to discharge AFFF.

For the large-scale tests, the agent was premixed in a 1700 l (450 gal) stainless steel premix tank. The solution was then supplied to the nozzle through 30.5 m (100 ft) of 3.8 cm (1.5 in.) diameter canvas-jacketed rubber-lined fire hose by a 3785 lpm (1000 gpm) fire department pumper which took suction off of the premixed tank. For the small-scale tests, the agent was premixed in a 189 l (50 gal) closed-top storage tank. The tank was then charged with nitrogen, and solution was supplied to the nozzle through 7.6 m (25 ft) of 1.9 cm (0.75 in.) diameter rubber garden hose.

### 6.4.2 Test Procedures

The procedures used for conducting these tests were in accordance with UL 162 [2]. The procedures were identical for both the small- and large-scale tests. After the foam solution was premixed, the nozzle was flowed to assure the nozzle pressure was properly set. The nozzle was positioned at a distance of 12-15 m (40-50 ft) away from the backboard for the large-scale test and 2 m (6 ft) away from the small-scale tests. The discharge stream was directed against the backboard, and foam was collected in the 1600 ml collection cylinder. Measurement of drainage time began when the collection cylinder was observed to be full. The cylinder was then removed from the backboard, cleaned, and placed in a holding stand. The solution which drained out of the foam was removed from the collection cylinder using the quarter-turn valve and the cumulative amount measured at 30-second intervals over a 5-10 minute period. At the end of this period, the solution was returned to the collection cylinder, and the entire sample was weighed. The net weight of solution was determined, and from that, the expansion ratio was calculated. The 25 percent drainage time was then interpolated from the recorded drainage volumes.

An initial series of tests was conducted with the small-scale test nozzle using several different orifices and Agent A to scope the effects of flow rate and pressure on expansion and drainage characteristics. Since these tests showed that flow rate had a more significant impact than nozzle pressure, it was decided to conduct the remaining tests with the small-scale test nozzle at the 11.4 lpm (3.04 gpm) and 22.7 lpm (6.00 gpm) flow rates. These were the two flow rates to be used initially in the 4.6 $m^2$ (50 $ft^2$) fire tests.

After testing was completed with the small-scale test nozzle, a series of tests were performed with the large-scale air-aspirating nozzle to confirm that it would produce approximately the same expansion and drainage characteristics as the small-scale nozzle. In addition to these scoping tests, expansion and drainage tests were also conducted after each fire test with the solution remaining in the premix tank or pressurized storage tank. It was during these post-fire test experiments that data were collected for the large-scale non air-aspirating nozzle.

### 6.4.3 Test Results

The results of all small-scale expansion and drainage tests, including those performed with solutions used for fire tests, are presented in Table 1.

**Table 1 Results of Expansion and Drainage Tests Conducted with Small-scale Nozzles**

| | **Orifice Size (mm (in.))** | **Pressure (kPa (psi))** | **Flow Rate (lpm (gpm))** | **Expansion Ratio** | **25% Drainage Time (s)** |
|---|---|---|---|---|---|
| Agent A, 1% Concentration | 2.69 (0.106) | 896 (130) | 11.4 (3.02) | 9.2 | 274 |
| | 3.05 (0.120) | 552 (80) | 11.5 (3.04) | 8.8 | 270 |
| | 4.24 (0.167) | 596 (85) | 22.7 (6.00) | 6.6 | 218 |
| | 3.73 (0.147) | 993 (144) | 22.7 (6.00) | 6.7 | 310 |
| | 3.05 (0.120) | 552 (80) | 11.5 (3.04) | 8.9 | 197 |
| | 4.24 (0.167) | 586 (85) | 22.7 (6.00) | 7.3 | 195 |
| | 4.24 (0.167) | 586 (85) | 22.7 (6.00) | 7.0 | 141 |
| Agent B, 1% Concentration | 3.05 (0.120) | 552 (80) | 11.5 (3.04) | 8.8 | 138 |
| | 4.24 (0.167) | 586 (85) | 22.7 (6.00) | 7.6 | 136 |
| | 4.24 (0.167) | 586 (85) | 22.7 (6.00) | 6.4 | 137 |
| | 4.24 (0.167) | 586 (85) | 22.7 (6.00) | 7.7 | 152 |
| | 3.05 (0.120) | 552 (80) | 11.5 (3.04) | 9.0 | 148 |
| Agent C, 6% Concentration | 4.24 (0.167) | 586 (85) | 22.7 (6.00) | 10.0 | 240 |
| | 3.05 (0.120) | 552 (80) | 11.5 (3.04) | 11.8 | 225 |
| | 4.24 (0.167) | 586 (85) | 22.7 (6.00) | 9.5 | 216 |
| | 3.05 (0.120) | 552 (80) | 11.5 (3.04) | 12.0[1] | 136[1] |
| Agent D, 3% Concentration | 4.24 (0.167) | 586 (85) | 22.7 (6.00) | 6.1 | 84 |
| | 3.05 (0.120) | 552 (80) | 11.5 (3.04) | 10.3 | 82 |
| | 3.05 (0.120) | 552 (80) | 11.5 (3.04) | 8.7 | 92 |
| | 4.24 (0.167) | 586 (85) | 22.7 (6.00) | 8.7 | 65 |
| | 3.05 (0.120) | 552 (80) | 11.5 (3.04) | 12.5[2] | 77[2] |
| AFFF, 3% Concentration | 3.05 (0.120) | 552 (80) | 11.5 (3.04) | 8.1 | 162 |
| | 3.05 (0.120) | 552 (80) | 11.5 (3.04) | 8.5 | 144 |
| | 2.31 (0.091) | 758 (110) | 7.7 (2.03) | 13.1 | 158 |
| | 4.24 (0.167) | 586 (85) | 22.7 (6.00) | 10.7 | 125 |

Notes:
1. Test conducted with solution mixed at a 3 percent concentration.
2. Test conducted with solution mixed at a 6 percent concentration.

The expansion and drainage results for all of the large-scale tests performed with both nozzles are presented in Table 2. Nozzle operating pressures and flow rates are included to show the impact on expansion and drainage characteristics, particularly evident with the small-scale test nozzle. A comparison between the small-scale and large-scale air-aspirating results shows that with three of the five agents tested, there is good agreement in expansion and drainage characteristics between small-scale and large-scale tests (Agents A, C, and AFFF). With Agents B and D, the large-scale air-aspirating nozzle produced an expansion ratio that was greater than that produced with the small-scale nozzle. It can also be seen from these data that the 25 percent drainage times obtained with the small-scale nozzle were generally longer than those obtained with the large-scale air-aspirating nozzle. Based on these results, it was decided that the degree of agreement between the small-scale and large-scale air-aspirating nozzle tests was sufficient to proceed with the 4.6 m$^2$ (50 ft$^2$) fire tests. Accordingly, the 2.31 mm (0.091 in.), 3.05 mm (0.120 in.), and 4.24 mm (0.167 in.) orifices were selected to conduct the fire suppression tests.

**Table 2 Results of Expansion and Drainage Tests Conducted with Large-scale Nozzles**

| | Nozzle Type | Pressure (kPa (psi)) | Flow (lpm (gpm)) | Expansion Ratio | 25% Drainage Time (s) |
|---|---|---|---|---|---|
| Agent A, 1% Concentration | Aspirated | 690 (100) | 454 (120) | 7.7 | 156 |
| | Non-aspirated | 690 (100) | 473 (125) | 2.8 | <30 |
| Agent B, 1% Concentration | Aspirated | 552 (80) | 227 (60) | 13.0 | 66 |
| | Aspirated | 552 (80) | 227 (60) | 13.4 | 90 |
| | Aspirated | 690 (100) | 454 (120) | 11.7 | 135 |
| | Non-aspirated | 690 (100) | 473 (125) | 4.4 | <30 |
| Agent C, 6% Concentration | Aspirated | 552 (80) | 227 (60) | 13.5 | 150 |
| | Aspirated | 552 (80) | 227 (60) | 18.0 | 102 |
| | Aspirated | 552 (80) | 227 (60) | 15.5 | 114 |
| | Aspirated | 690 (100) | 454 (120) | 17.2 | 114 |
| | Non-aspirated | 690 (100) | 473 (125) | 5.4 | <30 |
| Agent D, 3% Concentration | Aspirated | 690 (100) | 454 (120) | 9.5 | <30 |
| | Non-aspirated | 690 (100) | 473 (125) | 3.2 | <30 |
| AFFF, 3% Concentration | Aspirated | 690 (100) | 454 (120) | 10.0 | 62 |
| | Non-aspirated | 690 (100) | 473 (125) | 4.0 | <30 |

## 6.5 4.6 m$^2$ (50 ft$^2$) Fire Tests

### 6.5.1 Test Setup

The 4.6 m$^2$ (50 ft$^2$) fire tests were conducted using the equipment described in UL 162 [2] for Type III discharge devices. This discharge scenario is intended to simulate direct application of foam to a spill or pool fire, e.g., from handlines and monitors. The test pan, which was located outdoors on the concrete mini-deck at the Chesapeake Beach Detachment (CBD) of NRL, was made of 6.4 mm (0.25 in.) thick carbon steel and was built in accordance with Section 3.6 of UL 162. It was 30.5 cm (12 in.) deep and was elevated off the ground 7.6 cm (3 in.) by structural channel welded to the bottom. Fuel for these tests was commercial grade heptane. A total of 237 l (62.5 gal) was used for each test. The fuel was floated on a 5.1 cm (2.0 in.) deep water substrate, resulting in 20.3 cm (8 in.) of freeboard.

All tests were conducted with premixed solutions. The storage tank/small-scale test nozzle setup was identical to that described above for the small-scale expansion and drainage characteristics tests. Flow rates for these tests were as follows:

| Orifice Size (mm (in.)) | Pressure (kPa (psi)) | Flow (lpm (gpm)) | Application Rate (lpm/$m^2$ (gpm/$ft^2$)) |
|---|---|---|---|
| 2.31 (.091) | 758 (110) | 7.57 (2.0) | 1.67 (0.04) |
| 3.05 (.120) | 552 (80) | 11.4 (3.0) | 2.44 (0.06) |
| 4.24 (.167) | 586 (85) | 22.7 (6.0) | 4.88 (0.12) |

Tests with Agents A, B, C, and D were conducted at the 11.4 lpm (3.0 gpm) and 22.7 lpm (6.0 gpm) flow rates only because the performance at 11.4 lpm (3.0 gpm) was marginal, indicating that extinguishment would not be achieved at 7.6 lpm (2.0 gpm). Tests with the AFFF product were conducted at all three flow rates.

All tests were initially conducted at the manufacturer's recommended concentrations. After the initial set of tests, Agents C and D had not achieved 100 percent extinguishment at the 11.4 lpm (3.0 gpm) flow rate. Two additional tests were conducted, one with Agent C at 3 percent (half strength) concentration and the other with Agent D at 6 percent (double strength) concentration, to examine the difference, if any, in extinguishment performance.

### 6.5.2 Test Procedures

All test procedures were in accordance with Section 10 of UL 162 [2] except as noted. Prior to each test, ambient wind conditions and air, fuel, water substrate, and solution temperatures were measured and recorded. The preburn and extinguishment portions of the test were conducted as described in UL 162. After the fuel was poured, all temperature measurements were recorded, and the nozzle was flowed to check the pressure; the fire was ignited and allowed to preburn for a total of 60 seconds. The firefighter then began his attack from the upwind side of the pan. Agent was initially applied to the near side of the fire area, which resulted in a buildup of the foam blanket on the far side of the fire area. When it appeared that this foam blanket had extinguished about 30-50 percent of the fire, the nozzle was elevated slightly so that the foam was being applied to the far side of the fire pan on top of the established foam blanket. This allowed the foam blanket to flow back to the near side, extinguishing all of the fire around the edges. Up to this point, the firefighter was restricted to applying agent from one side of the pan only.

When 90 percent of the fire was extinguished, the firefighter was allowed to move around two sides of the pan to extinguish the last remaining fire at the edges. Complete extinguishment proved to be difficult because of the hot temperature of the steel and the amount of exposed steel freeboard. The time to achieve 50 percent control as well as 90 percent control and 100 percent extinguishment were recorded. Total application time for tests conducted at the 11.4 and 22.7 lpm (3.04 and 6.00 gpm) flow rates was 5 minutes. Total application time for tests conducted at the 7.6 lpm (2.0 gpm) flow rate was 3 minutes.

The burnback portion of the test was also conducted as described in UL 162. Immediately after the end of agent application, the first torch test was performed. A burning torch was passed over all areas of the foam blanket at an elevation of approximately 15.2 cm (6.0 in.) above the foam blanket. This procedure was performed over a one minute time period. In some cases, the first torch test resulted in candling (e.g., small flames usually not more than 15.2 cm (6.0 in.) tall) around the edges of the foam blanket which eventually self-extinguished. In other cases, the candling progressed to sustained burning of larger areas and eventually complete reinvolvement. In cases where the candling flames from the first torch test self-extinguished, the foam blanket was allowed to sit for a total of 13 minutes from completion of the first torch test (14 minutes from the end of agent application). At this time, a second torch test was performed using the same procedures. In all cases, the foam blanket was sufficiently broken down to allow reignition of the fuel. The major factor affecting the integrity of the foam blanket appeared to be ambient wind conditions, which tended to push the foam blanket away from the downwind side of the pan. Once the foam blanket had pulled away from the side of the pan, it never flowed back to reform a complete seal. UL 162 does not specify maximum wind speed for conducting the burnback test.

Since breakdown of the foam blanket was significant in all cases, the "stove pipe" test specified by UL was never performed. Burnback time, which was the time to achieve 100 percent reinvolvement, was recorded based on reignition from the torch test. Because some tests reignited after the first torch test, zero time for measurement of burnback was the end of agent application. At the end of each test, an expansion and drainage test was performed to provide additional foam quality data.

### 6.5.3 Test Results

The results of the 4.6 $m^2$ (50 $ft^2$) fire tests are presented in Table 3. In addition to 100 percent extinguishment time, the time to control 50 percent and 90 percent of the fire area is reported. The 50 percent control time provides a measure of initial knockdown ability and effectiveness of an agent. The 90 percent control time provides a measure of fire extinguishment in which the fire is essentially contained. In most cases, the time required to extinguish the last 10 percent of fire area was almost as long, if not longer, than the time to achieve 90 percent fire control. This is an indication of the difficulty for the foam to seal against the hot edges of the test pan. Air temperatures recorded during these tests were in the range 21-33EC (70-91EF), fuel temperatures were in the range 21-31EC (70-88EF), and solution temperatures were in the range 24-30EC (75-86EF).

None of the BEN agents performed as well as the MIL SPEC AFFF, which had 100 percent extinguishment times at the 7.6 lpm (2.0 gpm) flow rate that were comparable to the extinguishment times of the BEN agents for the 11.4 lpm (3.04 gpm) flow rate. At the 22.7 lpm (6.00 gpm) flow rate, Agents A and B performed best with extinguishment times only 12-22 seconds longer than those of MIL SPEC AFFF. It can also be seen that the performance of Agent C at the 11.5 lpm (3.04 gpm) flow rate was improved by reducing the concentration to 3 percent (half-strength of manufacturer's recommendation). Increasing the concentration of Agent D to 6 percent (twice the manufacturer's recommendation) provided no advantage at all.

The torch test results and 100 percent burnback time data are similar to the extinguishment data. Again, Agents A and B performed the best. Agent C progressed past the initial torch test only at the 22.7 lpm (6.00 gpm) flow rate. With Agent D, the first torch test resulted in complete reinvolvement in all cases. There were also differences between the burnback characteristics of the BEN agents and the MIL SPEC AFFF. With AFFF, the second torch test resulted in candling only even though there were what appeared to be exposed areas of fuel. While this candling did eventually become sustained burning, the length of time to achieve 25-60 percent reinvolvement was 2-4 minutes longer than the time for 100 percent reinvolvement with the best BEN agents.

## 6.6 92.9 $m^2$ (1000 $ft^2$) Fire Tests

### 6.6.1 Test Setup

The 92.9 $m^2$ (1000 $ft^2$) fire tests were also conducted on the mini-deck at CBD (Figure 1). The fire area was created using earth berms, built up on a non-permeable plastic lining placed on the concrete deck. The fire area was contained within a berm having inside dimensions of 9.6 m (31.6 ft) square. An outer berm measuring 13.7 m (45 ft) square enclosed the 92.9 $m^2$ (1000 $ft^2$) fire area and provided secondary containment for fuel or agent that splashed out of the fire area. Fuel used for these tests was unleaded motor gasoline. A total of 945-1134 l (250-300 gal) was used for each test. The fuel was floated on a 10.2 cm (4 in.) water substrate which leveled the bottom of the test area and protected the plastic liner.

All tests were conducted with premixed solutions. The premixed tank/fire department pumper setup was identical to that described above for the large-scale expansion and drainage characteristics tests. For safety purposes, an additional 3.8 cm (1.5 in.) backup handline was provided, supplied by a second fire department pumper which had onboard AFFF proportioning capabilities. This backup pumper discharged MIL-SPEC AFFF.

The original test plan called for the agents to be tested at an application rate of 2.44 lpm/$m^2$ (0.06 gpm/$ft^2$) in accordance with the design application for foam agents in UL 162 [2]. Since substantially better performance was observed in the 4.6 $m^2$ (50 $ft^2$) tests at application rates of 4.88 lpm/$m^2$ (0.12 gpm/$ft^2$), this rate was selected for the large-scale tests. The 4.88 lpm/$m^2$ (0.12 gpm/$ft^2$) application rate also approximates the minimum design rate for AFFF hand lines (4.07 lpm/$m^2$ (0.10 gpm/$ft^2$)) recommended by NFPA 11 [6]. For a 92.9 $m^2$ (1000 $ft^2$) fire area, this application rate was achieved by using a nominal flow rate of 454 lpm (120 gpm).

Two tests were conducted with each agent using the 4.88 lpm/$m^2$ (0.12 gpm/$ft^2$) application rate. In one test, the foam was generated using the large-scale air-aspirating nozzle. The orifice assembly of this nozzle was enlarged so that it could flow 454 lpm (120 gpm) at 690 kPa (100 psi). The second test was conducted using the large-scale non air-aspirating nozzle. This nozzle discharged 473 lpm (125 gpm) at 690 kPa (100 psi). This nozzle was also used for one additional baseline test where water only was discharged at a 4.88 lpm/$m^2$ (0.12 gpm/$ft^2$) application rate.

### 6.6.2 Test Procedures

Prior to each test, ambient wind conditions were recorded and video cameras were started. A torch was used to ignite the upwind edge of the fire area. The fire quickly spread to full area involvement within 5-8 seconds. The firefighter initiated the attack after a total preburn time of approximately 10 seconds. In some cases, the preburn time was extended to assure complete involvement of the fire area. The nozzleman, supported by a backup firefighter, attacked the fire from the upwind corner of the fire area. Foam was first applied to the upwind corner of the fire area to gain a "bite" (extinguished area). Agent was then applied to the upwind edge of the fire and swept across to the opposite edge of the fire area. This sweeping motion was continued with the firefighter pushing the fire to the back edge of the bermed area. When the non-aspirating nozzle was used, the initial nozzle pattern was a narrow angle fog (30° pattern). This pattern was adjusted to straight stream as needed for reach as the fire was controlled. Final extinguishment was then accomplished using either a gentle fog application or using a straight stream to push foam to extinguish flickering fires along the dirt berm. With Agent C, a plunging technique was used initially at the leading edge in accordance with the manufacturer's recommendations.

Total application time for all tests was two (2) minutes from the initiation of fire attack. If the fire was extinguished within this 2-minute period, a burnback test was performed by placing a lit torch in the upwind corner of the fire test area. This torch was positioned within 30 seconds of the end of agent application. The time for 25 percent of the total fire area to become reinvolved was recorded as the 25 percent burnback time. For those situations where the fire could not be extinguished within the 2-minute period, the backup AFFF handline was used to control and extinguish the fire. When needed, this handline was generally brought in at about 1.5 minutes after ignition, but in some cases where 75 percent or less of the fire was controlled it was used earlier (Tests LSC9 and LSC11). After each fire test, an expansion and drainage test was conducted to characterize the foam with these test nozzles.

### 6.6.3 Test Results

The results of the large-scale tests are shown in Tables 4 and 5 for air-aspirating and non air-aspirating nozzles respectively. In addition to the 50 percent and 90 percent control times, the significance of which was discussed previously, these tables also include a 99 percent control time value. This value can be used as a measure of performance for near-total extinguishment to address the variability resulting from dirt berm wicking and ambient wind effects. This is evident in Tests LSC1, LSC3, LSC6, LSC9, and LSC10 where the time between 99 percent control and total extinguishment generally equaled or exceeded the time to gain 90 percent control of the fire. In other words, as with the hot surfaces in the 4.6 $m^2$ (50 $ft^2$) test, extinguishment of the last residual fire often took as long as gaining control of the fire.

In the tests where the air-aspirating nozzle was used, Agents A and B extinguished the fire while the backup handline had to be used with Agents C and D. AFFF controlled and extinguished the fire more quickly than Agents A and B. Burnback time was substantially greater for AFFF (7 min 19 sec) compared to Agents A (55 sec) and B (1 min 49 sec).

**Table 4. Results of 92.9 $m^2$ (1000 $ft^2$) Fire Tests with the Air-aspirating Nozzle**

| Agent | Test No. | Control Time (min:sec) | | | 100% Exting. Time (min:sec) | 25% Burnback Time (min:sec) | Comments |
|---|---|---|---|---|---|---|---|
| | | 50% | 90% | 99% | | | |
| A | LSC1 | 0:16 | 0:30 | 0:45 | 1:11 | 0:55 | -- |
| B | LSC3 | 0:18 | 0:31 | 0:44 | 1:09 | 1:49 | -- |
| C | LSC5 | 0:20 | 0:56 | -- | -- | -- | Fire burned back after 90% control; AFFF applied at 2:08 |
| D | LSC7 | 0:30 | -- | -- | -- | -- | Fire control limited to 75% or less of fire area; AFFF applied 2 min. after initiation of fire attack |
| AFFF | LSC10 | 0:10 | 0:19 | 0:32 | 0:55 | 7:19 | -- |

**Table 5. Results of 92.9 $m^2$ (1000 $ft^2$) Fire Tests with the Non-aspirating Nozzle**

| Agent | Test No. | Control Time (min:sec) | | | 100% Exting. Time (min:sec) | 25% Burnback Time (min:sec) | Comments |
|---|---|---|---|---|---|---|---|
| | | 50% | 90% | 99% | | | |
| A | LSC2 | 0:17 | 0:38 | -- | -- | -- | Fire held to 80-90% control; AFFF applied at 1:49 |
| B | LSC4 | 0:26 | 0:46 | 1:40 | -- | -- | Fire held steady at 95-99% control; AFFF applied at 2:05; may have extinguished with longer flow duration |
| C | LSC6 | 0:18 | 0:32 | 0:50 | 1:37 | 0:08 | Residual fire outside bermed area ignited foam at 2:22; 25% burnback in 8 sec |
| D | LSC8 | 0:31 | -- | -- | -- | -- | Fire quickly flashed back after 50% control; AFFF applied 45 sec after initiation of fire attack |
| AFFF | LSC9 | 0:16 | 0:21 | 0:37 | 0:46 | 1:57 | Wind affected results (stronger than that of previous tests) |
| Water | LSC11 | 0:28 | -- | -- | -- | -- | 75% control at 47 sec; AFFF handline brought in at 47 sec |

In the tests where the non air-aspirating nozzle was used (i.e., standard firefighting nozzle), only Agent C and AFFF were able to fully extinguish the fire. AFFF was the only agent with any significant burnback resistance (1 min 57 sec), which was much less than that achieved with the air-aspirating nozzle. Control and extinguishment times with the AFFF were roughly equivalent between aspirated and non air-aspirated tests. Agent B was almost able to totally extinguish the fire although the last 10 percent of the fire area was difficult to extinguish. Similar results were observed with Agent A. Water was able to control a maximum of 75 percent of the fire area before the backup handline was brought in at 47 seconds.

## 6.7 Small- and Large-scale Comparison

A comparison of the small-scale and large-scale air-aspirating nozzle tests results for the 4.88 lpm/m$^2$ (0.12 gpm/ft$^2$) application rate shows very good agreement between extinguishment times for Agents A, B, and AFFF and good agreement for 50 percent and 90 percent control with Agent C. However, both Agent C and Agent D were not able to extinguish the 92.9 m$^2$ (1000 ft$^2$) fire even though they were able to extinguish the 4.6 m$^2$ (50 ft$^2$) fire.

## 6.8 References

1. U.S. Department of Agriculture, U.S. Forest Service, "Interim Requirements and Manufacturers Submission Procedures for Wildland Fire Foam," Special Report No. 86511803, August 1986.

2. Underwriters Laboratories Inc., "UL 162, Standard for Foam Equipment," Seventh Edition, Northbrook, IL, March 30, 1994.

3. Underwriters Laboratories Inc., "Fire Protection Equipment Directory," 1995 Edition, Northbrook, IL.

4. Qualified Products List, "Products Qualified under Military Specification MIL-F-24385, Fire Extinguishing Agent, Aqueous Film-forming Foam (AFFF) Liquid Concentrate, for Fresh and Salt Water," QPL-24385-25, May 1992.

5. Military Specification MIL-F-24385F, "Fire Extinguishing Agent, Aqueous Film-forming Foam (AFFF) Liquid Concentrate, for Fresh and Seawater," 7 January 1992.

6. National Fire Protection Association, "NFPA 11, Standard for Low Expansion Foam and Combined Agent Systems," 1994 Edition, Quincy, MA.

## Table 3 Results of 4.6 m² (50 ft²) Fire Tests

| Agent | Test No. | Solution Concentration | Flow Rate (Lpm (gpm)) | Control Times (min:sec) |  | 100% Exting. Time (min:sec) | Torch Test Results |  | 100% Burnback Time[1] (min:sec) | Maximum Wind (mph) |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | 50% | 90% |  | First | Second |  |  |
| A | FT7 | 1% | 11.5 (3.04) | 0:17 | 0:44 | 1:56 | Cand., SE | Reflash | 14:40 | 12 |
|  | FT8 | 1% | 22.7 (6.00) | 0:19 | 0:40 | 1:12 | Cand, SE | Reflash | 14:55 | 4 |
|  | FT9 | 1% | 22.7 (6.00) | 0:15 | 0:33 | 1:08 | Cand, SE | Reflash | 14:55 | 10 |
| B | FT6 | 1% | 11.5 (3.04) | 0:45 | 0:54 | 2:23 | Cand, SE | Reflash | 14:18 | 11 |
|  | FT4 | 1% | 22.7 (6.00) | 0:28 | 0:40 | 1:08 | Flash, SE | Reflash | 14:40 | 5 |
|  | FT5 | 1% | 22.7 (6.00) | 0:25 | 0:42 | 1:18 | Cand, SE | Reflash | 16:05 | 13 |
| C | FT14 | 3% | 11.5 (3.04) | 0:45 | 1:29 | 3:00 | Sust burning | -- | 2.55 | -- |
|  | FT1 | 6% | 11.5 (3.04) | 0:26 | 3:23 | NA | -- | -- | -- | 3 |
|  | FT2 | 6% | 22.7 (6.00) | 0:20 | 1:00 | 2:14 | Flash, SE | Reflash | 14:17[2] | -- |
|  | FT3 | 6% | 22.7 (6.00) | 0:26 | 0:46 | 2:00 | Flash, SE | Reflash | 14:30[3] | 7 |
| D | FT12 | 3% | 11.5 (3.04) | 0:40 |  |  | -- | -- | 1:00 | 9 |
|  | FT17 | 6% | 11.5 (3.04) | 0:24 | 1:20 | NA | -- | -- | 0:52 | 6 |
|  | FT10 | 3% | 22.7 (6.00) | 0:17 | 1:20 | NA | Sust burning | -- | 4:13 | 3 |
|  | FT11 | 3% | 22.7 (6.00) | 0:30 | 1:00 | 2:11 | Sust burning | -- | 3:44 | 4 |
|  |  |  |  |  | 0:55 | 2:27 |  |  |  |  |
| AFFF | FT15 | 3% | 7.68 (2.03) | 0:30 | 1:20 | 2:43 | Flash, SE | Candling | 18:27[4] | 8 |
|  | FT13 | 3% | 11.5 (3.04) | 0:18 | 0:37 | 1:14 | Cand, SE | Reignition | 16:55[5] | 11 |
|  | FT16 | 3% | 22.7 (6.00) | 0:15 | 0:35 | 0:56 | Flash, SE | Candling | 18:43 | 11 |

Notes:

1 Unless noted otherwise, all burnback times are measured from the end of agent application until 100 percent of the fuel surface is reinvolved.

2 Second torch test was not started until 14:17 after the end of agent application; immediate reflash and complete reinvolvement of the fuel surface resulted.

3 Second torch test was not started until 14:30 after the end of agent application; immediate reflash and complete reinvolvement of the fuel surface resulted.

4 At 18:27 after the end of agent application, only 25 percent of the fuel surface became reinvolved; the fire had to be suppressed due to possible damage to the concrete deck.

5 At 16:55 after the end of agent application, only 60 percent of the fuel surface became reinvolved; the fire had to be suppressed due to possible damage to the concrete deck.

NA = 100% extinguishment not achieved.
Cand = Candling around edges that continued in excess of 30 seconds, but eventually extinguished.
Flash = Quick flashes or candling that lasted less than 30 seconds.
Sust burning = Candling that never self-extinguished.
S.E. = Self-extinguished
Reflash = Reignition of an area of the fuel surface greater than 10 square feet.
Reignition = Reignition of an area of the fuel surface less than 10 square feet

Figure 1. Large scale (92.9 m $^2$) gasoline fire suppression experiment.

# CHAPTER 7

# CLASS D FIRE SUPPRESSION EXPERIMENTS

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# CLASS D FIRE SUPPRESSION EXPERIMENTS

## 7.1 Objective

To investigate the effectiveness of water based extinguishing agents on non alkali Class D fires, two series of fire suppression experiments were conducted. The first experimental series was conducted by Underwriters Laboratory at the facility located in Northbrook, Illinois. It consisted of magnesium chip fire tests as outlined in the Standard for Rating and Fire Testing of Fire Extinguishers, ANSI/UL 711 [1]. The second series of experiments, conducted by The Building and Fire Research Laboratory were performed at the University of Maryland Fire Rescue Institute training facility located in Princess Anne County, Maryland. This second series utilized titanium turnings as the fuel for the experiments.

## 7.2 Background

A Class D fire is defined as a fire in a combustible metal, such as magnesium, titanium, zirconium, sodium, lithium, or potassium [2]. In the proper environment, all metals except gold, silver, and platinum will burn [3] and perhaps the most important condition which regulates the combustibility of a metal is its form and shape [4]. In this respect, metals are no different than many other combustible solids. Some metals that are difficult to ignite in a large solid form, will ignite and burn readily as thin sheets, shavings, or particles. Additionally, many metals in the form of a powder or dust will ignite explosively. Several metal dusts, among them aluminum, magnesium, thorium, titanium, and uranium have explosibility indexes greater than 10 which is considered severe [5]. Some of these metals can produce maximum rates of pressure rise in excess of 68.95 MPa/s (10,000 psi/s).

The extinguishment of metal fires is difficult since many burning metals react violently with most of the common extinguishing agents used today. The reactivity of some metals, such as aluminum, magnesium, and zirconium, is so high that they continue to burn even in the presence of nitrogen forming their nitrides [6]. In addition, metals burn at very high temperatures, up to 4500 °C (8100 °F) [3]. In the combustion of ordinary hydrocarbons, the flame temperature is limited by dissociation of $CO_2$. This begins to become appreciable at temperatures about 1400 °C (2550 °F) and effectively limits hydrocarbon flame temperatures to less than 2200 °C (4000 °F) [7]. At 2500 °C (4500 °F) water is dissociated into hydrogen and hydroxide [8]. When water is applied to these burning metals, the hydrogen produced by this dissociation increases the combustion and explosion hazard. Dry chemicals, based on bicarbonates are also ineffective against metal fires since these metals react with the carbon dioxide, which is a decomposition product of bicarbonates. Some metals will burn in an atmosphere of carbon dioxide. Compounds containing halogen react violently with some burning metals. The use of halogen containing suppressant agents on pure metal fires is considered hazardous [9]. The use of a halogenated extinguishing agent, such as halon 1301, on magnesium or titanium, may evolve more heat than could be obtained from reaction with oxygen. Thus the suppressant could become an accelerant [10]. The alkali metals, lithium, sodium, potassium, rubidium, and cesium, react with water with an explosive violence. The melting point of the alkali metals are relatively low, ranging from 28°C to 180°C (83 °F to 356 °F). In contact with water these metals have an exothermic reaction which raises the temperature causing the metal to melt increasing the surface area for reaction. These metals may ignite spontaneously when exposed to the atmosphere. Alkali metals also react exothermically with the halogens. Therefore, halogenated hydrocarbons cannot be used to extinguish alkali metal fires. The reaction of alkali metals with halogenated hydrocarbons is nearly as violent as their reaction with water.

Over the years a great deal of effort has been expended in the study of different agents for the extinguishment of combustible metal fires [11,12,13]. Hundreds of agents have been tested in many different experimental scenarios. They include dry chemicals, dry powders, gases, and liquids, including water based extinguishing agents. Many different standard test fires were considered along with different requirements for what was considered a successful extinguishing agent. Many agents tested were considered highly toxic. Extinguishment of visible flame was not always considered the sole requirement for an extinguishing agent, since metals sometimes continued to burn under a coating of agent until completely consumed. Control, rather than extinguishment was often the goal. Other requirements included a reduction in temperature of the burning metal, or a requirement of a specific percentage of the metal that would be salvageable after a test fire. Often, an agent was tested at various concentrations and flow rates on a specific combustible metal. Numerous agents have been developed to extinguish combustible metal fires, but a given agent does not necessarily control or extinguish all metal fires. Although some agents are valuable in working with several metals, other agents are useful in extinguishing only one type of metal. Additionally, some agents provide only partial control and cannot be classed as an actual extinguishing agent. An additional problem related with the use of some extinguishing agents is the amount needed to control or extinguish a metal fire. Many times the amount of extinguishing agent needed greatly exceeds the amount of metal that is burning. Presently, Underwriters Laboratory test Class D fire extinguishers, or an extinguishing agent arranged for manual handling, on a given combustible metal. Unlike Class A and Class B extinguishers there are no numerical components for Class D ratings. Extinguishing agents for use on Class D fires are rated for the amount of agent and the method of application needed to control a fire involving a particular quantity and type of metal. The type of combustible metal for which the extinguisher or agent is applicable and the area, depth, and other characteristics of the fire which may be controlled or extinguished are as stated in published literature from the manufacturer and as described in the manufacturer's recommendations for use. An example of an Underwriters Laboratories listing for a specific extinguishing agent states that the ratio of extinguishing agent to metal is 5 to 1 when used on a magnesium fire and 15 to 1 when the same agent is used on a molten sodium potassium alloy fire.

## 7.3 Magnesium

Fires in magnesium and magnesium alloys, similar to other combustible metals, present severe extinguishing problems in that the great reactivity of magnesium precludes the use of common fire extinguishing agents. Magnesium has such a strong affinity for oxygen that it extracts the oxygen from oxygen containing compounds [14]. Magnesium reacts with water to form hydrogen and magnesium hydroxide in such a manner that the combustion of the magnesium is accelerated, and the hydrogen burns, supplying increased fuel to the fire. This reaction is expressed by the following equation:

$$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2$$

Because ordinary water based foam agents contain more than 90% water, they are ineffective in extinguishing burning magnesium. In a confined space, magnesium will continue to burn in air after the available oxygen has been used by combining with nitrogen to form magnesium nitride. In an inert atmosphere of carbon dioxide, magnesium will react to produce magnesium oxide and carbon monoxide. These reactions are described as follows:

$$Mg + CO_2 \rightarrow MgO + CO$$

$$3Mg + N_2 \rightarrow Mg_3N_2$$

The National Fire Protection Association (NFPA) Fire Protection Handbook, 17th edition [15], indicates that water may be used to extinguish magnesium fires if it can be applied rapidly and in large enough quantities to have a cooling effect. Small streams from portable extinguishers will accelerate a magnesium chip fire violently. Well advanced fires in several hundred pounds of magnesium scrap have been extinguished in less than 1 minute using two 38 mm (1½ in) fire hoses [15]. The total quantity or application rate of the water is not indicated. Tests conducted by the Chicago Fire Department showed that the use of large quantities of water may cool magnesium below its ignition temperature and so control the fire [16]. Two tests are described. Both consisted of burning magnesium in a shed with the dimensions of 3.04 x 3.04 x 3.04 m. (10 x 10 x 10 ft). Sprinklers installed in the shed consisted of six open heads with orifices of 8 mm (5/16 in). The first test with 40 kg (72½ lbs) of magnesium fines, chips, and solids in the form of castings was ignited and allowed to burn for 15 minutes before water was applied through the sprinklers. Although the amount of water flow was not described in the text, the sprinklers were supplied at an initial pressure of 861 kPa (125 psi) for the first 5 minutes, 1034 kPa (150 psi) for five minutes and then 1379 kPa (200 psi) for five minutes. There was a momentary flare up or intensification of burning upon application of water. After this 15 minute application, the water was shut off due to the appearance of the fire being extinguished. The remaining magnesium was stirred in an effort to check for complete extinguishment. It re-ignited spontaneously. Water was again applied for an additional eight minutes before the magnesium was finally extinguished. The second test consisted of 95 kg (210 lbs) of magnesium fines and solids. The magnesium was ignited and allowed to burn for 12 minutes before water was applied through the sprinklers. For this test, the sprinklers were replaced by standard heads with 12.7 mm (½ in) orifices. After 8 minutes of water application through the sprinklers, three 63.5 mm (2 ½ inch) hose lines equipped with 28.6 mm (1 1/8 inch) tips supplied at a pressure of 1206 kPa (175 psi) were used to extinguish the fire. As with the first test there was a momentary flare up upon water application and additional mild flashes and explosive reactions upon water application from the hoses. As can be seen from the number of sprinklers, hoses and the supply pressures, copious amounts of water were needed to control and extinguish these magnesium fires. One of the hoses, if supplied at a standard pressure of 345 kPa (50 psi) [17,18] would supply 1000 l/min (265 g/min). Therefore the three hoses alone supplied almost 3000 l/min (800 g/min) of water or a density of 325 $l/min/m^2$ (8 $g/min/ft^2$).

The National Fire Protection Association Standard 480, Storage, Handling, and Processing of Magnesium Solids and Powders, 1993 Edition [19] recommends against the use of water as an extinguishing agent. This standard does not permit the use of automatic sprinklers in areas where molten magnesium is produced or handled, in areas where heat treating furnaces are located, or in areas where magnesium chips or powders are produced or handled. It strictly prohibits the use of automatic sprinklers in buildings where magnesium powder may be stored and only allows the use of sprinklers in buildings used to store heavy or light magnesium castings if other ordinary combustible materials are present. NFPA Standard 49 Hazardous Chemical Data, 1994 Edition [20] advises not to use carbon dioxide, halogenated extinguishing agents, water or foam on magnesium fire. The method of extinguishing magnesium fires depends largely on the form of the material. The National Fire Protection Association Fire Protection Handbook, 17th edition recommends that burning chips, shavings, and small parts be extinguished by smothering and cooling with a suitable dry extinguishment agent. Where magnesium dust is present care must be taken not to cause a dust cloud from forming during agent application, as this may result in a dust explosion. If surrounding materials can be removed and the amount of magnesium is small, it may be best to let the magnesium burn itself out.

In two recent incidents involving large amounts of magnesium on fire, water was never considered as an extinguishing agent [21,22]. The first involved approximately 2270 kg (5000 lbs) of magnesium scrap in the form of hollow tubes of 3.8 cm ( 1 ½ inch) diameter and rectangular poles 5 cm x 10 cm x 3.7 m (2 in x 4 in x 12 ft). This fire was extinguished with the use 1140 kg (2500 lbs) of soda ash. The second fire involving approximately 4100 kg (9000 lbs) of magnesium chips and turnings was extinguished with the use of approximately 10500 kg (23000 lbs) of sand.

## 7.4 Titanium

Titanium also has an extremely high affinity for oxygen and nitrogen. Additionally the oxides of titanium are readily soluble in the molten metal. Thus, heated titanium can not only easily reduce many of the compounds or liquids normally used as extinguishing agents, and the absence of a protective oxide film results in the presence of a continuously reactive surface on the molten metal [12]. Although water has been used successfully in some cases, in others, violent reactions were reported. [12, 15]. The National Fire Protection Association Fire Protection Handbook, 17th edition, indicates that water may not be used on titanium powder, but can be used with caution in other titanium fires. Hose streams have been used effectively on fires outside piles of scrap, but violent reactions resulting in serious injuries have been reported in other cases where water was applied to hot or burning titanium. Tests on titanium machining and in open drums showed that a coarse water spray was effective in relative small quantities of material. Neither the amount of burning titanium involved, the amount of water used, nor the application rate of the water was indicated. The National Fire Protection Association Standard 481, Production, Processing, Handling, and Storage of Titanium, 1995 Edition [23] recommends against the use of water-based extinguishers as extinguishing agents. Buildings or portions of buildings of non combustible construction used principally for titanium storage or handling shall not be permitted to be equipped with automatic sprinkler protection unless combustibles other than titanium create a more severe hazard than the titanium. Carbon dioxide also reacts with titanium. The equilibrium reaction of equal masses of titanium and carbon dioxide results in carbon monoxide, titanium oxide and titanium dioxide at a temperature of 3099 °C (5600 °F), well above its ignition temperature. Extinguishment tests using carbon dioxide on titanium fires showed that a 23% concentration of carbon dioxide increased the burning rate by 50%, while tests with nearly 100% carbon dioxide showed an increase in the burning rate of about 300% [24]. Nitrogen also encouraged the combustion of bulk titanium in air, rather than suppressing it. Reaction of either liquid or gaseous nitrogen with titanium will produce temperatures of 3200 °C (5800 °F).

## 7.5 Experiments

The experiments conducted by Underwriters Laboratories Inc. were done as outlined in the Standard for Rating and Fire Testing of Fire Extinguishers, ANSI/UL 711. The Underwriters Laboratories report is attached in its entirety in Appendix E. The Underwriters Laboratories tested four biodegradable, environmentally safe, nontoxic, liquid fire suppression agents; water; and an Underwriters Laboratories listed Class D dry powder agent on a magnesium chip fire (Figures 1 and 2). The magnesium chip fire consisted of 9 or 18 kg (20 or 40 lbs) of dry grignard magnesium grade chips arranged in a 61 cm x 61 cm (2 ft x 2 ft) area on a 6 mm (1/4 in) steel plate. The grignard chips were approximately 6 to 9 mm (1/4 to 3/8 in) long, 3 mm (1/8 in) wide, and 2 mm (1/10 in) thick. The grignard chips were ignited using a hand torch along one side and allowed to burn undisturbed until a deep seated condition was observed such that approximately 50 percent of the magnesium was consumed. Following this freeburn period, suppression began with the extinguishing agents. For the tests involving the Underwriters Laboratories Class D dry powder, a nominal 14 kg (30 lb) dry powder extinguisher was used to apply the agent. The dry powder was applied from a distance of approximately 1.5 m (5 ft) from the fire and for a duration of approximately 35 seconds. For the tests involving the liquid agents or water, a single adjustable pattern discharge nozzle was used to discharge the liquid agents or water at a flow rate of 38 l/min (10 g/min). The nozzle was adjusted to a straight stream pattern and fitted with an air aspirating attachment for one series of fire tests and used as a spray nozzle without the air aspirating attachment for a send series of tests. The liquid agents or water were applied from a distance of approximately 4.5 m (15 ft) from the fire and for a duration of 5 minutes. During each fire test, observations were made for fire extinguishment, reaction of the applied agent with the magnesium, approximate amount of magnesium consumed, and fire spread.

The experiments conducted by the Building and Fire Research Laboratory consisted of 9 kg (20 lbs) piles of oiled titanium turnings arranged in a 61 x 61 x 15 cm high pile (2 ft x 2 ft x 6 in) placed on a 6 mm (1/4 in) steel plate. The steel plate was placed inside a 2.14 m (84 in) diameter steel containment pan. The steel plate was supported on cinder blocks so that the steel plate was at the same level as the rim of the pan. The titanium was ignited using a MAPP gas burner along one side of the pile and allowed to burn undisturbed until a deep seated burning condition was observed such that the flame front had traveled approximately half of the distance across the pile. Following this free burn period, suppression began with the extinguishing agents. For all the tests, the extinguishing agent was applied with a hand held nozzle a distance of approximately 1 m (3 ft) from the fire. During agent application, observations were made for fire extinguishment and reaction of the applied agent with the titanium.

Base line tests were conducted with water to identify a lower limit of application that would not immediately suppress the fire. These baseline tests started at an application rate of 37 l/min (10 g/min), which was the flow used in the magnesium test fires. Unlike the magnesium test fires, this flow rate easily extinguished the titanium fires. The base line experiments indicated a flow rate of 3.7 l/min (1 g/min) of water did not always extinguish the fire. This flow rate was used for all extinguishing agents.

### 7.6 Results and Discussion

The results of the magnesium chip fire tests presented in Table 1. The results indicate that the biodegradable, environmentally safe, non toxic, liquid fire suppression agents were unable to extinguish a Class D combustible metal fire involving magnesium chips. The spray application method offered some advantage over the stream application method by providing a gentler application of agent onto the fire. This gentler application also resulted in smaller quantities of burning magnesium being scattered beyond the test bed area. When the magnesium material was scattered beyond the test bed area, it continued to burn intensely and had the potential to ignite other combustibles. The tests conducted with the Underwriters Laboratories Listed Class D dry powder agent resulted in complete extinguishment of the test fires and no scattering of burning magnesium beyond the test bed area.

Results for the titanium fire experiments are presented in Tables 2. The results of the titanium fire tests show 7 of the 11 tests using water based extinguishing agents successfully extinguished the test fire. All the fire tests using water or water based extinguishing agent initially increased the intensity of the fire. This increase in intensity lasted approximately 10 to 50 seconds after initial application. After this initial increase in intensity, the flame height of the fire and intensity appeared to return to the burning level before agent application. With continued agent application, 7 of the 11 test fires were extinguished within 2 minutes of the start of agent application. In test number 21 a Class D extinguishing agent was used. This particular agent was not listed for use on titanium fires. Although this agent did not completely extinguish the fire it greatly reduced the burning intensity of the fire and was the only agent used that did not cause an initial increase in the fire intensity upon application. Although all the water based extinguishing agents initially increased the intensity of the fire, none appeared to have caused the level of sparking or fuel scattering as seen in the magnesium fire tests.

## 7.7 Conclusions

When tested on magnesium fires the water based extinguishing agents performed similarly to water. Water failed to extinguish the fire and caused the fire to increase in intensity and spread beyond the area of origin. All four of the water based extinguishing agents did the same. When tested on the titanium fires, results were again similar to water. Water alone extinguished one of the two titanium test fires. The water based extinguishing agents extinguished 6 of the 9 titanium test fires. In all cases the water and water based extinguishing agents increased the intensity of the fire upon initial application. However neither water nor the water based extinguishing caused the fire to spread beyond the area of origin as they did in the magnesium test fires. This may have been due to the very slow application rate of the agent in the titanium test fires compared to the application rate in the magnesium test fires. In both series of tests there did not appear to be any benefit gained by using the water based extinguishing agent over that of water.

The Underwriter's Laboratory ANSI/UL 711, Standard for Rating and Fire Testing of Fire Extinguishers test scenario appears to be an acceptable test method for testing Class D extinguishing agents on a small scale. However if fire departments are to use these extinguishing agents on large fires as is shown in references 21 and 22, then a large scale test method should be developed. Several attempts at developing large scale tests have been attempted in the past [25,26]. These test methods often used quantities of burning metals in the hundreds of kg [lbs] range.

## 7.8 References

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## Table 1 - Magnesium Chip Fire Test Results

| Test Number | Pounds of Magnesium | Extinguishing Agent | Preburn Min:Sec | Method of Application | Rate of Application | Duration of Application Min:Sec | Visual Adverse Reaction | Increased Intensity of Fire | Fire Spread Beyond Steel Plate | Fire Extinguished |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 20 | Class D Powder | 15:00 | Direct | na | 0:32 | None | No | No | Yes |
| 2 | 40 | Class D Powder | 25:00 | Direct | na | 0:34 | None | No | No | Yes |
| 3 | 20 | Water | 25:00 | Stream | 10 GPM | 5:00 | Sparking | Substantial | Yes | No |
| 4 | 20 | Water | 25:00 | Spray | 10 GPM | 5:00 | Sparking | Moderate | Yes | No |
| 5 | 20 | Liquid-A 1% | 25:00 | Stream | 10 GPM | 5:00 | Sparking | Substantial | Yes | No |
| 6 | 20 | Liquid-A 1% | 25:00 | Spray | 10 GPM | 5:00 | Sparking | Moderate | Yes | No |
| 7 | 20 | Liquid-B 1% | 25:00 | Stream | 10 GPM | 5:00 | Sparking | Substantial | Yes | No |
| 8 | 20 | Liquid-B 1% | 25:00 | Spray | 10 GPM | 5:00 | Sparking | Moderate | Yes | No |
| 9 | 20 | Liquid-C 1% | 25:00 | Stream | 10 GPM | 5:00 | Sparking | Substantial | Yes | No |
| 10 | 20 | Liquid-C 1% | 25:00 | Spray | 10 GPM | 5:00 | Sparking | Moderate | Yes | No |
| 11 | 20 | Liquid-D 1% | 25:00 | Stream | 10 GPM | 5:00 | Sparking | Substantial | Yes | No |

## Table 2 - Titanium Turnings Fire Test Results

| Test Number | Pounds of Titanium | Extinguishing Agent | Preburn Min:Sec | Method | Rate of Application | Duration of Application Min:Sec | Visual Adverse Reaction | Fire Spread Beyond Steel Plate | Increased Intensity of Fire | Fire Extinguished |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 20 | Water | 2:55 | Stream | 1 GPM | 2:00 | None | No | Yes | No |
| 11 | 20 | Water | 2:20 | Stream | 1 GPM | 2:00 | None | No | Yes | Yes |
| 12 | 20 | 1% Agent A | 4:08 | Stream | 1 GPM | 2:00 | None | No | Yes | Yes |
| 13 | 20 | 1% Agent A | 5:55 | Stream | 1 GPM | 2:25 | None | No | Yes | Yes |
| 14 | 20 | 1% Agent B | 3:00 | Stream | 1 GPM | 2:00 | None | No | Yes | Yes |
| 15 | 20 | 1% Agent B | 3:30 | Spray | 1 GPM | 2:00 | None | No | Yes | Yes |
| 16 | 20 | 6% Agent C | 3:02 | Stream | 1 GPM | 2:00 | None | No | Yes | Yes |
| 17 | 20 | 6% Agent C | 1:30 | Spray | 1 GPM | 2:00 | None | No | Yes | No |
| 18 | 20 | 6% Agent C | 2:00 | Spray | 1 GPM | 2:00 | None | No | Yes | No |
| 19 | 20 | 3% Agent D | 2:00 | Stream | 1 GPM | 2:00 | None | No | Yes | No |
| 20 | 20 | 3% Agent D | 2:23 | Spray | 1 GPM | 2:00 | None | No | Yes | Yes |
| 21 | 20 | Class D | 21:45 | Direct | na | 0:23 | None | No | No | No |

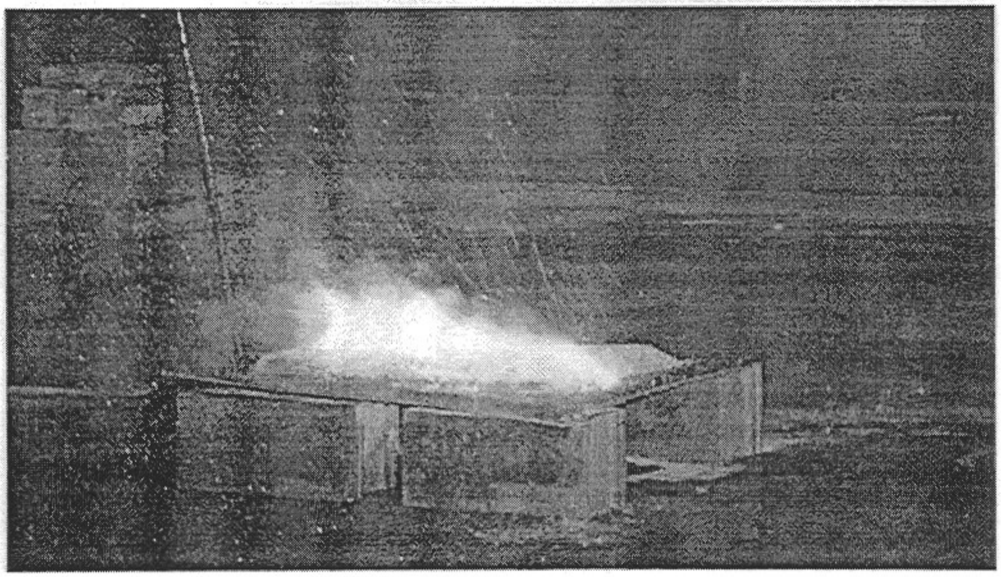

Figure 1. Magnesium fire before suppression

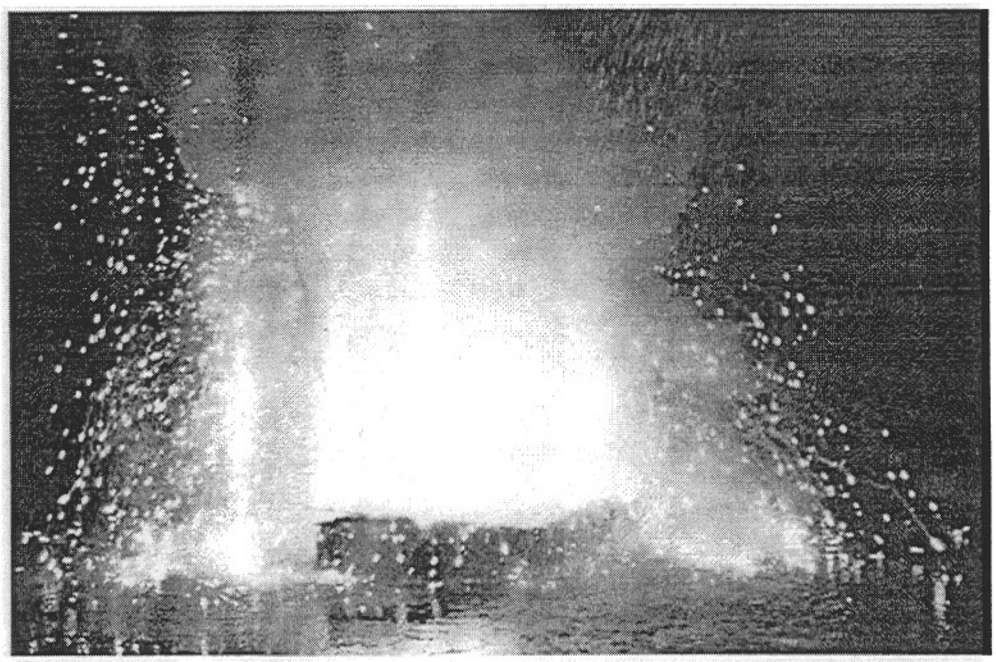

Figure 2. Magnesium fire during suppression with liquid agent.

# CHAPTER 8

# FINDINGS

# FINDINGS

This broad-based study on fire-suppression effectiveness of water-based fire fighting agents utilized laboratory-scale experiments and large-scale fire suppression experiments. Four commercially available fire suppression agent solutions were selected. Water was used as the basis for developing performance data because of its well know physical characteristics and wide use in the fire fighter community. It was found that some of the test methods provide a basis for clear differentiation of fire fighting effectiveness between water and fire-fighting agents. Others demonstrated little capability to differentiate fire-fighting effectiveness. This does not mean that these properties are do not effect fire fighting efficiency, rather that the measurement is not particularly sensitive to the application.

## 1. Physical Characteristic Test Methods for Fire Fighting Agents

### A. The following test methods have the highest degree of differentiation between water and fire-fighting agents.

**Surface Cooling and Fuel Penetration**

Surface cooling of the fuel and penetration of the fuel are important aspects in the suppression of Class A fires. Hardboard, 6 mm (0.24 in) thick, was used as the fuel material for the cooling and penetration experiments because while it is still a "wood product" it is also a homogeneous material. This fact makes the affected-area measurement easier since the liquid is not following grain lines but is spreading radially in a fairly uniform manner. Water and agent solution droplets would be placed on the top surface of the hardboard sample. An infrared camera was focused on the bottom side of the hardboard sample. Time to penetration was measured as was the temperature and the area of the hardboard being cooled by each droplet. The initial penetration time through the hardboard was similar for water and the four agent solutions. However, the area being cooled by the agents was approximately 4 times the area being affected by the water. At the end of each experiment, a portion of the droplet of water was still beaded up on the surface of the hardboard, while the agents had all been absorbed into the sample. This experiment clearly differentiates between the agent solutions and water and demonstrates one of the most distinct advantages of the agents, a wetting capability superior to that of water.

**Agent Retention on Surfaces**

Retention of an agent on an exterior siding material is an important factor for exposure protection. Three different substrates were used for this study: unpainted T1-11 textured plywood, stained T1-11 textured plywood and vinyl siding. A 1.2 m x 2.4 m (4 ft x 8 ft) sample of each siding material was supported by a load cell. After the siding samples had been coated with one of the agents, the mass of each sample was monitored for 6 hours to observe the mass loss (i.e. water loss) from each sample. The temperature and relative humidity were also measured and recorded. Each agent was to be tested with two types of application: fog nozzle and compressed air foam. Again water served as the benchmark.

All of the agent solutions were retained on the wood siding material for a longer period of time. On the vinyl siding material the agent solutions drained off the sample panel faster than water. At the end of the six-hour measurement period the unstained plywood samples, which were treated with agent solutions, retained approximately twice the mass as those treated with water. Similarly the stained plywood samples retained approximately four times the mass as those treated with water. The unstained and stained plywood when treated with the solutions in the form of compressed air foam yielded mass retention effectiveness of 3 and 6 respectively, relative to treatment with water. The results from these tests were then used for the ignition inhibition experiments.

### Ignition inhibition

Ignition inhibition experiments utilizing the cone calorimeter were conducted. Unstained and stained samples of T1-11 textured plywood, treated with agent solutions, foamed and non-foamed were exposed to a 30 kW/m$^2$ external radiant heat source. The time to ignition was measured. Tests were conducted at three different times: immediately after agent application, 3 hours after agent application and 6 hours after agent application. When applied as solutions, the agents performed best at the three hours after application for both the unstained and stained samples. The increase in time to ignition ranged from 4 to 56% relative to samples treated with plain water. When the agents were applied as compressed air foams, the increase in time to ignition ranged from 13 to 100%.

## B. The following test methods have small or no discernable capability to differentiate between water and fire-fighting agents.

### Specific Heat

The specific heat of each agent and each concentrate was tested to determine the amount of heat the solutions and the concentrates absorb relative to plain water. The tests were conducted with a scanning differential calorimeter. The specific heat of the agent concentrates were 9 to 30 percent lower than that of water. The four agent solutions, which were composed of at least 97 percent water, had specific heats lower than water by an amount reflecting a simple mixture of the two liquids.

### Drop Size

An optical array probe water droplet measurement system was used to measure the drop size generated with solutions as compared to those generated with water. A water spray from a 38mm (1 ½ in) fog nozzle at a given pressure was characterized by droplet size and distribution. The experiment was then repeated with solutions of the four fire-fighting agents using the same nozzle and pressure. The droplet distribution indicates a shift in the droplet diameter in various portions of the spray. The median drop size, $D_{v90}$, for the solutions was within 20% of that of water. A change in droplet size could be beneficial or detrimental depending on the application. This potential effect as well as the droplet measurements could benefit from further research.

### Contact Angle

Contact angle also provides a measure of the fire fighting material's ability to coat and cool a fuel surface. Previous research conducted on a hot steel plate showed that by decreasing the contact angle of a drop of water from 90° to 20° by using a surfactant, the heat transfer to the droplet increased by a factor of two. The contact angle measurements were attempted with: stainless steel, unstained and stained plywood siding, hardboard and rubber from automotive tires. For stainless steel and rubber the agents typically reduced the contact angle of water by a factor of four thereby increasing the area of contact by a factor of 2. Comparative contact angle measurements could not be made on the stained plywood and hardboard since the agent solutions would soak into the substrates within a few seconds. Because both water and the agent solutions were absorbed rapidly by the unstained plywood, measurements were not possible.

## 2. Large-Scale Experiments

The following is a listing of the results of the large-scale tests in terms of their effectiveness of fire fighting agent in comparison to water. To provide a measure of fire suppression effectiveness, the water-based agents were evaluated relative to water. In addition to water, aqueous film-forming foam (AFFF) was used as a reference for comparison on the Class B fires and a dry agent powder was used as a reference for the Class D fires.

### *Class A Fires*

Controlled experiments were conducted to examine the fire-fighting effectiveness of water-based fire suppression agents for two types of fire situations: fuel limited fires and ventilation-limited structure fires. The ventilation limited structure fire experiments were completed in March of 1998. The results will be reported by NIST at a later date.

### Automobile Tires

Piles of nine automobile tires were used as the fuel package for a series of 31 fire suppression experiments. The tire pile was ignited from a diesel fuel fire located in a pan underneath the tires. After the tire pile was well involved in the fire and the diesel fuel fire had burned out, suppression began. After fire knockdown, the tire pile was observed for re-ignition, up to 30 minutes. The suppression agents were applied manually at a flow rate of approximately 30 L/min (8 gpm). In addition to comparing water with the four agents, each of the agents was applied in three different ways: spray nozzle, "tube type" aspirating nozzle and compressed air foam. Based on this limited set of experiments application of approximately one third the amount of agent solutions appeared to produce the same results as plain water, with similar rekindle times.

### Smoke Generation

NIST also examined smoke generation during the crib suppression experiments. The qualities which this test methodology examined as critical smoke characteristics were mass concentration and sized distribution of smoke particulates and concentration of combustion gases, carbon dioxide, carbon monoxide, hydrogen cyanide, hydrogen chloride, and nitrogen oxides. These properties of suppressant agents were evaluated in a series of laboratory scale experiments that also utilized water as a benchmark. While these experimental measurements did provide data for post-extinguishment smoke, the qualities of the smoke during extinguishment can not be ascertained from these measurements. The reduction in mass concentration of smoke particulates and combustion gases appears to be dominated by the extinguishment process itself which makes it more difficult to ascertain the impact of specific suppressant agents during the extinguishment process. If the smoke properties during extinguishment are deemed crucial elements, then additional measurements which focus on this aspect should be incorporated in future versions of this protocol.

**Crib Fires**

Suppression experiments using cribs composed of wood and plastic as the fuel were conducted. Each crib consisted of 10 layers, with each layer containing seven 55.9 cm (1.8 ft) long sticks of 3.8 cm (1.5 in) x 3.8 cm (1.5 in) cross section and each successive layer laid crosswise to the previous layer. Fixed spray nozzles were located next to each side of the crib so that the spray pattern from each nozzle covered two thirds of the top surface and three-fourths of the side facing the nozzle. Flow rates used during the suppression experiments ranged from 4.8 L/min (1.3 gpm) to 8.4 L/min (2.2 gpm). Plain water was compared with the four agent solutions; no significant differences in fire suppression capability were observed for this limited set of tests. As noted earlier similar using a fire fighter rather than the fixed position nozzles used in this test lead to results very similar to the tire fire results. This may indicate that the method of application of the suppressant is very important.

*Class B Fires*

A series of Class B fire suppression tests were conducted in conformance with UL 162, Standard for Foam Equipment and Liquid Concentrates. These tests utilize a 4.6 $m^2$ (50 $ft^2$) **heptane** pool fire and consist of the suppression of the fire and then testing for re-ignition and burn-back resistance. Agent was applied at 2.44 and 4.88 $L/min/m^2$ (0.06 and 0.12 $gpm/ft^2$), which is one and a half and three times the rate required by the standard for AFFF application. The higher flow rates were used because the agents could not extinguish the fire at the standard AFFF application rate. The four agents had fire knockdown (control) times similar to AFFF but two of the agents C and D did not completely extinguish the fire in all of the tests. AFFF had a higher resistance to burn-back, longer time to re-ignition, than the other four agents.

Full-scale fire experiments were conducted with 92.9 $m^2$ (1000 $ft^2$) **gasoline** pool fires. Agent application was made with a 454 L/min (120 gpm) hose stream (i.e. 4.88 $L/min{\cdot}m^2$ (0.12 $gpm/ft^2$)). Two application techniques were used with each of the four agents in the large-scale tests. One application was made with a self-aspirating tube nozzle and one application was made with a non-aspirating adjustable fog nozzle. AFFF and water were used as benchmark agents for these tests. Plain water could not extinguish this fire. Based on this data set, the results of the UL 162 fire suppression tests correlated well with the full-scale fire suppression demonstration, especially for the aspirated application.

*Class D Fires*

A series of Class D fire suppression experiments has been conducted based on UL 711, Standard for Rating and Testing of Fire Extinguishers, Chapter 8. The fuel bed was composed of **magnesium** chips. Water and a UL listed Class D dry powder were used as bench mark agents in these tests. The four agents were applied as a straight stream and as a spray. In the case of the liquid agents, the application rate was 38 Lpm (10 gpm). Only the dry powder was effective in extinguishing the fire. When water was applied the fire intensity increased and sparks were produced. This limited set of experiments produced results, which did not allow differentiation between the liquid agents and plain water.

A second series of experiments using oiled, **titanium** turnings was conducted. A 9 kg (20 lb) fuel bed similar 0.6 m (2 ft) on a side and 150 mm (6 in.) high was easily suppressed with 38 Lpm (10 gpm) of plain water. When the flow rate of water was reduced to 3.8 Lpm (1 gpm), suppression was no longer accomplished with the plain water. Again, the results from this limited set of experiments were similar for the liquid agents and plain water.

**Summary**

For demonstration purposes, tests examining the following properties and conducted in accordance with the methods identified in this report can be used to provide information on some important characteristics contributing to measures of the fire fighting effectiveness of liquid fire suppression agents relative to water.

- specific heat
- fuel cooling and penetration
- mass retention
- ignition inhibition
- tire fire suppression
- wood crib fire suppression
- heptane fire suppression
- magnesium fire suppression

The results presented here provide preliminary data upon which fire fighting effectiveness tests may be developed. Certain plausible scenarios can be constructed regarding the action of the agents in extinguishing fires. However, additional research efforts are necessary to develop a broader based for such development. Areas recommended for further study include:

- effectiveness of agent application technique (i.e. fog nozzle vs. compressed-air foam),
- fire suppression effectiveness test methods should be designed to reflect the training of fire fighter to include the complexities necessary to expeditiously extinguish a fire,
- investigation into a test to measure emulsification capability, and
- additional tests involving structural-fire suppression.

The fuel cooling and penetration experiment should be developed further, since it incorporates the benefits of the surface tension and contact-angle tests as well as cooling and penetration aspects for a given fuel.

# APPENDIX A

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# APPENDIX B

# ALTERNATIVE FIRE EXTINGUISHING AGENTS

# Alternative Fire Extinguishing Agents Marketed in the United States as Being Suitable for Class A Fires, Class A and B Fires, and Class A, B. and D Fires

Report Prepared for the National Institute of Standards And Technology, Gaithersburg, Maryland, by the Alliance for Fire and Emergency Management, Ashland, Massachusetts, under Order Number 43NANB609885

Principal Investigator: John Liebson
Submitted: May 1996

## Methodology

The Principal Investigator used the following methods of finding as much information as possible about the extinguishing agents listed in this report:

1. Review of articles and advertisements in the fire service press.

2. Contacts with known manufacturers of subject agents.

3. Contacts with manufacturers of foam proportioning devices.

4. Internet search for product information, including World Wide Web, Gopher, and WAIS.

5. Search of relevant databases such as those at BFRL, Intermountain Fire Sciences Laboratory, U.S. Fire Academy.

6. Telephone conversations with knowledgeable people in this area of fire protection such as Paul Schlobohm (BLM-NIFC), Chief David Abernathy (Texas State Forest Service), Chuck George and Ceci Johnson (Intermountain Fire Sciences Laboratory-USFS.)

7. On-line requests for input through such sources as Safetynet on CompuServe, misc.emerg-services and bit.listserv.fire-l on Usenet, electronic mailing list maintained by the National Association of Fire Equipment Dealers.

8. Thorough vetting of all exhibitors' booths at the 1996 Fire Department Instructors' Conference (FDIC).

The following list is of all identified "Alternative Fire Extinguishing Agents" that are marketed in the U.S. as being suitable for Class A Fires, Class A and B Fires, or Class A, B. and D Fires. Section I is alphabetical by manufacturer, giving name and address and name(s) of extinguishing agents; the number in square brackets [] after each agent name refers to the number of the tab (In the index which follows this text) under which the relevant literature is indexed. Section II of the list is of those extinguishing agents for which the Principal Investigator, having the name of an agent, was either unable to locate the relevant supplier or for which the supplier, having been contacted, failed to provide any information.

### I. Known Manufacturers

1. Angus Fire, Angier-Kennebec Road & Broad Street, Angler, North Carolina 27501. Forexpan 'S'. [1]

2. Ansul Incorporated, 1 Stanton Street, Marinette, Wisconsin 54143-2542. Silv-Ex Foam Concentrate. [2]

3. Baum's Castorine Co., Inc., 200 Matthew Street, Rome, New York. Pyrocool. [3]

4. Chemguard Inc., 204 South Sixth Avenue, Mansfield, Texas 76063. Class A Plus. [4]

5. Chemonics Industries, Inc., P.O. Box 21568, Phoenix, Arizona 85036. Fire-Trol Class A Foams Firefoam 103, 103B, 104. [5]

6. Delta-Omega Technologies, Ltd., P.O. Box 81518, Lafayette, Louisiana 70598-1518. Blackout Class A Foam and HazClean WA/TP. [6]

7. Denko, 414 West Sunrise Highway, Patchogue, New York 11772. Drench. [7]

8. Drexel Chemical Company, 1700 Channel Avenue, Memphis, Tennessee 38113-0327. Control-A. [8]

9. Eco-Foam, USA, Inc., 1120 Richmond Street, Reading, Pennsylvania 19604. Eco-Foam 2004. [9]

10. Environmental Products Inc., 393 Locust Street, Denver, Pennsylvania 17517. FireXPlus and Gem Enviro-Skin. [ 10]

11. Fine Water Products, 205 N. Cornell Avenue, Fullerton, California 92631. Fine Water DP30 and Fine Water HS 10.80. [11]

12. Firefreeze Worldwide, Inc., 270 Route 46, Rockaway, New Jersey 07866. ColdFIre. [12]

13. Fire Protection, Inc., 18425 S.E. Federal Highway, Jupiter, Florida 33469-1725. Barricade. [13]

14. Fuel Buster Laboratories, Inc., 261 Tiger Way #1, Peachtree City, Georgia 30269. Fuel Buster. There appears to be some question as to this product being listed for class A applications, as shown on appended literature. [14]

15. Macs Fire and Safety, Inc., 104 S. Jackson, Litchfield, Illinois 62056. Wetting Agent--Class A Concentrate. [15]

16. Monsanto Wildfire Center, 810 East Main Street, Ontario, California 91761. Phos-Chek WD-881.[16]

17. National Foam, 150 Gordon Drive, Exton, Pennsylvania 19341-1350. 1st Defense Class A Foam Concentrate. [17]

18. Neel Associates, Inc., P.O. Box 20126, Waco, Texas 76702-0126. Water Stretcher Class A Foam; product appears to be a commercial version of Fire Quench, a foam produced by the Texas Department of Corrections, P.O. Box 99-Industry, Huntsville, Texas 77342, and sold only to other government agencies. [18]

19. Nochar, Inc., 10333 N. Meridian Street, Suite 215, Indianapolis, Indiana 46290-1074. Nochar E112. [19]

20. Old Firehand Corporation, 21930 Third Place West, Bothell, Washington 98021. FIreBlok series. [20]

21. Pyrocap International Corporation, 15010-B Farm Creek Drive, Woodbridge, Virginia 22191. Pyrocap B-136. [21]

22. Stevens Co., P.O. Box 23312, Toledo, Ohio 43623. Fire Quencher and Penetro Wet. [22]

23. Sunrise Environmental Scientific, P.O. Box 10207, Reno, Nevada 89510. Water Plus. [23]

24. The Westford Chemical Corporation, P.O. Box 798, Westford, Massachusetts 01886-0798. BloSolve PinkWater. [24]

25. Winsol Laboratories, 1417 N.W. 51st Street, Seattle, Washington 98107-3188. Wetter Water, Water Extender. [25]

II. Unidentifiable Products

26. Del Bueno Co., supposedly a California; could find no references to the company or to the: product, Fire Foam.

27. Real Ideas, Inc., FireOut; this product has been marketed in the U.S., but no current references to either it or the company could be located.

28. BB. Schaeffer Manufacturing, 102 Barton, St. Louls, Missouri 63104. Fire Water 990; company was contacted, failed to provide any information.

29. Stockhouse Chemical, supposedly in North Carolina, Cease Fire: Unable to locate this company.

# APPENDIX C

# AGENT CHARACTERISTICS

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Note: In this section, non-SI units have been used, in certain cases, since those are the customary terms that are widely used and recognized.

## 1 Background

In 1986 when the USDA Forest Service began using foam as a tool in its wildfire management program, products were evaluated and procured using a set of Interim Requirements [1]. The requirements were fundamental to all wildland fire chemicals being used at the time. Although these requirements did not include all of the performance characteristics known to be desired in a wildland fire foam product, they included characteristics deemed to be necessary for chemicals used in existing wildland fire operations. The characteristics were defined in requirements for health and safety, stability, and corrosion.

In 1992 an International Foam Specification Workshop was held in Missoula, Montana. The participants compiled a list of the characteristics of foam concentrate, foam solution, and foam thought to impact effectiveness, be of importance to users, or cause concern to any of the user agencies. These characteristics were incorporated into a draft "International Wildland Fire Foam Specification." This document was reviewed by representatives of the firefighting branches of natural resource agencies and chemical suppliers from the United States, Canada, France, and Australia. Comments were incorporated into a revised specification [2].

Test methods and performance requirements were specified if they were readily available and known to be applicable. In other cases test methods were specified without performance requirements (for information and classification purposes). In a few cases even the test method had to be modified or developed. A Wildland Fire Foam Characterization Study was undertaken to provide the information necessary to transform the resulting characteristics and requirements list into a formal specification.

The characteristics to be studied can be grouped into several broad categories:

Health, Safety, and Environment
Corrosion and Materials Effects
Physical/Chemical Properties
Effectiveness
Stability

For each characteristic a suitable test method was defined, the performance of foams currently in use evaluated in accordance with the selected method, and a range of acceptable performance levels determined for those tests that were still considered to be necessary. Some characteristics that did not provide useful information were eliminated from the study. The performance results were then packaged in a form that was accessible to the end users to assist in product selection. This chapter is a summary of that performance information and of experimental work still in progress.

## 2 Health Safety, and Environment

### 2.1 Review of Product Composition and Risk Assessment

Forest Service policy requires that all chemicals used for fire fighting be evaluated prior to use [3]. As a part of the evaluation, an initial submission package including a confidential disclosure of all ingredients is required. This information is reviewed for compliance with Forest Service Policy which precludes the use of products containing ingredients on certain regulatory lists unless a Risk Assessment determines the use will not result in increased risks to the firefighters, the general public, or the environment. The regulatory lists to be used are:

1. 40 CFR 355 Appendix A, CERCLA Extremely Hazardous Substances (EHS)
2. National Toxicology Program's (NTP) Annual Report on Carcinogens (U.S. Department of Health and Human Services)
3. International Agency for Research on Cancer (IARC) monographs (potential carcinogens)

Additional lists are also reviewed by the Forest Service and other natural resources agencies to determine the status of ingredients and any regulatory requirements. The regulatory lists are shown below:

1. 40 CFR 302.4, CERCLA Hazardous Substances
2. 40 CFR 261.33, RCRA Acutely Hazardous and Toxic Products
3. 40 CFR 372, SARA Title III, sec. 313

Ingredients present in small amount in various concentrates were found on these lists. In most cases the quantities present were far below any threshold for reporting. One ingredient was found on the list of extremely hazardous ingredients. This ingredient was included in the Risk Assessment performed by Labat-Anderson. Its effect on total risk was found to be insignificant.

### 2.2 Risk Assessment

In keeping with the National Environmental Policy Act (NEPA), the Forest Service conducted a risk assessment to determine the risk from the use of wildland fire fighting chemicals and whether an environmental assessment was required. Labat-Anderson under contact to the Forest Service performed a risk assessment on the use of all Forest Service qualified/approved wildland fire fighting chemicals. Risks to humans, both firefighters and the general public, aquatic species, terrestrial and avian species, and vegetation were determined using existing information available to the public and confidential information supplied by the product manufacturers.

Little information is available on the formulated products, although there is currently work being done by several Department of the Interior agencies to determine the impacts of these products on aquatic and terrestrial species. More information is available on the individual ingredients and this was included in the risk assessment. All of the information was consolidated, summarized, and incorporated into human health and ecological models to determine the potential impacts. These impacts were studied in relation to the predicted impact from unsuppressed fire.

Under typical use conditions there is little risk from using any of these products in the intended manner. The complete report "Chemicals Used in Wildland Fire Suppression; A Risk Assessment" [4] is available through the Forest Service's National Wildfire Suppression Technology Program.

## 2.3 Mammalian Toxicity

Health and safety testing on laboratory mammals has been a part of the required testing from the time the first foam was evaluated. These tests are based on standard toxicology procedures. Standard protocols [5-9] were followed by Stillmeadow, Inc. to determine the performance of foam concentrates and 1.0-percent foam solutions. All products were tested for acute oral and dermal toxicity, and skin and eye irritation. Table 1 shows the results of the tests; Table 1A shows the grading scheme for the skin and eye irritation results.

In the event that acute oral or acute dermal toxicity exceeds the main performance level, there is provision to perform an inhalation toxicity test. If the results are satisfactory, the product may be used. To date, this provision has not been used by the Forest Service for approval of Class A foams.

All of the foam concentrates cause moderate to severe irritation to eyes. To prevent eye injury splash goggles should be worn when handling the concentrates. In addition, exposure can cause slight to moderate skin irritation and chapping. Wearing suitable impervious gloves will prevent exposure.

The results of the health and safety testing, requirements, and protective equipment and safe handling procedures were reviewed by the Forest Service Safety and Health Branch. All manufacturers have listed appropriate protective equipment on their Material Safety Data Sheets (MSDS). These guidelines should be followed when handling these products.

## 2.4 Inhalation/Smoke Toxicity

The inhalation toxicity of fire fighting chemicals, including foams, alone and when applied to Ponderosa pine needles and then burned is being investigated in a pilot study.

In phase 1, each concentrate or powder was injected into the breathing zone of the test rats. Powders were suspended as fine particulate. Liquids were misted as fine aerosols. The concentration of each chemical that could be put into the breathing zone is a limiting factor in the preliminary study. The maximum amount of each product in the air is less than the $LC_{50}$ for that product. This results in the maximum amount of material that can be put into the aerosol being shown as the $LC_{50}$.

In phase 2, finely chopped Ponderosa pine needles were gently heated, the smoke and vapors trapped in the breathing zone of the test animals, and an $LC_{50}$ determined for the needles. Each product was then added to Ponderosa pine needles and the tests repeated to determine the effects of breathing smoke from chemically treated fuels. This work is in progress.

Following completion of the pilot study and review of the results, additional testing may be added to the study.

## 2.5 Biodegradability

The Class A foam concentrates were tested for biodegradability using two similar test methods. The first method, the aerobic aquatic biodegradability test (as required by the National Fire Protection Association standard 298, 1994[10]) [11], is most applicable for use in sewer treatment and industrial effluent plants where the bacterial cultures are exposed to the same chemicals continually or frequently. The aerobic aquatic biodegradability test may also be applicable when dealing with the concerns of fixed-wing tanker bases. This test specifies a period of time for the bacterial medium to acclimate to the test product. The progress of the biodegradation is determined by measurement of the carbon dioxide formed. Progress of the reaction is followed for 28 days by classical wet chemistry techniques.

The second method, the ready biodegradability or closed bottle test [12] appears to more closely fit a typical wildland fire use scenario. There is a single or short-term exposure to a chemical during fire fighting operations. In most cases additional exposures will occur at widely spaced time intervals, possibly years or decades. This test calls for the inoculation of the bacterial medium with the product to be tested, with no acclimation period, and the decrease in oxygen content monitored for 28 days by instrumental methods to determine the extent of biodegradation.

Table 2 shows the results of the biodegradability tests. Using the ready biodegradability method, four of the foam concentrates were determined to be readily biodegradable while two were not biodegradable. Using the aerobic aquatic biodegradability test method, one product was determined to be readily biodegradable, one product was partially biodegradable, and four products were determined to be not biodegradable.

There were unexpected differences in results from some of the tests, when compared to results of supplier-sponsored biodegradability tests performed using the same general test method. Further work needs to be performed to address this inconsistency prior to imposing a specific biodegradability test limit of foam concentrates. If the test is sensitive to interlaboratory variability or the foams are at the boundary between biodegradable and not biodegradable, this type of contradictory results can occur. Further work on this problem is being discussed.

Based on the similarity between test exposures and actual field exposures, the ready biodegradability test is the preferred method to determine the biodegradability of wildland fire fighting foams.

## 2.6 Fish Toxicity

In 1993, the Midwest Sciences Center, U.S. Fish and Wildlife Service (now the Biological Resources Division of the U.S. Geological Survey) laboratory in Yankton, South Dakota performed a series of toxicity tests to determine the effect of several representative wildland fire control chemicals on aquatic organisms throughout the food chain from green algae, through daphnids and hyallelas to rainbow trout, fathead minnows, and chinook salmon. Several different lifestages were tested for each species. The testing was performed in accordance with ASTM method E-729-88a, "Standard Guide for Conducting Acute Toxicity Tests with Fishes, Macroinvertebrates, and Amphibians" [13] using both ASTM hard and soft water.

The results of these tests suggest that young (60 days post hatch) rainbow trout (Oncorhynchus mykiss) are as sensitive as any and more sensitive than most of the tested organisms [14]. Based on this finding, further testing can be done on a plentiful species with reasonable assurance that acceptable levels of toxicity to trout will provide an adequate level of safety for species of potentially greater concern. Generally, toxicity in hard water is similar to toxicity in soft water. Further testing will use soft water since that is the more common laboratory test condition and additional information would be more readily available.

Following the work performed in 1993, an additional study was undertaken in 1996, to determine the effect of all of the approved wildland fire fighting chemicals to a single lifestage of rainbow trout. As part of the study, exposures of 60 days (±15) days post hatch (dph) rainbow trout to each of the foam concentrates in ATSM soft water were conducted and evaluated [15].

The results of the toxicity tests on rainbow trout using all of the approved foams are summarized in Table 3. Although there is a wide range of results, all meet proposed requirements of $LC_{50} > 10$ mg/liter of ASTM soft water when measured after 96 hours [16].

NFPA 298 [10] uses a slightly different set of protocols. Depending on the conditions specified, the protocols may be equivalent. In any case, it is important that all conditions and procedures be defined as completely as possible, to minimize variation.

## 2.7 Flash/Fire Point

Several methods of determining flash point have applicability to the varied ways in which foam concentrate is used, handled and stored in practice. The open-cup method (and fire point) is a measure of the hazard in the workplace, such as when the concentrate is being transferred into reservoir tanks, especially at high temperatures or near hot equipment. Closed-cup methods are more applicable in determining the hazards involved in storing and transporting the concentrate.

All of the approved products were submitted to an outside testing laboratory for determination of both the open-cup and closed-cup flash point and fire point. The Pensky-Martens method (D-93) was chosen for the closed cup flash point tests [17] and the

Cleveland method (D-92) was used for the open cup flash and fire point tests [18]. The results are shown in Table 4. Only one of the concentrates had a flash point by either open or closed cup method. The closed-cup flash point was substantially lower than the open-cup flash point for this product [19,20].

### 2.8 Vapor Pressure

The Reid vapor pressure [21] was determined on all of the concentrates. There is concern that the alertness and general abilities of the flight crews of aircraft with open storage systems could be impaired by the vapors of some of the products. Vapor pressure values can assist in determining this.

The vapor pressure of each of the concentrates on the qualified/approved products list has been determined by an outside laboratory. As shown in Table 5, all of the values are between 4.1 kPa (0.6 psi) and 6.9 kPa (1.0 psi) [19,20]. For comparison, the vapor pressure of methanol is 12.9 kPa (1.9 psi) and of gasoline is 53.3 kPa (7.7 psi).

It is possible that looking up the vapor pressure of the solvents and the health categories of these solvents will provide similar information.

## 3 Corrosion and Materials Effects

### 3.1 Uniform Corrosion

All of the approved products were tested to determine the corrosivity of the foam concentrates and solutions (0.1-percent and 1.0-percent) to four alloys (2024-T3 aluminum, 4130 steel, yellow brass, and Az31B magnesium) at two temperatures (20 °C and 50 °C) and two immersion conditions: totally immersed and partially immersed (half in vapor and half in the solution) following the procedures in Forest Service Interim Requirements [1].

Table 6A shows the specific requirements for each category of product and alloy. Table 6 lists the results of the corrosion tests on fresh material and from solutions prepared from stored concentrate. With one exception, all of the results are within the required limits of 2 to 5 mils (thousandths of an inch), dependent on the specific alloy, temperature, and immersion conditions for use from fixed-wing airtankers, helicopter buckets, and ground engines. Only one of the products meets the requirements for corrosion to magnesium alloys, which is part of the criteria for application from fixed-tank helicopters. If the corrosion rate exceeds that limit, it may not be used from fixed-tank helicopters but it may still be used in other applications.

Individual agencies may further restrict use based on other policies and considerations. Currently, the Forest Service does not approve the use of foams from fixed-wing airtankers.

### 3.2 Intergranular Corrosion

Intergranular corrosion is the removal of small quantities of material from the grain boundaries. Weakening of the structural parts is out of proportion to the amount of material corroded. Representative aluminum coupons exposed to the foam solutions under all conditions were sliced, mounted, etched, and examined for intergranular corrosion following accepted methods [1]. No intergranular corrosion is allowed, and none was found.

In addition, if the foam is to be approved for use from fixed-tank helicopters, there must be no intergranular corrosion found on representative magnesium coupons exposed under all test conditions. No intergranular corrosion was found on magnesium coupons exposed to the product that met the uniform corrosion requirements for magnesium.

### 3.3 Corrosion to 6061-T6 Aluminum

There are currently no requirements, pertaining to the corrosion of 6061-T6 aluminum, for any of the wildland fire chemicals. However, as a result of severe pitting corrosion to the tank doors (made of 6061-T6 aluminum) of several aircraft following a single fire season of use, work has been on-going to determine the specific type and/or sequence of exposure that caused the corrosion. Three foam concentrates were included in the tests, which also included exposure to several of the commonly used long-term retardants. The study has been conducted in several parts; the results of each affecting the specific conditions used in the next. When completed this study may provide information that will result in additional requirements for all wildland fire chemicals.

The test method described in the Interim Requirements [1] but substituting 6061-T6 aluminum for 2024-T3 was used to determine the uniform corrosion rate. Corrosion results were less than 1.0 mils-per-year (mpy). The limit set for 2024-T3 aluminum is 2.0 mpy.

During phase 2 the test pieces of 6061-T6 aluminum were totally immersed in long-term retardant for 2 weeks. After air drying, the coupons were totally immersed in water for 24 hours and again allowed to air dry. The coupons were then totally immersed in foam concentrate or solution at room temperature for 24 hours and again allowed to air dry. Finally the coupons were totally immersed in room temperature water and for an extended period of time. Half of the coupons were removed from the water, cleaned, weighed, and the uniform corrosion rate determined. A second coupon was exposed in the same manner but removed from water at 90, 120, 150, and 180 days, visually inspected and reimmersed in water. After 180 days these coupons were cleaned, weighed, and the uniform corrosion rate determined. All coupons exhibited pitting, ranging from slight to severe, and the typical flower growth on the surface.

In the third phase of the study, the coupons were alternately immersed in retardant for 23 hours and foam solution for 1 hour, for three days and then totally immersed in room temperature water for 90 or 180 days as described for phase 2. Pitting and flower growths were found on all test specimens.

For the fourth phase, coupons were alternately exposed to foam solution for 8 hours and air for 16 hours for three days, followed by 90-day and 180-day immersion in water.

Again, pitting was found on all test specimens.

Based on the results of the laboratory tests and the field surveys conducted immediately following discovery of the pitting, exposure to foam and water rather than exposure to long-term retardants seems to be the factor that allows the pitting to occur.

### 3.4 Effects on Non-metallic Components

For some time, Canadair has had their own specification for foam products used in their water-scooping aircraft. The specification contains requirements that the foam concentrates and solutions not significantly degrade (determined by changes in volume or hardness) several non-metallic materials of construction. These materials are primarily found in their foam kits but may also be found elsewhere. These same materials are commonly used throughout the industry for storage and handling of foam concentrates and therefore the test results are of interest beyond that originally expressed by Canadair.

The materials originally considered were nitrile rubber, cross-linked polyethylene/nylon, PVC, fiberglass with epoxy resin and S-8802 sealant. Additional materials were added as they were incorporated into new foam kits. These include S-81733 sealant, neoprene rubber, high-density polyethylene, teflon and flexible polyolefin.

A pilot study using two foam concentrates was performed. Canadair supplied NWST with several of the test materials listed in their specification [22]. The tests followed the Canadair requirements for materials and exposures. Their in-house procedures (alternately immersing the materials in the test liquid and then allowing them to drain and air dry) were followed as closely as possible.

Some materials showed changes in hardness or volume following exposure. The changes in hardness were within limits set by Canadair; however, several of the volume changes exceeded the limit. Due to size and shape of the test samples and the method of measuring the volume, change in fluid level before and after sample immersion, the volume changes are probably not significant.

### 3.5 Effects on Protective Coatings

Canadair makes extensive use of protective coatings to minimize the corrosion damage to its aircraft. This has been so successful that its warranties may be voided if unacceptable products are used in its aircraft. The Canadair specification for Class A foams has a fairly long list of alloys (2024-T3 aluminum, 5052-T6 aluminum, 4130 steel, 6Al-4V titanium, and corrosion resistant steel 302) and protective coatings through all steps in the finishing process that are tested [22]. The test itself is straightforward, involving repetitions of alternately exposing the materials to the foam (concentrate or solution) and to the air. At the end of 20 repetitions, the integrity of the coating is determined.

NWST performed a pilot study using test materials (alloys and coatings) provided by Canadair. These were exposed to two foam concentrates and 1.0-percent solutions following

Canadair procedures. Some blistering and changes in the surface finish were noted.

Additional consultation with Canadair will be required to determine whether this testing responsibility will be transferred to NWST or whether it will continue to be conducted by Canadair as needed. Transfer of testing to NWST would likely make the results more generally available; however, these results may not be as widely applicable as those on the non-metallic components.

## 4 Physical/Chemical Properties

### 4.1 Viscosity, Density and pH

The general physical and chemical properties may be measured easily and used to track some changes in the product over time or with changing temperatures. Baseline measurements on the viscosity, density, and pH [23] of the foam concentrates at room temperature (approximately 21 °C) have been made.

These results, shown in Table 7. Viscosities range from 30 to 145 centipoise; densities from 1.010 to 1.042 grams per milliliter; and pH from 6.6 to 8.9.

Many of the physical/chemical characteristics do not have a numeric requirement but instead the determination of a baseline value is made and, in some cases, comparison to values determined after storage or other treatment [2].

The changes from the baseline values, especially for viscosity, vary significantly. Some products perform more consistently across a wide range of temperatures while others are significantly affected by fairly small temperature variations.

### 4.2 Surface Tension

Surface tension is related to the wetting ability of the foam solution, either unaerated or drained from an aerated foam. While this is an indirect measurement, it lends itself to reproducible, quantifiable results in the laboratory.

Surface tension tests were performed on all of the foam products, using dilutions from 0.01 percent to 6.0 percent. All tests were performed following the procedures found in ASTM D-1331 [24]. Dilutions were made using laboratory tap water. All products were tested at concentrations from 0.01 percent to 6.0 percent. This exceeds the Forest Service approved use levels, 0.1 percent and 1.0 percent, at both ends of the range, but does show the relative stability of the surface tension measurement. As shown in Table 8, the measured surface tension values are contained in a fairly narrow range. Within the approved use range, values varied from 21.9 to 27.0 dynes/cm. For comparison, water has a surface tension of approximately 73 dynes/cm and a Forest Service approved wetting agent had surface tension values of 28.5 to 48.3 dynes/cm over the same range of dilutions.

## 4.3 Conductivity

Measuring the conductivity of a foam solution using an inexpensive, hand-held conductivity-pen is a simple means of determining the concentration of the solution. However, both water quality and temperature have a significant affect on the measured values, in some cases the changes are at least as large as the changes due to concentration differences. Using the same water, both quality and temperature, to prepare calibration standards for the specific foam concentrate will minimize these impacts.

Table 9A shows the results of concentration changes for the selected foam solutions when the same source of water is used for all dilutions and the solution temperature is held constant. Table 9B shows the effect of changing the solution temperature for a solution of fixed concentration.

Measurements of conductivity are used by several equipment manufacturers to determine the concentration of a foam solution. With care this is a fairly reliable, accurate, and simple method; however, a better approach may be to calibrate the equipment before field use rather than in the field.

Care should also be taken when using some of the commercially available concentration measuring devices. These often use conductivity to determine the concentration, and work well for the several foam concentrates with similar conductivity characteristics. However, some of the products have significantly different conductivity ranges and the meters must be calibrated specifically for that product.

## 4.4 Refractive Index

Simple hand-held refractometers incorporating an arbitrary scale are recommended to determine the concentration of Class B foam in some widely used standards. Class B foam is typically used at 3 or 6 percent, with no intermediate points, which makes it fairly easy to determine whether or not the concentrate level is acceptable. In theory this can also be done for Class A foam; but the changes in refractive index with small changes in concentration are very slight.

Less than one full unit on either of two typical refractometers covering the range of concentration from 0.1 percent to 1.0 percent. Typical readability of these refractometers is 0.25 and the precision is about ±0.5. This makes it very difficult to get meaningful measurements.

A benchtop refractometer was used to determine the refractive indices of several dilutions, covering the approved range, of one of the foam products. The change in readings over that range was so slight that it is unlikely that currently available hand-held instruments will be able to distinguish between them.

## 5 Effectiveness

### 5.1 Pour Point

The pour point is the lowest temperature at which a liquid will flow. It is a very simple test that can be performed easily in the field or the laboratory. It provides a value similar to the freezing point of a simple liquid but without the more complex equipment needed to determine freezing points, which are often not meaningful when dealing with mixtures, especially if several components are of near equal volume but very different freezing points.

The method used for the Class A foams followed the general procedure found in ASTM D-97 [25] but used a stepped test to determine the ability of the concentrate to flow at three specific temperatures, rather than to determine the actual temperature at which the concentrate would no longer flow. The three temperatures used for this test are 4 °C, 0.6 °C, and –15 °C.

All of the approved products were tested to determine pour point. The results are shown in Table 10. All of the products were fluid at 4 °C but became less so at 0.6 °C and were solid at –15 °C.

This test does not measure how easily the concentrates flow or how fast, but just that they will flow. Additional testing by another method would be needed to determine flow rates under specific conditions.

### 5.2 Viscosity as a Function of Temperature

The viscosity of the concentrate is related to the ability of the concentrate to flow and the ease, accuracy and reproducibility of proportioning. The viscosity of each concentrate was measured using a viscometer as the concentrate warmed, beginning at 2 °C (35 °F), and at ten-degree intervals from 4 °C to 49°C (40 °F to 120 °F) [26].

Table 11 shows the changes in viscosity as temperature is decreased. Maximum viscosities for the various concentrates range from 65 to 1120 centipoise at the lowest temperatures and from 18 to 40 centipoise at the highest temperatures.

With this amount of variation it is likely that products will have different flow characteristics at different temperatures, and that different products will have different flow characteristics at some temperatures, especially at the extremes of the test range.

### 5.3 Flow-Through Time as a Function of Temperature

Other tests which may be more direct measures of the ability of the concentrate to flow consistently regardless of temperature can also be made. A Marsh funnel, about 2 liters capacity [27], and a Zahn cup [28], about 50 milliliters capacity, have been used. In each case the reservoir is filled with the concentrate and the time for a fixed volume to flow out of an orifice in the bottom is measured.

Measurements using the Marsh Funnel with a small tip insert [29] were made. Initially, two products were tested at 5 °C, 21 °C, and 38 °C (40 °F, 70 °F, and 100 °F). Times for 1 quart of concentrate to flow from the funnel ranged from 40 second to 168 seconds.

This method shows some promise for a simple laboratory test of flow that may better relate proportionability. All of the currently approved foam concentrates have been tested using the Marsh Funnel. Results, shown in Table 16, indicate differences at 21 °C (70 °F) and 38 °C (100 °F), with some overlap of values. The flow-through times at 21°C (70 °F) range from 49 seconds to 77 seconds. The values at 38 °C (100 °F ) range from 41 seconds to 58 seconds. There are much larger differences in flow-through times at 5 °C (40 °F), with different concentrates taking from 76 seconds to 234 seconds for 1 quart of concentrate.

The Zahn cup has a fixed orifice. A different cup is selected when a different size orifice is needed. Three different orifice sizes were purchased that represented the typical viscosities encountered with foam concentrates. There is some overlap such that some viscosities could be measured with more than one orifice size.

To take a measurement, the Zahn cup is immersed in the test fluid then quickly pulled straight up out of the fluid when it is full (50 ml). The time is measured from when the cup rises above the surface of the fluid until concentrate stream flowing out of the cup separates rather than being a straight stream. The results of testing all of the approved products are shown in Table 17. The results are similar to those found using the Marsh funnel and related well to the Brookfield viscosity values.

The Zahn cup has an advantage over the Marsh funnel of using a small volume of concentrate and being small enough to fit directly through the drum or bucket opening of the foam concentrate containers. Because the concentrate can flow from the cup directly back into the container mess and cleanup are minimized. This is convenient in the laboratory, but would be a real plus for field use.

## 5.3 Effect of Temperature Changes on Proportioning

Several of the tests that have been performed over a range of temperatures are attempts to determine how a product might behave during proportioning typical field situations. Recently several very low flow proportioners have become available that would make direct measurement of proportioning possible in the laboratory. It may be possible to develop a test method for laboratory trials.

## 5.4 Miscibility

Many of the aerial foam generating systems in use, helicopter buckets and fixed-tanks, do not contain mixers to assure that foam concentrate and water are well mixed prior to application. Therefore the ease with which concentrate goes into water solution, miscibility, application. Therefore the ease with which concentrate goes into water solution, miscibility, is of interest.

The foam concentrate and water at several temperatures were combined with controllable agitation to determine miscibility. The general method is similar to that for determining the foaming properties of wetting agents [29].

A pre-measured volume of foam concentrate is added to water, while stirring slowly at 60 ± 10 rpm. After each 10 revolutions, the stirrer is stopped and the contents of the beaker examined. If the contents were not visually homogeneous, the process is repeated, with 10 revolution increments of stirring between observations. If the solution was not uniform after 100 revolutions of mixing, the concentrate was considered to be not miscible.

In the first series of tests all solutions were prepared using tap water. The four combinations of 4.4 °C and 21 °C water and 4.4 °C and 21 °C foam concentrate were used. Most of the solutions prepared with 21 °C water and concentrate were homogeneous after 10 revolutions of the stirrer, and all were homogeneous after 90 revolutions. As temperatures decrease it generally takes more revolutions before the solutions became homogeneous. When both water and concentrate were cold, four products were homogeneous, three products required 90 to 100 revolutions, and one never dispersed.

The next series of tests were performed with distilled, tap, and synthetic seawater. Table 12 summarizes the results of these tests. Warm concentrates were readily miscible in warm distilled and tap water. Other solutions produced a variety of results. Mixing foam concentrate with seawater often results in a cloudy liquid, a gelatinous mixture, or a layer of precipitate on the bottom of the test vessel. Clearly some products are not salt water compatible under these conditions. It should be noted that some of the products that produced a cloudy solution when added to seawater did produce reasonable foam expansions and drain times under the same conditions.

This test may have some significance when selecting a foam provided that the results are considered, in context, along with the results of the other tests to determine suitability to a particular situation. In general, products that will not disperse easily probably should not be used in dipping and scooping operations without good on-board mixing systems.

### 5.5 Wetting Ability (Drave's Skein Test)

The Drave's skein test is commonly used in the detergent industry to assess the effectiveness of the wetting agents in their products. The time is takes for a standard skein of cotton thread, attached to a weight, to sink when dropped into a graduated cylinder containing the test solution is measured. Other than the test skeins, the only equipment needed to perform this simple test is a graduated cylinder, a stop watch or watch with a second hand, and a standard weight.

Test measurements were made in accordance with ASTM D-2281, "Standard Method for

Evaluation of Wetting Agents by the Skein Test" [30]. Using the standard weight (3.0 grams), very fast sink times were obtained with the products tested. The very fast sink times made accurate time measurements difficult and did not allow for differentiation between products.

A modification, recommended in the ASTM standard, was made to the procedure and a lighter, 0.8 gram, S-hook was used. This resulted in slower sink times and showed differences in performance for different products and for different concentrations of the same product. This looked promising until measurements at low concentrations were being run. With some products and especially the lower, 0.1 percent, concentrations of most products inconsistent results were sometimes noted. In some cases the skein did not sink even after long periods of time. This suggested that the weight was too light.

A second modification was made, using an intermediate weight, about 1.5 gram, hook. This resulted in moderate sink times, changes between products and between dilutions of the same product and gave sink times in all cases.

Table 13 shows the results from testing all of the approved foam concentrates at four concentrations over the approved use range. The effects of changes in concentration on the wetting effectiveness of each of the foams are readily apparent. Unlike surface tension, which tends to be constant throughout the use range, there are significant differences in the wetting behavior of different products and different concentrations of the same product. Either the test is much more sensitive than surface tension or some factor other than surface tension is influencing the wetting effectiveness.

While a skein of spun cotton thread is certainly not the same as natural forest fuels, the skein test may be a reasonable method of determining the wetting characteristics of foam solutions.

### 5.6 Foaming Ability

A simple shake test was used to provide a simple assessment of the foaming ability of a foam solution. Ten milliliters of a solution of a known concentration and temperature were poured into a 100-milliliter graduated cylinder and the stopper inserted. The cylinder was agitated vigorously for ten seconds, then the volume of foam in the cylinder determined. Immediately after shaking, and at one-minute intervals for 5 minutes, then at 10 and 15 minutes, the volume of solution drained from the foam was measured.

A preliminary test was performed on two products with distinct visual differences in foam producing capabilities. Differences were also seen using this test. The product that was a better foamer when tested in the foam generator also produced more, longer lasting foam in the graduated cylinder.

Tests were performed on all of the approved products at several different concentrations and water types. The visible foam structure remains intact through most of the test period, so that the more meaningful values are the total height of foam in the cylinder and the amount of solution drained out at 1 or 2 minutes. Additional tests were run to determine the repeatability of the method. This test shows sufficient repeatability that it may be suitable as a field quality control test. It may also be suitable as a simple test to assure that a product is a foam rather than a non-foaming wetting agent.

Table 14 shows the effect of varying the solution concentration on the total volume of foam produced and on the drain time of the foam. Table 15 shows the effects of altering the water temperature and/or quality for the same test.

This test is not designed to be quantitative or to relate directly to the foam produced from an operational system. What is shows is whether or not the product will produce foam. There is not a specific relationship between the expansion and drain time produced in this test and what would be produced using a specific set of field equipment. It is simply a means of monitoring performance of a specific foam over time or from batch to batch.

The test has several features that are preferred for field quality control testing; it is simple, quick, and relatively reproducible. It also shows different performance for different foams and concentrations. This test may be useful to field units when determining relative behavior of stored concentrate. It may also be used to determine whether a new brand of foam concentrate can be expected to give the same performance as the familiar product, at the same concentration.

## 5.7 Blender Foam Tests

Tests have been done on foam prepared in a standard household type, multi-speed blender. The findings from a matrix of mixing speeds and times show the following:

> Distilled water yields a greater foam volume than tap water but the drain rates are similar for the same blending speed and time.
>
> Blending at slow speeds for a longer time yields the most stable foam. High speeds break the foam down.
>
> Foam volume did not vary much with mix time or speed until the greatest times and speeds were reached, when the foam volume tended to decrease.

While a blender can be used for generating and evaluating foam, it is not as desirable as a foam generator. The foams tend to have very small bubbles and very long drain times, which are not typical of many foams produced in the field. A blender may be able to be used in somewhat the same manner as the foaming ability test to do comparative testing for field information.

## 6 Expansion and Drain Time

Expansion and drain time are a function of the foam concentrate, concentration, generating system, water quality, and temperatures. The combination of all of these factors, and probably others, determines the quality of the foam produced.

## 6.1 Foam Generator

NWST has been using a laboratory generator built on-site to determine the behavior of foam produced from the test concentrates. This generator is not likely to be reproduced but another of the same general type should give similar results. This generator functions on building-supplied compressed air. The foam solution is batch mixed into a cone-bottomed stainless steel container with the exit at the lowest point. Compressed air is used to push the foam solution through the system where it is aerated by the addition of compressed air into the fluid stream. The aerated solution then goes through a short mixing chamber containing glass beads. The final foam is delivered through a slotted tube that allows application to a fuel bed or standard collection vessel.

The pressure of the compressed air flowing into the generator can be controlled at each point to produce a variety of foam types from the same solution. Following some preliminary testing and evaluation, four settings have been adopted as test standards. The foam produced by this system is consistent from test to test and day to day for the same settings.

Because of the concerns expressed at the earlier workshop about having a test system that could not be repeated at other locations, a second foam generator has been built from readily available components. It shares the same general features as the first generator but is somewhat smaller and includes flow meters so that the same production parameters can be developed in several laboratories. Quick disconnect components were added at some points to make it easier to modify the system and also to clean it at the end of a test.

The foams produced from this system are similar but not identical to those from the original generator. Additional work is proceeding that should allow description of a set of generation parameters to give a standard foam for interlaboratory comparisons. It has been used to study the changes in foam characteristics when flows are changed and when nozzle length or diameter is varied.

## 6.2 Test Matrix

There are many factors that will potentially affect the characteristics of the foam that is generated. The factors that can be controlled and measured were identified. Several points were selected for testing. It is likely that trends in performance will carry over to points between test points. It is also likely that other factors will influence performance.

The basic matrix, shown below, looks simple, but results in many hundreds of tests.

Foam concentrate: All approved and candidate products
Water: Distilled, tap, artificial seawater
Temperature: 4 °C, 21 °C, and 38 °C (40 °F, 70 °F, and 100 °F)
Concentration: 0.1%, 0.3%, 0.6%, and 1.0%
Concentrate condition: Fresh, frozen (2-3 days), aged (1 year)
Generator: 4 settings to simulate dry foam, fluid foam, and wet foam, and very wet (near or barely) foam

Generator: 4 settings to simulate dry foam, fluid foam, and wet foam, and very wet (near or barely) foam

A simplified sea water formula was included in the last draft of the specification. The simplified formula is preferable to many of the more complex recipes for several reasons. The complex formulas may be very representative of seawater in one location but much less representative for another. The generic formula representatives (to a degree) seawater as opposed to tap or municipal water. The complex formulas contain a large number of minerals including several heavy metal salts, increasing complexity, increasing the likelihood of error in making the sea water, and also increasing the expense. The heavy metal salts must be disposed of in accordance with the applicable hazardous waste regulations.

The original test matrix, including all of the approved products, has been completed using the original laboratory generator. Additional tests are being performed as needed to check and verify results and as new products are submitted.

### 6.3 Drain Time

The time that it takes for 25 percent of the fluid to drain from a foam, the 25-percent drain time, is a fairly standard measure of foam quality used for Class B foams. Class A foams used in natural resource fire suppression tend to be fast draining foams. The drain time is dependent not only on the foam but also on the method used to measure the drain time.

The standard vessel used to measure drain time of a Class B foam (National Fire Protection Association 1994) is a 1-liter graduated cylinder having a diameter of approximately two inches. The volume of solution in the bottom of the cylinder is measured at specific times. The data can then be used to prepare a graph of time versus the drain volume, and a 25-percent drain time determined.

A dry foam does not readily flow into the cylinder; as a result large holes often form in the foam. The very fluid foams drain so quickly that it is difficult to determine the proper volume of foam to add. One solution to the first problem is to use a foam collection container with a flat, broad profile similar to a show box. This is easier to fill evenly. This style of container is also easier to fill quickly. Provided that the foam generator being used is capable of higher production, it is possible to get a more accurate fill of a fast draining foam with the type of container. The volume of foam solution drained out is more difficult to measure accurately in a flat container. One method of determining the volume drained from the foam is by weight differences.

Each container, of known volume, has a series of thirteen, 0.043-inch holes, arranged in a roughly circular pattern having about a 0.5-inch diameter. The holes can be covered with a small piece of masking tape and the container weighed. After filling with foam the container is again weighed to determine the weight of foam solution. The container is placed on a balance so that as the corner with the holes is over a receiving flask, not on the balance. When the tape is removed from the holes, the solution drains from the holes, and the weight of solution decreases. The weight loss is monitored by computer, which calculates the 25-

percent, 50-percent, and 75-percent drain times. The percent drained in 5, 10, and 15 minutes is also calculated. Figure 1 shows drain curves for a fast and a slow draining foam.

In general except for the dry foams at the highest concentrations, all of the foams drained in one to three minutes. Decreasing the number and/or size of the drain holes could increase the differentiation between different drain times.

Looking at the results from the opposite perspective some foams have only drained five or ten percent in 10 minutes while others have drained more than ninety percent in 5 minutes. This information would be useful in selecting foams or foam types for a specific job such an exposure protection or building wet line for backfiring.

## 6.4 Expansion

The data have been summarized in a series of bar charts. Figures 2 through 9 illustrate the variations of expansion that can be obtained. The results of these tests show that some products are more sensitive to the presence of chemical salts in the water than others, some perform nearly as well in hot or cold water (assuming that the initial mixing of the concentrate and water is adequate), and some seem to have a much greater range of readily attainable expansions and drain times than others.

Expansions from 1.5:1 to nearly 25:1 have been produced. Combinations of some foam brands and generator settings yield distinctly different foams, especially with the high and low water temperatures. Using the bar graphs rather than precise values when analyzing the results is helpful in seeing trends and more accurately reflects the level of repeatability of the expansion tests.

Comparing the results of distilled water foam and tap water foam suggests that some products are much more sensitive to water quality especially the presence of some mineral salts. Similarly, some products perform equally well in cold or warm water, while others show significant differences in performance.

## 6.5 Stability

Stability of foam concentrates is assessed by comparing the performance of the fresh concentrate to an aged concentrate. The comparison may also be between solutions made from fresh and aged concentrate. Aged concentrate may or may not have undergone specific changes in temperature, daylight, or other factors.

Fresh solutions made from concentrates that have been stored for one to three years generally have the same performance as fresh solutions made from fresh concentrate. Solutions that are stored as solution, however, degrade quickly. In a day or less the foam expansion and drain time characteristics change. Expansions decrease from what is typical with fresh solution and drain times are faster.

Changes in corrosivity are typically minor and within the usual range of repeatability. Most characteristics have only minor changes or do not change at all. The viscosity temperature relationships appear to be the one exception. Once they undergo heating and cooling, some products do not behave in the same manner as when fresh. Other characteristics have not been systematically studied, but this should be included in future work.

## 7 Foam Fire Testing

### 7.1 Moisture Retention

One aspect of the fire performance of any suppressant is the moisture retention or rate of evaporation. Because suppressants depend on the water they contain for their effectiveness, a product that slows evaporation will be considered more effective than another with a faster rate of evaporation.

A series of drying tests were performed comparing water and all of the foams, both as solutions and fairly wet and dry foams. Using the general procedures and experimental parameters of "Influence of Moisture on Effectiveness of Fire Retardants" [31] each product or water was applied to fuel beds of shredded aspen excelsior or Ponderosa pine needles in a consistent manner using the NWST foam generator. Standard applications of 3.8 liters (1 gal) and 7.6 liters (2 gal) of solution per 9.3 $m^2$ (100 $ft^2$) of fuel surface (1 GPC and 2 GPC) were used.

A series of nine test beds on individual balances, monitored by a computer, were set up in the wind tunnel and conditioned for four hours at 32 °C (90 °F), 20% relative humidity, and 2.2 m/s (5 mph) of wind. The weight loss of each bed was continuously recorded by computer until all added moisture was driven off.

Figure 10 shows representative data sets from the drying study. In all cases, the variations in time to reach dryness were within the experimental variation of the test so that no differences were seen.

### 7.2 Long-term Combustion Retarding Effectiveness

A pilot study was conducted to determine whether or not the foam fire suppressants may have long-term retardant effects. Two of the approved foams and 10.6-percent diammonium phosphate (DAP) solution were applied to the fuel beds and burned in accordance with the procedures described in the Forest Service specification for long-term retardants.

In each case at least three fuel beds containing aspen excelsior and three fuel beds containing pine needles were treated with 1 gallon-per-hundred-square-feet (GPC) of test product. Three additional beds of each fuel type were treated with 2 GPC of product. All beds were dried under standard test conditions, 32 °C (90 °F) and 20-percent relative humidity, until 95 to 100 percent of the added moisture was driven off. All beds were burned in the wind tunnel with 5 mph of wind. Rate of weight loss and rate of flame spread were determined and compared with the same parameters from untreated beds.

product. The foams had superiority factors of -1 and -3.

## 7.3 Fire Suppression Effectiveness Testing

Lack of a fire effectiveness test has been recognized as a deficiency in the current requirements and proposed specification. There are a large number of types of tests that have been proposed, and some have been tried with varying degrees of success.

No one test is likely to be suitable as a single evaluation tool for fire foams. Following the 1994 meeting at Thunder Bay, a series of interrelated tests was proposed. It included tests to determine moisture retention, stability, and insulation on vertical surfaces, direct attack of low to moderate intensity fires, and penetration into surface fuels.

Working for several different groups, Underwriters Laboratory (UL) and National Institutes of Standards and Technology (NIST) have performed series of fire tests with inconclusive results. Hopefully, a method can be defined that will differentiate between different foams in a manner consistent with field reports. A great deal of time and effort remain before the development of a standardized fire suppression effectiveness test is completed.

## 8 Foam Compatibility

The compatibility of foam concentrates and the possible effects on performance of non-compatibility have always been a concern. That concern has become greater as more engines and aircraft go to on-board holding tanks for concentrate. It is seldom possible to completely empty the tank before refilling and some intermixing is likely. Because of the numbers of possible combinations of products and effects little work has been done.

Anecdotal evidence suggests that some combinations of foams may decrease the foaming and wetting ability of the resulting solution. Limiting the effects to look for would make this type of testing much more attainable. It is likely to remain a low priority until other work has been completed.

In the interim it is important to minimize intermixing. Empty the concentrate reservoir as completely as possible. Do not refill a partially full reservoir but add several buckets and use. Repeating this process several times will result in a small amount of intermixing and use of the mixtures quickly.

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Table 1

**Toxicity of Fire Suppressant Foams**[1]

| **Product** | **Concentration** | **Acute Oral $LD_{50}$** | **Acute Dermal $LD_{50}$** | **Skin Irritation**[2] | **Eye Irritation Unwashed Eyes** | **Eye Irritation Washed Eyes** |
|---|---|---|---|---|---|---|
| **Requirement** | Concentrate | >500 mg/Kg[3] | >2000 mg/Kg[4] | P.I. score: <5.0[5] | ≤Mildly irritating[5] | ≤Mildly irritating[5] |
| | 1.0% (V/V) | >5000 mg/Kg | >2000 mg/Kg | P.I. score: <5.0 | ≤Mildly irritating | ≤Mildly irritating |
| Phos-Chek WD 861 | Concentrate | **>5000 mg/Kg** | **>2000 mg/Kg** | **P.I. score: 3.2**<br>Moderately irritating<br>Toxicity category III | **Severely irritating**<br>Irritation score: 56.0<br>Toxicity category I | **Severely irritating**<br>Irritation score: 61.0<br>Toxicity category I |
| | 1.0% (V/V) | **>5000 mg/Kg** | **>2000 mg/Kg** | **P.I. score: 0.3**<br>Slightly irritating<br>Toxicity category IV | **Minimally irritating**<br>Irritation score: 7.3<br>Toxicity category IV | **Minimally irritating**<br>Irritation score: 10.0<br>Toxicity category IV |
| Ansul Silv-Ex | Concentrate | **>5050 mg/Kg** | **>2020 mg/Kg** | **P.I. score: 2.7**<br>Moderately irritating<br>Toxicity category III | **Severely irritating**<br>Irritation score: 42.2<br>Toxicity category I | **Severely irritating**<br>Irritation score: 40.3<br>Toxicity category I |
| | 1.0% (V/V) | **>5050 mg/Kg** | **>2020 mg/Kg** | **P.I. score: 0.4**<br>Slightly irritating<br>Toxicity category IV | **Minimally irritating**<br>Irritation score: 4.0<br>Toxicity category III | **Minimally irritating**<br>Irritation score: 6.0<br>Toxicity category III |

[1] Scores and ratings for acceptance under Forest Service specification and requirements are shown in bold face. All others are for informational purposes.

[2] P.I. score is the primary irritation score based on the first 72 hours of observation.

[3] If $LD_{50} \geq 50$ but $\leq 500$, then recommend protective gear and safe handling procedures. No $LD_{50} < 50$ is acceptable.

[4] If $LD_{50} \geq 200$ but $\leq 2000$, then recommend protective gear and safe handling procedures. No $LD_{50} < 200$ is acceptable.

[5] If more irritating, recommend protective gear and safe handling procedures.

Table 1 (continued)

**Toxicity of Fire Suppressant Foams[1]**

| **Product** | **Concentration** | **Acute Oral $LD_{50}$** | **Acute Dermal $LD_{50}$** | **Skin Irritation[2]** | **Eye Irritation Unwashed Eyes** | **Eye Irritation Washed Eyes** |
|---|---|---|---|---|---|---|
| **Requirement** | Concentrate | >500 mg/Kg[3] | >2000 mg/Kg[4] | P.I. score: <5.0[5] | $\leq$Mildly irritating[5] | $\leq$Mildly irritating[5] |
| | 1.0% (V/V) | >5000 mg/Kg | >2000 mg/Kg | P.I. score: <5.0 | $\leq$Mildly irritating | $\leq$Mildly irritating |
| Fire-Trol FireFoam 103B | Concentrate | **>5050 mg/Kg** | **>2010 mg/Kg** | **P.I. score: 1.8**<br>Slightly irritating<br>Toxicity category IV | **Moderately irritating**<br>Irritation score: 22.5<br>Toxicity category I | **Moderately irritating**<br>Irritation score: 23.0<br>Toxicity category I |
| | 1.0% (V/V) | **>5050 mg/Kg** | **>2010 mg/Kg** | **P.I. score: 0.3**<br>Slightly irritating<br>Toxicity category IV | **Minimally irritating**<br>Irritation score: 4.0<br>Toxicity category III | **Minimally irritating**<br>Irritation score: 4.7<br>Toxicity category III |
| Phos-Chek WD 881 | Concentrate | **>5000 mg/Kg** | **>2000 mg/Kg** | **P.I. score: 4.0**<br>Moderately irritating<br>Toxicity category III | **Severely irritating**<br>Irritation score: 63.5<br>Toxicity category I | **Severely irritating**<br>Irritation score: 57.7<br>Toxicity category II |
| | 1.0% (V/V) | **>5000 mg/Kg** | **>2000 mg/Kg** | **P.I. score: 0.3**<br>Slightly irritating<br>Toxicity category IV | **Minimally irritating**<br>Irritation score: 2.0<br>Toxicity category III | **Practically non-irritating**<br>Irritation score: 2.0<br>Toxicity category IV |

[1] Scores and ratings for acceptance under Forest Service specification and requirements are shown in bold face. All others are for informational purposes.

[2] P.I. score is the primary irritation score based on the first 72 hours of observation.

[3] If $LD_{50} \geq 50$ but $\leq 500$, then recommend protective gear and safe handling procedures. No $LD_{50} < 50$ is acceptable.

[4] If $LD_{50} \geq 200$ but $\leq 2000$, then recommend protective gear and safe handling procedures. No $LD_{50} < 200$ is acceptable.

[5] If more irritating, recommend protective gear and safe handling procedures.

Table 1 (continued)

**Toxicity of Fire Suppressant Foams**[1]

| **Product** | **Concentration** | **Acute Oral $LD_{50}$** | **Acute Dermal $LD_{50}$** | **Skin Irritation**[2] | **Eye Irritation Unwashed Eyes** | **Eye Irritation Washed Eyes** |
|---|---|---|---|---|---|---|
| **Requirement** | Concentrate | >500 mg/Kg[3] | >2000 mg/Kg[4] | P.I. score: <5.0[5] | ≤Mildly irritating[5] | ≤Mildly irritating[5] |
| | 1.0% (V/V) | >5000 mg/Kg | >2000 mg/Kg | P.I. score: <5.0 | ≤Mildly irritating | ≤Mildly irritating |
| Fire-Trol FireFoam 104A | Concentrate | **>5050 mg/Kg** | **>2020 mg/Kg** | **P.I. score: 3.9**<br>Moderately irritating<br>Toxicity category III | **Moderately irritating**<br>Irritation score: 29.3<br>Toxicity category I | **Moderately irritating**<br>Irritation score: 20.016.0<br>Toxicity category II |
| | 1.0% (V/V) | **>5050 mg/Kg** | **>2020 mg/Kg** | **P.I. score: 0.5**<br>Slightly irritating<br>Toxicity category IV | **Minimally irritating**<br>Irritation score: 5.3<br>Toxicity category III | **Minimally irritating**<br>Irritation score: 5.3<br>Toxicity category III |
| Angus ForExpan S | Concentrate | **>505 mg/Kg** | **>2020 mg/Kg** | **P.I. score: 2.0**<br>Moderately ir9itating<br>Toxicity category III | **Moderately irritating**<br>Irritation score: 19.5<br>Toxicity category I | **Moderately irritating**<br>Irritation score: 19.3<br>Toxicity category II |
| | 1.0% (V/V) | **>5050 mg/Kg** | **>2020 mg/Kg** | **P.I. score: 0.7**<br>Slightly irritating<br>Toxicity category IV | **Minimally irritating**<br>Irritation score: 3.7<br>Toxicity category IV | **Minimally irritating**<br>Irritation score: 6.3<br>Toxicity category IV |

[1] Scores and ratings for acceptance under Forest Service specification and requirements are shown in bold face. All others are for informational purposes.

[2] P.I. score is the primary irritation score based on the first 72 hours of observation.

[3] If $LD_{50} \geq 50$ but $\leq 500$, then recommend protective gear and safe handling procedures. No $LD_{50} < 50$ is acceptable.

[4] If $LD_{50} \geq 200$ but $\leq 2000$, then recommend protective gear and safe handling procedures. No $LD_{50} < 200$ is acceptable.

[5] If more irritating, recommend protective gear and safe handling procedures.

Table 1 (continued)

**Toxicity of Fire Suppressant Foams[1]**

| **Product** | **Concentration** | **Acute Oral $LD_{50}$** | **Acute Dermal $LD_{50}$** | **Skin Irritation[2]** | **Eye Irritation Unwashed Eyes** | **Eye Irritation Washed Eyes** |
|---|---|---|---|---|---|---|
| **Requirement** | Concentrate | >500 mg/Kg[3] | >2000 mg/Kg[4] | P.I. score: <5.0[5] | ≤Mildly irritating[5] | ≤Mildly irritating[5] |
| | 1.0% (V/V) | >5000 mg/Kg | >2000 mg/Kg | P.I. score: <5.0 | ≤Mildly irritating | ≤Mildly irritating |
| Pyrocap B-136 | Concentrate | **>5050 mg/Kg** | **>2020 mg/Kg** | **P.I. score: 2.3**<br>Moderately irritating<br>Toxicity category IV | **Moderately irritating**<br>Irritation score: 18.7<br>Toxicity category I | **Moderately irritating**<br>Irritation score: 16.0<br>Toxicity category II |
| | 1.0% (V/V) | **>5050 mg/Kg** | **>2020 mg/Kg** | **P.I. score: 0.3**<br>Slightly irritating<br>Toxicity category IV | **Minimally irritating**<br>Irritation score: 3.0<br>Toxicity category IV | **Minimally irritating**<br>Irritation score: 4.0<br>Toxicity category IV |
| Fire Quench | Concentrate | **>5050 mg/Kg** | **>2020 mg/Kg** | **P.I. score: 2.0**<br>Moderately irritating<br>Toxicity category IV | **Moderately irritating**<br>Irritation score: 20.5<br>Toxicity category I | **Moderately irritating**<br>Irritation score: 16.7<br>Toxicity category I |
| | 1.0% (V/V) | **>5050 mg/Kg** | **>2020 mg/Kg** | **P.I. score: 0.1**<br>Slightly irritating<br>Toxicity category IV | **Minimally irritating**<br>Irritation score: 8.3<br>Toxicity category III | **Minimally irritating**<br>Irritation score: 8.0<br>Toxicity category III |

[1] Scores and ratings for acceptance under Forest Service specification and requirements are shown in bold face. All others are for informational purposes.

[2] P.I. score is the primary irritation score based on the first 72 hours of observation.

[3] If $LD_{50} \geq 50$ but $\leq 500$, then recommend protective gear and safe handling procedures. No $LD_{50} < 50$ is acceptable.

[4] If $LD_{50} \geq 200$ but $\leq 2000$, then recommend protective gear and safe handling procedures. No $LD_{50} < 200$ is acceptable.

[5] If more irritating, recommend protective gear and safe handling procedures.

## Table 1A

## Key to Toxicity Ratings for Skin Irritation Tests

### Primary Irritation Index - Calculation

An irritation score for each rabbit is determined. Two factors, inflammation and swelling, are scored at each observation with a maximum score of 4 for each factor at each observation.

The irritation scores for each rabbit, determined at 0.5, 24, 48, and 72 hours, are averaged

The average for each rabbit is added to determine "total irritation"

The total is divided by the number of rabbits tested to determine the primary irritation index

### Primary Irritation Descriptive Rating

A descriptive rating is assigned, based on the primary irritation index, as shown below:

| Descriptive Rating | Primary Irritation Index |
|---|---|
| Non irritating | 0.0 |
| Slightly irritating | 0.1-1.9 |
| Moderately irritating | 2.0-5.0 |
| Severely irritating | 5.1-8.0 |

### Dermal Irritation Toxicity Categories (40 CFR 162.10)

| Toxicity Category | Irritation Level at 72 Hours |
|---|---|
| I | Corrosive |
| II | Severe irritation |
| III | Moderate irritation |
| IV | Mild or slight irritation |

Table 1B

## Key to Toxicity Ratings for Eye Irritation Tests

### Eye Irritation Grading Scale

The cornea, iris, and conjunctivae are examined and scores assigned based on a standard scale for several factors of appearance, swelling, discharge, and area of irritation. The total score is the simple sum of all of the category scores. The maximum score is 110.

A rating category is assigned, based on the maximum eye irritation score. If the eye irritation continues at a specific level beyond the allotted time, the category may be increased by one level.

The rating categories are described below:

| Rating Category | Average Score | Category Description |
|---|---|---|
| Non-irritating | 0.0-0.5 | All scores must be zero at 24 hours; otherwise, increase category one level |
| Practically Non-irritating | 0.5-2.5 | All scores must be zero at 24 hours; otherwise, increase category one level |
| Minimally Irritating | 2.5-15.0 | All scores must be zero at 72 hours; otherwise, increase category one level |
| Mildly Irritating | 15.0-25.0 | All scores must be zero at 7 days; otherwise, increase category one level |
| Moderately Irritating | 25.0-50.0 | Scores must be $\leq$10 for 60% or more of the rabbits. The mean score at 7 days must be $\leq$20. If the 7-day mean score is $\leq$20, but <60% of rabbits have scores <10, then no rabbit can have a score >30; otherwise, increase category one level |
| Severely Irritating | 50.0-80.0 | Scores must be $\leq$30 for 60% or more of the rabbits. The mean score at 7 days must be $\leq$40. If the 7-day mean score is $\leq$40, but <60% of rabbits have scores <30, then no rabbit can have a score >60; otherwise, increase category one level |
| Extremely Irritating | 80.0-110.0 | |

## Eye Irritation Toxicity Categories

| Category | Descriptive Criteria for Eye Irritation Ratings |
|---|---|
| I | Corrosive (irreversible destruction of ocular tissue) or corneal involvement or conjunctival irritation persisting through Day 21. |
| II | Corneal involvement or conjunctival irritation clearing in 8-21 days. |
| III | Corneal involvement or conjunctival irritation clearing in 7 days or less. |
| IV | Minimal effects clearing in less than 24 hours. |

Table 2

## Biodegradability
## Summary of Results by Two Methods

| Product | Aerobic Aquatic Biodegradability[1] | Ready Biodegradability Closed Bottle Test[2] |
|---|---|---|
| Ansul Silv-Ex | Readily Biodegradable<br>100% DOC at 28 days | Readily Biodegradable<br>≥60% at 28 days |
| Fire-Trol FireFoam 103B | Not Biodegradable | Not Biodegradable<br>< 45% at 28 days |
| Phos-Chek WD 881 | Not Biodegradable | Readily Biodegradable<br>≥60% at 28 days |
| Angus ForExpan S | Not Biodegradable | Readily Biodegradable<br>≥60% at 28 days |
| Pyrocap B-136 | Partially Biodegradable<br>27% DOC at 28 days | Not Biodegradable<br><55% at 28 days |
| Fire Quench | Not Biodegradable | Readily Biodegradable<br>≥60% at 28 days |

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[1] Results of the aerobic aquatic biodegradability tests are based on the initial dissolved oxygen content.

[2] Results of the ready biodegradability tests have been corrected for the amount of water in the concentrate.

Table 3

## Toxicity of Foam Concentrates To Selected Life-Stages of Rainbow Trout[1]

| Product | 96-Hr $LC_{50}$[2] at Each Life State<br>Egg | <br>Embryo larvae | <br>Swim-up fry | <br>60 DPH[3] | <br>90 DPH[3] |
|---|---|---|---|---|---|
| | milligrams/liter | | | | |
| Ansul Silv-Ex | >78 | 15 | 20 | 22 | 22 |
| Fire-Trol FireFoam 103B | | | | 12[4] | |
| Phos-Chek WD 881 | 44 | 13 | 13 | 15 | 20 |
| Fire-Trol FireFoam 104 | | | | 13[4] | |
| Angus ForExpan S | | | | 22[4] | |
| Pyrocap B-136 | | | | 156[4] | |
| Fire Quench | | | | 39[4] | |

[1] Testing was performed by National Biological Service at Yankton, SD.

[2] ASTM soft water was used for all of the tests.

[3] DPH = days post hatch; a deviation from nominal of ± 15 days is acceptable.

[4] These tests were performed in 1996. The remaining tests were performed in 1993.

Table 4

## Flash Point and Fire Point

| Product | Pensky-Martens[1]<br>Closed Cup Flash Point<br>°C (°F) | Cleveland Open Cup[2]<br>Flash Point<br>°C (°F) | Cleveland Open Cup[2]<br>Fire Point<br>°C (°F) |
|---|---|---|---|
| Phos-Chek WD 861 | None | None | None |
| Ansul Silv-Ex | 46 (115) | 85 (185) | 85 (185) |
| Fire-Trol FireFoam 103B | None | None | None |
| Phos-Chek WD 881 | None | None | None |
| Fire-Trol FireFoam 104 | None | None | None |
| Angus ForExpan S | None | None | None |
| Pyrocap B-136 | None | None | None |
| Fire Quench | None | None | None |

[1] Tested in accordance with ASTM D-93.

[2] Tested in accordance with ASTM D-92.

Table 5

## Vapor Pressure[1] of Foam Concentrates

| Product | Vapor Pressure |
|---|---|
| Phos-Chek WD 861 | 4137 Pa |
| Ansul Silv-Ex | 4137 Pa |
| Fire-Trol FireFoam 103B | 3447 Pa |
| Phos-Chek WD 881 | 6895 Pa |
| Fire-Trol FireFoam 104 | 6895 Pa |
| Angus ForExpan S | 4137 Pa |
| Pyrocap B-136 | 6205 Pa |
| Fire Quench | 6895 Pa |

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[1] All tests were conducted in accordance with ASTM D-323; Standard Methods of Test for Vapor Pressure of Petroleum Products (Reid Method).

Table 6A

**Maximum Allowable Corrosion Rates (mil-per-year) for Wildland Fire Chemicals.[1]**

| Alloy: | 2024-T3 Aluminum | | | | 4130 Steel | | | | Yellow Brass | | | | Az-31-B Magnesium | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Immersion: | Total | | Partial | | Total | | Partial | | Total | | Partial | | Total | | Partial | |
| Temperature: °F | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 |
| | mils-per-year | | | | | | | | | | | | | | | |
| Premix Components | | | | | | | | | | | | | | | | |
| Liquid components & concentrates (except fixed-tank helicopters)[2] | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | --- | --- | --- | --- |
| Liquid components & concentrates for fixed-tank helicopters | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 10.0 | 10.0 | 10.0 | 10.0 |
| Mixed Retardants | | | | | | | | | | | | | | | | |
| Fixed-wing airtankers[3] | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 5.0 | 5.0 | 2.0 | 2.0 | 5.0 | 5.0 | --- | --- | --- | --- |
| Helicopter with internal or fixed tank[4] | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 5.0 | 5.0 | 2.0 | 2.0 | 5.0 | 5.0 | 2.0 | 4.0 | 2.0 | 4.0 |
| Ground application or helicopter with bucket[2] | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 5.0 | 5.0 | 2.0 | 2.0 | 5.0 | 5.0 | --- | --- | --- | --- |

[1] All corrosion rates will be determined by 90-day weight loss tests. All uniform corrosion rates are the maximum allowable average of at least 3 replicates.

[2] Magnesium corrosion tests will be performed for performance information.

[3] Intergranular corrosion tests will be performed on aluminum coupons; no intergranular corrosion is allowed. Magnesium corrosion tests will be performed for performance information.

[4] Intergranular corrosion tests will be performed on aluminum and magnesium coupons; no intergranular corrosion is allowed.

Table 6

**Uniform corrosion rates determined by 90-day weight loss tests for coupons exposed to fire fighting foams**

| Alloy: | 2024-T3 Aluminum | | | | 4130 Steel | | | | Yellow Brass | | | | Az-31-B Magnesium | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Immersion: | Total | | Partial | | Total | | Partial | | Total | | Partial | | Total | | Partial | |
| Temperature: °F | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 |
| | mils-per-year | | | | | | | | | | | | | | | |
| Phos-Chek WD 861 | | | | | | | | | | | | | | | | |
| Concentrate | | | | | | | | | | | | | | | | |
| Fresh | 1.0 | 3.1 | .58 | 3.7 | .66 | 1.7 | .78 | 2.1 | .29 | .13 | .24 | .38 | 4.8 | 1.9 | 2.0 | 1.2 |
| | No intergranular attack on magnesium; pitting attack up to 0.056" on magnesium. | | | | | | | | | | | | | | | |
| 1.0-percent solution | | | | | | | | | | | | | | | | |
| Fresh | .03 | .14 | .04 | .11 | .32 | 1.6 | .61 | 2.2 | .38 | .79 | .21 | .65 | 2.4 | 2.3 | 1.9 | 1.9 |
| | No intergranular attack on aluminum or magnesium; pitting attack up to 0.001" on aluminum, up to 0.0072" on magnesium. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .09 | .04 | .05 | .37 | 1.5 | .73 | 2.4 | .12 | .12 | .12 | .09 | --- | --- | --- | --- |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .01 | .08 | .02 | .06 | .50 | 1.3 | .61 | 2.5 | .06 | .08 | .05 | .06 | --- | --- | --- | --- |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 0.1-percent solution | | | | | | | | | | | | | | | | |
| Fresh | .01 | .07 | .01 | .06 | .75 | 2.0 | .67 | 2.4 | .08 | .12 | .08 | .10 | 2.1 | 1.4 | 2.0 | 1.1 |
| | No intergranular attack on aluminum or magnesium; pitting attack up to 0.001" on aluminum, up to 0.066" on magnesium. | | | | | | | | | | | | | | | |
| 1 year Missoula | .03 | .05 | .04 | .01 | .73 | 1.7 | .78 | 2.1 | .03 | .03 | .03 | .03 | --- | --- | --- | --- |
| | No intergranular attack on aluminum; pitting attack up to 0.0056"on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .02 | .03 | .02 | .03 | .93 | 1.5 | .86 | 2.0 | .04 | .01 | .02 | .02 | --- | --- | --- | ---s |
| | No intergranular attack on aluminum, no pitting attack on aluminum. | | | | | | | | | | | | | | | |

Table 6 (continued)

**Uniform corrosion rates determined by 90-day weight loss tests for coupons exposed to fire fighting foams**

| Alloy: | 2024-T3 Aluminum | | | | 4130 Steel | | | | Yellow Brass | | | | Az-31-B Magnesium | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Immersion: | Total | | Partial | | Total | | Partial | | Total | | Partial | | Total | | Partial | |
| Temperature: °F | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 |
| | mils-per-year | | | | | | | | | | | | | | | |
| Ansul Silv-Ex | | | | | | | | | | | | | | | | |
| Concentrate<br>Fresh | .05 | .08 | .02 | .06 | .98 | 2.9 | 1.3 | 4.9 | 1.7 | 1.8 | 1.7 | 3.5 | 25. | 31. | 15. | 23. |
| 1.0-percent solution<br>Fresh | .15 | .03 | .10 | .02 | .31 | 1.8 | .87 | 2.8 | .01 | .01 | .06 | .06 | 2.7 | 1.5 | 3.0 | 1.0 |
| | No intergranular attack on aluminum or magnesium; pitting attack up to 0.001" on aluminum, up to 0.0028" on magnesium. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .04 | .09 | .02 | .55 | 2.0 | .91 | 4.4 | .23 | .09 | .11 | .08 | --- | --- | --- | --- |
| | No intergranular attack on aluminum; pitting attack up to 0.0014" on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .01 | .02 | .04 | .01 | .70 | 2.0 | .74 | 3.9 | .28 | .07 | .06 | .07 | --- | --- | --- | --- |
| | No intergranular attack on aluminum; pitting attack up to 0.0062" on aluminum. | | | | | | | | | | | | | | | |
| 0.1-percent solution<br>Fresh | .01 | .06 | .01 | .04 | .58 | 1.7 | .64 | 1.9 | .01 | .02 | .02 | .03 | 1.9 | 1.4 | 1.0 | .91 |
| | No intergranular attack on aluminum or magnesium; pitting attack up to 0.001" on aluminum, up to 0.0038" on magnesium. | | | | | | | | | | | | | | | |
| 1 year Missoula | .12 | .45 | .09 | .24 | .69 | 1.9 | .74 | 2.4 | .04 | .02 | .06 | .05 | --- | --- | --- | --- |
| | No intergranular attack on aluminum; pitting attack up to 0.0058" on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .10 | .32 | .13 | .26 | .52 | 1.5 | .70 | 2.2 | .07 | .03 | .06 | .08 | --- | --- | --- | --- |
| | No intergranular attack on aluminum; pitting attack up to 0.0056" on aluminum. | | | | | | | | | | | | | | | |

Table 6 (continued)

**Uniform corrosion rates determined by 90-day weight loss tests for coupons exposed to fire fighting foams**

| Alloy: | 2024-T3 Aluminum | | | | 4130 Steel | | | | Yellow Brass | | | | Az-31-B Magnesium | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Immersion: | Total | | Partial | | Total | | Partial | | Total | | Partial | | Total | | Partial | |
| Temperature: °F | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 |
| | mils-per-year | | | | | | | | | | | | | | | |
| Fire-Trol FireFoam 103 | | | | | | | | | | | | | | | | |
| Concentrate<br>Fresh | .01 | .03 | .02 | .02 | 1.2 | 1.5 | 1.3 | 3.8 | .01 | .15 | .01 | .18 | .86 | .67 | .67 | .77 |
| | No intergranular attack on magnesium; pitting attack up to 0.0038" on magnesium. | | | | | | | | | | | | | | | |
| 1.0-percent solution<br>Fresh | .03 | .19 | .02 | .09 | .98 | 1.9 | .99 | 2.7 | .01 | .06 | .02 | .06 | 1.4 | 2.3 | 1.1 | 1.7 |
| | No intergranular attack on aluminum or magnesium; no pitting attack on aluminum, up to 0.0040" on magnesium. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .09 | .01 | .04 | .77 | 1.5 | .76 | 2.0 | .02 | .06 | .03 | .04 | 2.0 | 2.6 | 1.5 | 1.8 |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .01 | .08 | .01 | .01 | .86 | 2.1 | 1.1 | 3.4 | .03 | .03 | .02 | .02 | 1.7 | 2.1 | .86 | 1.2 |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 0.1-percent solution<br>Fresh | .01 | .03 | .01 | .01 | 1.0 | 1.6 | 1.0 | 2.1 | .07 | .08 | .04 | .12 | 2.6 | 2.2 | 2.0 | 1.2 |
| | No intergranular attack on aluminum or magnesium; no pitting attack on aluminum, up to 0.0026" on magnesium. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .01 | .01 | .01 | .87 | 1.7 | .56 | 2.1 | .02 | .06 | .01 | .05 | 1.9 | 2.0 | 1.2 | 1.2 |
| | No intergranular attack on aluminum; pitting attack up to 0.0058" on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .01 | .03 | .01 | .01 | 1.2 | 2.3 | .89 | 2.5 | .05 | .10 | .02 | .08 | 1.7 | 2.7 | 1.5 | 1.7 |
| | No intergranular attack on aluminum, no pitting attack on aluminum. | | | | | | | | | | | | | | | |

Table 6 (continued)

**Uniform corrosion rates determined by 90-day weight loss tests for coupons exposed to fire fighting foams**

| Alloy: | 2024-T3 Aluminum | | | | 4130 Steel | | | | Yellow Brass | | | | Az-31-B Magnesium | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Immersion: | Total | | Partial | | Total | | Partial | | Total | | Partial | | Total | | Partial | |
| Temperature: °F | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 |
| | mils-per-year | | | | | | | | | | | | | | | |
| Phos-Chek WD 881 | | | | | | | | | | | | | | | | |
| Concentrate | | | | | | | | | | | | | | | | |
| Fresh | .04 | .12 | .19 | .78 | 1.3 | 1.9 | 1.2 | 2.2 | .01 | .03 | .08 | .59 | .90 | .74 | .54 | .89 |
| | No intergranular attack on magnesium; pitting attack up to 0.0060" on magnesium. | | | | | | | | | | | | | | | |
| 1.0-percent solution | | | | | | | | | | | | | | | | |
| Fresh | .02 | .06 | .01 | .01 | .75 | 1.6 | .74 | 2.6 | .03 | .05 | .03 | .03 | 1.8 | 2.5 | 1.5 | 1.1 |
| | No intergranular attack on aluminum or magnesium; no pitting attack on aluminum, up to 0.0034" on magnesium. | | | | | | | | | | | | | | | |
| 1 year Missoula | .02 | .14 | .03 | .14 | .24 | 2.3 | .53 | 3.4 | .13 | .22 | 1.1 | .10 | 2.8 | 3.1 | 2.1 | 1.6 |
| | No intergranular attack on aluminum or magnesium; no pitting attack on aluminum, up to 0.0058" on magnesium. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .06 | .12 | .05 | .13 | .59 | 1.4 | 1.6 | 3.2 | .14 | .08 | .06 | .11 | 2.4 | 3.2 | 1.6 | 2.3 |
| | No intergranular attack on aluminum or magnesium; no pitting attack on aluminum, up to 0.0060" on magnesium. | | | | | | | | | | | | | | | |
| 0.1-percent solution | | | | | | | | | | | | | | | | |
| Fresh | .01 | .01 | .01 | .01 | 1.2 | 1.8 | .87 | 2.3 | .04 | .03 | .01 | .01 | 1.7 | 2.2 | 1.5 | 1.4 |
| | No intergranular attack on aluminum or magnesium; no pitting attack on aluminum, up to 0.0082" on magnesium. | | | | | | | | | | | | | | | |
| 1 year Missoula | .03 | .01 | .01 | .06 | .91 | 1.7 | .75 | 2.0 | .05 | .04 | .02 | .04 | 2.1 | 2.2 | 1.7 | 1.5 |
| | No intergranular attack on aluminum or magnesium; no pitting attack on aluminum, up to 0.0064" on magnesium. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .02 | .03 | .02 | .04 | .75 | 2.0 | .71 | 2.2 | .06 | .04 | .07 | .03 | 2.9 | 2.1 | 2.0 | 1.5 |
| | No intergranular attack on aluminum or magnesium, no pitting attack on aluminum, up to 0.0056" on magnesium. | | | | | | | | | | | | | | | |

Table 6 (continued)

**Uniform corrosion rates determined by 90-day weight loss tests for coupons exposed to fire fighting foams**

| Alloy: | 2024-T3 Aluminum | | | | 4130 Steel | | | | Yellow Brass | | | | Az-31-B Magnesium | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Immersion: | Total | | Partial | | Total | | Partial | | Total | | Partial | | Total | | Partial | |
| Temperature: °F | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 |
| | mils-per-year | | | | | | | | | | | | | | | |
| Fire-Trol FireFoam 104 | | | | | | | | | | | | | | | | |
| Concentrate | | | | | | | | | | | | | | | | |
| Fresh | .05 | .21 | .11 | .16 | 1.1 | 2.8 | .92 | 2.5 | .41 | .88 | .94 | .84 | .44 | .93 | .82 | .81 |
| 1.0-percent solution | | | | | | | | | | | | | | | | |
| Fresh | .01 | .07 | .01 | .04 | .24 | 1.8 | .58 | 2.7 | .22 | .12 | .15 | .13 | 2.6 | 2.4 | 1.7 | 1.6 |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .05 | .01 | .03 | .26 | 1.9 | .64 | 3.4 | .12 | .16 | .15 | .07 | 2.4 | 3.5 | 1.6 | 2.1 |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .01 | .08 | .01 | .02 | .39 | 1.8 | .50 | 3.2 | .20 | .16 | .12 | .11 | 2.4 | 3.8 | 1.7 | 2.3 |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 0.1-percent solution | | | | | | | | | | | | | | | | |
| Fresh | .02 | .02 | .01 | .02 | 1.4 | 1.8 | 1.0 | 1.9 | .07 | .07 | .06 | .07 | 1.9 | 2.2 | 1.2 | 1.3 |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .01 | .01 | .01 | .62 | 1.6 | .57 | 1.7 | .03 | .08 | .01 | .02 | 1.9 | 1.9 | 1.2 | 1.1 |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .01 | .01 | .01 | .01 | .77 | 1.8 | .67 | 2.2 | .03 | .06 | .02 | .02 | 2.5 | 2.3 | 1.4 | 1.4 |
| | No intergranular attack on aluminum, no pitting attack on aluminum. | | | | | | | | | | | | | | | |

Table 6 (continued)

**Uniform corrosion rates determined by 90-day weight loss tests for coupons exposed to fire fighting foams**

| Alloy: | 2024-T3 Aluminum | | | | 4130 Steel | | | | Yellow Brass | | | | Az-31-B Magnesium | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Immersion: | Total | | Partial | | Total | | Partial | | Total | | Partial | | Total | | Partial | |
| Temperature: °F | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 |
| | mils-per-year | | | | | | | | | | | | | | | |
| Angus ForExpan | | | | | | | | | | | | | | | | |
| Concentrate<br>Fresh | .06 | .07 | .02 | .03 | .04 | .14 | .15 | .64 | .02 | .06 | .03 | .17 | 1.1 | 1.9 | 1.1 | 2.2 |
| 1.0-percent solution<br>Fresh | .01 | .02 | .01 | .01 | .14 | 1.6 | .54 | 3.2 | .03 | .02 | .04 | .05 | 5.4 | 1.9 | 4.1 | 1.5 |
| | No intergranular attack on aluminum; pitting attack up to 0.0014" on aluminum. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .01 | .01 | .01 | .24 | 1.8 | .33 | 3.5 | .01 | .01 | .01 | .01 | --- | --- | --- | --- |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .02 | .03 | .01 | .01 | .16 | 1.8 | .40 | 2.7 | .01 | .01 | .01 | .02 | --- | --- | --- | --- |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 0.1-percent solution<br>Fresh | .01 | .08 | .01 | .04 | .62 | 1.5 | 1.1 | 2.1 | .03 | .03 | .03 | .06 | 2.5 | 1.4 | 1.6 | 1.2 |
| | No intergranular attack on aluminum; pitting attack up to 0.0012" on aluminum. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .01 | .01 | .01 | .37 | 1.6 | .47 | 1.6 | .01 | .01 | .01 | .01 | --- | --- | --- | --- |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .01 | .02 | .01 | .02 | .44 | 1.8 | .62 | 2.3 | .01 | .01 | .01 | .04 | --- | --- | --- | --- |
| | No intergranular attack on aluminum; no pitting attack on aluminum. | | | | | | | | | | | | | | | |

Table 6 (continued)

**Uniform corrosion rates determined by 90-day weight loss tests for coupons exposed to fire fighting foams**

| Alloy: | 2024-T3 Aluminum | | | | 4130 Steel | | | | Yellow Brass | | | | Az-31-B Magnesium | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Immersion: | Total | | Partial | | Total | | Partial | | Total | | Partial | | Total | | Partial | |
| Temperature: °F | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 |
| | mils-per-year | | | | | | | | | | | | | | | |
| Pyrocap B-136 | | | | | | | | | | | | | | | | |
| Concentrate<br>Fresh | .03 | .01 | .06 | .08 | .76 | .42 | .27 | 1.6 | .07 | .11 | .24 | .15 | 7.1 | 9.7 | 4.8 | 19. |
| 1.0-percent solution<br>Fresh | .01 | .28 | .02 | .06 | .51 | 1.9 | .65 | 2.7 | .04 | .01 | .03 | .04 | 3.0 | 1.8 | 1.6 | 1.6 |
| | No intergranular attack on aluminum; pitting attack up to 0.0015" on aluminum. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .10 | .01 | .09 | .52 | 1.8 | .46 | 2.7 | .07 | .03 | .04 | .03 | --- | --- | --- | --- |
| | No intergranular or pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .01 | .15 | .01 | .15 | .47 | 1.9 | .54 | 2.3 | .07 | .03 | .04 | .03 | --- | --- | --- | --- |
| | No intergranular or pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 0.1-percent solution<br>Fresh | .01 | .07 | .01 | .02 | .55 | 1.3 | .64 | 1.9 | .01 | .02 | .01 | .03 | 1.4 | 1.0 | 1.1 | 1.0 |
| | No intergranular or pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .10 | .01 | .09 | .52 | 2.1 | .46 | 2.7 | .07 | .03 | .04 | .03 | --- | --- | --- | --- |
| | No intergranular or pitting attack on aluminum. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .01 | .06 | .03 | .03 | .86 | 1.8 | .87 | 1.7 | .02 | .03 | .01 | .03 | --- | --- | --- | --- |
| | No intergranular or pitting attack on aluminum. | | | | | | | | | | | | | | | |

Table 6 (continued)

**Uniform corrosion rates determined by 90-day weight loss tests for coupons exposed to fire fighting foams**

| Alloy: | 2024-T3 Aluminum | | | | 4130 Steel | | | | Yellow Brass | | | | Az-31-B Magnesium | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Immersion: | Total | | Partial | | Total | | Partial | | Total | | Partial | | Total | | Partial | |
| Temperature: $^{O}F$ | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 | 70 | 120 |
| | mils-per-year | | | | | | | | | | | | | | | |
| Fire Quench | | | | | | | | | | | | | | | | |
| Concentrate | | | | | | | | | | | | | | | | |
| Fresh | .01 | .06 | .03 | .03 | .27 | 1.0 | .64 | 1.9 | .21 | .25 | .13 | .26 | 2.5 | 2.9 | 1.5 | 1.6 |
| 1.0-percent solution | | | | | | | | | | | | | | | | |
| Fresh | .01 | .11 | .01 | .03 | .94 | 1.5 | .93 | 2.2 | .01 | .02 | .02 | .04 | 1.5 | 2.5 | 1.2 | 1.7 |
| | No intergranular attack on aluminum or magnesium; pitting attack up to 0.0018" on aluminum, up to 0.0284" on magnesium. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .05 | .02 | .01 | .78 | 1.5 | .88 | 1.6 | .02 | .02 | .02 | .02 | 1.6 | 2.8 | 1.4 | 2.0 |
| | No intergranular attack on aluminum or magnesium; pitting attack up to 0.0018" on aluminum, up to 0.0028" on magnesium. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .01 | .13 | .02 | .03 | .76 | 1.3 | .85 | 2.0 | .03 | .04 | .02 | .04 | 2.0 | 2.8 | 1.4 | 1.9 |
| | No intergranular attack on aluminum or magnesium; pitting attack up to 0.0066" on aluminum, up to 0.0050" on magnesium. | | | | | | | | | | | | | | | |
| 0.1-percent solution | | | | | | | | | | | | | | | | |
| Fresh | .01 | .02 | .01 | .01 | 1.3 | 1.9 | 1.1 | 1.9 | .01 | .01 | .01 | .04 | 1.2 | 1.7 | .85 | 1.2 |
| | No intergranular attack on aluminum or magnesium; no pitting attack on aluminum, up to 0.0054" on magnesium. | | | | | | | | | | | | | | | |
| 1 year Missoula | .01 | .03 | .03 | .01 | 1.4 | 2.0 | 1.3 | 2.0 | .01 | .01 | .01 | .02 | 1.6 | 1.8 | 1.2 | 1.3 |
| | No intergranular attack on aluminum or magnesium; pitting attack up to 0.0072" on aluminum, up to 0.0052" on magnesium. | | | | | | | | | | | | | | | |
| 1 year San Dimas | .01 | .04 | .04 | .01 | 1.2 | 1.8 | 1.2 | 2.0 | .01 | .01 | .01 | .04 | 1.8 | 1.5 | 1.4 | 1.3 |
| | No intergranular attack on aluminum or magnesium; pitting attack up to 0.0068" on aluminum, up to 0.0044" on magnesium. | | | | | | | | | | | | | | | |

Table 7

## Physical Properties[1] of Foam Concentrates

| Product | Viscosity[2] centipoise | Density[3] g/cm$^3$ | pH |
|---|---|---|---|
| Phos-Chek WD 861 | 49 | 1.026 | 7.8 |
| Ansul Silv-Ex | 25 | 1.010 | 7.9 |
| Fire-Trol FireFoam 103B | 48 | 1.028 | 8.9 |
| Phos-Chek WD 881 | 52 | 1.029 | 7.2 |
| Fire-Trol FireFoam 104 | 32 | 1.010 | 6.6 |
| Angus ForExpan S | 30 | 1.042 | 7.3 |
| Pyrocap B-136 | 145 | 1.037 | 8.1 |
| Fire Quench | 385 | 1.024 | 7.8 |

[1] All values were determined at room temperature.

[2] Viscosity measurements were made with a Brookfield model LVF viscometer and number 2 spindle.

[3] Density measurements were made with a Mettler/Paar model DMA 35 density meter.

Table 8

## Surface Tension
## of Dilutions of Foam Concentrates[1]

| | Surface Tension at Indicated Concentration[2] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Product | 0.01% | 0.05% | 0.1% | 0.3% | 0.6% | 1.0% | 2.0% | 3.0% | 6.0% |
| | dynes/centimeter | | | | | | | | |
| Phos-Chek WD 861 | 36.9 | 29.0 | 26.6 | 23.4 | 23.8 | 23.8 | 27.9 | 27.9 | 27.0 |
| Ansul Silv-Ex | 37.8 | 29.0 | 24.6 | 21.9 | 22.4 | 21.9 | 22.4 | 22.7 | 22.4 |
| Fire-Trol FireFoam 103B | 33.5 | 24.2 | 24.4 | 24.6 | 24.6 | 26.6 | 28.2 | 27.3 | 25.7 |
| Phos-Chek WD 881 B | 38.4 | 26.6 | 24.6 | 23.8 | 24.2 | 22.1 | 23.2 | 23.8 | 23.8 |
| Fire-Trol FireFoam 104 | 36.9 | 27.3 | 26.0 | 25.5 | 24.4 | 25.5 | 27.9 | 27.9 | 27.9 |
| Angus ForExpan S | 37.4 | 28.8 | 25.5 | 22.9 | 24.6 | 23.2 | 25.5 | 26.6 | 28.2 |
| Pyrocap B-136 | 40.7 | 28.2 | 24.5 | 24.5 | 24.5 | 24.5 | 25.5 | 25.5 | 26.0 |
| Fire Quench | 39.8 | 27.9 | 26.6 | 26.6 | 24.6 | 27.0 | 26.6 | 26.6 | 27.9 |

[1] Surface tension values have been corrected for the diameter of the wire and the diameter of the ring used in the determinations.

[2] Concentrations between 0.1 and 1.0 percent are approved for use by the Forest Service. Additional values are given to show trends in surface tension behavior.

## Table 9

## Conductivity as a Function of Concentration

| Product | Conductivity[1] | | | | |
|---|---|---|---|---|---|
| | 0.0% | 0.2% | 0.3% | 0.6% | 1.0% |
| | micro Siemens | | | | |
| Foam A | 370 | 440 | 500 | 630 | 830 |
| Foam B | 360 | 410 | 490 | 630 | 820 |
| Foam C | 370 | 430 | 460 | 560 | 730 |
| Foam D | 370 | 380 | 410 | 440 | 510 |

[1] All test solutions were prepared with tap water.

## Table 9A - Conductivity of Foam Solutions[1] as a Function of Concentration

| Product | Concentration<br>0.0% | <br>0.1% | <br>0.3% | <br>0.6% | <br>1.0% |
|---|---|---|---|---|---|
| | Conductivity, micro Siemens | | | | |
| Phos-Chek WD 861 | 360 | 410 | 490 | 630 | 830 |
| Ansul Silv-Ex | 370 | 440 | 500 | 630 | 830 |
| Fire-Trol FireFoam 103B | 360 | 420 | 490 | 630 | 860 |
| Phos-Chek WD 881 | 360 | 410 | 490 | 630 | 830 |
| Fire-Trol FireFoam 104 | 360 | 420 | 470 | 730 | 880 |
| Angus ForExpan S | 370 | 400 | 500 | 690 | 870 |
| Pyrocap B-136 | 370 | 440 | 460 | 570 | 740 |
| Fire Quench | 370 | 380 | 410 | 440 | 510 |

[1] All solutions were prepared with tap water and measured at 70 °F.

## Table 9B - Conductivity[1] of Foam Solutions, at 0.6%, as a Function of Temperature

| Temperature: | 40 °F | 50 °F | 60 °F | 70 °F | 80 °F | 90 °F | 100 °F | 110 °F | 120 °F |
|---|---|---|---|---|---|---|---|---|---|
| | Conductivity of Foam Solution, micro Siemens | | | | | | | | |
| Phos-Chek WD 861 | 344 | 415 | 470 | 465 | 809 | 893 | 1005 | 1100 | 1221 |
| Ansul Silv-Ex | 240 | 287 | 362 | 554 | 642 | 705 | 787 | 823 | 892 |
| Fire-Trol FireFoam 103B | 372 | 431 | 512 | 565 | 640 | 710 | 683 | 888 | 985 |
| Phos-Chek WD 881 | 482 | 555 | 632 | 510 | 595 | 651 | 731 | 840 | 918 |
| Fire-Trol FireFoam 104 | 331 | 392 | 445 | 511 | 580 | 620 | 709 | 798 | 880 |
| Angus ForExpan S | 370 | 415 | 500 | 519 | 639 | 725 | 804 | 820 | 982 |
| Pyrocap B-136 | 374 | 433 | 500 | 513 | 629 | 700 | 769 | 841 | 920 |
| Fire Quench | 226 | 288 | 338 | 368 | 432 | 489 | 531 | 578 | 648 |

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[1] All test solutions were prepared with tap water.

## Table 9C - Conductivity[1] of Foam Solutions, at 70 °F, as a Function of Concentration

| Concentrations: | 0.1% | 0.2% | 0.3% | 0.4% | 0.5% | 0.6% | 0.7% | 0.8% | 0.9% | 1.0% |
|---|---|---|---|---|---|---|---|---|---|---|
| | Conductivity of Foam Solution, micro Siemens | | | | | | | | | |
| Phos-Chek WD 861 | 372 | 430 | 485 | 520 | 532 | 465 | 534 | 862 | 925 | 979 |
| Ansul Silv-Ex | 351 | 397 | 448 | 487 | 511 | 554 | 600 | 362 | 680 | 730 |
| Fire-Trol FireFoam 103B | 376 | 408 | 440 | 483 | 514 | 565 | 586 | 645 | 697 | 718 |
| Phos-Chek WD 881 | 362 | 379 | 405 | 440 | 485 | 510 | 548 | 578 | 610 | 642 |
| Fire-Trol FireFoam 104 | 342 | 381 | 404 | 436 | 475 | 511 | 532 | 595 | 611 | 648 |
| Angus ForExpan S | 358 | 391 | 422 | 455 | 495 | 519 | 562 | 617 | 645 | 700 |
| Pyrocap B-136 | 370 | 389 | 421 | 458 | 492 | 513 | 558 | 600 | 630 | 655 |
| Fire Quench | 332 | 331 | 340 | 355 | 368 | 368 | 360 | 384 | 402 | 405 |

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[1] All test solutions were prepared with tap water.

Table 10

## Pour Point of Foam Concentrates[1]

| Product | Measured Pour Point | ---- Fluidity of Concentrate ---- 40 °F | 33 °F | 5 °F |
|---|---|---|---|---|
| Phos-Chek WD 861 | 32 °F | Fluid | Semi Solid | Solid |
| Ansul Silv-Ex | 18 °F | Fluid | Fluid | Solid |
| Fire-Trol FireFoam 103B | 12 °F | Fluid | Fluid | Semi Fluid-Solid |
| Phos-Chek WD 881 | 27 °F | Fluid | Fluid | Solid |
| Fire-Trol FireFoam 104 | 16 °F | Fluid | Fluid | Semi Fluid-Solid |
| Angus ForExpan S | 14 °F | Fluid | Fluid | Semi Fluid-Solid |
| Pyrocap B-136 | 10 °F | Fluid | Fluid | Solid |
| Fire Quench | 33 °F | Fluid | Semi Solid | Solid |

[1] Pour point determination is based on ASTM D-97.

Table 11

## Viscosity of Foam Concentrates as a Function of Temperature

| Product | Viscosity of Foam Concentrate[1] 35 °F | 40 °F | 50 °F | 60 °F | 70 °F | 80 °F | 90 °F | 100 °F | 110 °F | 120 °F |
|---|---|---|---|---|---|---|---|---|---|---|
| | centipoise | | | | | | | | | |
| Phos-Chek WD 861 | 650 | 165 | 85 | 65 | 48 | 40 | 30 | 29 | 23 | 22 |
| Ansul Silv-Ex | 55 | 43 | 39 | 31 | 25 | 23 | 21 | 17 | 15 | 13 |
| Fire-Trol FireFoam 103B | 119 | 92 | 74 | 56 | 41 | 34 | 28 | 24 | 22 | 19 |
| Phos-Chek WD 881 | 233 | 113 | 75 | 59 | 45 | 38 | 29 | 27 | 22 | 20 |
| Fire-Trol FireFoam 104 | 84 | 65 | 53 | 42 | 33 | 28 | 23 | 20 | 18 | 16 |
| Angus ForExpan S | 63 | 53 | 44 | 35 | 29 | 25 | 20 | 19 | 18 | 15 |
| Pyrocap B-136 | 1200 | 1025 | 700 | 404 | 312 | 282 | 311 | 326 | 370 | |
| Fire Quench | 1750 | 1338 | 925 | 800 | 580 | 298 | 143 | 52 | 54 | 33 |

[1] All viscosities were measured using a Brookfield model LVF viscometer.

Table 12

## Miscibility of Foam Concentrates[1]

| Product (0.6% Dilutions) | Water Quality | Warm Water: Warm Conc | Warm Water: Cold Conc | Cold Water: Warm Conc | Cold Water: Cold Conc |
|---|---|---|---|---|---|
| Phos-Chek WD 861 | Distilled Water | 20 rev | 90 rev | 100 rev | NM |
|  | Tap Water | 10 rev | 30 rev | 25 rev | 85 rev |
|  | Sea Water | 50 rev | 90 rev | 90 rev | NM |
| Ansul Silv-Ex | Distilled Water | 10 rev | 30 rev | 40 rev | 60 rev |
|  | Tap Water | 10 rev | 10 rev | 10 rev | 15 rev |
|  | Sea Water | 20 rev | 20 rev | NM | 90 rev |
| Fire-Trol FireFoam 103B | Distilled Water | 20 rev | 70 rev | 40 rev | NM |
|  | Tap Water | 15 rev | 10 rev | 15 rev | 50 rev |
|  | Sea Water | 70 rev | 60 rev | NM | NM |
| Phos-Chek WD 881 | Distilled Water | 20 rev | 80 rev | 30 rev | 30 rev |
|  | Tap Water | 15 rev | 10 rev | 15 rev | 20 rev |
|  | Sea Water | NM | NM | NM | NM |
| Fire-Trol FireFoam 104 | Distilled Water | 20 rev | 30 rev | 50 rev | 80 rev |
|  | Tap Water | 10 rev | 10 rev | 10 rev | 40 rev |
|  | Sea Water | 10 rev | NM | NM | NM |
| Angus ForExpan S | Distilled Water | 10 rev | 10 rev | 40 rev | 30 rev |
|  | Tap Water | 15 rev | 10 rev | 15 rev | 20 rev |
|  | Sea Water | 10 rev | 10 rev | 30 rev | 25 rev |
| Pyrocap B-136 | Distilled Water | NM | NM | NM | NM |
|  | Tap Water | 65 rev | NM | NM | NM |
|  | Sea Water | NM | NM | NM | NM |
| Fire Quench | Distilled Water | 50 rev | 60 rev | NM | 50 rev |
|  | Tap Water | 20 rev | 40 rev | 40 rev | 90 rev |
|  | Sea Water | NM | NM | NM | NM |

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[1] Concentrate was rated as not miscible (NM) if the solution was not homogeneous after 100 revolutions, if the solution was too cloudy to evaluate, or if there was a precipitate in the bottom of the container. Foam quality may or may not be affected depending on the amount of concentrate that di go into solution.

Table 13

## Wetting Ability of Foam Solutions[1]
## As a Function of Concentration

| Product | Time for Skein to Sink (seconds)[2] | | | | | |
|---|---|---|---|---|---|---|
| | 0.1% | 0.3% | 0.6% | 1.0% | 3.0% | 6.0% |
| Phos-Chek WD 861 | | | | | | |
| 0.8-gram hook | >300 | 47 | 27 | 24 | | |
| **1.5-gram hook** | **>180** | **36** | **18** | **13** | **10** | **7** |
| 3.0-gram hook | >225 | 22 | 13 | 10 | | |
| Ansul Silv-Ex | | | | | | |
| 0.8-gram hook | >300 | 60 | 26 | 62 | | |
| **1.5-gram hook** | **>180** | **32** | **22** | **11** | **4** | **2** |
| 3.0-gram hook | >300 | 28 | 14 | 6 | | |
| Fire-Trol FireFoam 103B | | | | | | |
| 0.8-gram hook | >300 | 35 | 27 | 21 | | |
| **1.5-gram hook** | **>180** | **27** | **12** | **8** | **5** | **–** |
| 3.0-gram hook | 176 | 16 | 12 | 6 | | |
| Phos-Chek WD 881 | | | | | | |
| 0.8-gram hook | >300 | 74 | 37 | 21 | | |
| **1.5-gram hook** | **>180** | **54** | **28** | **12** | **5** | **5** |
| 3.0-gram hook | >300 | 41 | 16 | 10 | | |

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[1] Wetting ability was determined by Drave's Skein Test, ASTM 2281.

[2] Tests with the 0.8-gram and 3.0-gram hooks used skeins that were not corrected to 5.0 grams.

Table 13 (continued)

## Wetting Ability of Foam Solutions[1]
## As a Function of Concentration

| Product | Time for Skein to Sink (seconds)[2] | | | | | |
|---|---|---|---|---|---|---|
| | 0.1% | 0.3% | 0.6% | 1.0% | 3.0% | 6.0% |
| Fire-Trol FireFoam 104 | | | | | | |
| 0.8-gram hook | >300 | 37 | 23 | 20 | | |
| **1.5-gram hook** | **>180** | **35** | **17** | **9** | **4** | **–** |
| 3.0-gram hook | 197 | 21 | 9 | – | | |
| Angus ForExpan S | | | | | | |
| 0.8-gram hook | >300 | 48 | 32 | 21 | | |
| **1.5-gram hook** | **>180** | **40** | **20** | **14** | **–** | **2** |
| 3.0-gram hook | 211 | 24 | 13 | 8 | | |
| Pyrocap B-136 | | | | | | |
| 0.8-gram hook | >300 | 50 | 24 | 13 | | |
| **1.5-gram hook** | **>180** | **50** | **16** | **9** | **3** | **–** |
| 3.0-gram hook | >300 | 30 | 11 | 6 | | |
| Fire Quench | | | | | | |
| 0.8-gram hook | >300 | 35 | 22 | 14 | | |
| **1.5-gram hook** | **>180** | **29** | **12** | **7** | **3** | **3** |
| 3.0-gram hook | >300 | 20 | 8 | 5 | | |

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[1] Wetting ability was determined by Drave's Skein Test, ASTM 2281.

[2] Tests with the 0.8-gram and 3.0-gram hooks used skeins that were not corrected to 5.0 grams.

Table 14

## Foaming Ability of Foam Solutions As a Function of Concentration

| Product | Total Foam Volume | Volume of Drained Solution | | |
|---|---|---|---|---|
| | | 1 min | 5 min | 10 min |
| | milliliters | - - - - - - - - - milliliters - - - - - - - - - | | |
| Phos-Chek WD 861 | | | | |
| 1.0% | 80 | 5.5 | 9.0 | 9.0 |
| 0.6% | 70 | 4.0 | 7.0 | 8.0 |
| 0.3% | 60 | 5.5 | 8.0 | 9.0 |
| 0.1% | 50 | 4.5 | 8.0 | 9.0 |
| Ansul Silv-Ex | | | | |
| 1.0% | 70 | 4.0 | 7.5 | 9.0 |
| 0.6% | 60 | 4.0 | 7.5 | 9.0 |
| 0.3% | 53 | 3.0 | 7.0 | 8.5 |
| 0.1% | 35 | 5.5 | 9.0 | 9.5 |
| Fire-Trol FireFoam 103B | | | | |
| 1.0% | 90 | 8.0 | 10.5 | 10.5 |
| 0.6% | 70 | 7.5 | 9.5 | 10.0 |
| 0.3% | 70 | 7.5 | 10.0 | 10.5 |
| 0.1% | 55 | 6.0 | 9.5 | 10.0 |
| Phos-Chek WD 881 | | | | |
| 1.0% | 75 | 4.5 | 7.5 | 9.0 |
| 0.6% | 65 | 4.0 | 7.5 | 9.0 |
| 0.3% | 55 | 2.5 | 7.0 | 8.5 |
| 0.1% | 45 | 5.5 | 9.0 | 9.5 |
| Fire-Trol FireFoam 104 | | | | |
| 1.0% | 87 | 8.0 | 10.0 | 10.5 |
| 0.6% | 78 | 8.0 | 10.0 | 10.0 |
| 0.3% | 61 | 8.0 | 10.0 | 10.5 |
| 0.1% | 70 | 8.0 | 10.0 | 10.0 |

Table 14 (continued)

## Foaming Ability of Foam Solutions As a Function of Concentration

| Product | Total Foam Volume milliliters | Volume of Drained Solution 1 min | 5 min | 10 min |
|---|---|---|---|---|
| | | --------- milliliters | | --------- |
| Angus ForExpan S | | | | |
| 1.0% | 70 | 5.0 | 7.5 | 9.0 |
| 0.6% | 65 | 5.5 | 8.5 | 9.0 |
| 0.3% | 55 | 4.0 | 7.5 | 9.0 |
| 0.1% | 40 | 8.0 | 9.5 | 10.0 |
| Pyrocap B-136 | | | | |
| 1.0% | 55 | 4.0 | 9.0 | 10.0 |
| 0.6% | 47 | 6.5 | 10.0 | 10.0 |
| 0.3% | 37 | 7.0 | 9.5 | 10.0 |
| 0.1% | 30 | 9.0 | 10.0 | 10.0 |
| Fire Quench | | | | |
| 1.0% | 65 | 7.0 | 9.5 | 10.0 |
| 0.6% | 55 | 7.0 | 10.0 | 10.0 |
| 0.3% | 34 | 7.5 | 9.5 | 9.5 |
| 0.1% | 23 | 9.0 | 10.0 | 10.0 |

Table 15

## Foaming Ability of Foam Solutions[1] As a Function of Water Quality and Temperature

| Product Water Quality & Temperature | Total Foam Volume milliliters | Volume of Drained Solution | | |
|---|---|---|---|---|
| | | 1 min | 5 min | 10 min |
| | | milliliters | | |
| Phos-Chek WD 861 | | | | |
| Tap - 40 °F | 65 | 3.0 | 7.0 | 8.0 |
| Tap - 70 °F | 72 | 7.0 | 8.5 | 9.0 |
| Distilled - 40 °F | 62 | 4.0 | 7.0 | 7.5 |
| Distilled - 70 °F | 88 | 8.0 | 9.5 | 10.0 |
| Sea - 40 °F | 53 | 3.0 | 6.0 | 8.0 |
| Sea - 70 °F | 60 | 4.0 | 8.0 | 9.0 |
| Ansul Silv-Ex | | | | |
| Tap - 40 °F | 54 | 3.0 | 6.5 | 8.0 |
| Tap - 70 °F | 60 | 7.0 | 8.5 | 9.0 |
| Distilled - 40 °F | 54 | 4.0 | 7.0 | 8.0 |
| Distilled - 70 °F | 68 | 5.0 | 8.0 | 9.0 |
| Sea - 40 °F | 45 | 3.0 | 6.5 | 8.0 |
| Sea - 70 °F | 45 | 2.5 | 6.0 | 8.0 |
| Fire-Trol FireFoam 103B | | | | |
| Tap - 40 °F | 68 | 6.0 | 10.0 | 10.0 |
| Tap - 70 °F | 83 | 8.5 | 9.5 | 10.0 |
| Distilled - 40 °F | 83 | 8.0 | 9.0 | 9.0 |
| Distilled - 70 °F | 80 | 9.0 | 10.0 | 10.0 |
| Sea - 40 °F | 52 | 4.0 | 8.5 | 9.0 |
| Sea - 70 °F | 58 | 5.0 | 9.5 | 10.0 |
| Phos-Chek WD 881 | | | | |
| Tap - 40 °F | 57 | 5.0 | 8.0 | 9.0 |
| Tap - 70 °F | 52 | 7.0 | 8.5 | 8.5 |
| Distilled - 40 °F | 58 | 5.0 | 8.0 | 9.0 |
| Distilled - 70 °F | 70 | 7.0 | 9.0 | 9.5 |
| Sea - 40 °F | 55 | 5.0 | 9.0 | 9.5 |
| Sea - 70 °F | 45 | 4.5 | 9.0 | 9.5 |

---

[1] All tests were performed on 0.6-percent solutions of the concentrate in water.

Table 15 (continued)

### Foaming Ability of Foam Solutions[1] As a Function of Water Quality and Temperature

| Product<br>Water Quality & Temperature | Total Foam Volume<br>milliliters | Volume of Drained Solution<br>1 min | <br>5 min | <br>10 min |
|---|---|---|---|---|
| | | milliliters | | |
| Fire-Trol FireFoam 104 | | | | |
| Tap - 40 °F | 64 | 7.0 | 10.0 | 10.0 |
| Tap - 70 °F | 65 | 8.0 | 9.0 | 9.5 |
| Distilled - 40 °F | 75 | 8.0 | 9.5 | 9.5 |
| Distilled - 70 °F | 87 | 7.0 | 10.0 | 10.0 |
| Sea - 40 °F | 50 | 4.0 | 8.0 | 9.0 |
| Sea - 70 °F | 63 | 5.0 | 9.0 | 10.0 |
| Angus ForExpan S | | | | |
| Tap - 40 °F | 65 | 4.0 | 7.0 | 8.0 |
| Tap - 70 °F | 88 | 6.5 | 8.0 | 9.0 |
| Distilled - 40 °F | 64 | 5.5 | 8.0 | 9.0 |
| Distilled - 70 °F | 79 | 7.0 | 9.0 | 9.5 |
| Sea - 40 °F | 40 | 3.5 | 7.0 | 8.5 |
| Sea - 70 °F | 48 | 5.0 | 9.0 | 9.0 |
| Pyrocap B-136 | | | | |
| Tap - 40 °F | 35 | 5.0 | 9.0 | 9.5 |
| Tap - 70 °F | 50 | 7.0 | 9.0 | 9.0 |
| Distilled - 40 °F | 45 | 6.5 | 9.0 | 9.0 |
| Distilled - 70 °F | 65 | 9.0 | 10.0 | 10.0 |
| Sea - 40 °F | 15 | 9.5 | 10.0 | 10.0 |
| Sea - 70 °F | 15 | 9.5 | 10.0 | 10.0 |
| Fire Quench | | | | |
| Tap - 40 °F | 25 | 8.0 | 9.5 | 9.5 |
| Tap - 70 °F | 29 | 8.0 | 9.0 | 9.0 |
| Distilled - 40 °F | 64 | 6.0 | 9.0 | 9.0 |
| Distilled - 70 °F | 83 | 9.0 | 10.0 | 10.0 |
| Sea - 40 °F | 15 | 10.0 | 10.0 | 10.0 |
| Sea - 70 °F | 15 | 10.0 | 10.0 | 10.0 |

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[1] All tests were performed on 0.6-percent solutions of the concentrate in water.

Table 16

## Viscosity Measured by Marsh Funnel[1] as a Function of Temperature

| Product | ---- Flow-Through Time (min:sec)[2] ---- | | |
|---|---|---|---|
| | 40 °F | 70 °F | 100 °F |
| Phos-Chek WD 861 | 2:27 (210 cP) | 1:10 (48 cP) | 0:50 (28 cP) |
| Ansul Silv-Ex | 1:11 (48 cP) | 0:47 (50 cP) | 0:41 (20 cP) |
| Fire-Trol FireFoam 103B | 4:10 (555 cP) | 1:04 (41 cP) | 0:48 (25 cP) |
| Phos-Chek WD 881 | 2:20 (101 cP) | 1:08 (53 cP) | 0:48 (25 cP) |
| Fire-Trol FireFoam 104 | 1:28 (56 cP) | 0:51 (28 cP) | 0:42 (18 cP) |
| Angus ForExpan S | 1:18 (55 cP) | 0:46 (28 cP) | 0:40 (15 cP) |
| Pyrocap B-136 | 1:46 (850 cP) | 1:01 (208 cP) | 0:59 (47 cP) |
| Fire Quench | 27:59 (1270 cP) | 9:39 (575 cP) | 1:55 (72 cP) |

[1] Corresponding Brookfield viscosities are shown in parentheses.

[2] Time for 1 quart of concentrate to flow through the small orifice of a Marsh Funnel.

Table 17

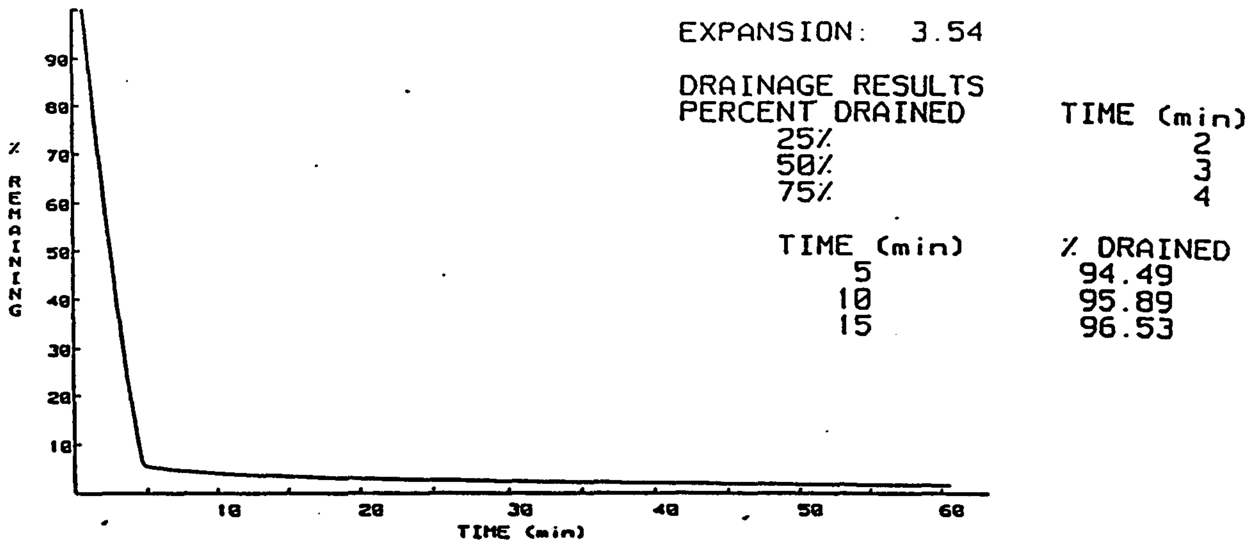
## Viscosity Measured by Zahn Cup Flow-Through Time[1]

| Product | Brookfield Viscosity | Flow-Through Time[2] Zahn Cup Number #1 | #2 | #3 |
|---|---|---|---|---|
| | centipoise | seconds | | |
| Phos-Chek WD 861 | 41 | 64 (41) | **24 (36)** | 9 (20) |
| Ansul Silv-Ex | 23 | **46 (19)** | 19 (14) | 8 (13) |
| Fire-Trol FireFoam 103B | 36 | 61 (37) | **23 (30)** | 9 (20) |
| Phos-Chek WD 881 | 40 | 62 (38) | **23 (30)** | 8 (13) |
| Fire-Trol FireFoam 104 | 31 | **51 (26)** | **21 (19)** | 8 (13) |
| Angus ForExpan S | 25 | **46 (19)** | 19 (14) | 8 (13) |
| Pyrocap B-136 | 123 | 61 (37) | **52 (131)** | **22 (195)** |
| Fire-Quench | 244 | 277 (239) | 111 (303) | **29 (267)** |

[1] Highlighted values are within the manufacturer's recommended drain times for the specific cup used for the measurement.

[2] Numbers in parentheses are the viscosity values related to the measured flow-through times.

## Figure 1 - Typical Drain Curves for a Fast Draining Foam and a Slow Draining Foam

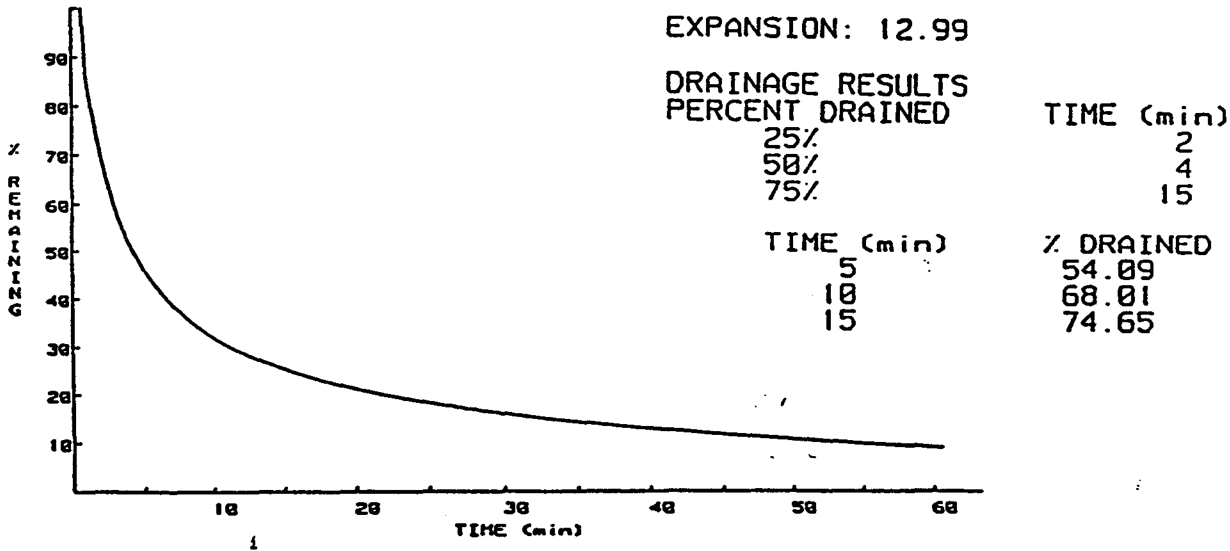


EXPANSION: 3.54

DRAINAGE RESULTS

| PERCENT DRAINED | TIME (min) |
|---|---|
| 25% | 2 |
| 50% | 3 |
| 75% | 4 |

| TIME (min) | % DRAINED |
|---|---|
| 5 | 94.49 |
| 10 | 95.89 |
| 15 | 96.53 |

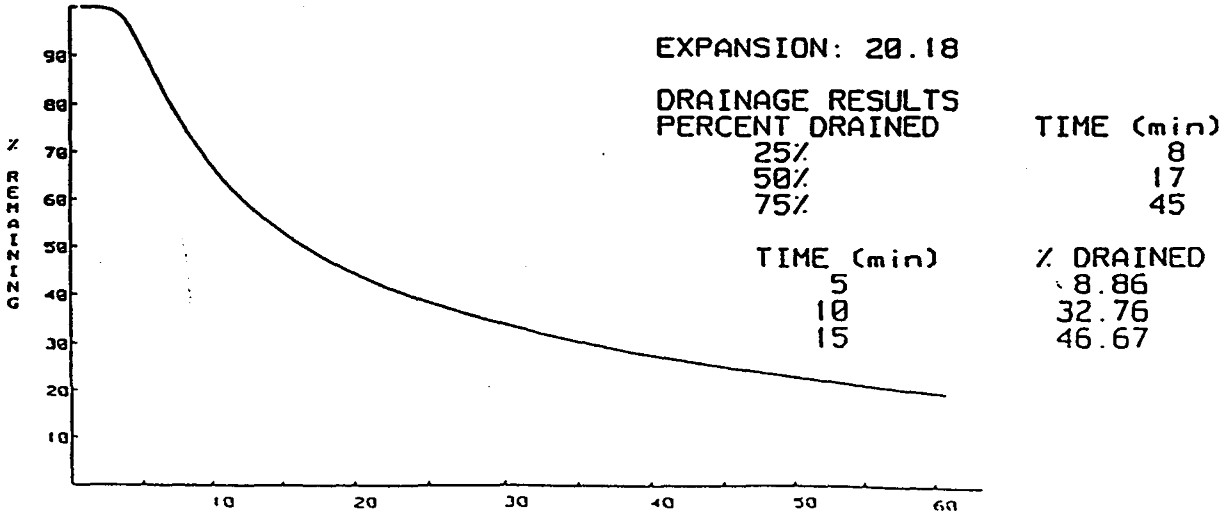


EXPANSION: 12.99

DRAINAGE RESULTS

| PERCENT DRAINED | TIME (min) |
|---|---|
| 25% | 2 |
| 50% | 4 |
| 75% | 15 |

| TIME (min) | % DRAINED |
|---|---|
| 5 | 54.09 |
| 10 | 68.01 |
| 15 | 74.65 |



EXPANSION: 20.18

DRAINAGE RESULTS

| PERCENT DRAINED | TIME (min) |
|---|---|
| 25% | 8 |
| 50% | 17 |
| 75% | 45 |

| TIME (min) | % DRAINED |
|---|---|
| 5 | 8.86 |
| 10 | 32.76 |
| 15 | 46.67 |

Figure 2 - Expansion of Phos-Chek WD 861 as a Function of Production Variables.

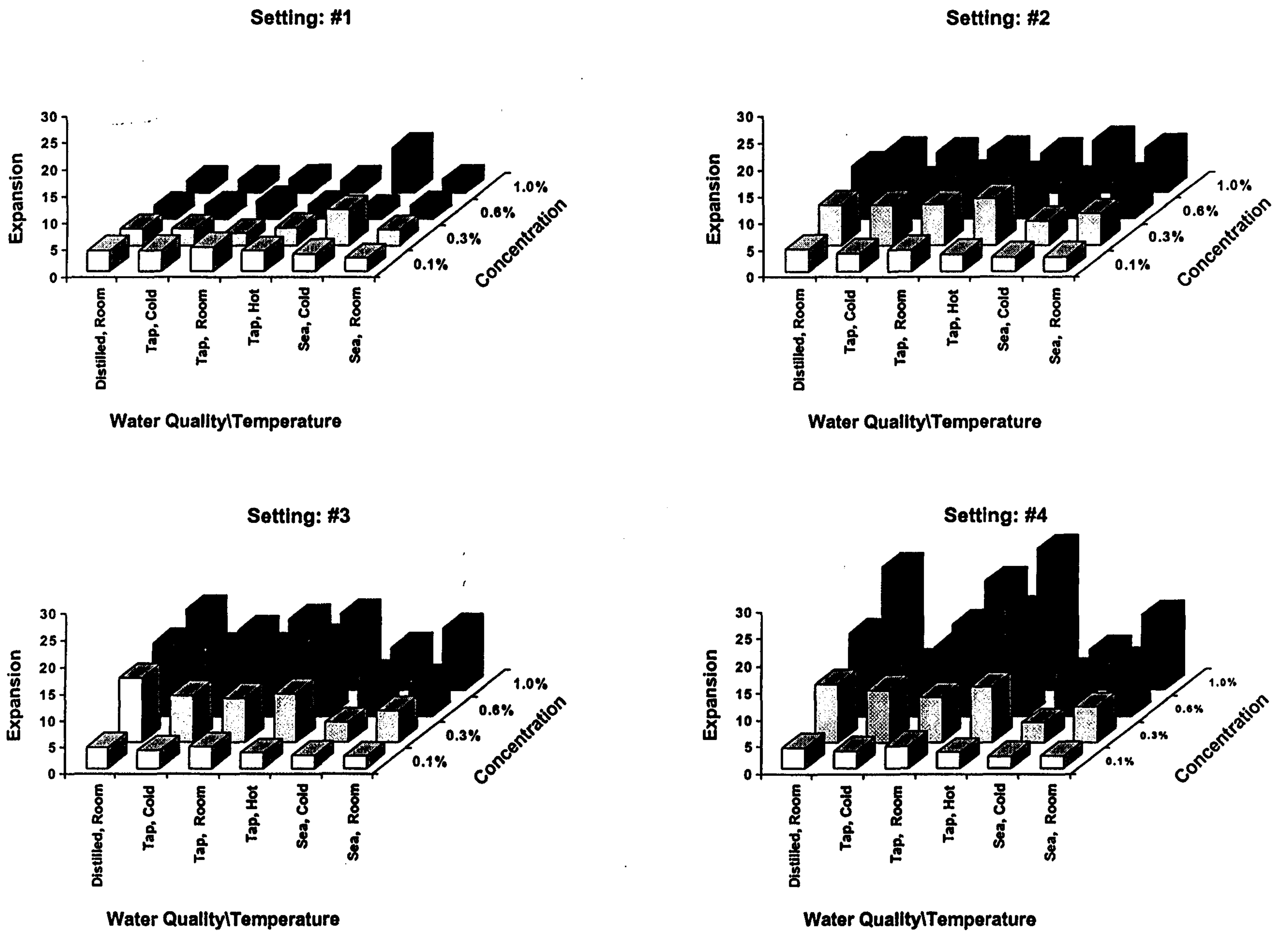
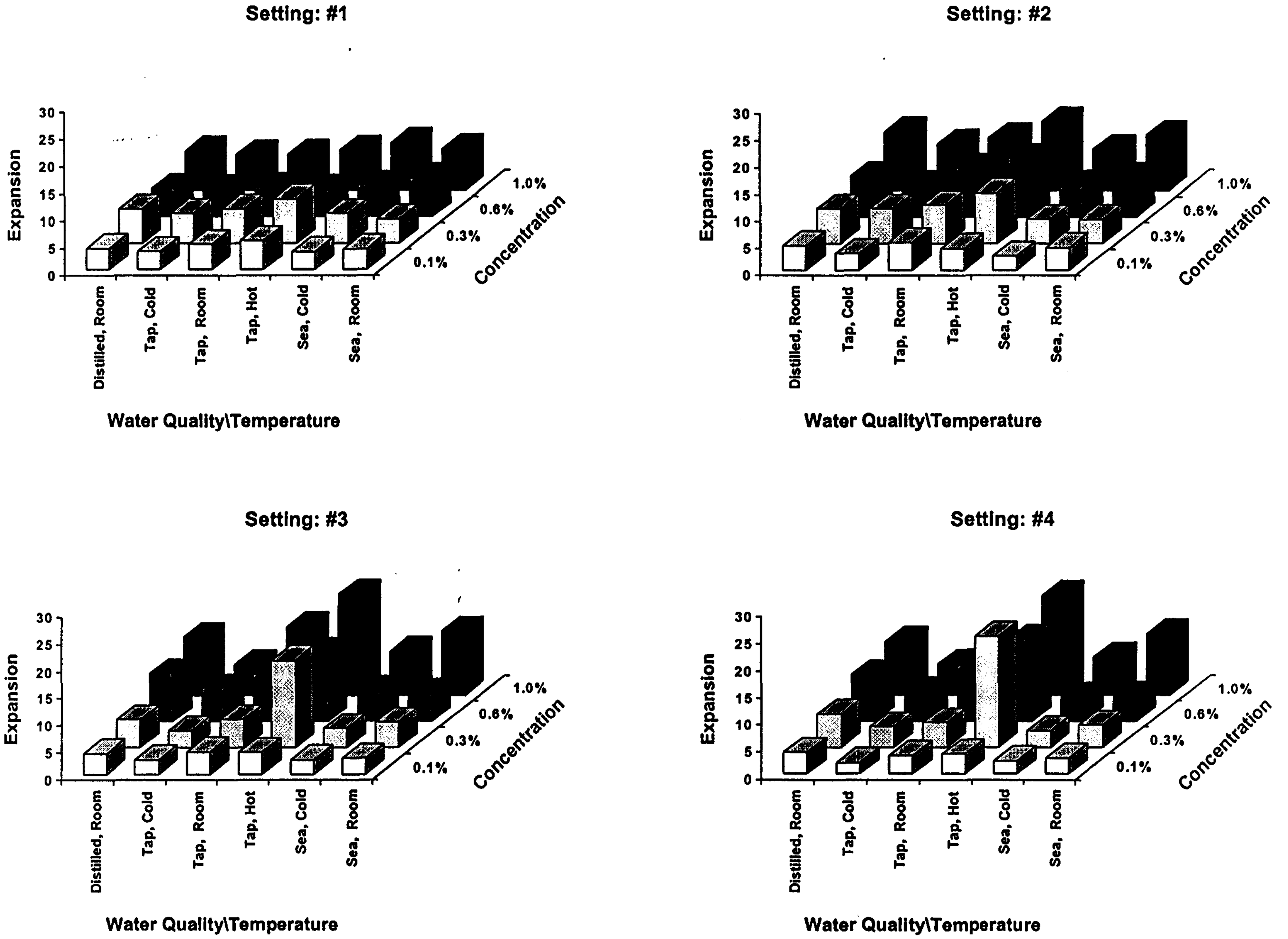


Figure 3 - Expansion of Ansul Silv-Ex as a Function of Production Variables.



## Figure 4 - Expansion of Fire-Trol FireFoam 103B as a Function of Production Variables

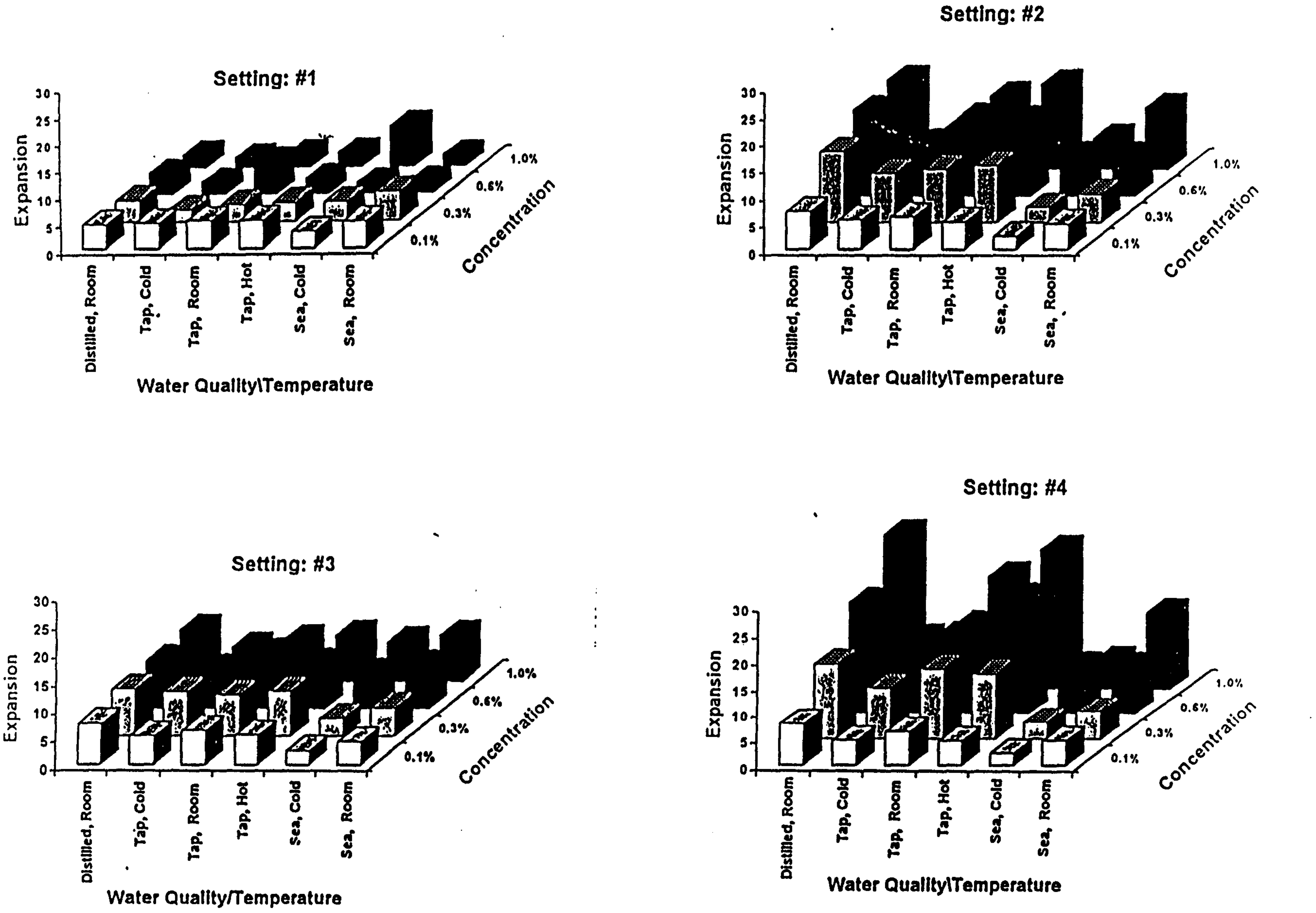
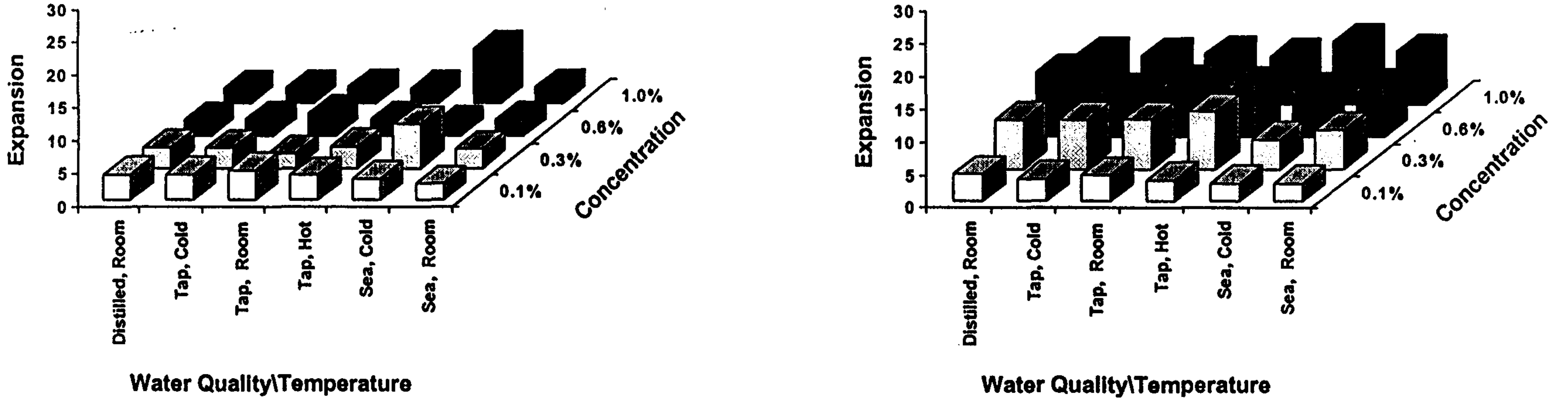
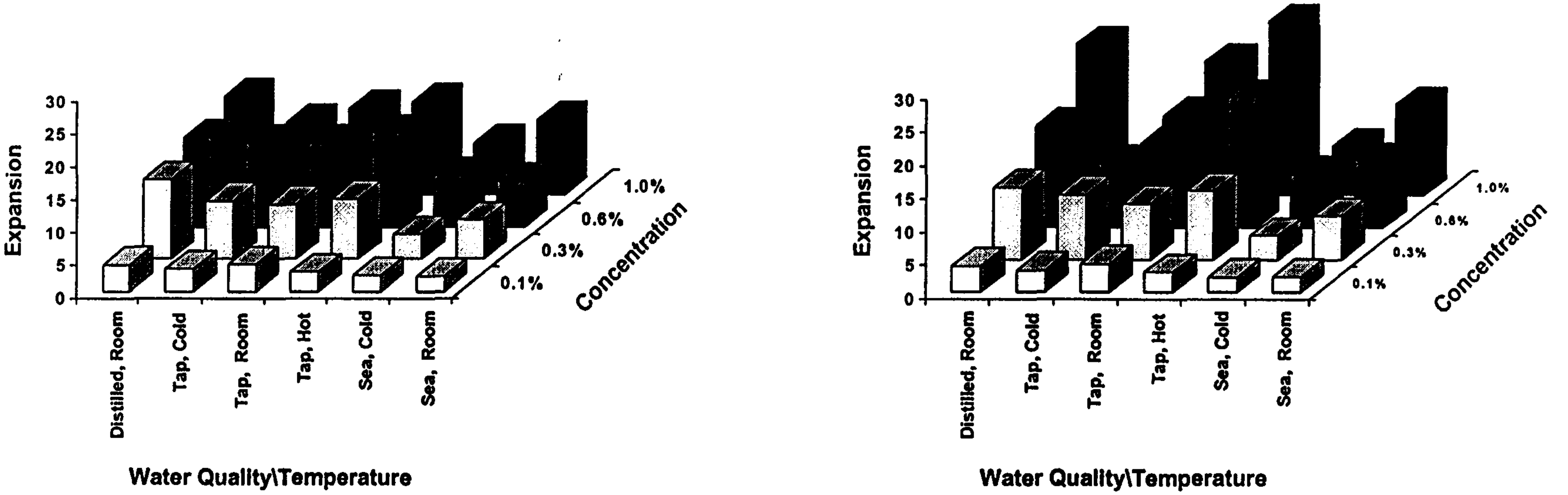


Figure 5 - Expansion of Phos-Chek WD 881 as a Function of Production Variables.


Setting: #1

Setting: #2


Setting: #3

Setting: #4

Figure 6 - Expansion of Fire-Trol FireFoam 104 as a Function of Production Variables

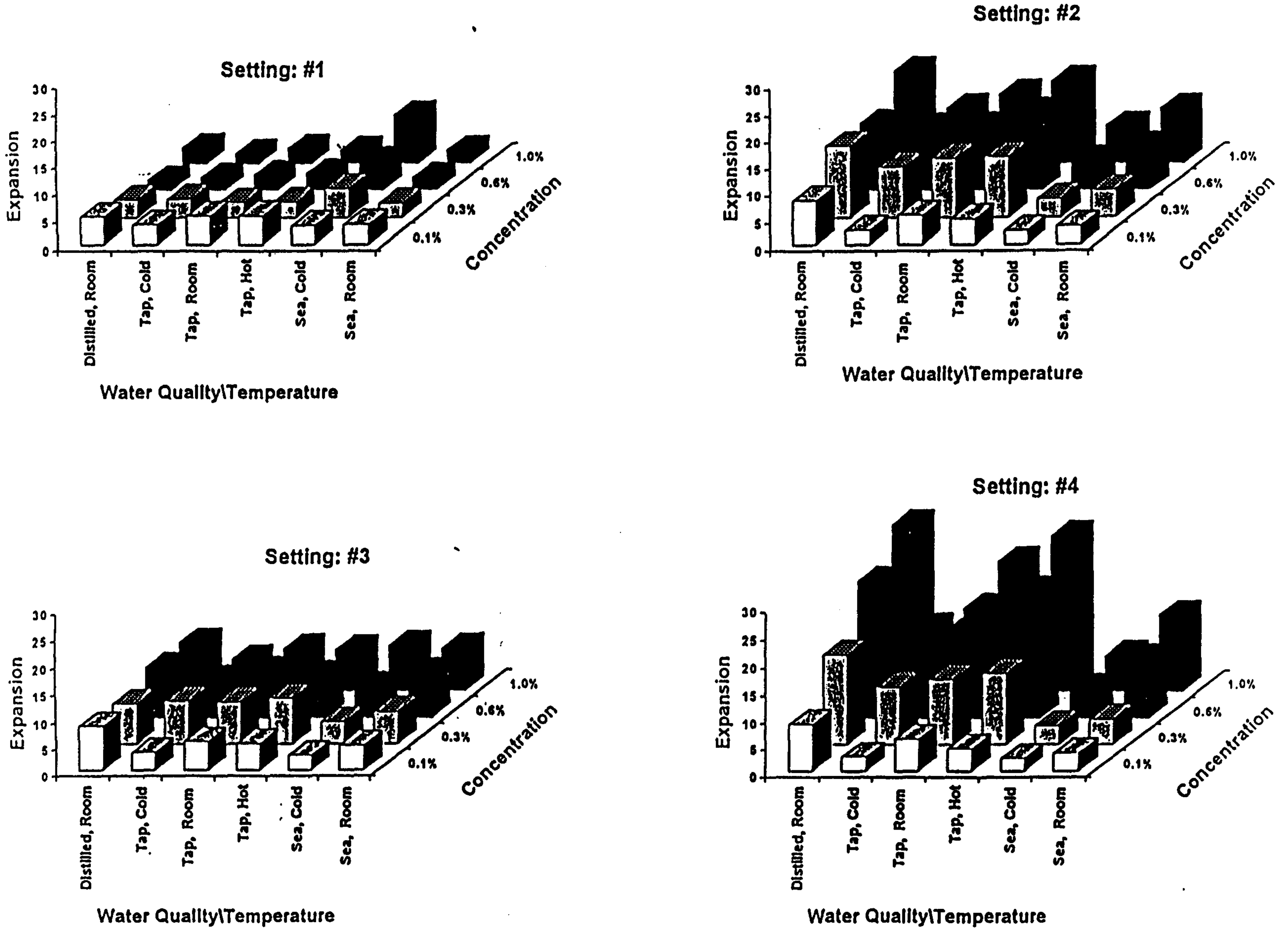


Figure 7 - Expansion of Angus ForExpan S as a Function of Production Variables

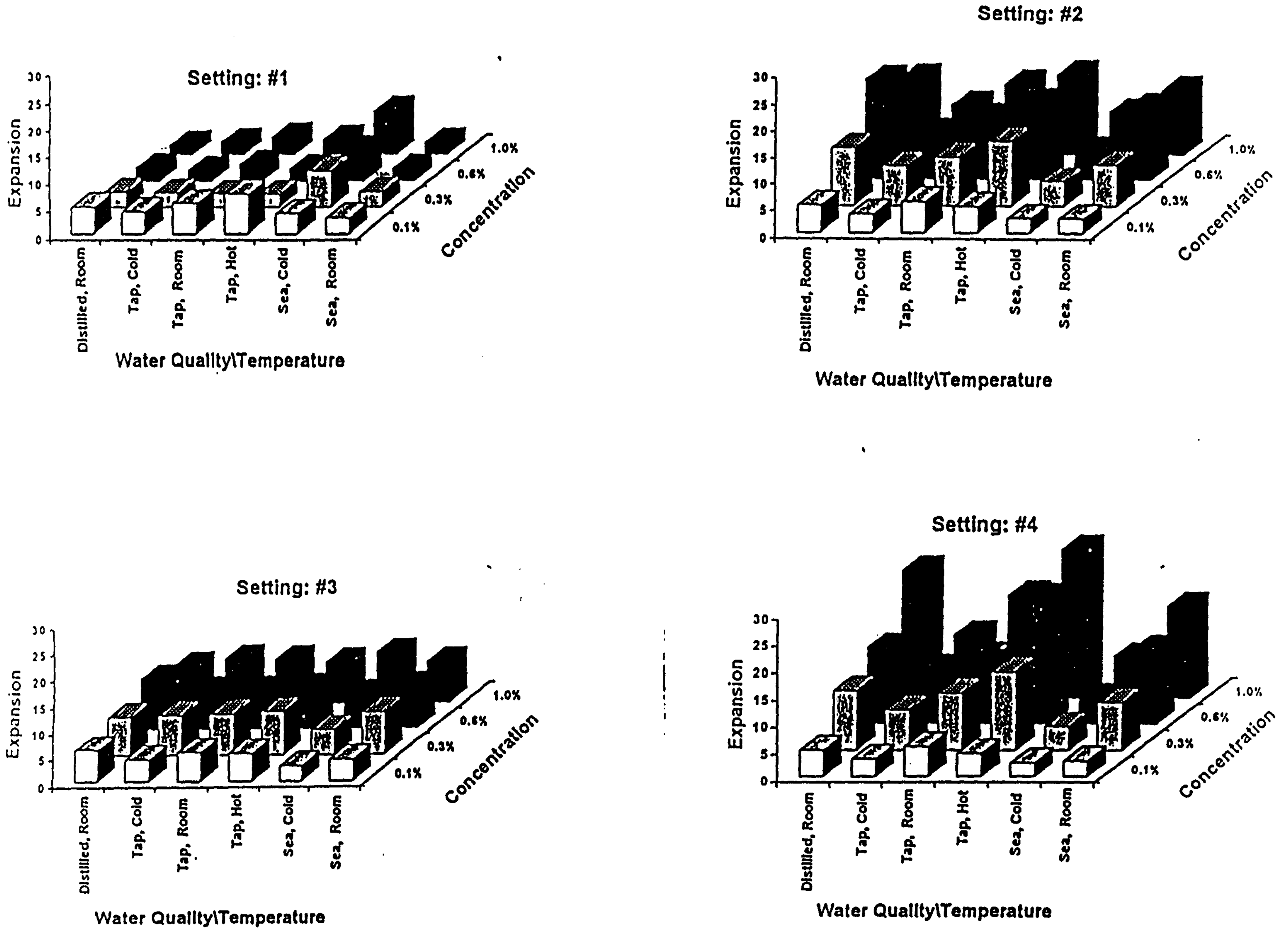


Figure 8 - Expansion of Pyrocap B-136 as a Function of Production Variables.

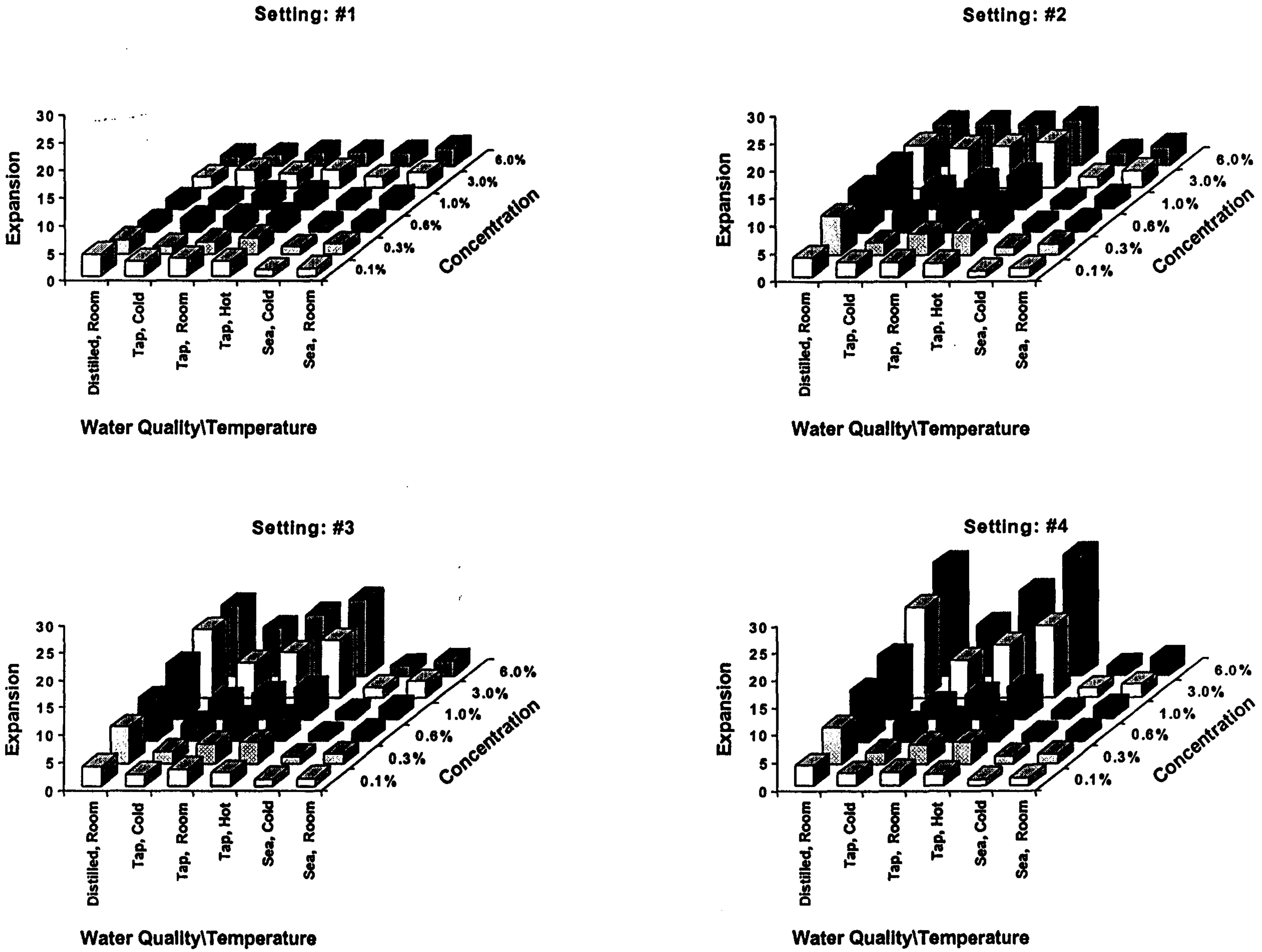


Figure 9 - Expansion of Fire Quench as a Function of Production Variables.

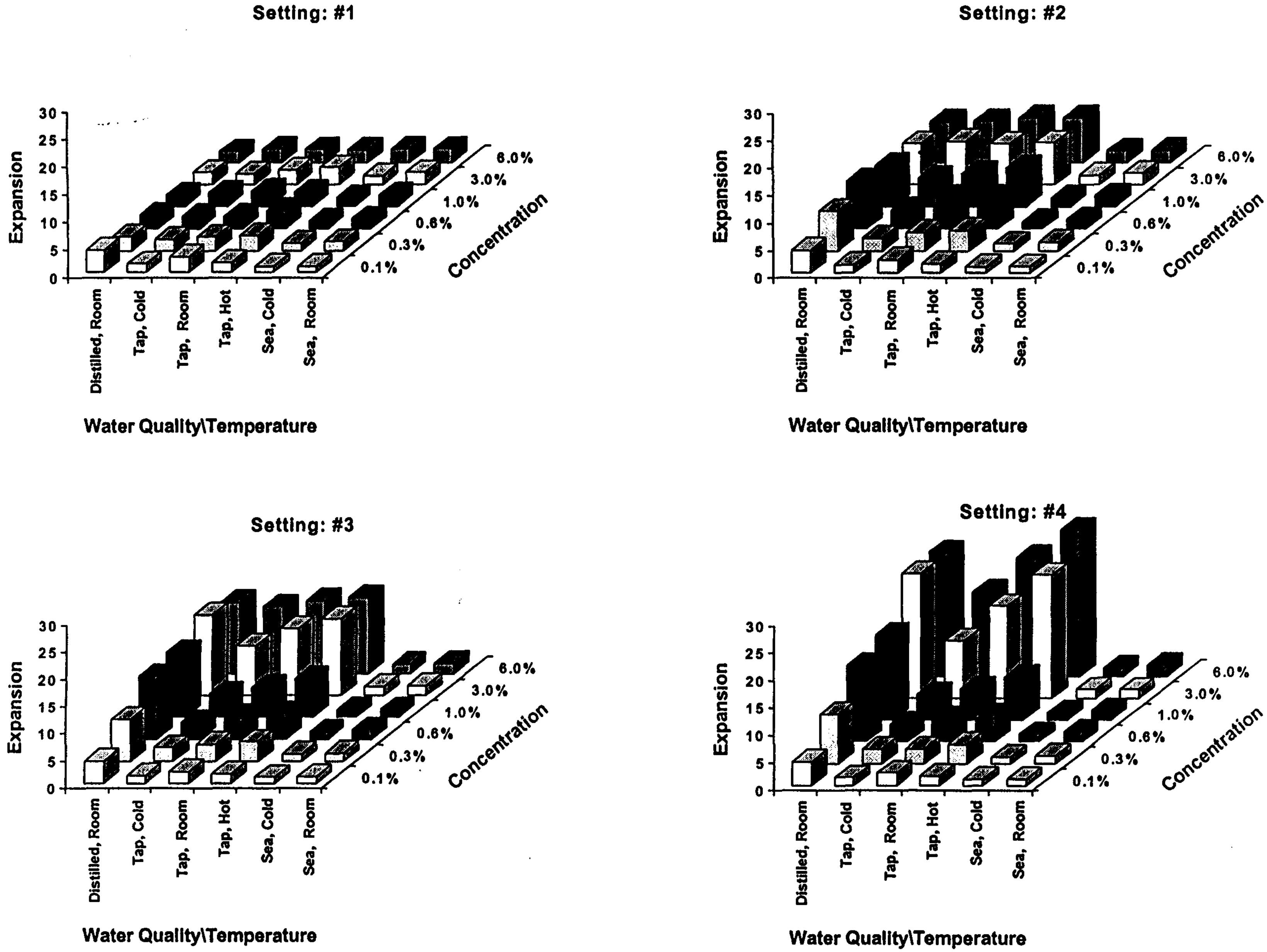
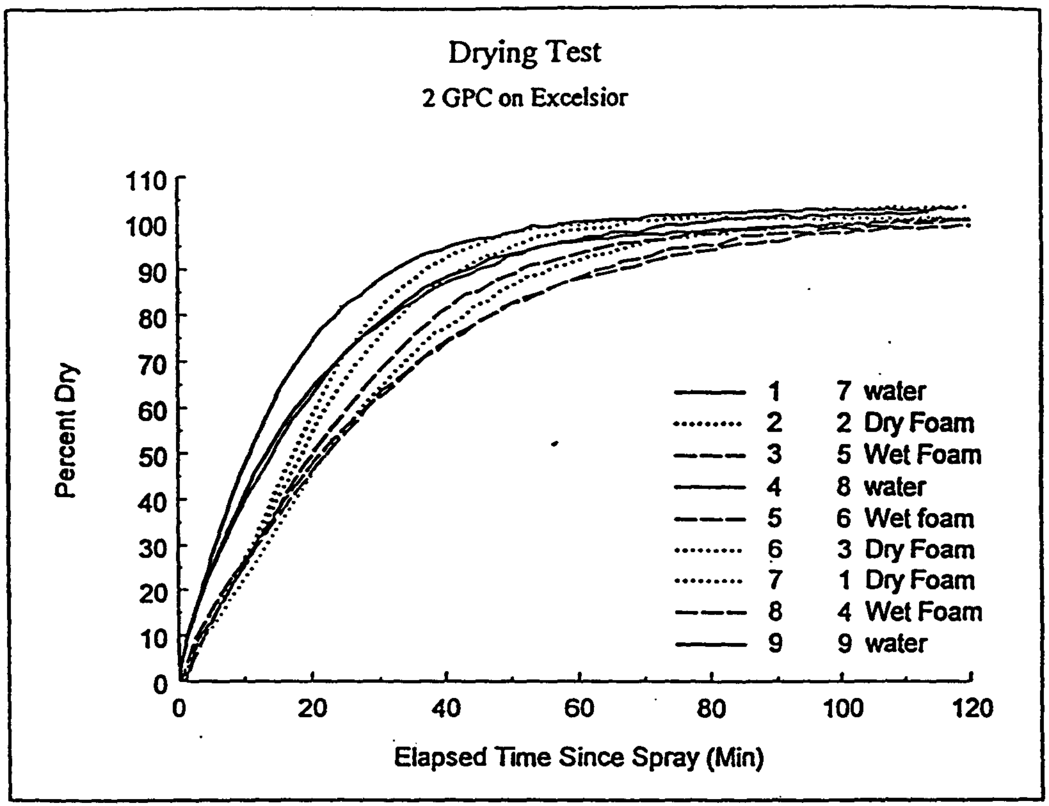


Figure 10 - Typical Drying Curves for Water and Foam on Aspen Excelsior and P. Pine Needles



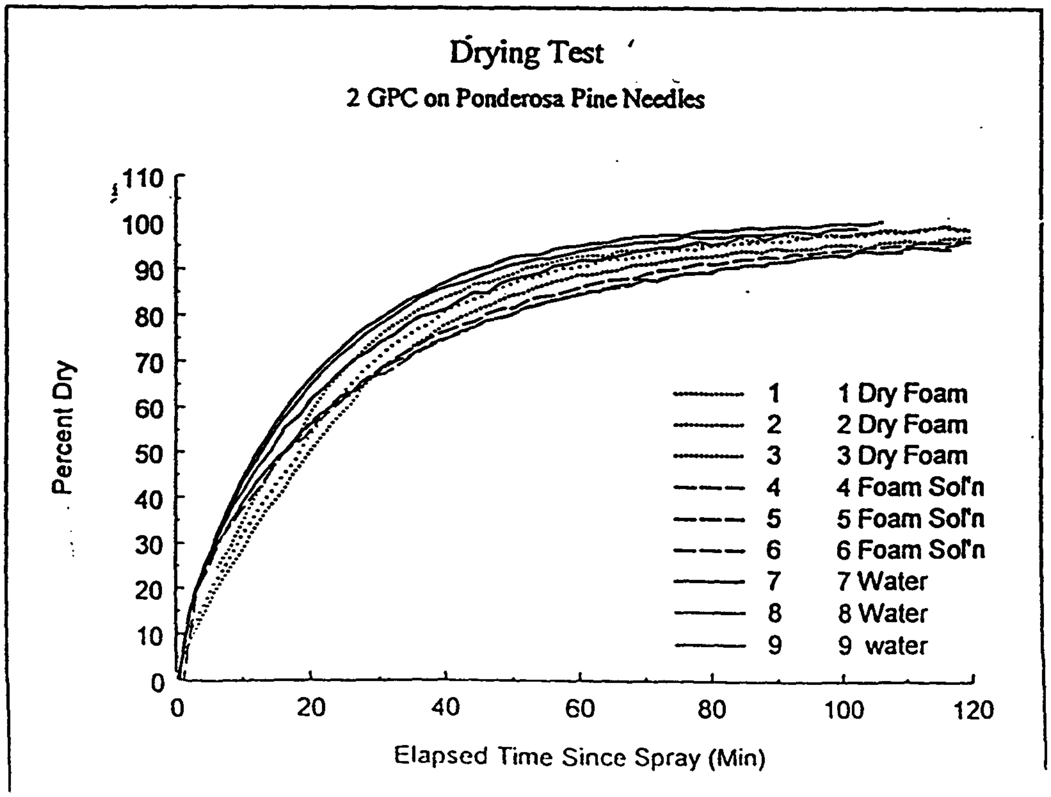
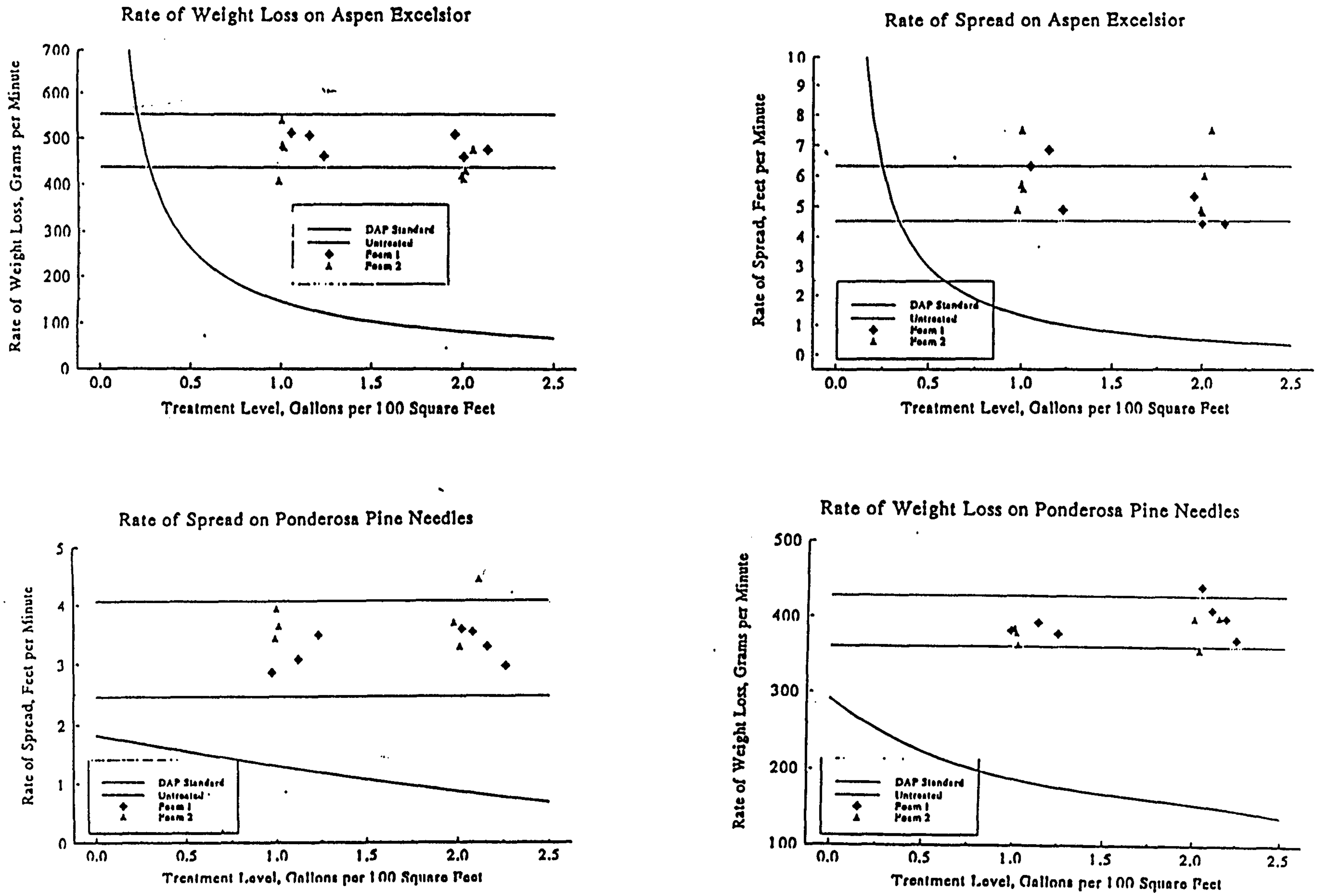


Figure 11 - Burning Curves for Rate of Weight Loss and Rate of Spread for Two Foams Tested as Long-Term Retardants



Rate of Weight Loss on Aspen Excelsior

Rate of Spread on Aspen Excelsior

Rate of Spread on Ponderosa Pine Needles

Rate of Weight Loss on Ponderosa Pine Needles

# APPENDIX D

# COMPUTER ACQUIRED DATA FROM MASS-RETENTION EXPERIMENTS 1-27

William J. Josler
National Institute of Standards and Technology
Building and Fire Research Laboratory
Fire Safety Engineering Division
Large Fire Research
Gaithersburg, Maryland

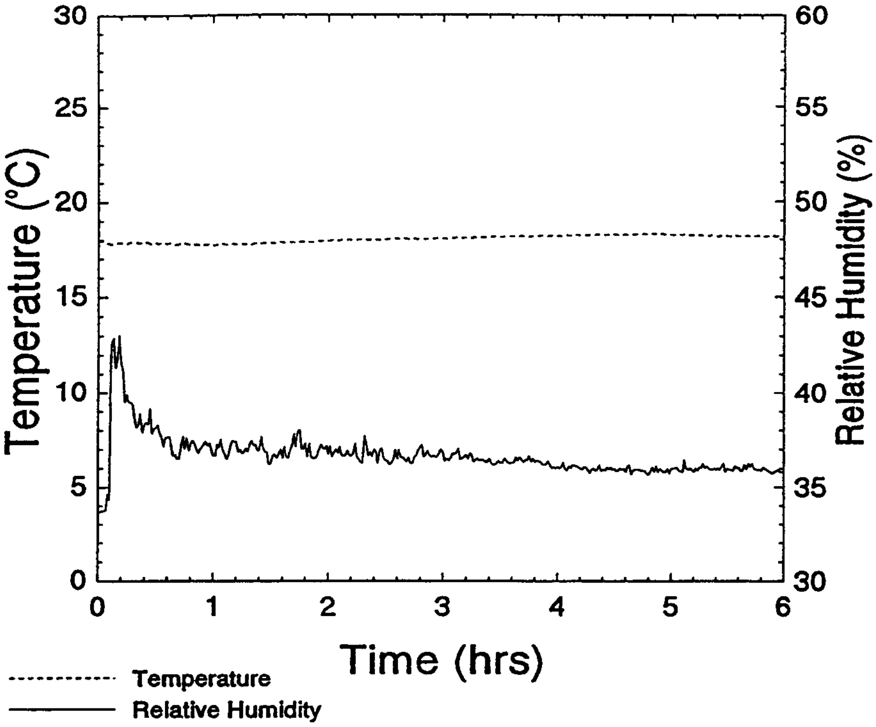


Figure 1 - Water, experiment 1, environmental conditions

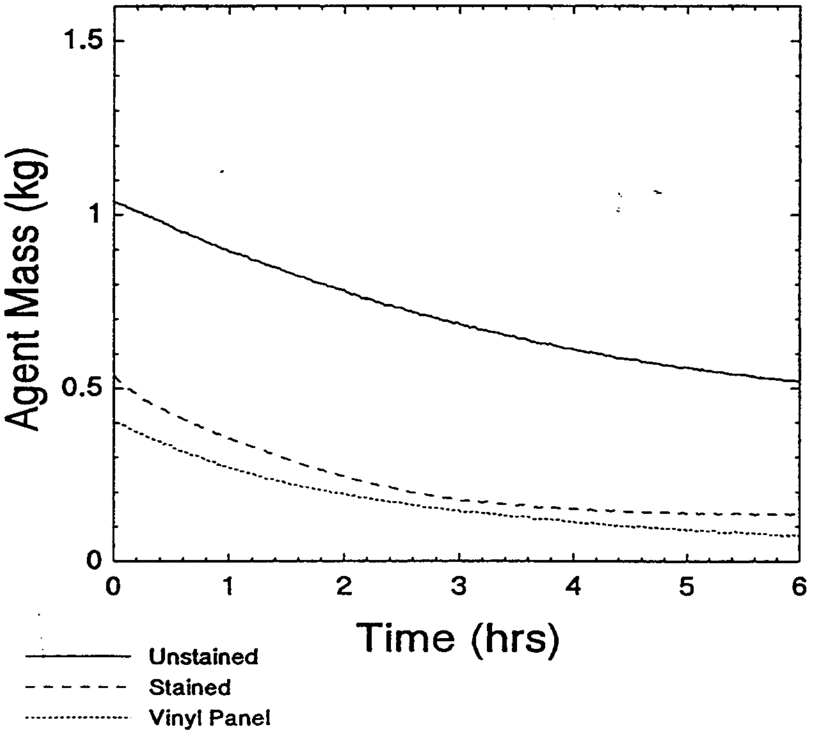


Figure 2 - Water, experiment 1, mass retention

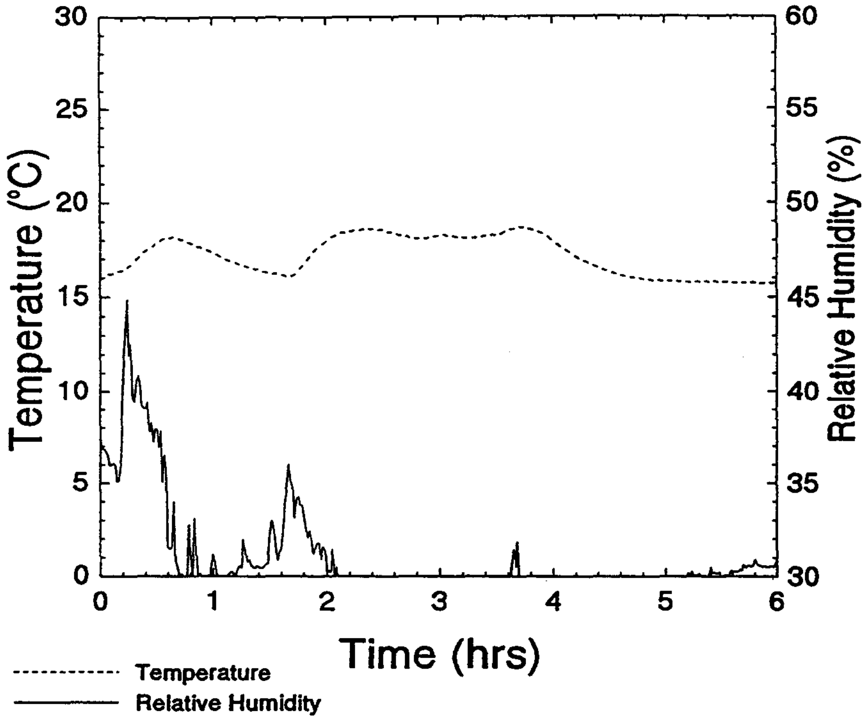


Figure 3 - Water, experiment 2, environmental conditions

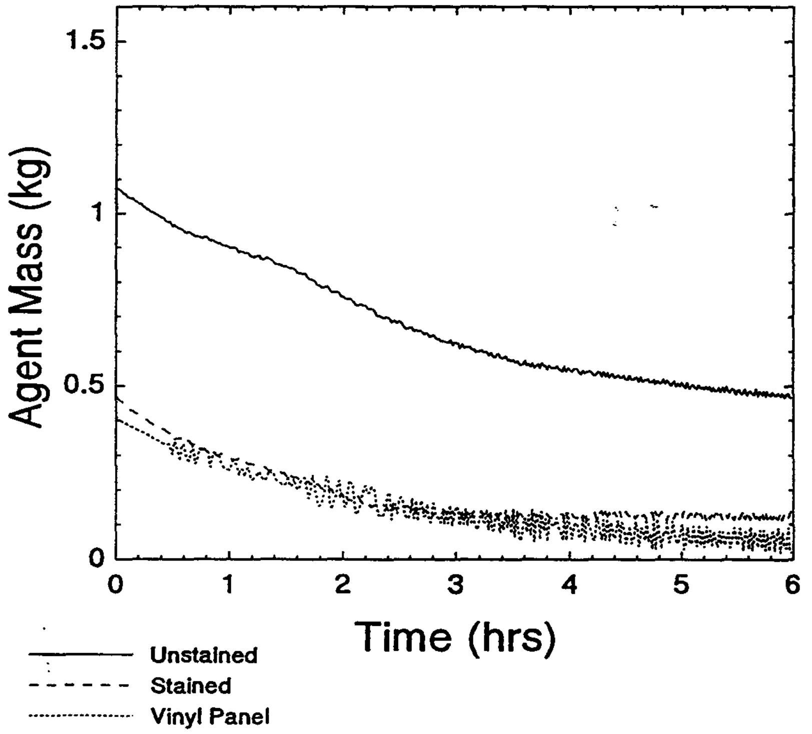


Figure 4 - Water, experiment 2, mass retention

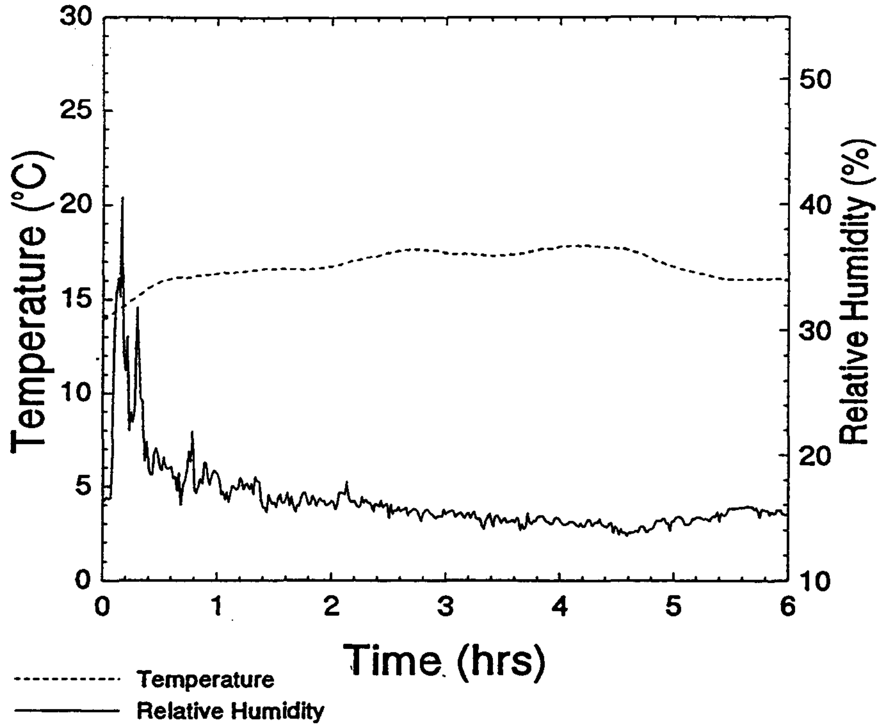


Figure 5 - Water, experiment 3, environmental conditions

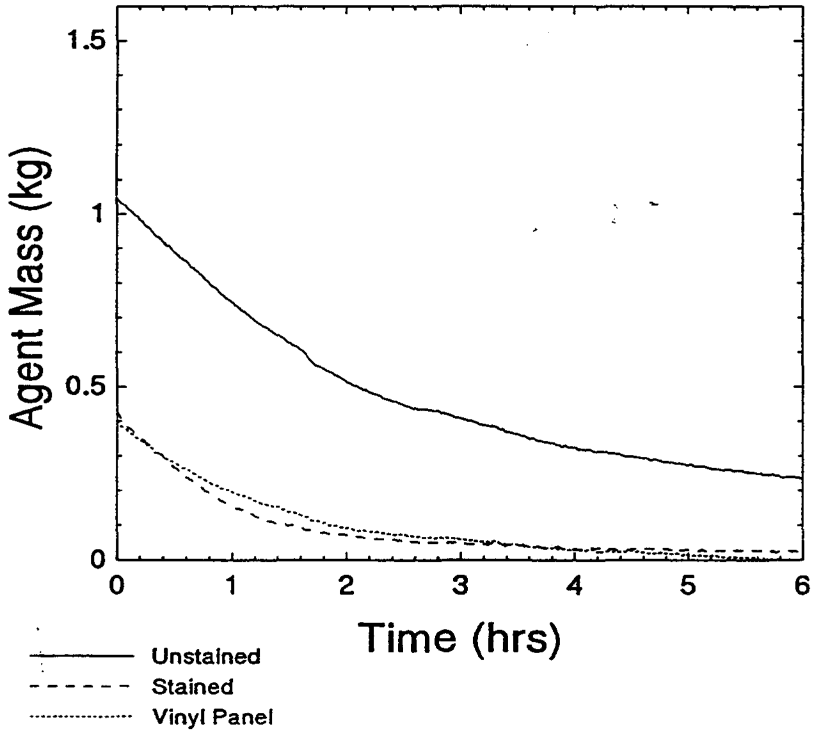


Figure 6 - Water, experiment 3, mass retention

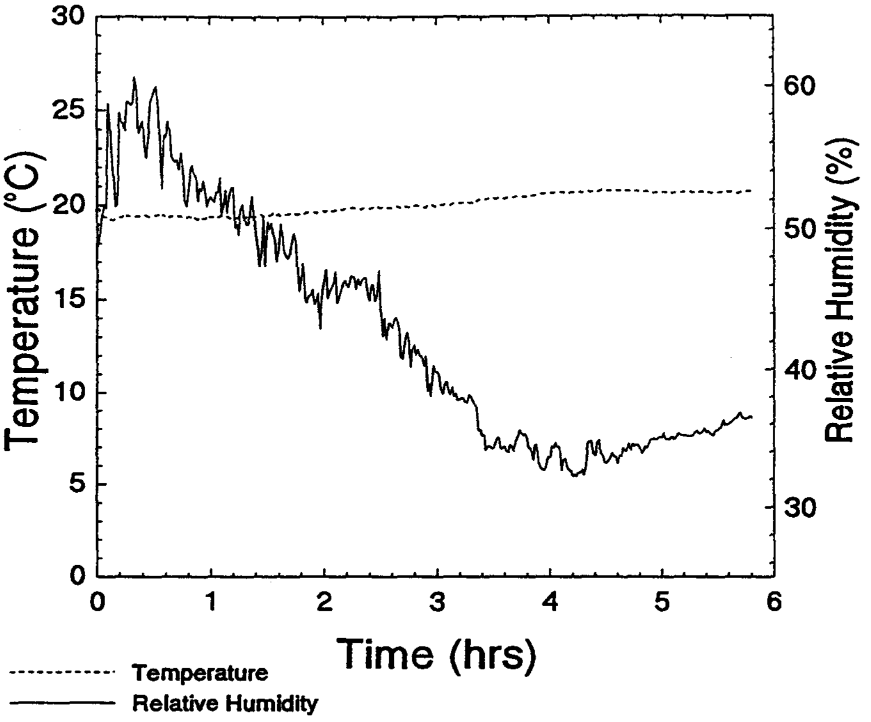


Figure 7 - Solution A, experiment 1, environmental conditions

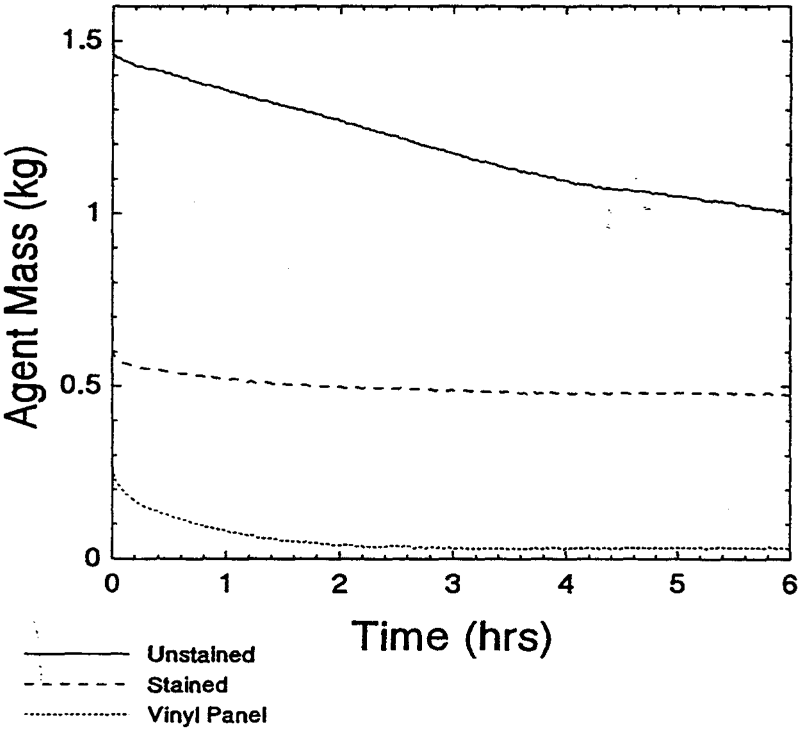


Figure 8 - Solution A, experiment 1, mass retention

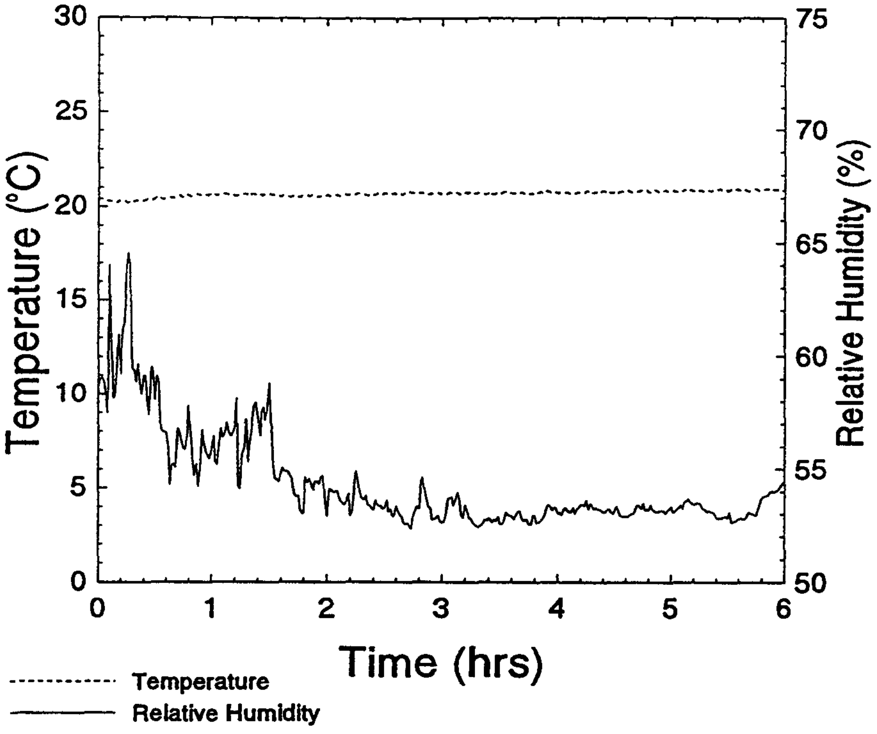


Figure 9 - Solution A, experiment 2, environmental conditions

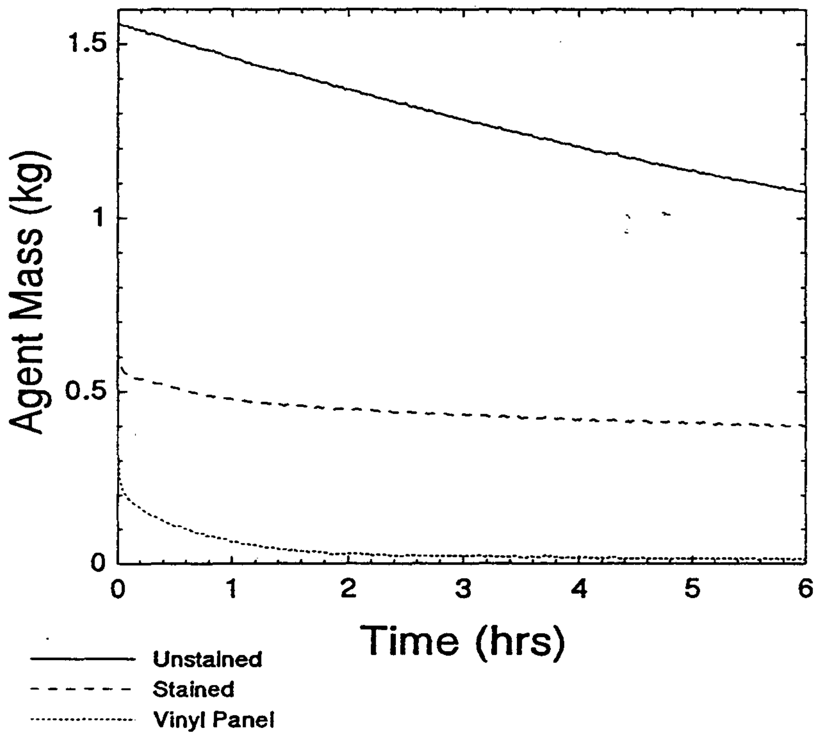


Figure 10 - Solution A, experiment 2, mass retention

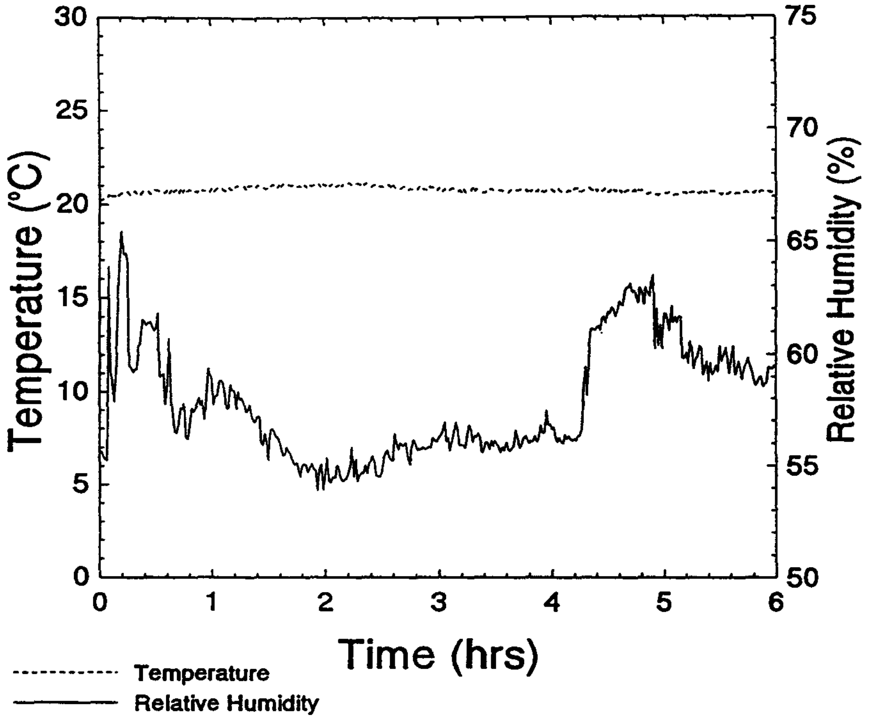


Figure 11 - Solution A, experiment 3, environmental conditions

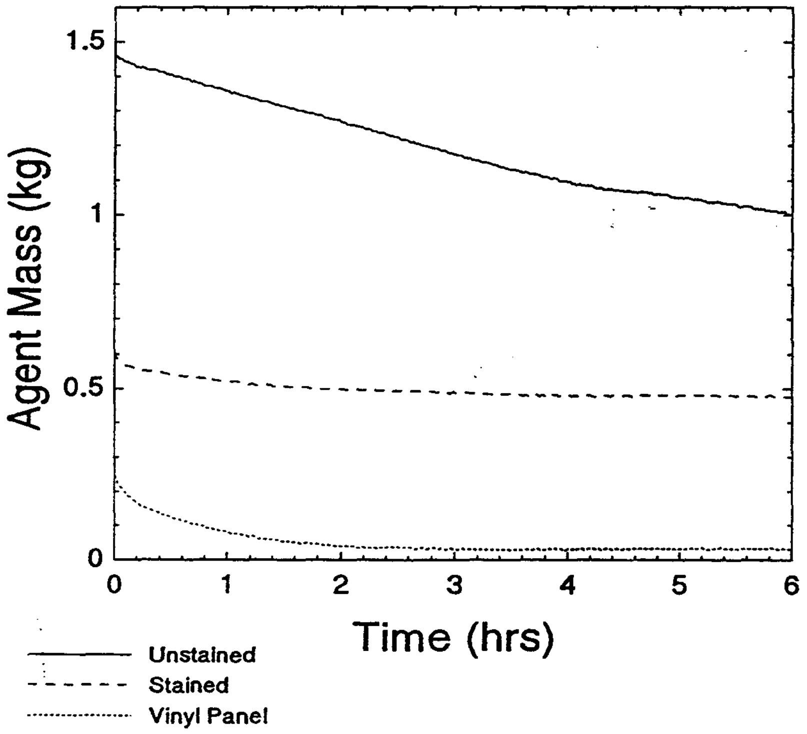


Figure 12 - Solution A, experiment 3, mass retention

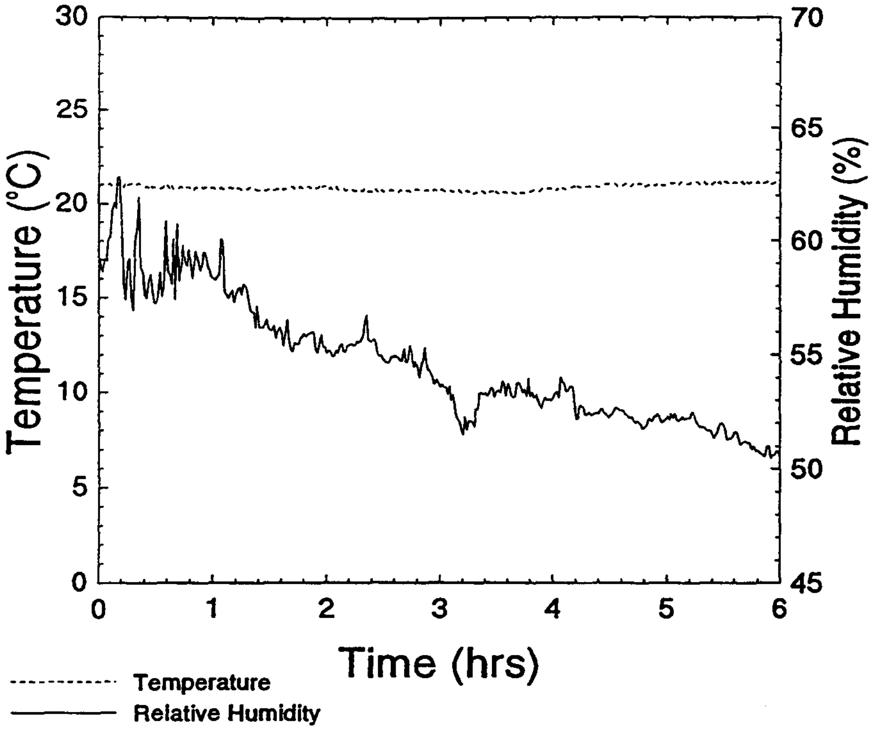


Figure 13 - Solution B, experiment 1, environmental conditions

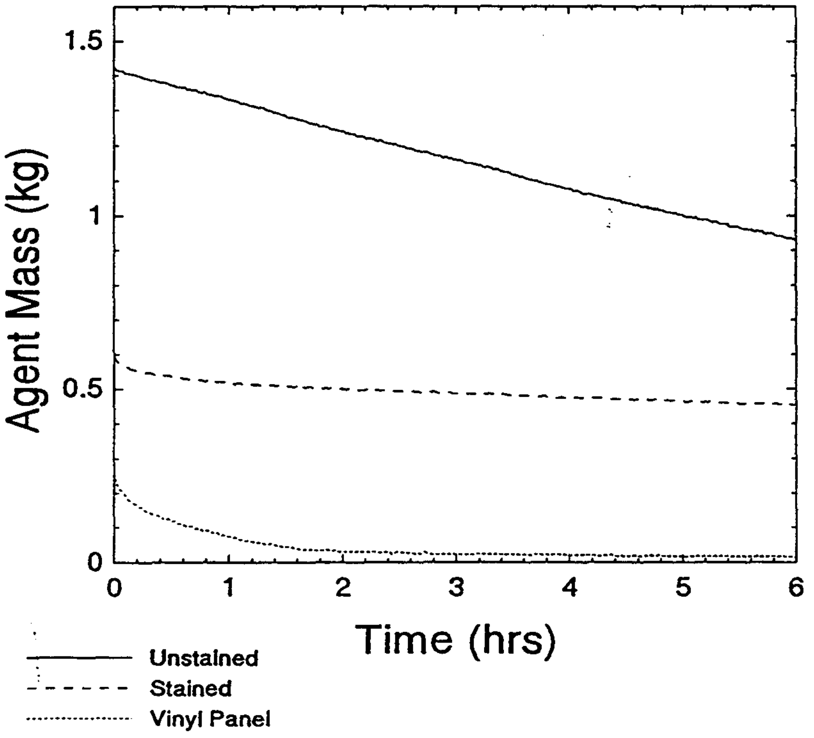


Figure 14 - Solution B, experiment 1, mass retention

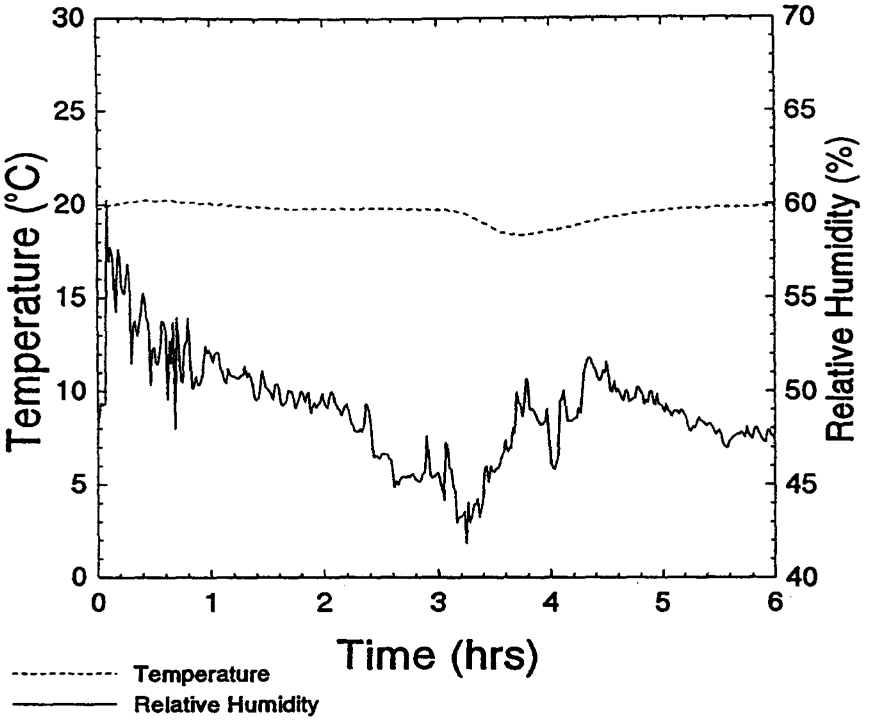


Figure 15 - Solution B, experiment 2, environmental conditions

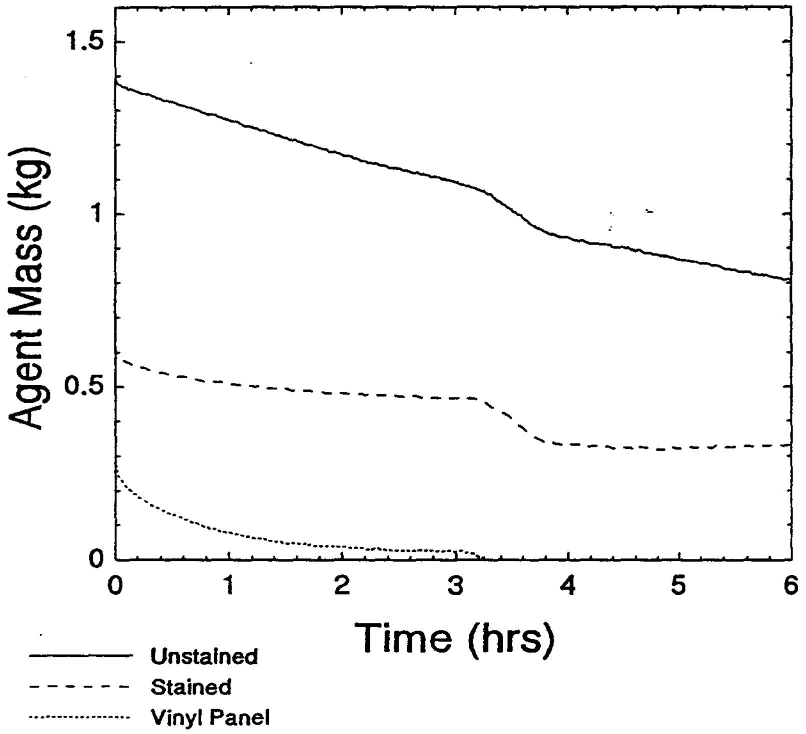


Figure 16 - Solution B, experiment 2, mass retention

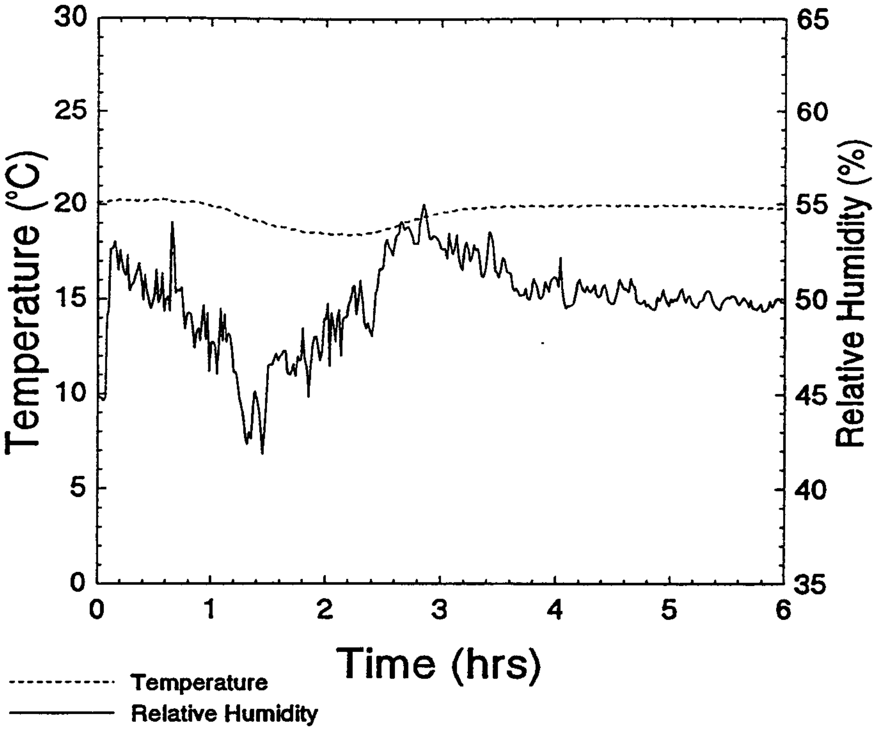


Figure 17 - Solution B, experiment 3, environmental conditions

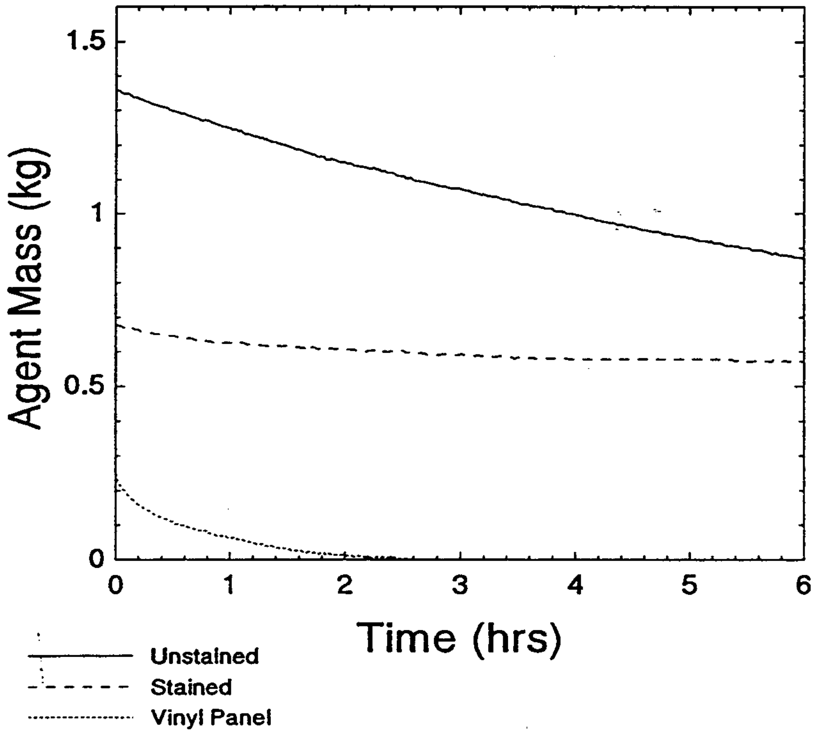


Figure 18 - Solution B, experiment 3, mass retention

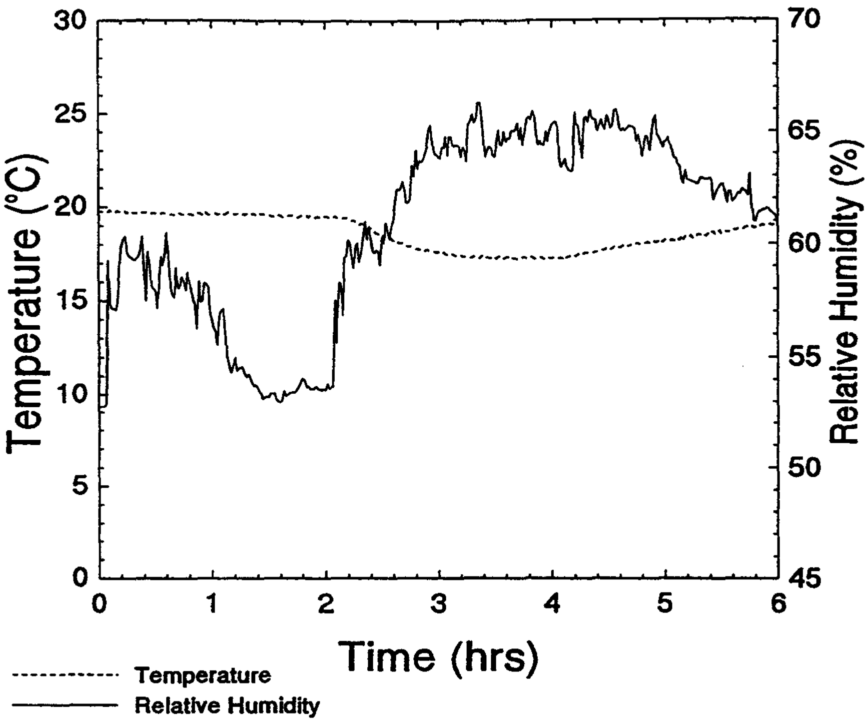


Figure 19 - Solution C, experiment 1, environmental conditions

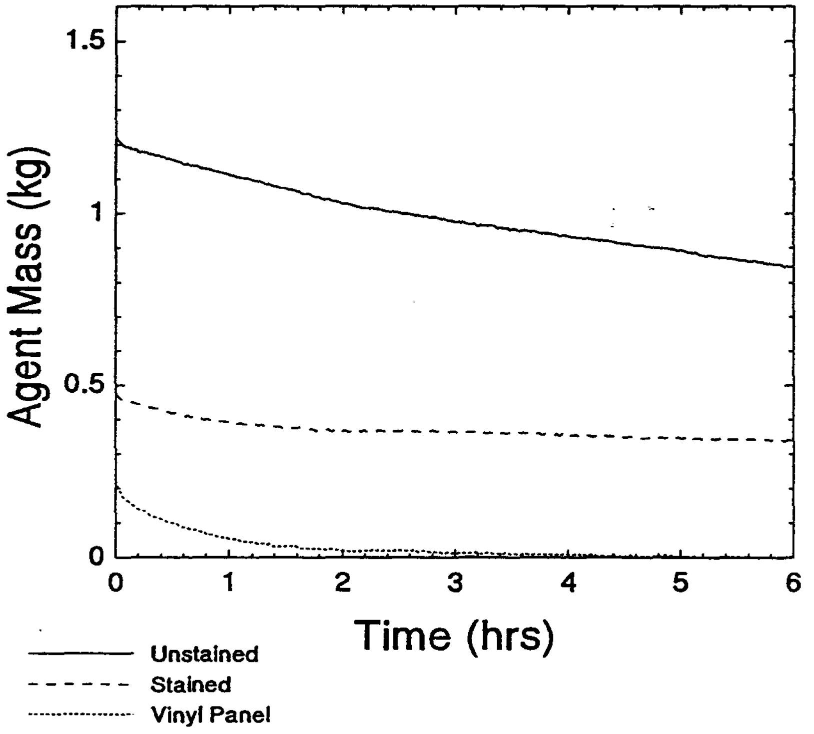


Figure 20 - Solution C, experiment 1, mass retention

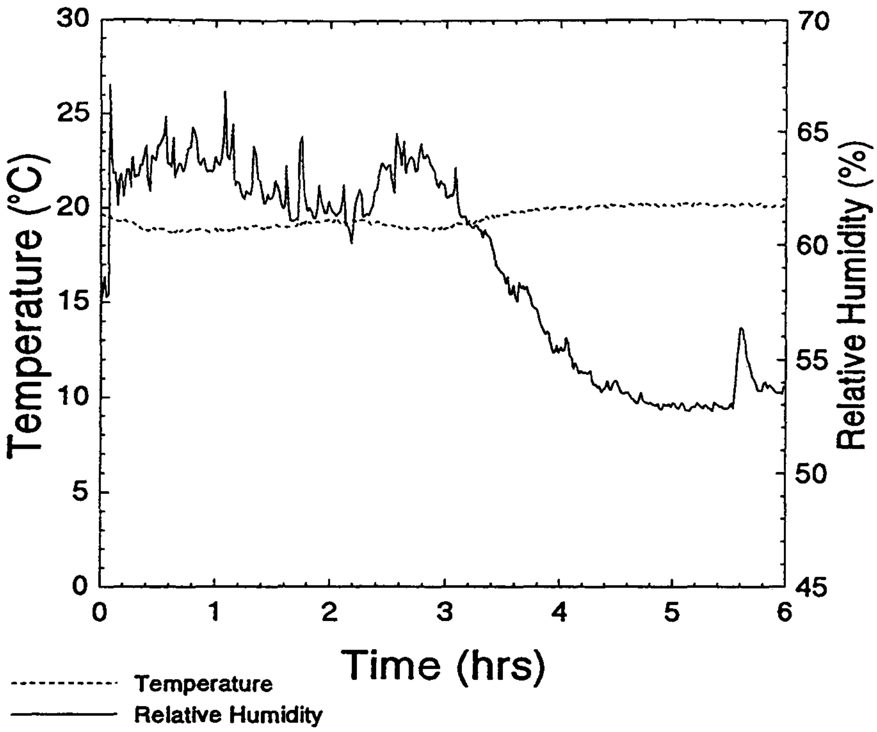


Figure 21 - Solution C, experiment 2, environmental conditions

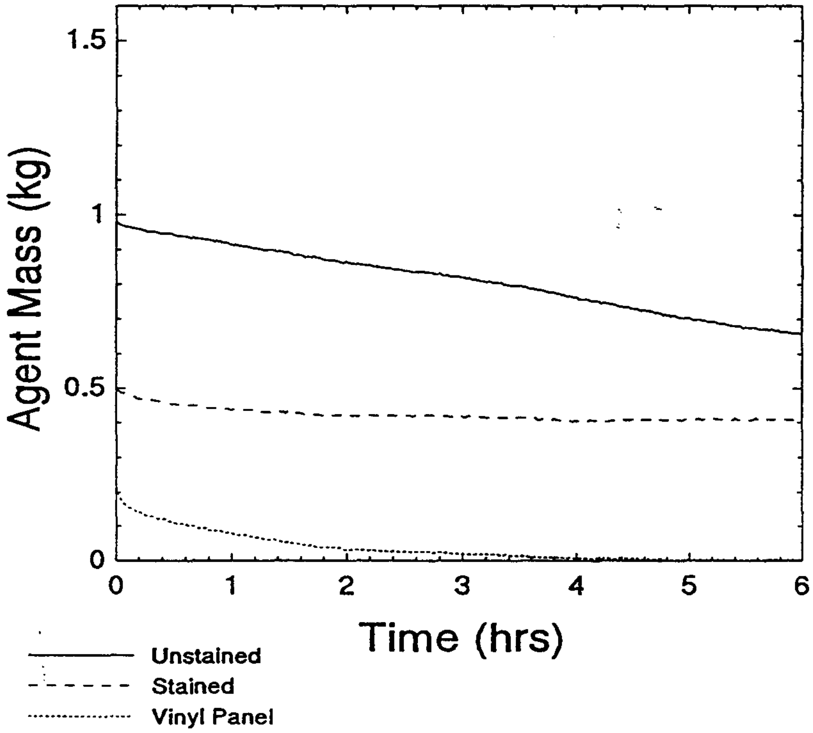


Figure 22 - Solution C, experiment 2, mass retention

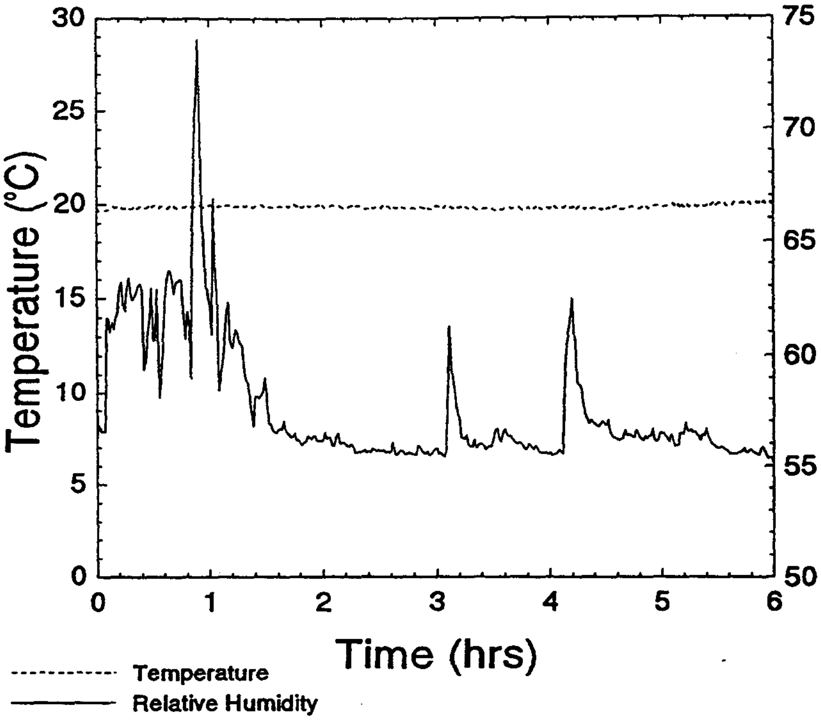


Figure 23 - Solution C, experiment 3, environmental conditions

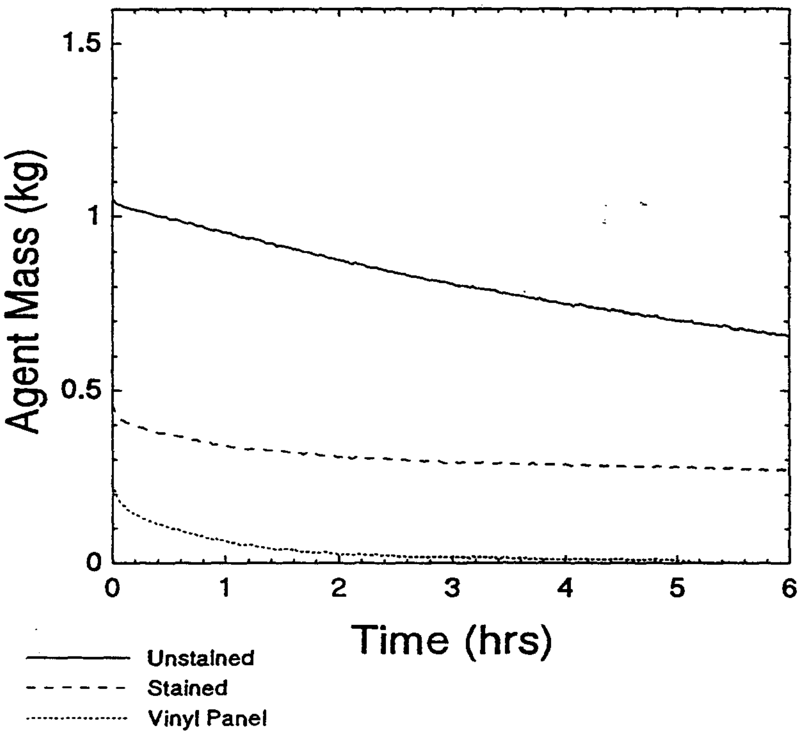


Figure 24 - Solution C, experiment 2, mass retention

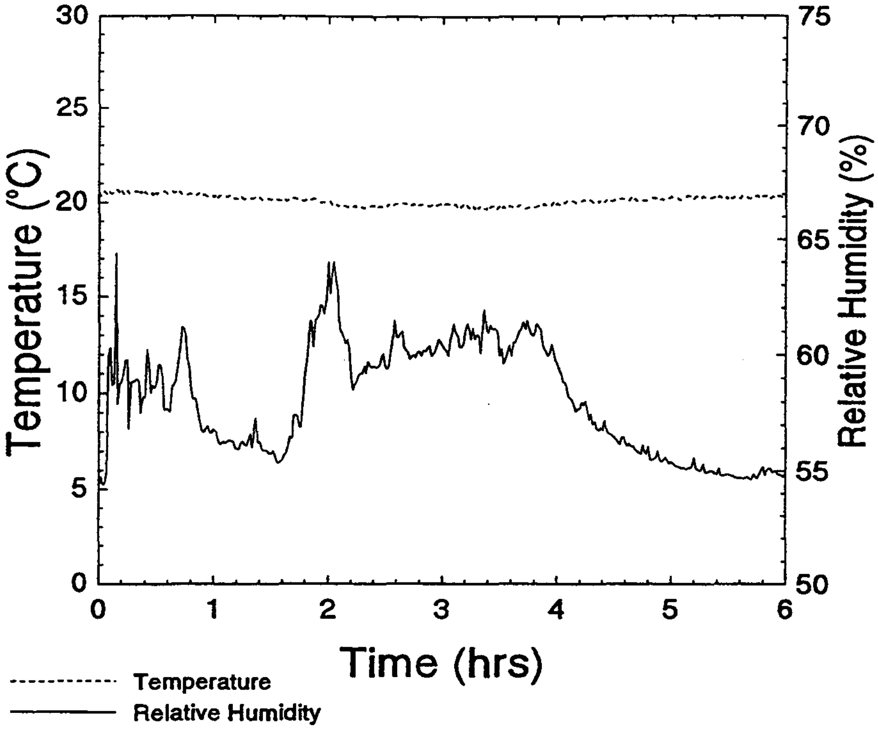


Figure 25 - Solution D, experiment 1, environmental conditions

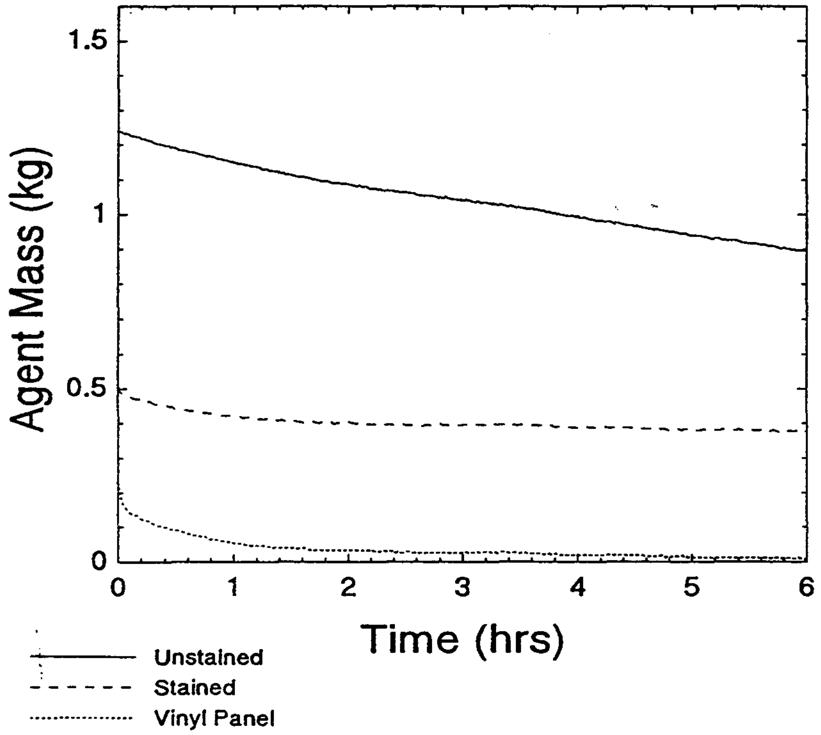


Figure 26 - Solution D, experiment 1, mass retention

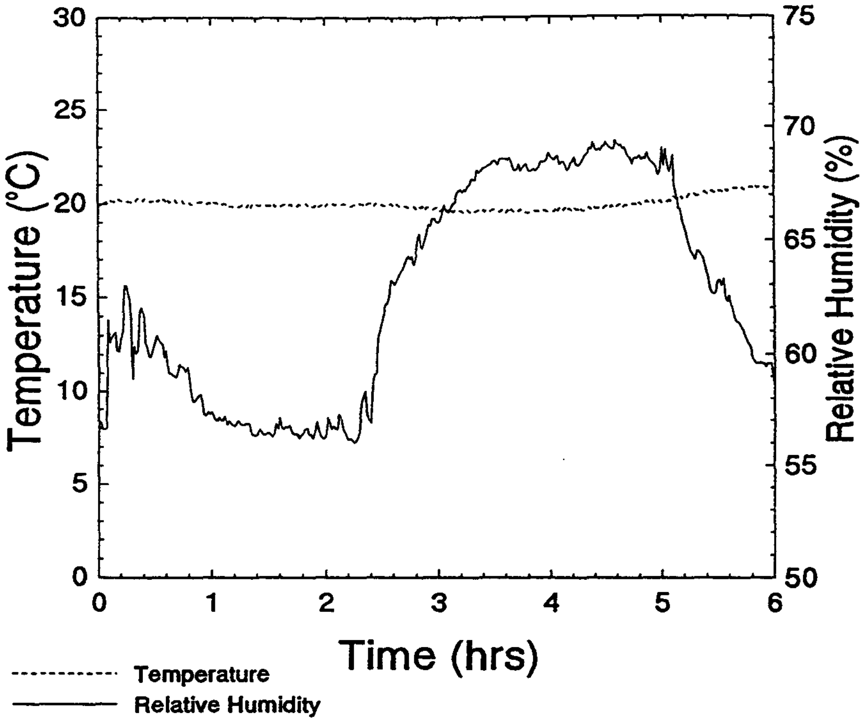


Figure 27 - Solution D, experiment 2, environmental conditions

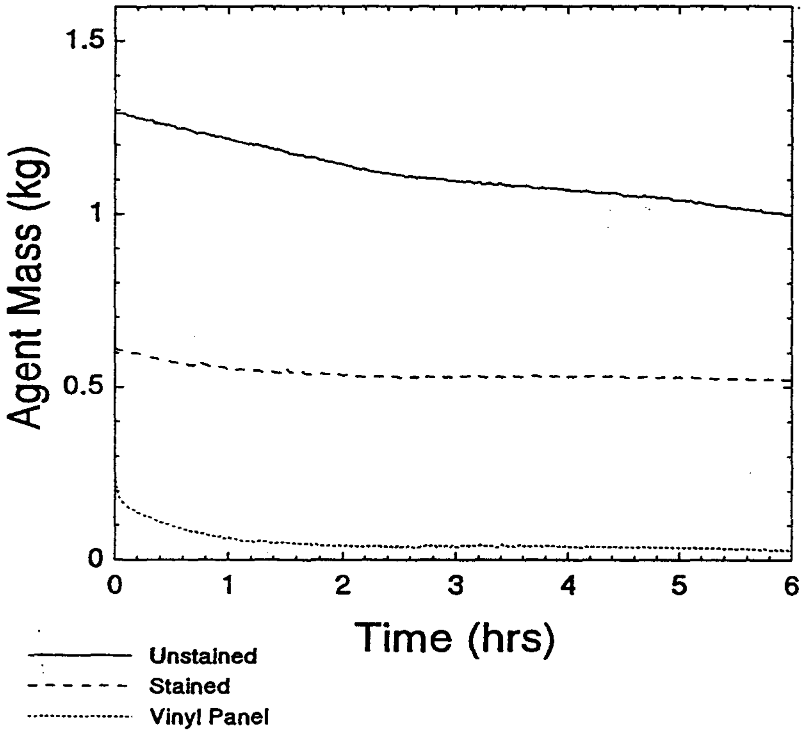


Figure 28 - Solution D, experiment 2, mass retention

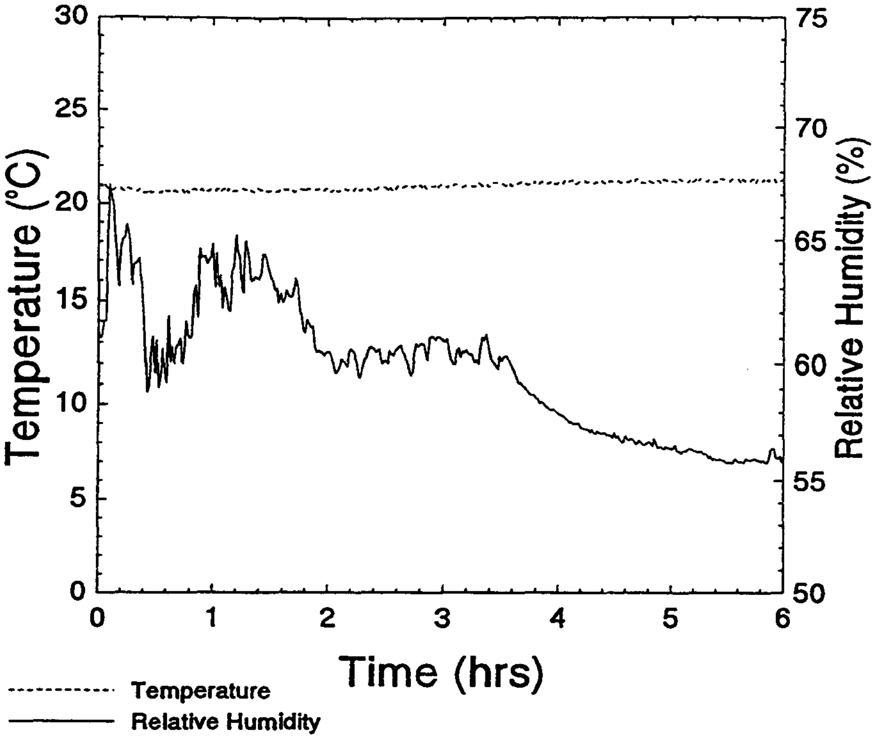


Figure 29 - Solution D, experiment 3, environmental conditions

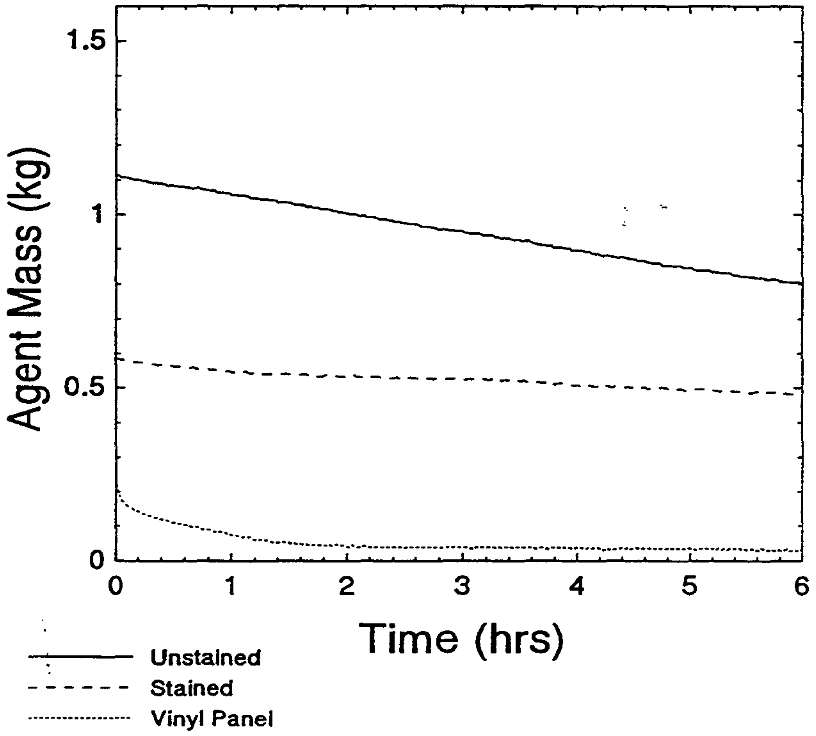


Figure 30 - Solution D, experiment 3, mass retention

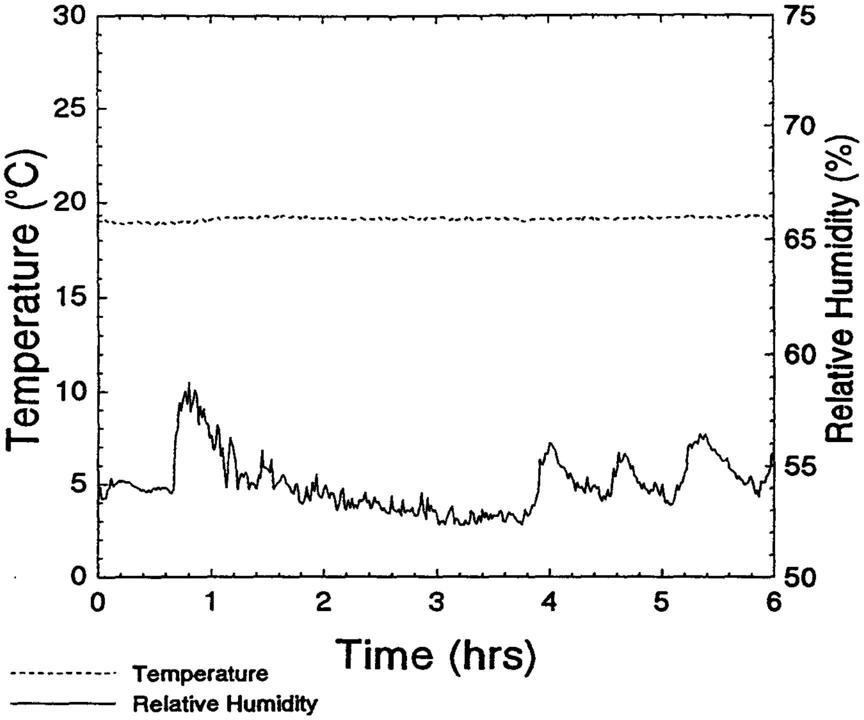


Figure 31 - Foam A, experiment 1, environmental conditions

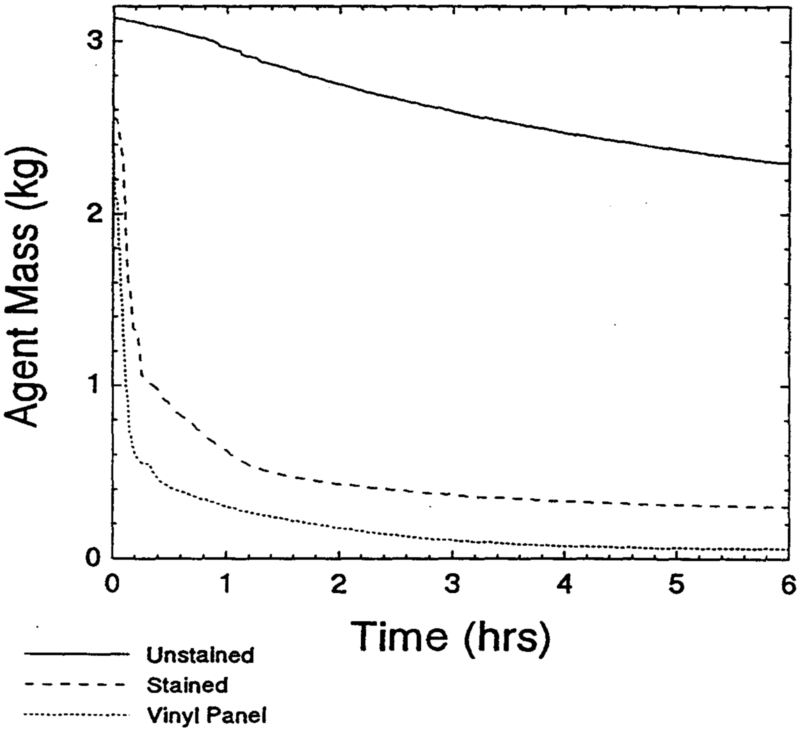


Figure 32 - Foam A, experiment 1, mass retention

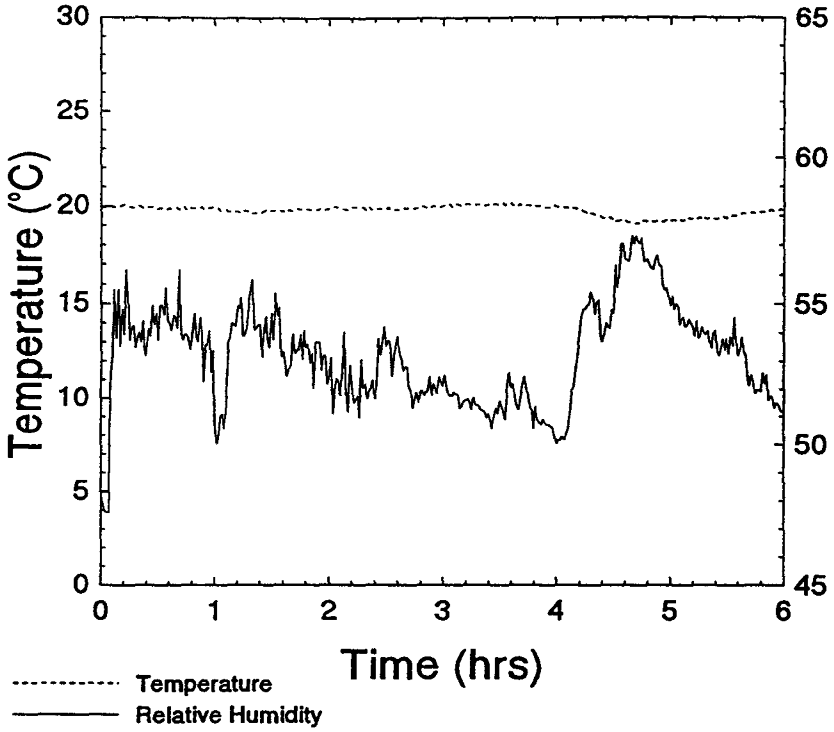


Figure 33 - Foam A, experiment 2, environmental conditions

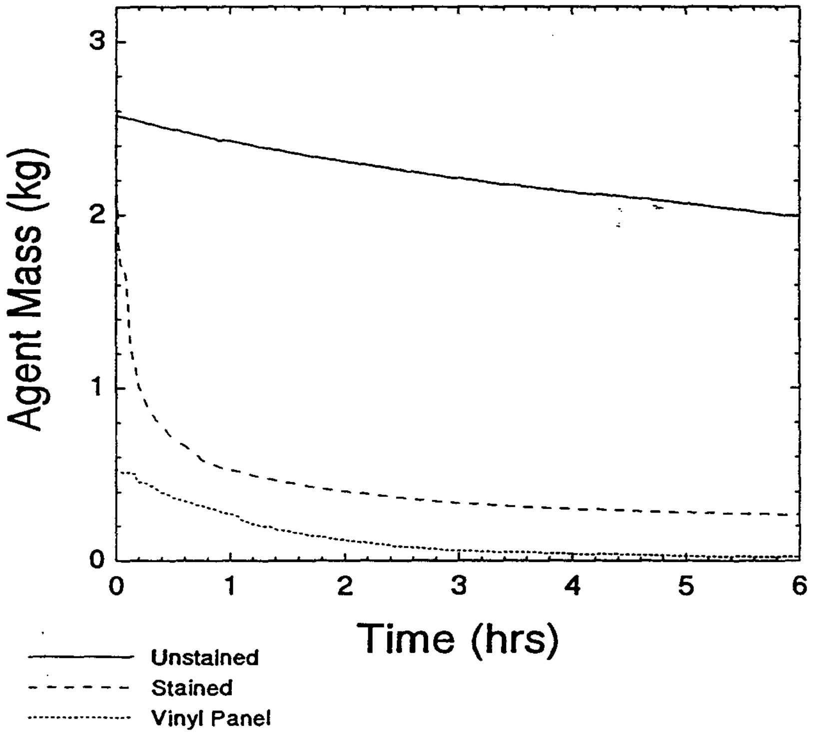


Figure 34 - Foam A, experiment 2, mass retention

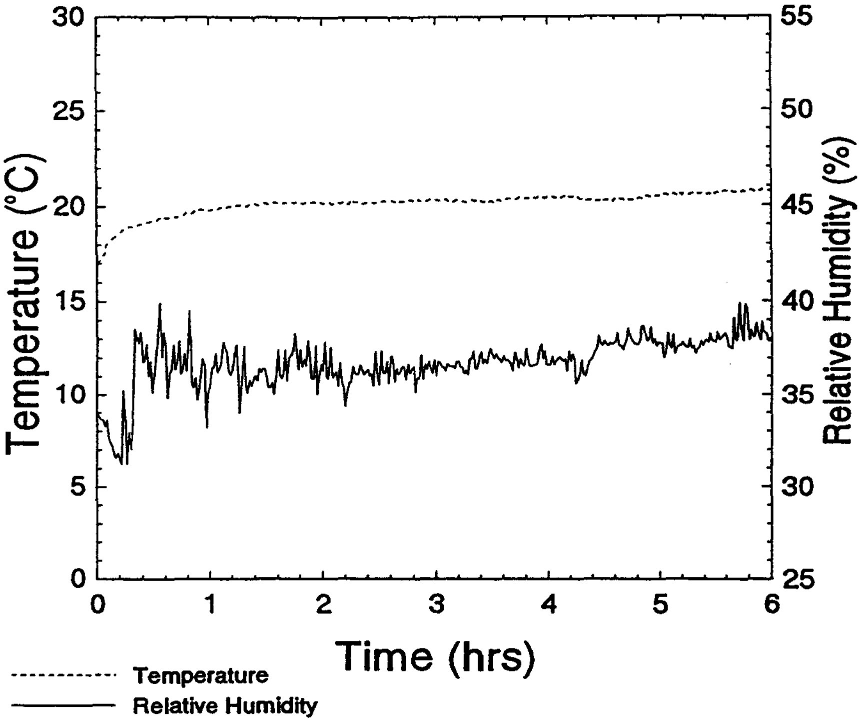


Figure 35 - Foam A, experiment 3, environmental conditions

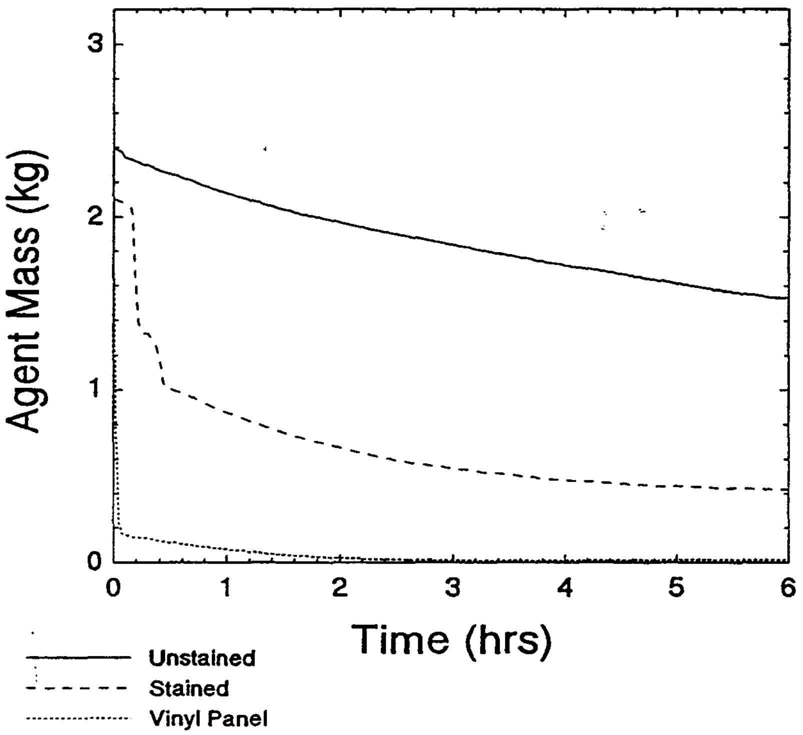


Figure 36 - Foam A, experiment 3, mass retention

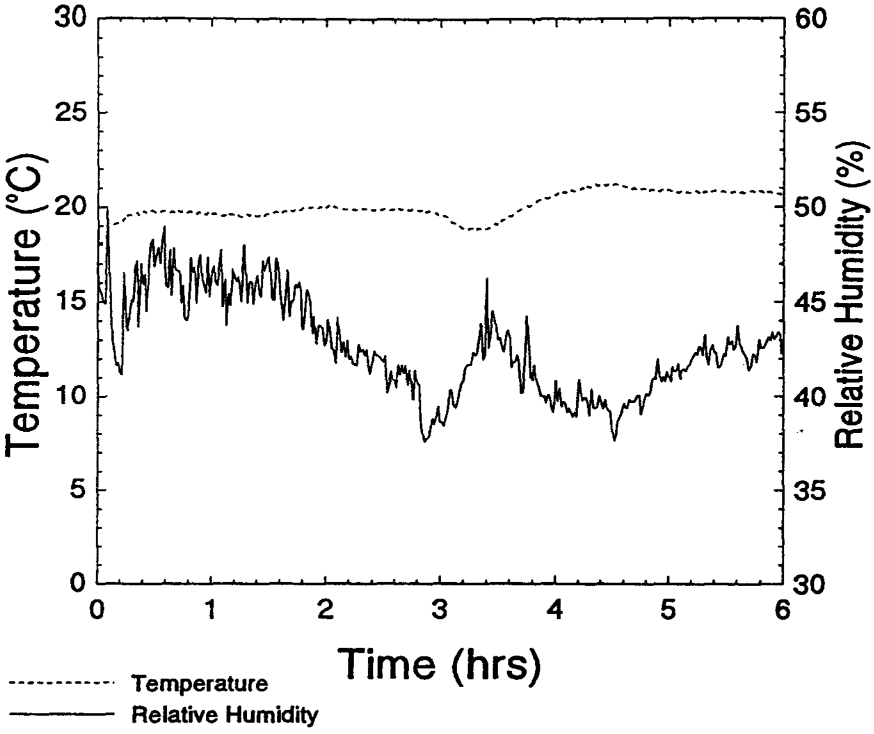


Figure 37 - Foam B, experiment 1, environmental conditions

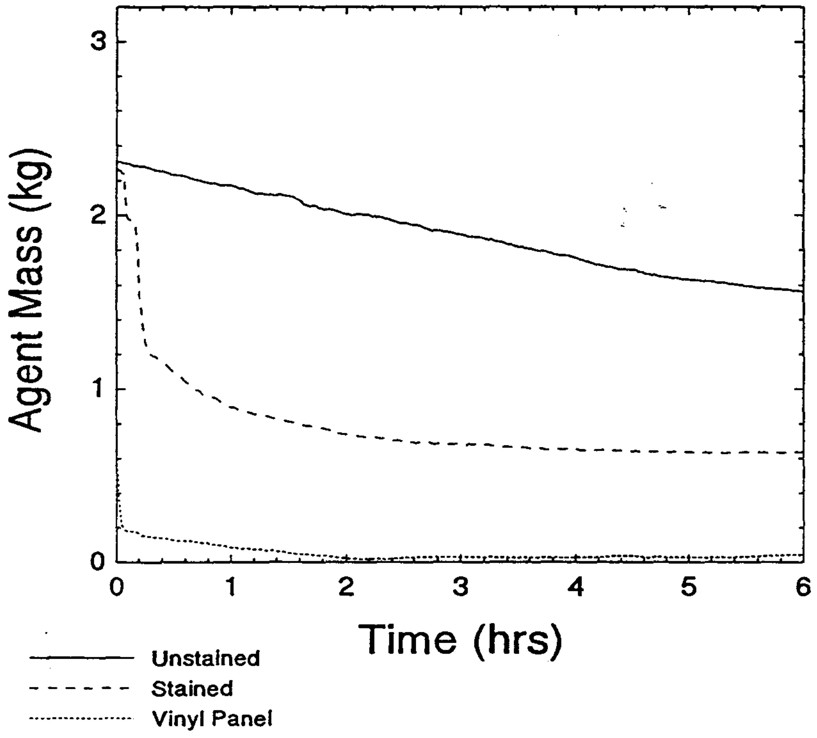


Figure 38 - Foam B, experiment 1, mass retention

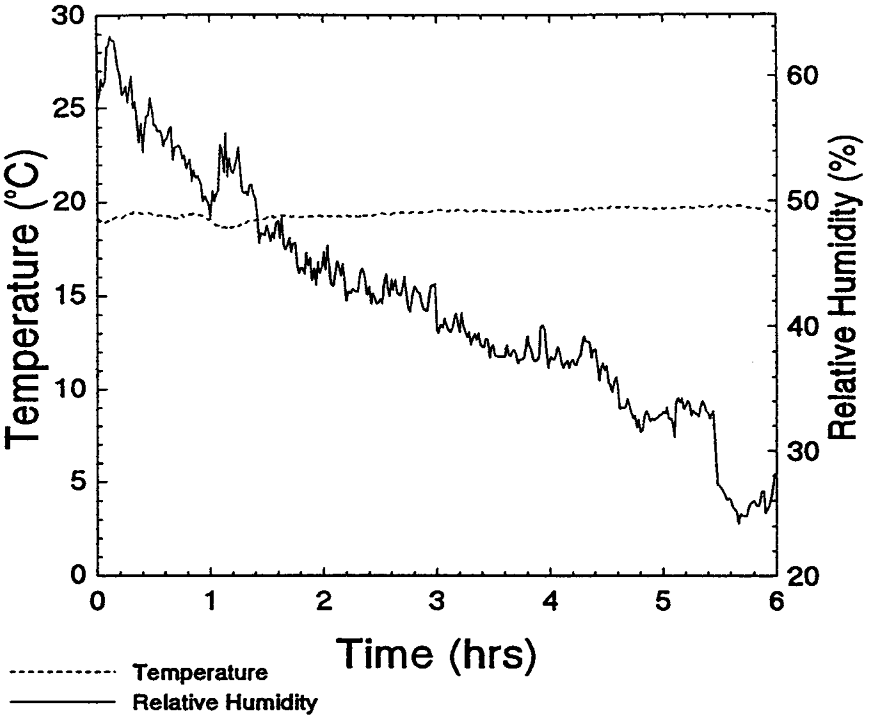


**Figure 39** - Foam B, experiment 2, environmental conditions

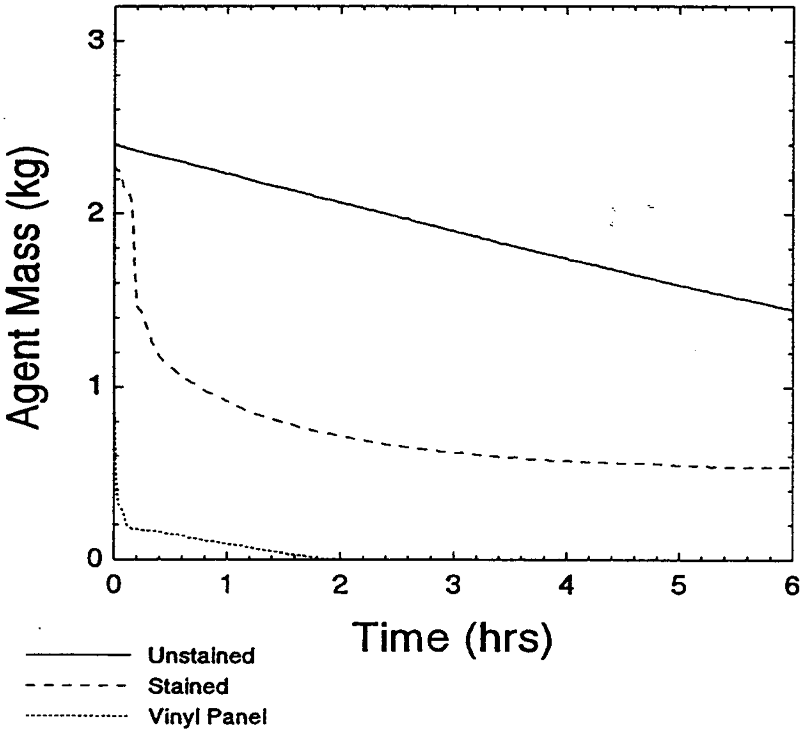


**Figure 40** - Foam B, experiment 2, mass retention

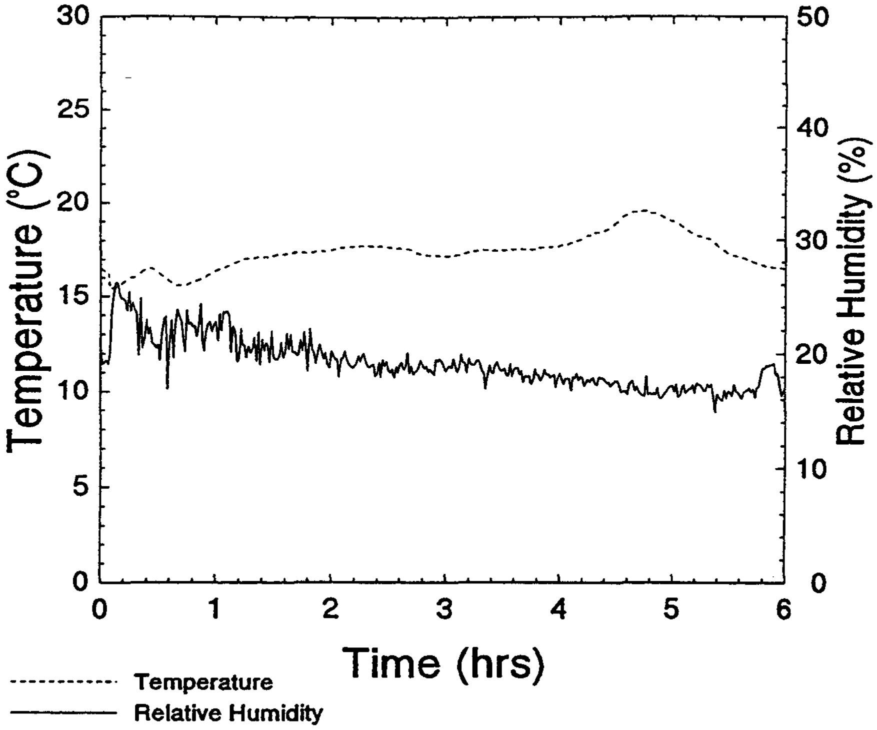


Figure 41 - Foam B, experiment 3, environmental conditions

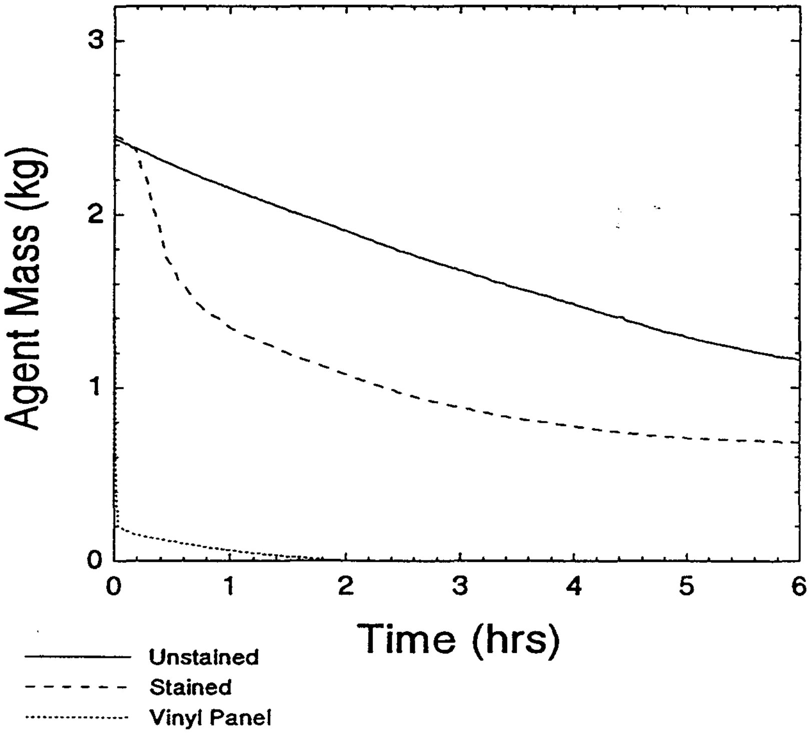


Figure 42 - Foam B, experiment 3, mass retention

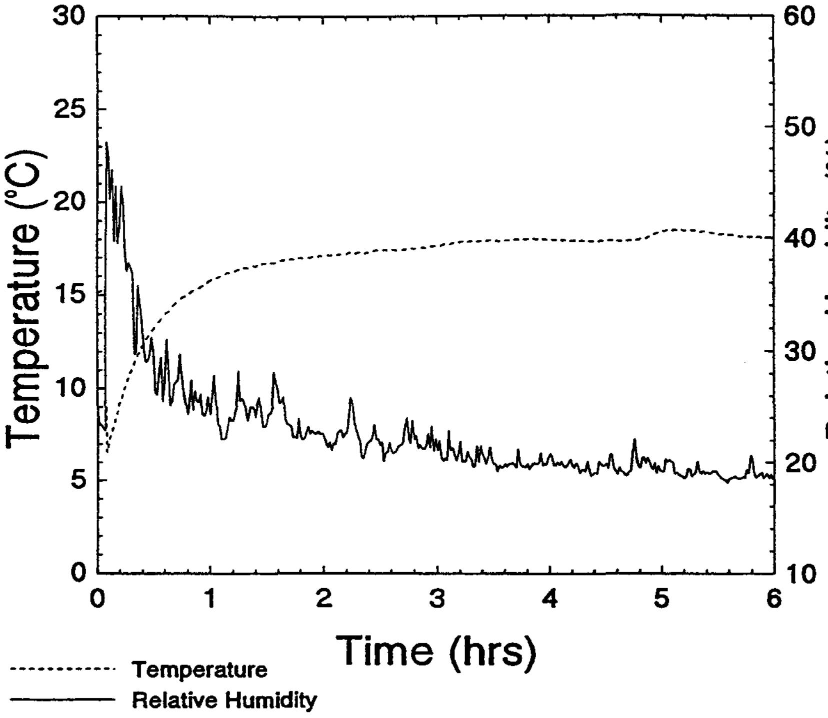


Figure 43 - Foam C, experiment 1, environmental conditions

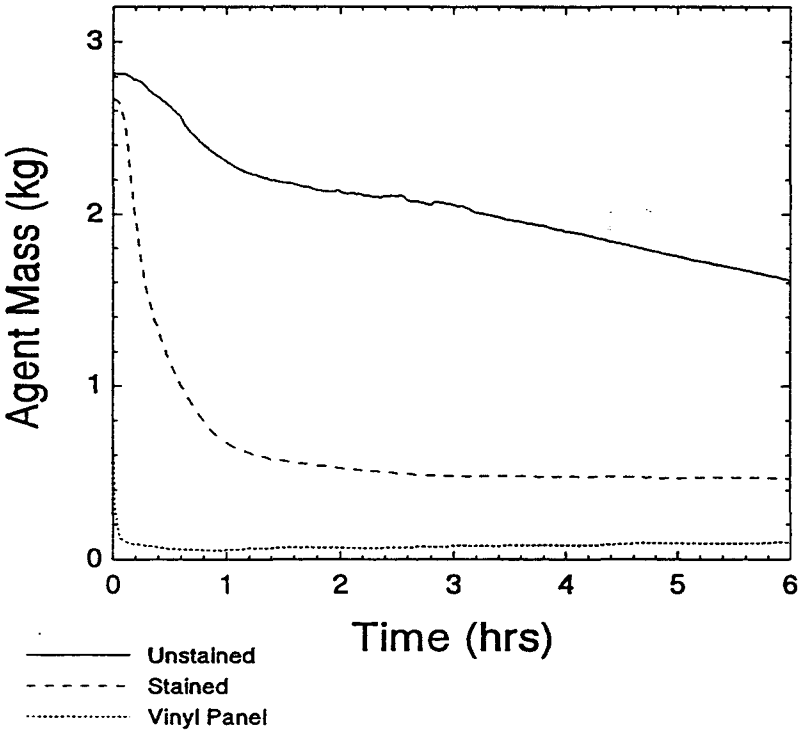


Figure 44 - Foam C, experiment 1, mass retention

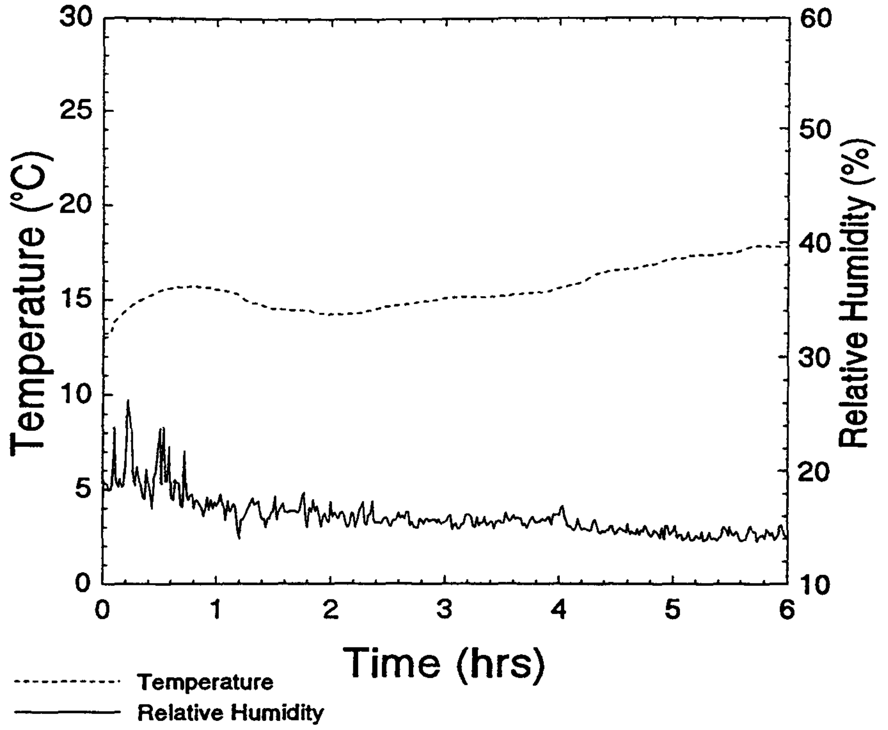


**Figure 45** - Foam C, experiment 2, environmental conditions

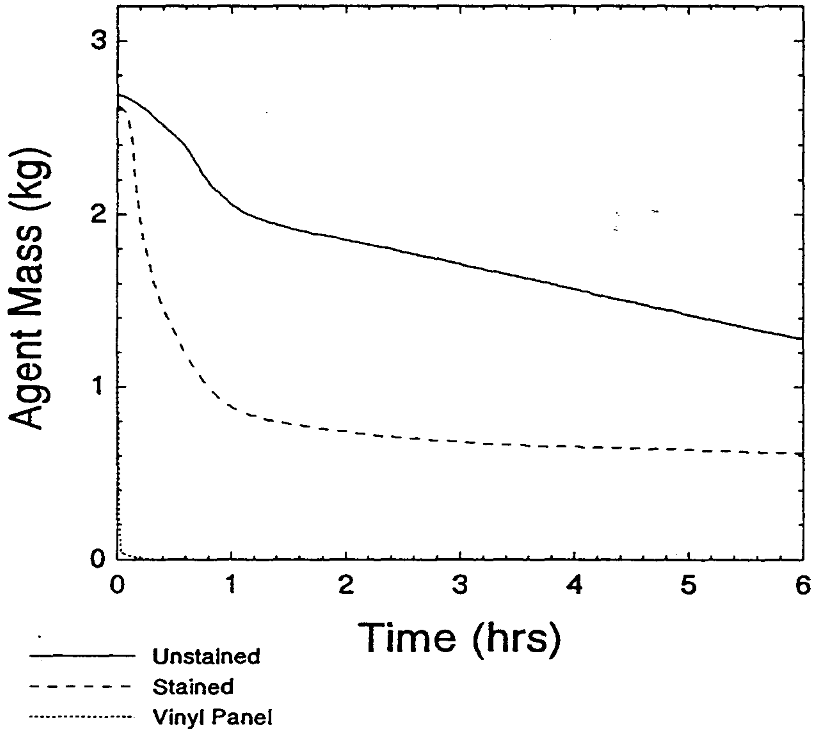


**Figure 46** - Foam C, experiment 2, mass retention

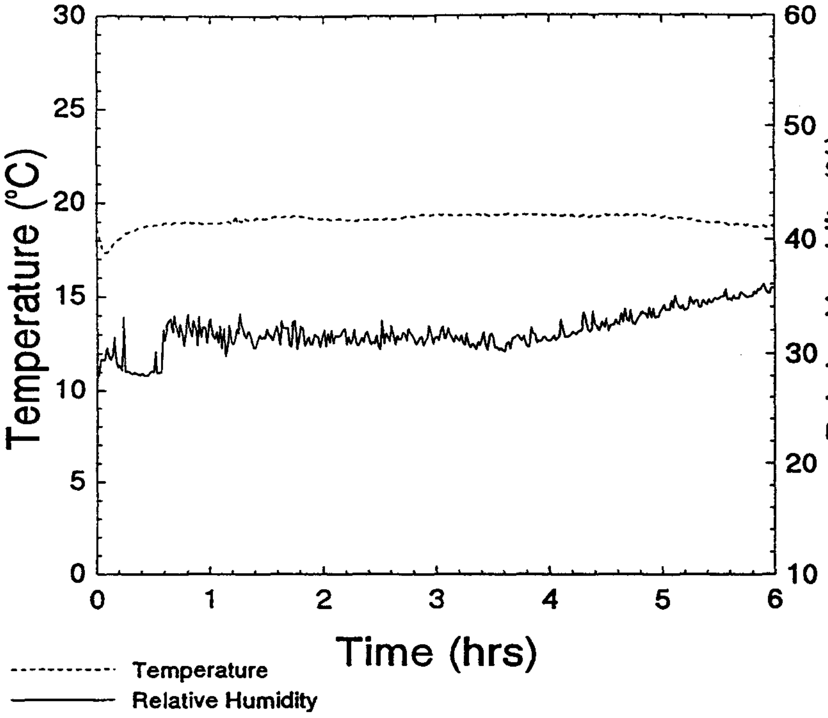


Figure 47 - Foam C, experiment 3, environmental conditions

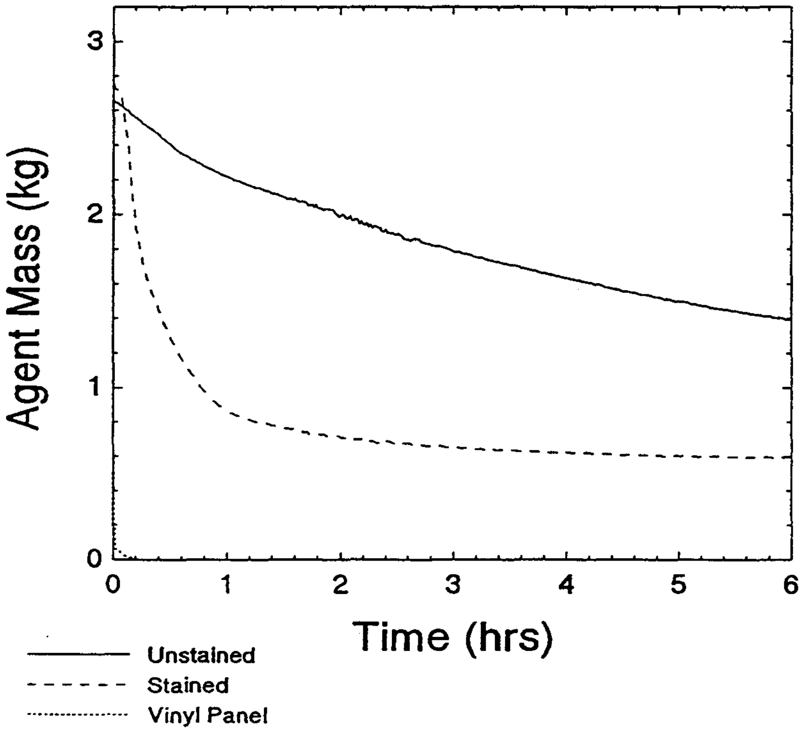


Figure 48 - Foam C, experiment 3, mass retention

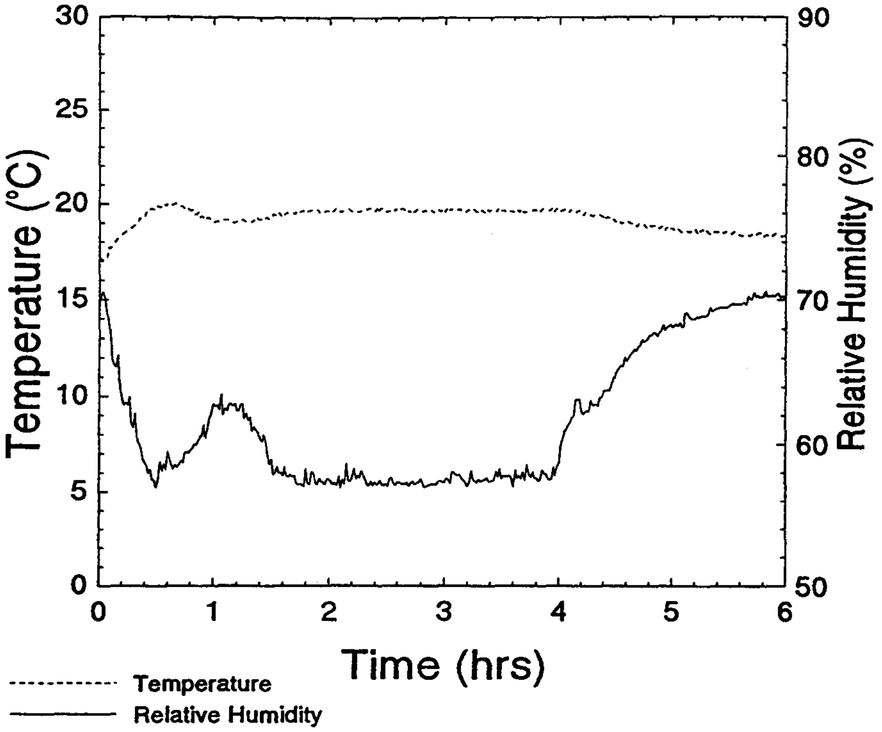


Figure 49 - Foam D, experiment 1, environmental conditions

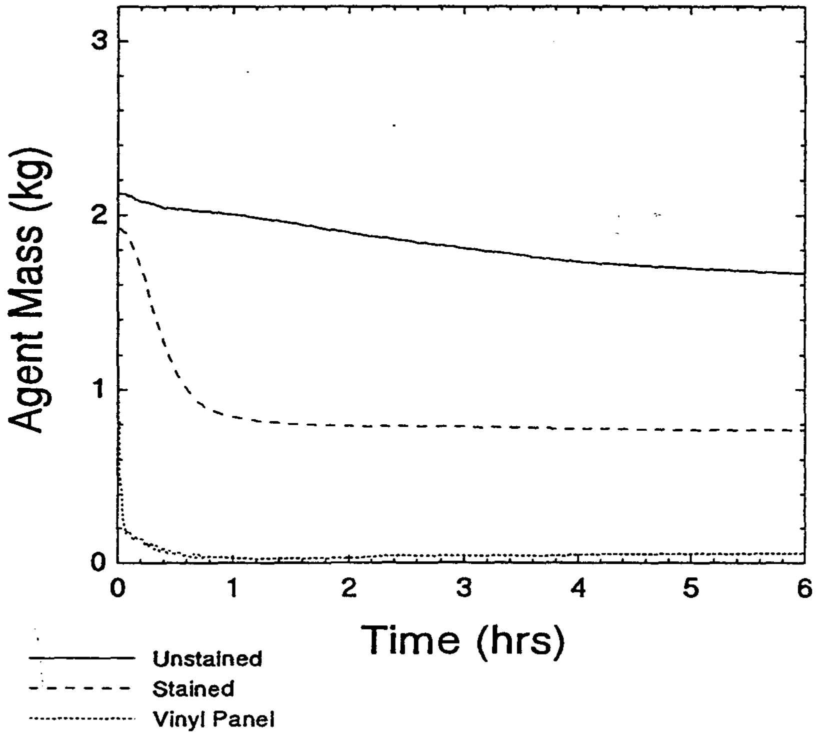


Figure 50 - Foam D, experiment 1, mass retention

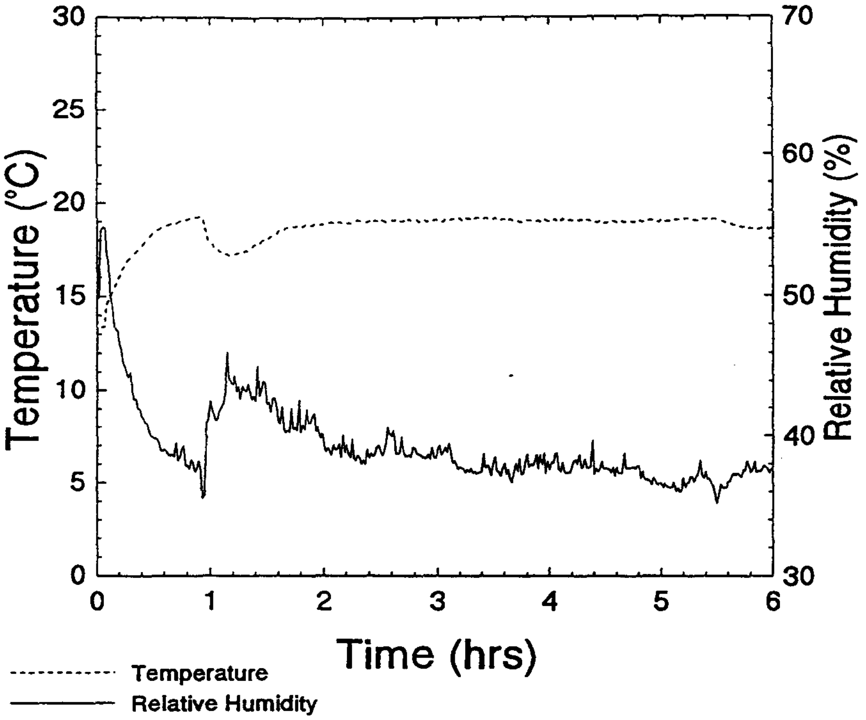


Figure 51 - Foam D, experiment 2, environmental conditions

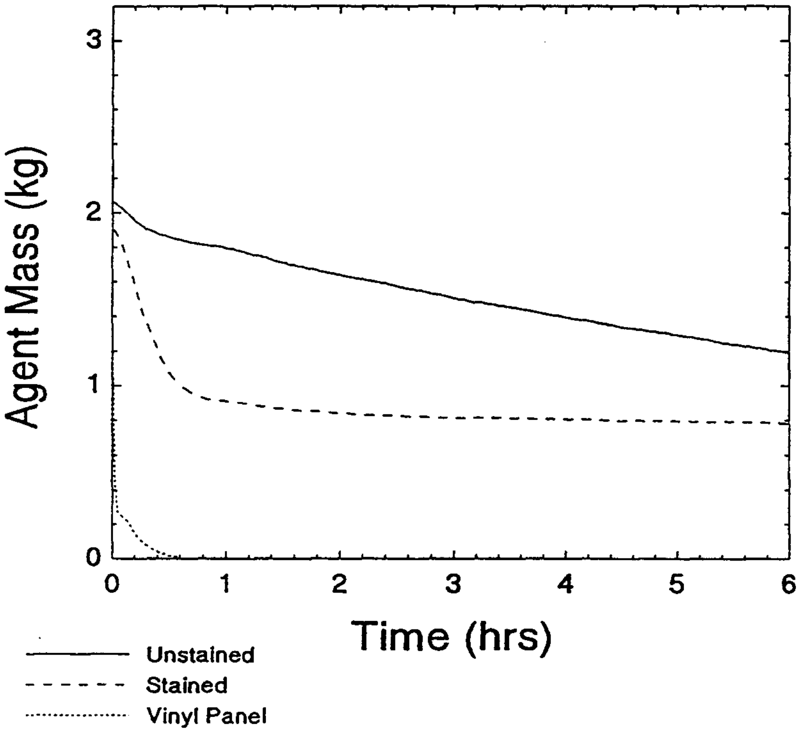


Figure 52 - Foam D, experiment 2, mass retention

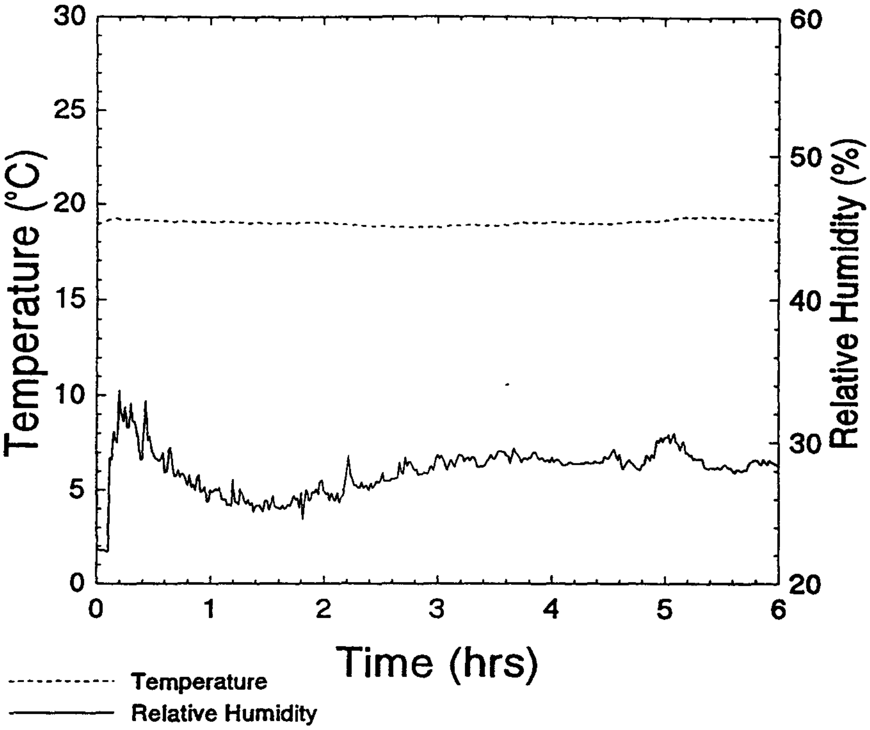


Figure 53 - Foam D, experiment 3, environmental conditions

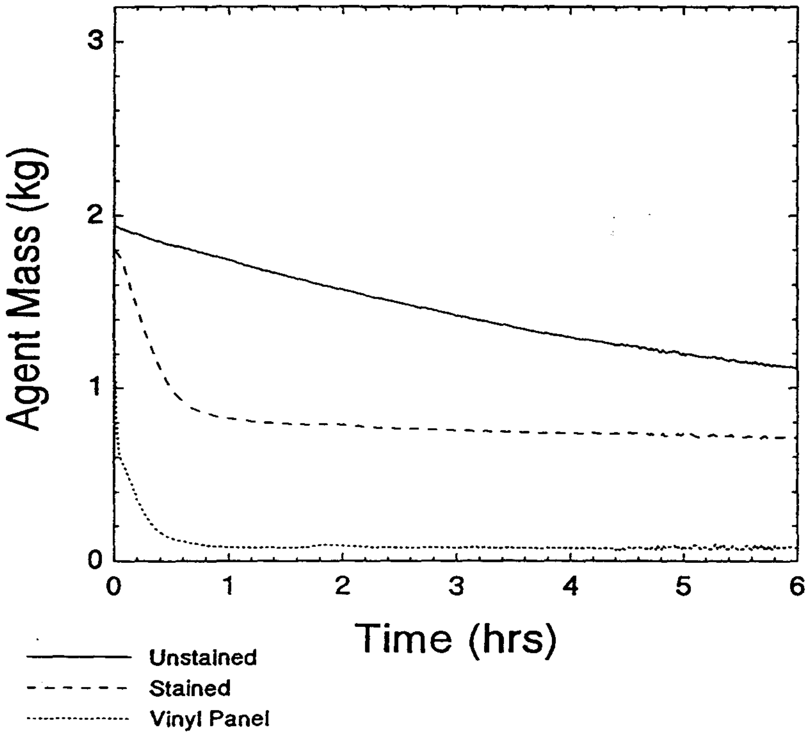


Figure 54 - Foam D, experiment 3, mass retention

# APPENDIX E

# UNDERWRITERS LABORATORIES REPORT
## CLASS D TESTS

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Northbrook, Illinois 60062-20
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# REPORT OF

# MAGNESIUM CHIP FIRE TESTS UTILIZING BIODEGRADABLE, ENVIRONMENTALLY SAFE, NONTOXIC, LIQUID FIRE SUPPRESSION AGENTS

PREPARED BY

UNDERWRITERS LABORATORIES INC.
PROJECT 95NK22435/NC3067

FOR THE

NATIONAL INSTITUTE OF
STANDARDS & TECHNOLOGY

Gaithersburg, MD
OCTOBER, 1995

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# EXECUTIVE SUMMARY

Under this project, magnesium chip fire tests as outlined in the Standard for Safety for Rating and Fire Testing of Fire Extinguishers, ANSI/UL 711, were conducted to evaluate the fire fighting effectiveness on this combustible metal using liquid fire suppression agents, identified by NIST as biodegradable, environmentally safe, and nontoxic, when applied using hand hoselines. For comparison purposes, fire tests were also conducted using water only and a UL Listed Class D dry powder agent. Only the UL Listed Class D dry powder agent demonstrated compliance with the fire extinguisher criteria outlined in ANSI/UL 711.

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# ACKNOWLEDGEMENTS

UL wishes to thank Mr. Dan Madrzykowski of the National Institute of Standards and Technology for his support during the conduct of these fire tests.

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# 1.0 INTRODUCTION

**OBJECTIVE:**

The objective of this investigation was to develop test data and investigate test methods as related to the fire fighting effectiveness of water only and biodegradable, environmentally safe, nontoxic, liquid fire suppression agents discharged from hand hoselines as compared to a UL Listed Class D dry powder agent when used on fires involving magnesium chips a Class D combustible metal.

**TEST PLAN:**

A series of magnesium chip fire tests, as described in ANSI/UL 711, were planned to be conducted under this project.

# 2.0 SAMPLES AND FACILITIES

**AGENTS**:

Four biodegradable, environmentally safe, nontoxic, liquid fire suppression agents, water, and a UL Listed Class D dry powder agent were used in this investigation.

**DISCHARGE DEVICES**:

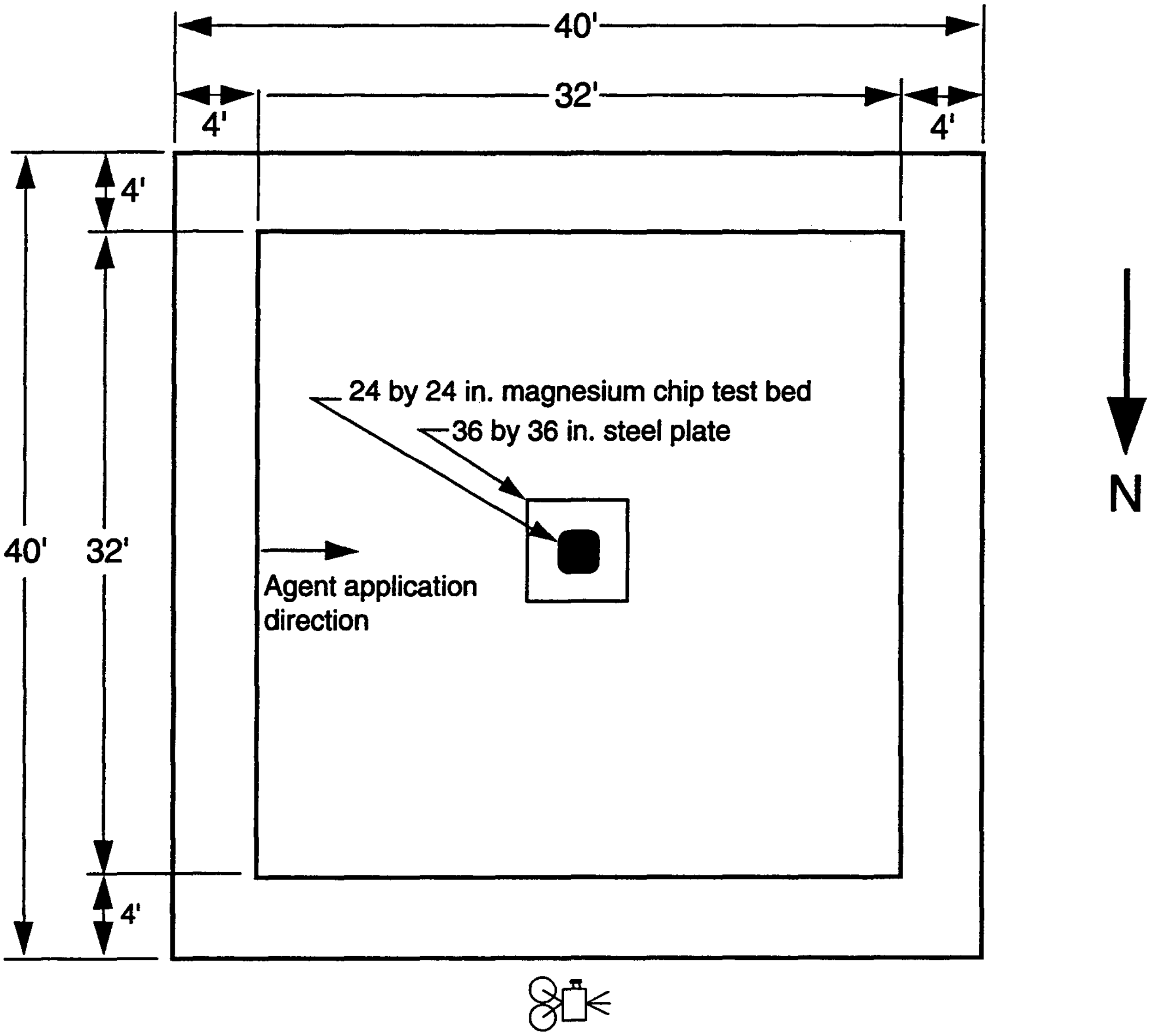
Hand held discharge devices were used to apply the liquid agents, water or Class D dry powder for the fire tests.

For the fire tests involving the liquid agents or water, a single adjustable pattern discharge nozzle was used to discharge the liquid agents or water at a flow rate of 10 gpm. The nozzle was adjusted to a straight stream pattern and fitted with an air aspirating attachment for one series of fire tests and used as a spray nozzle without the air aspirating attachment for a second series of tests.

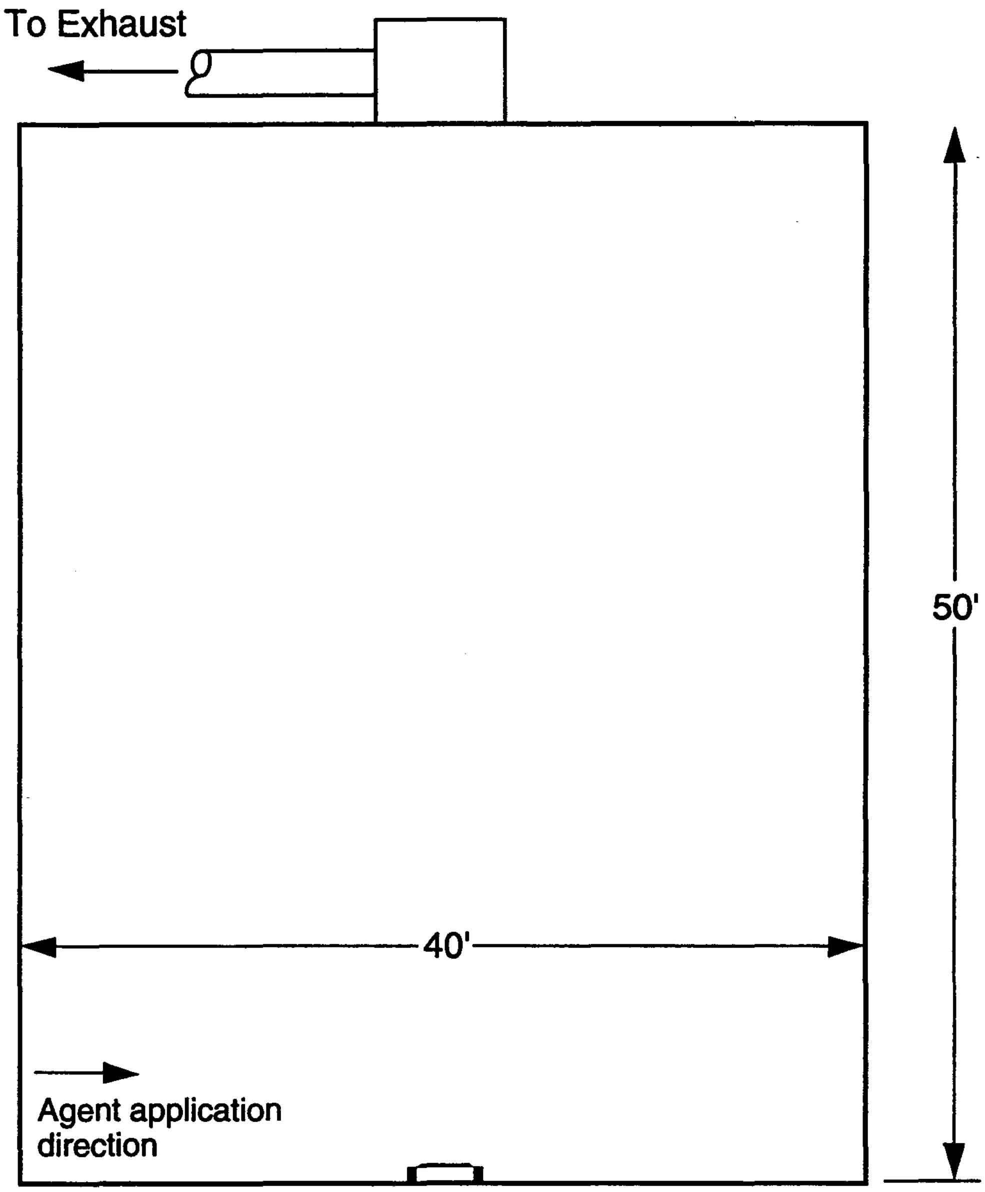
For the fire tests involving the Class D dry powder, a nominal 30 lb dry powder extinguisher was used to apply the agent onto the fire.

**FIRE TEST BUILDING**:

The fire tests were conducted at UL's test facilities located in Northbrook, IL. The test building measured 40 by 40 by 50 ft in height and was equipped with a 30,000 cfm regenerative incinerator for smoke abatement purposes. The unit was operated at a rate of approximately 10,000 cfm for these tests. See ILLS. 1 and 2.



General Fire Test Arrangement
Plan View



UL'S Highrise Test Building
40' x 40' x 50' High

General Fire Test Arrangement
Elevation View

# 3.0 PERFORMANCE TESTS

## MAGNESIUM CHIP FIRE TESTS:

### METHOD

The magnesium chip fire tests involved the use of 20 or 40 lbs of dry grignard magnesium grade chips arranged in a 2 by 2 ft area on a 1/4 in. thick steel plate. The grignard chips were approximately 1/4 to 3/8 in. long, 1/8 in. wide and 1/10 in. thick.

The grignard chips were ignited using a hand torch. For Fire Test Nos. 1-12, the bed of chips was ignited along one side and allowed to burn undisturbed until a deep seated condition was observed such that approximately 50 percent of the magnesium was consumed. For Fire Test No. 13, the magnesium was ignited on all four sides.

Following the freeburn period, the magnesium chip fire was attacked with the fire suppression agent. For Fire Test Nos. 1 and 2, the fire was attacked using a fire extinguisher containing a UL Listed Class D dry powder agent from a distance of approximately 5 ft. For Fire Test Nos. 3-13, the fire was attacked using a hand held nozzle discharging water or agent at a rate of 10 gpm from a distance of approximately 15 ft and for a duration of 5 min.

During each fire test, observations were made for the following:

- Fire extinguishment.
- Reaction of applied agent with the magnesium.
- Approximate amount of magnesium consumed.
- Fire spread.

### RESULTS

The results of the magnesium chip fire tests are presented in Table 2 and Figs. 1-7. The fire tests utilizing the Class D dry powder extinguishing agent were rapidly extinguished with no visual adverse reaction. Fire extinguishment was not achieved in any of the fire tests involving the use of water or liquid fire suppression agents.

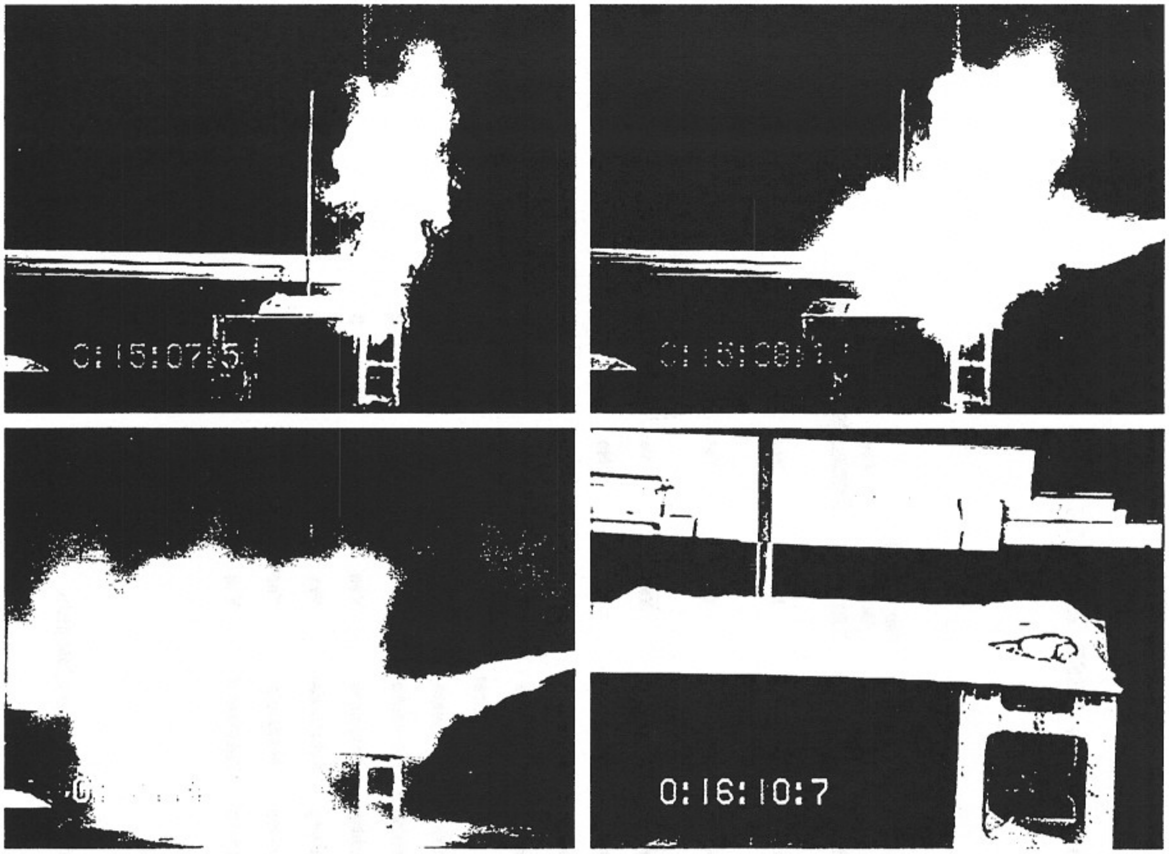
## TABLE I - MAGNESION CHIP FIRE TEST RESULTS

| | | | | Extinguishing Agent Application | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test No. | Pounds Of Magnesium | Extinguishing Agent Type | Approx. Preburn min:sec | Method | Rate (gpm) | Duration (min:s) | Visual Adverse Reaction | Increased Intensity of Fire | Fire Spread Beyond Steel Plate | Fire Extinguished | Comments |
| 1 | 20 | Class D Powder | 15:00 | Direct | NA | 0:32 | None | No | No | Yes | 1 |
| 2 | 40 | Class D Powder | 25:00 | Direct | NA | 0:34 | None | No | No | Yes | 1 |
| 3 | 20 | Water | 25:00 | Stream | 10 | 5:00 | Sparking | Substantial | Yes | No | 2 |
| 4 | 20 | Water | 25:00 | Spray | 10 | 5:00 | Sparking | Moderate | Yes | No | 3 |
| 5 | 20 | Liquid-A 1% | 25:00 | Stream | 10 | 5:00 | Sparking | Substantial | Yes | No | 2 |
| 6 | 20 | Liquid-A 1% | 25:00 | Spray | 10 | 5:00 | Sparking | Moderate | Yes | No | 3 |
| 7 | 20 | Liquid-B 1% | 25:00 | Stream | 10 | 5:00 | Sparking | Substantial | Yes | No | 2 |
| 8 | 20 | Liquid-B 1% | 25:00 | Spray | 10 | 5:00 | Sparking | Moderate | Yes | No | 3 |
| 9 | 20 | Liquid-C 6% | 25:00 | Stream | 10 | 5:00 | Sparking | Substantial | Yes | No | 2 |
| 10 | 20 | Liquid-C 6% | 25:00 | Spray | 10 | 5:00 | Sparking | Moderate | Yes | No | 3 |
| 11 | 20 | Liquid-D 3% | 25:00 | Stream | 10 | 5:00 | Sparking | Substantial | Yes | No | 2 |
| 12 | 20 | Liquid-D 3% | 25:00 | Spray | 10 | 5:00 | Sparking | Moderate | Yes | No | 3 |
| 13 | 40 | Water | 25:00 | Stream/ Spray | 15 | 5:00 | Sparking | Substantial | Yes | No | 2 |

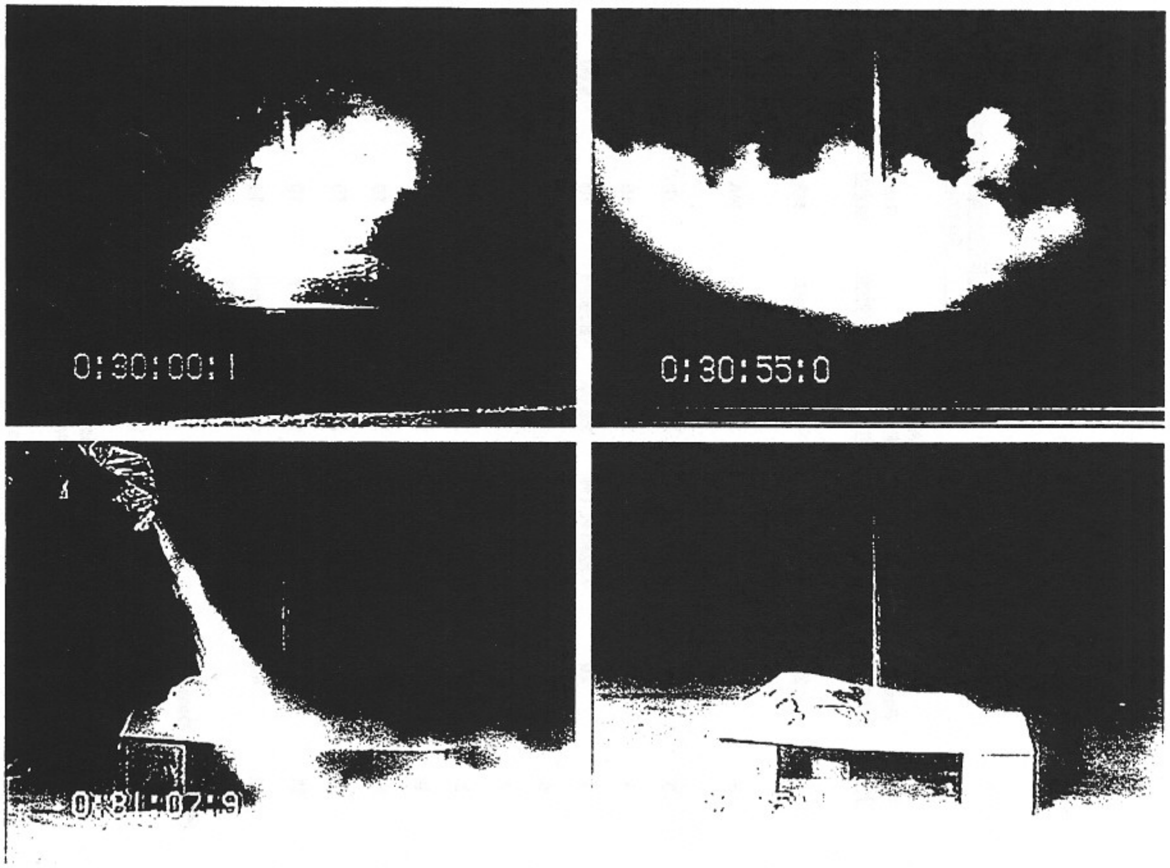
Comments Description:

1. No flare-up or increase in burning intensity. Fire rapidly extinguished.
2. Substantial flare-up and sparking of burning magnesium even after burning fuel was displaced from test plate. Magnesium completely consumed.
3. Moderate flare-up and sparking of burning magnesium. Magnesium completely consumed.

NA - Not applicable

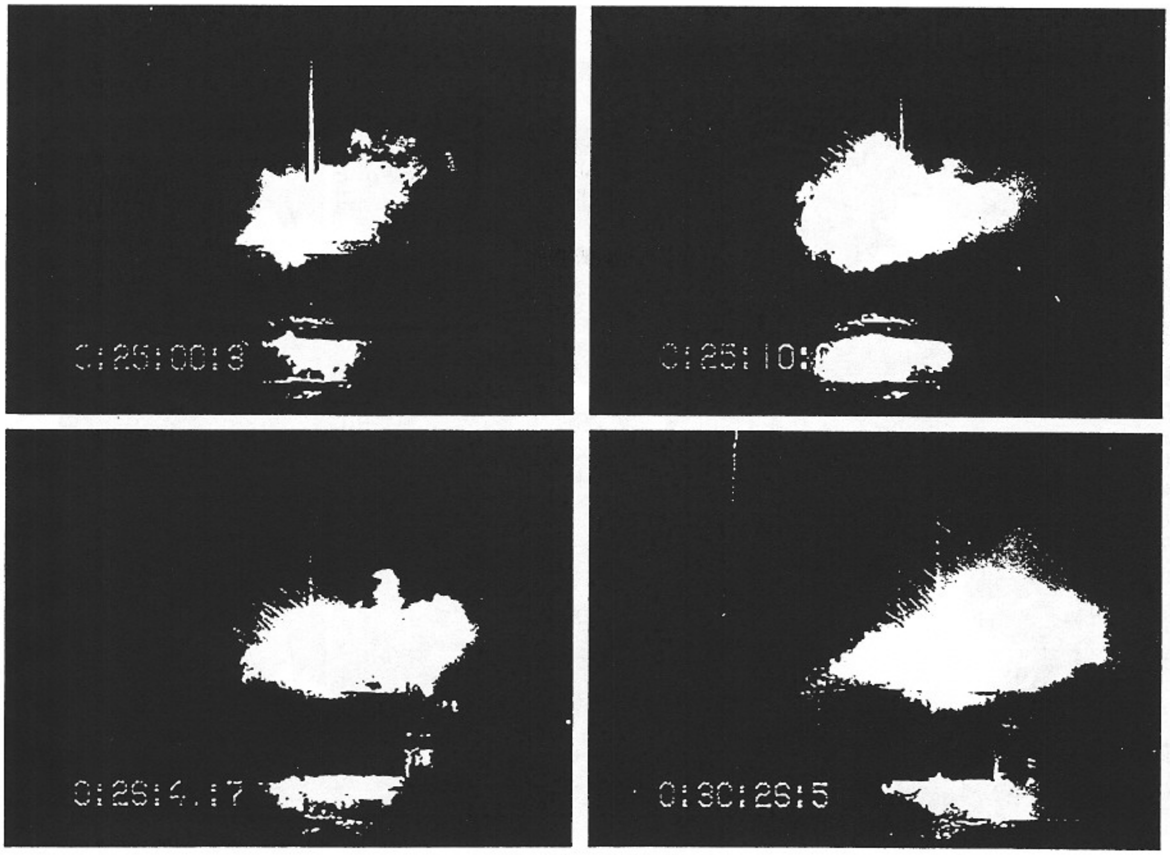


TEST NO.1

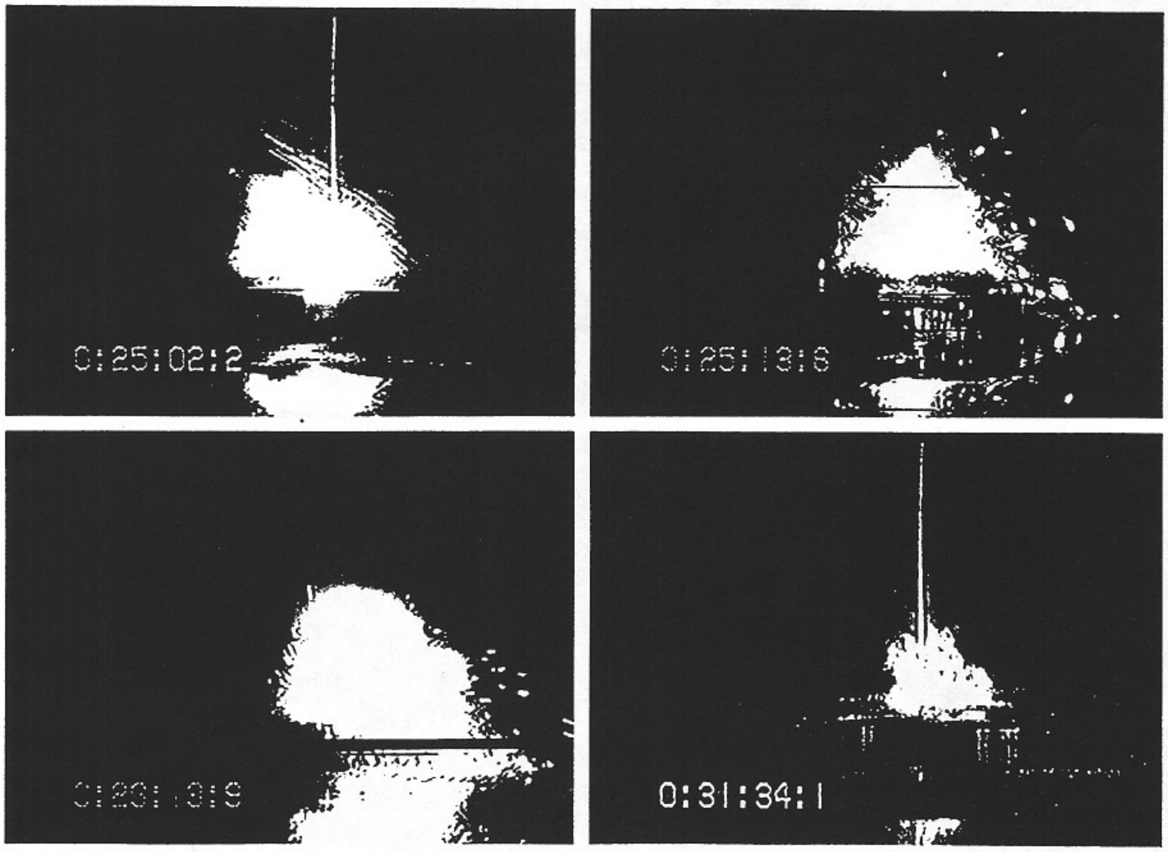


TEST NO.2

Figure 1. Magnesium chip fire tests, Class D dry powder

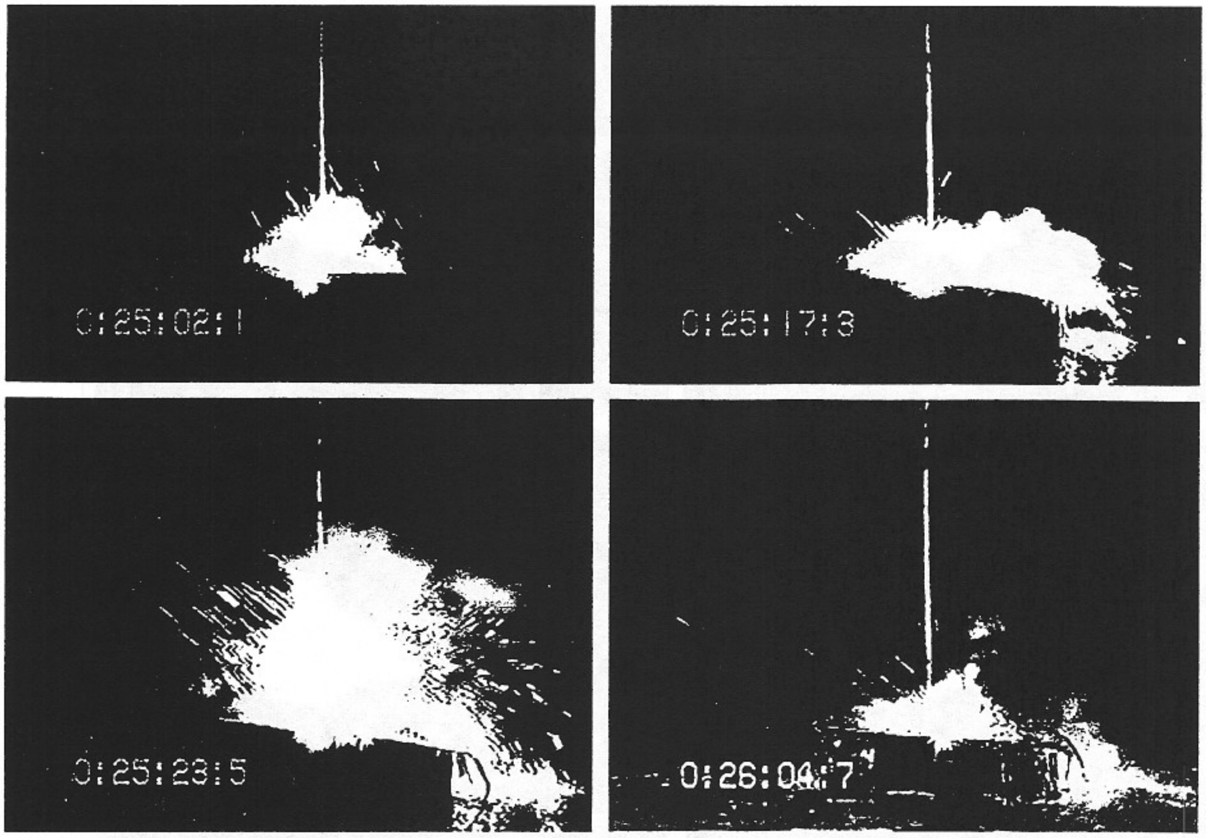


TEST NO.3

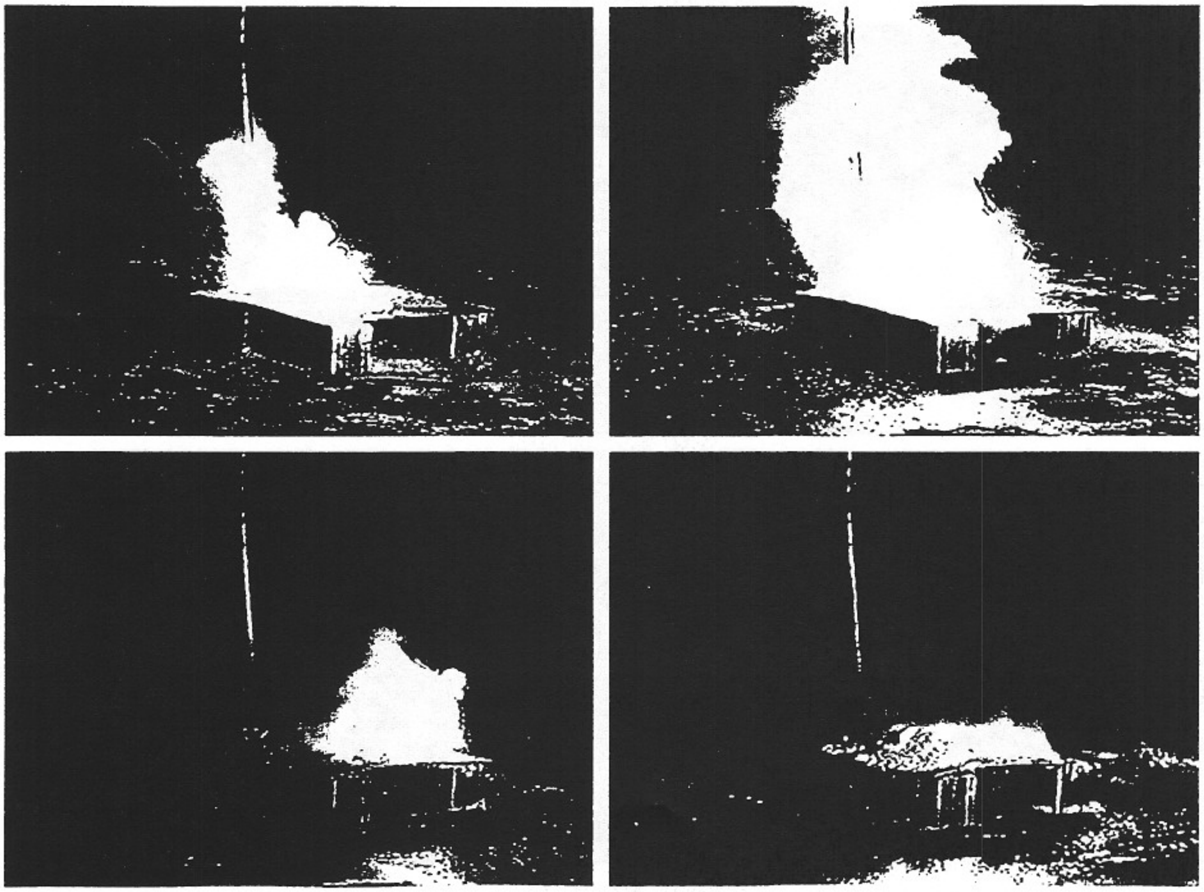


TEST NO.4

Figure 2. Magnesium chip fire tests, water only

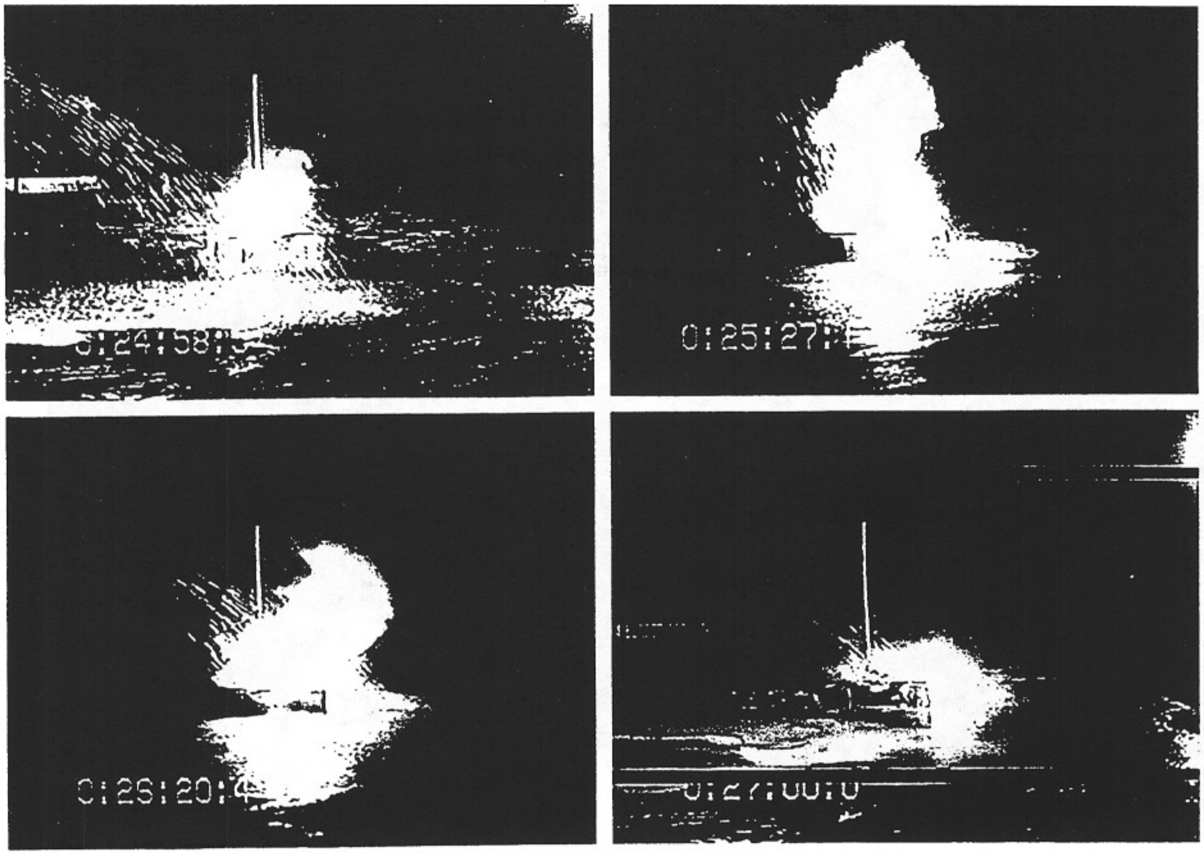


TEST NO.5

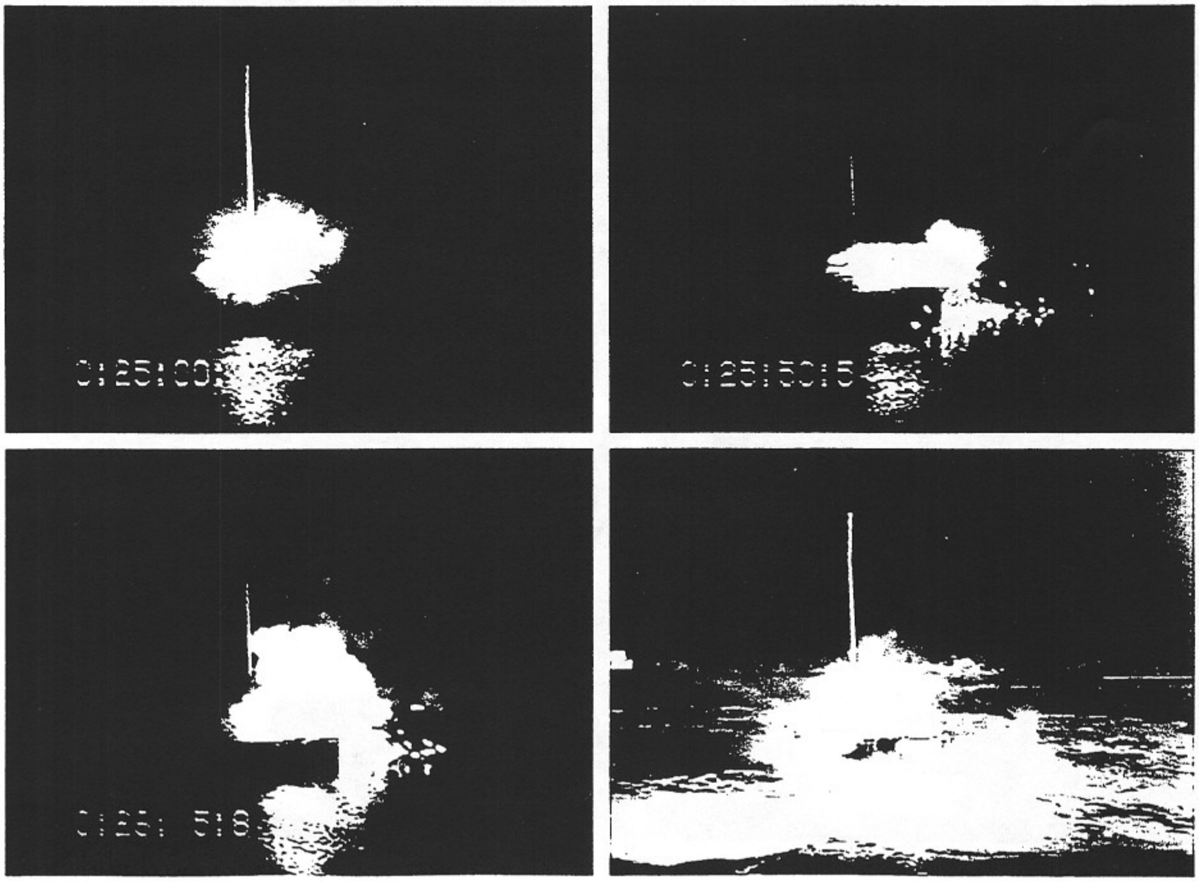


TEST NO.6

Figure 3. Magnesium chip fire tests, liquid agent A

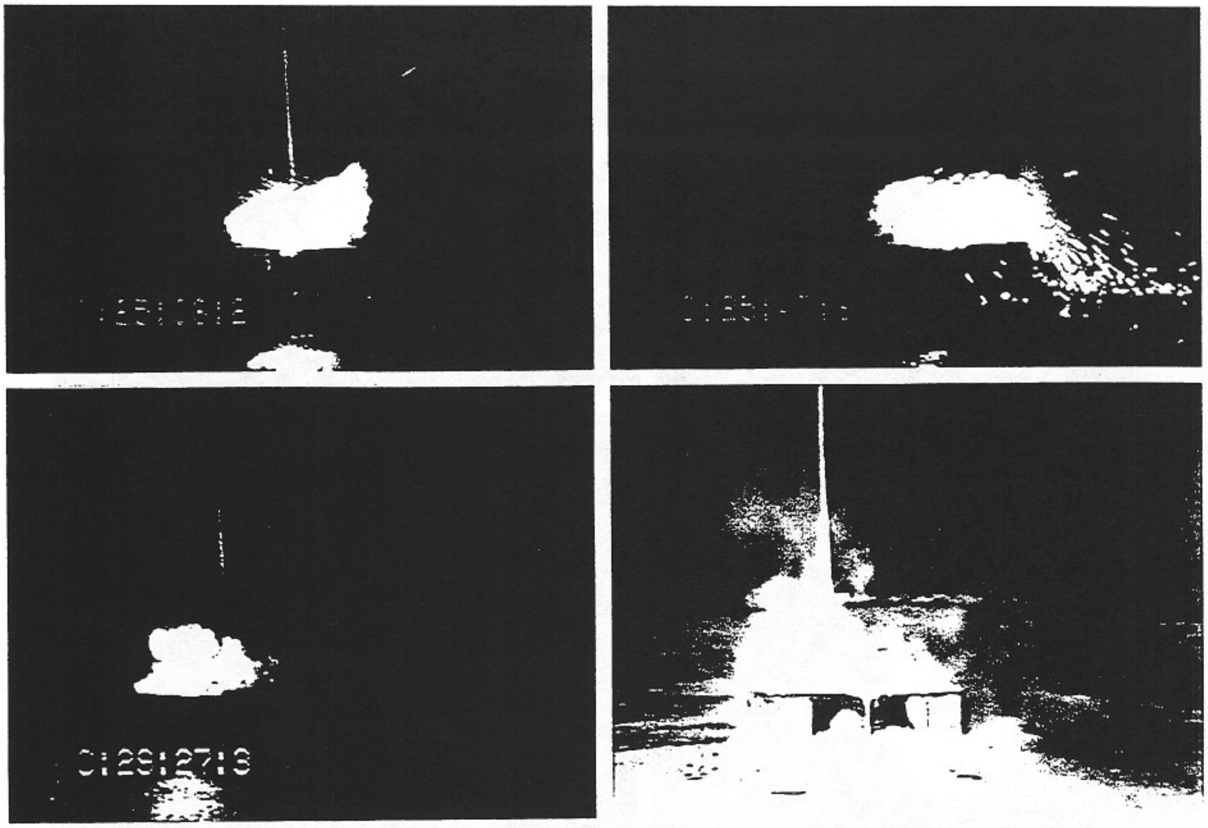


TEST NO.7

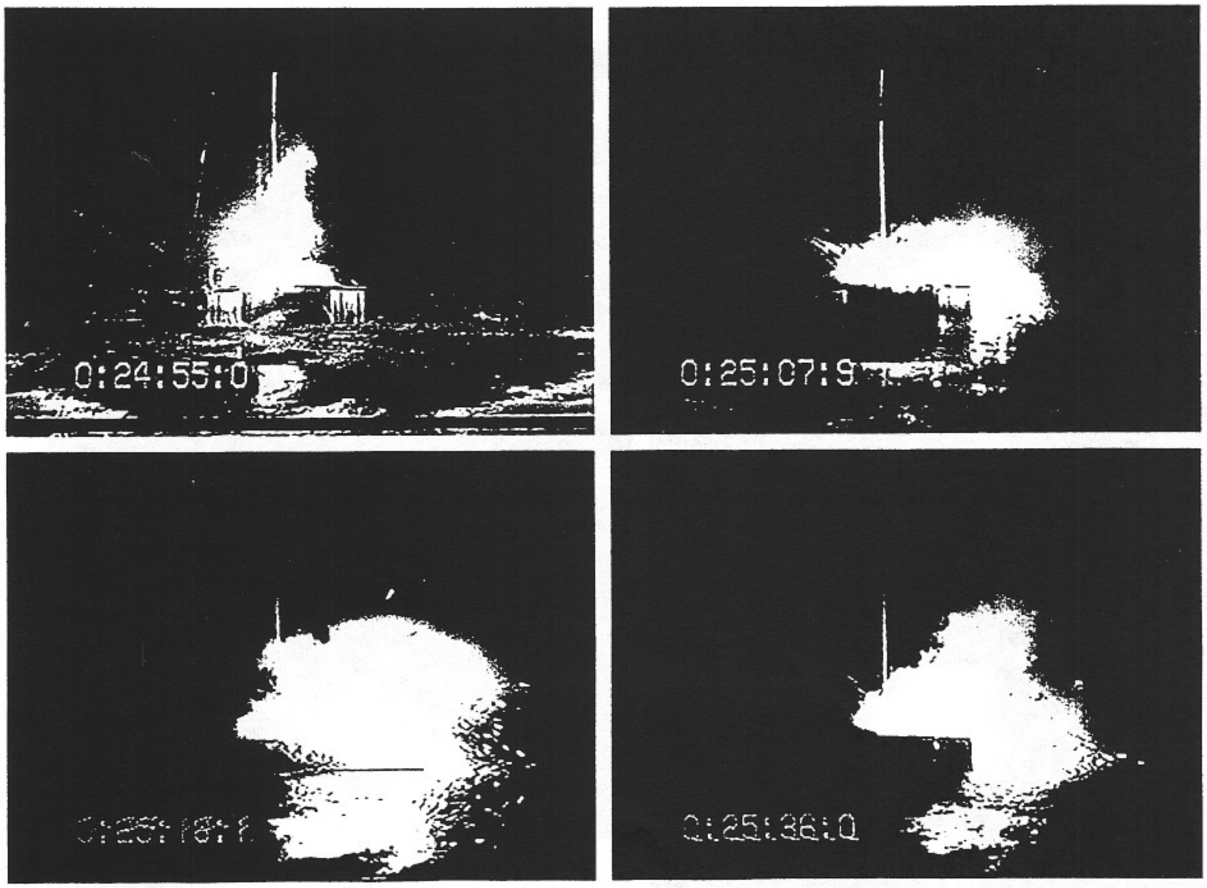


TEST NO.8

Figure 4. Magnesium chip fire tests, liquid agent B

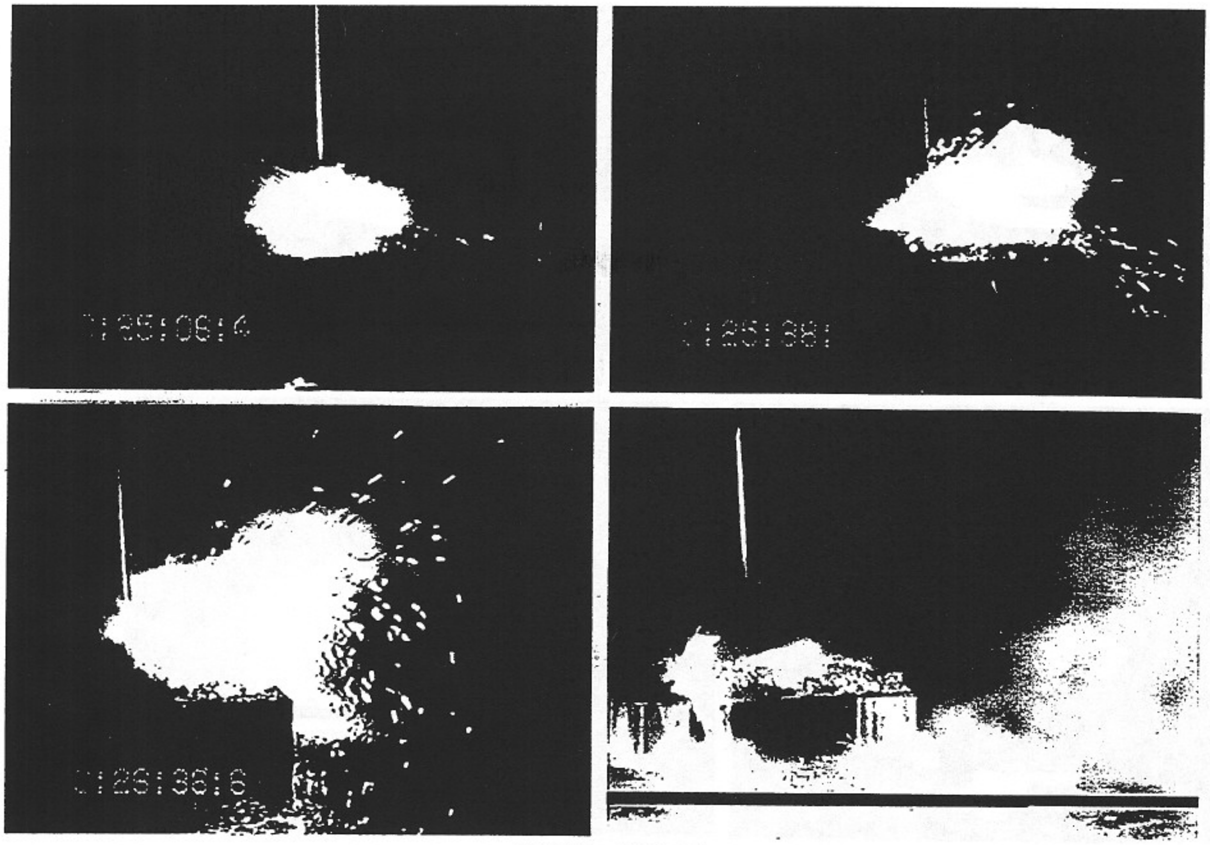


TEST NO.9

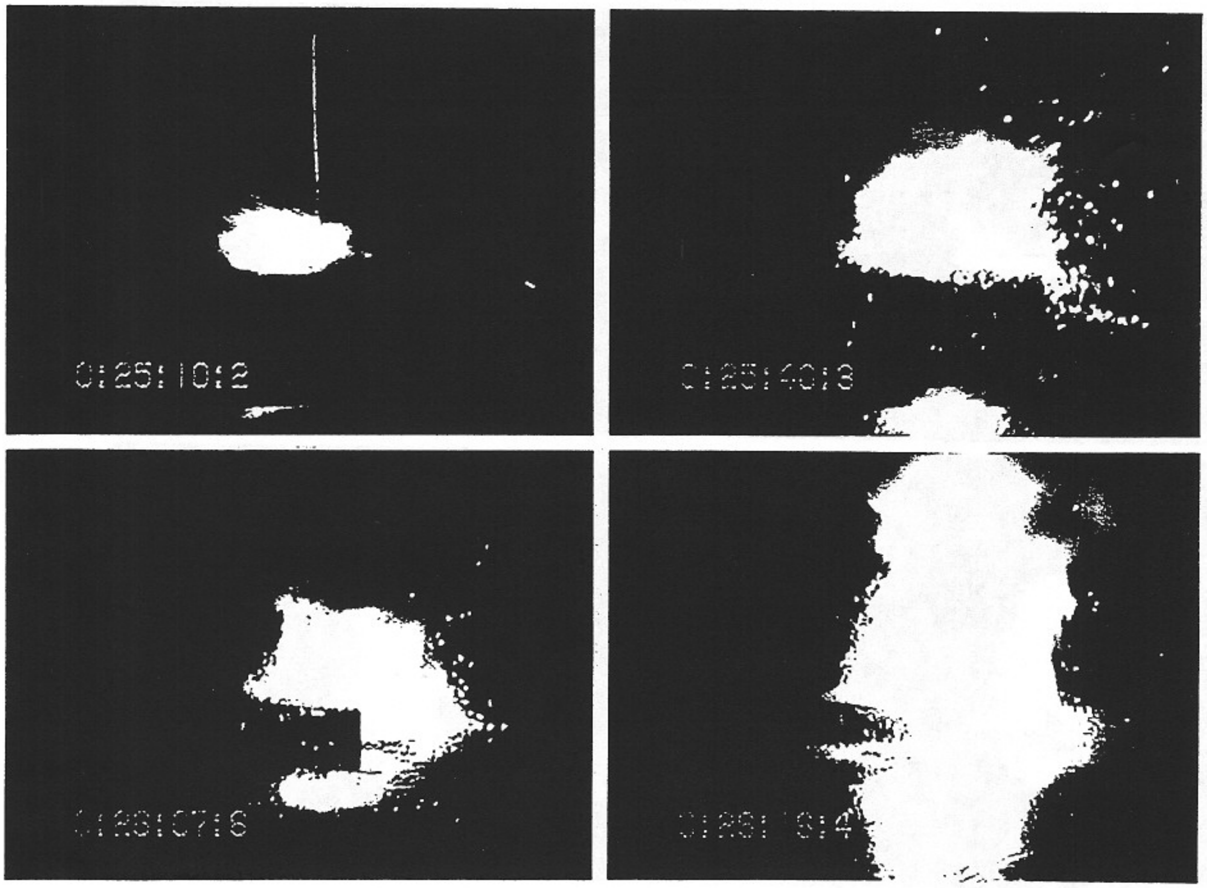


TEST NO.10

Figure 5. Magnesium chip fire tests, liquid agent C

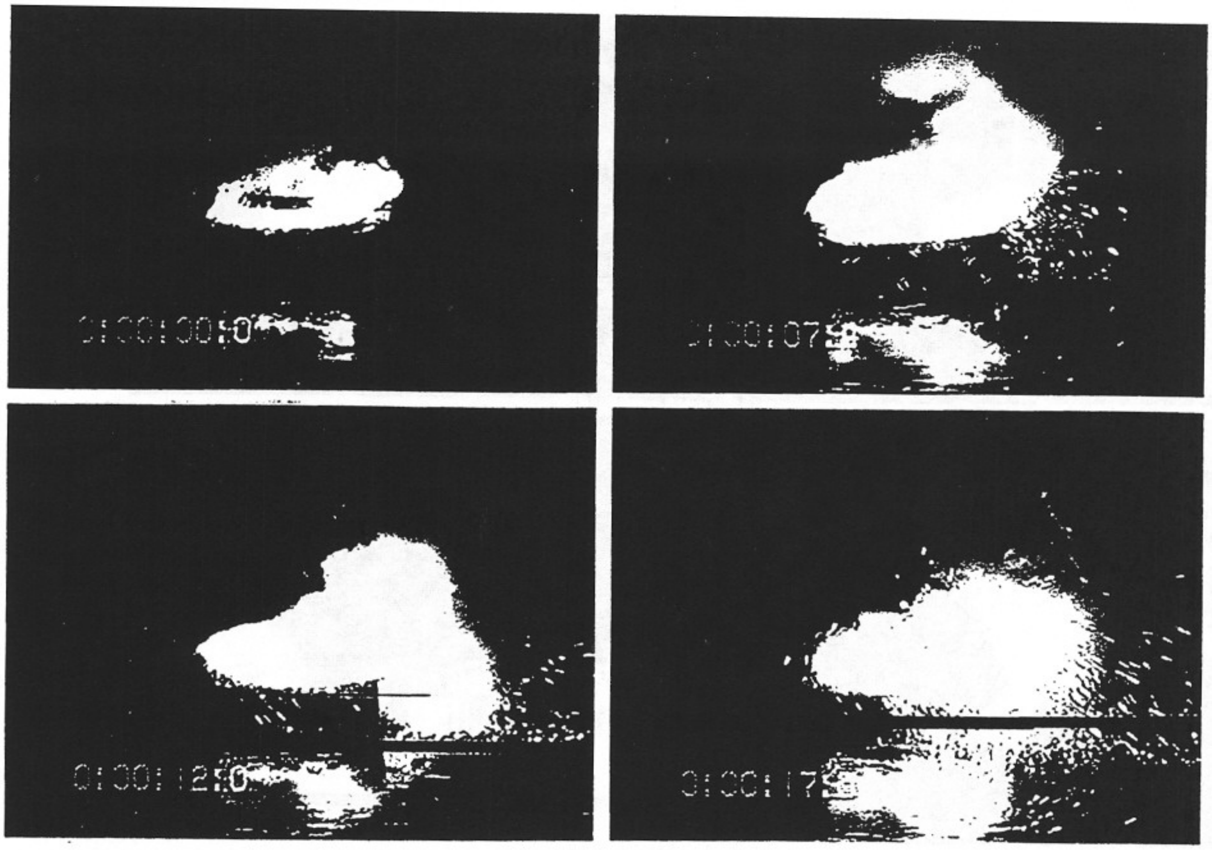


TEST NO.11

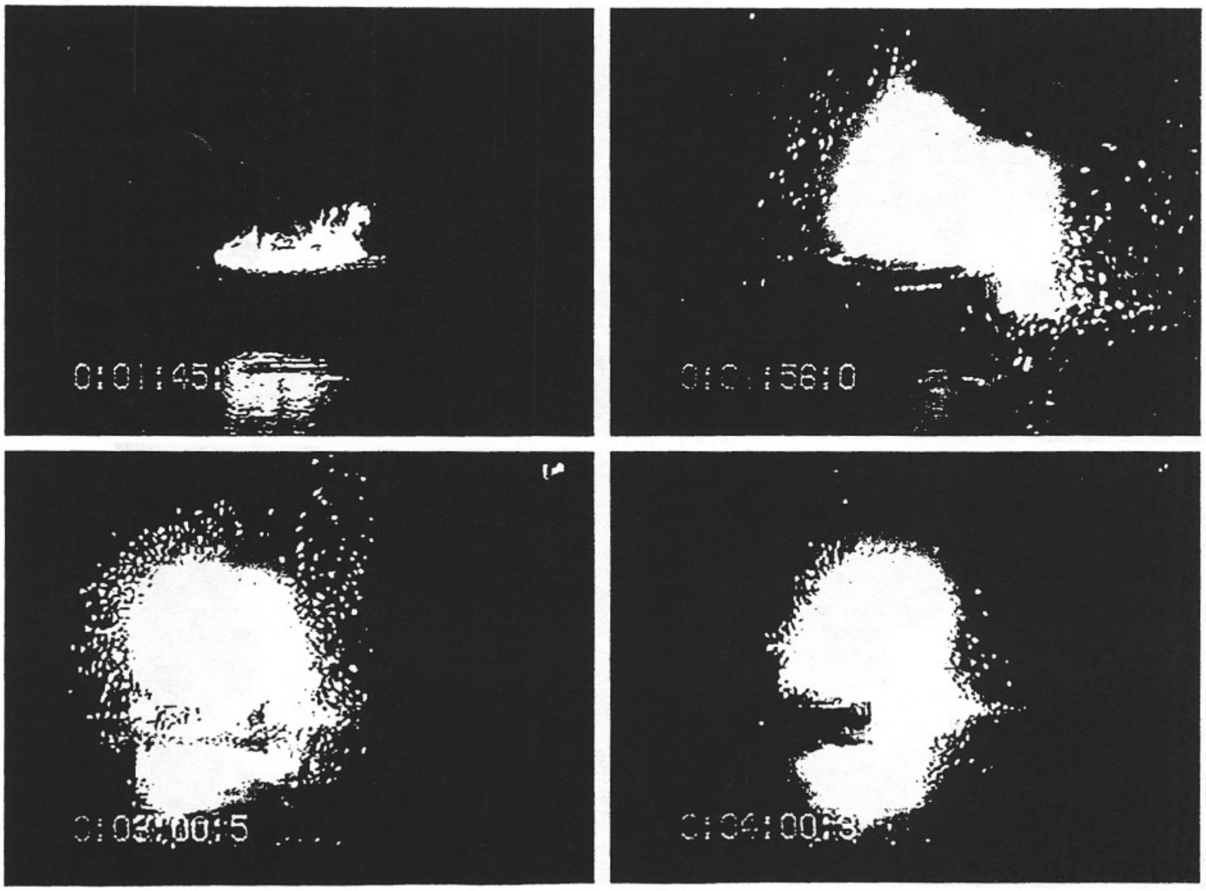


TEST NO.12

Figure 6. Magnesium chip fire tests, liquid agent D



TEST NO.13



TEST NO.13

Figure 7. Special magnesium chip fire test, water only

# 4.0 DISCUSSION AND RECOMMENDATIONS

## DISCUSSION:

The results of the Class D, magnesium chip fire tests described herein indicate that the biodegradable, environmentally safe, nontoxic, liquid fire suppression agents were unable to extinguish a Class D combustible metal fire involving magnesium chips. The spray application method offered some advantage over the stream application method by providing a gentler application of agent onto the fire. This gentler application also resulted in smaller quantities of burning magnesium being scattered beyond the test bed area. When the magnesium material was scattered beyond the test bed area, it continued to burn intensely and had the potential to ignite other combustibles.

The tests conducted with the UL Listed Class D dry powder agent resulted in complete extinguishment of the test fires.

## RECOMMENDATIONS:

Additional testing should be undertaken to further investigate the fire fighting performance of biodegradable, environmentally safe, nontoxic, liquid fire suppression agents, when applied to other common combustible metals.

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The Building and Fire Research Laboratory at the National Institute of Standards and Technology, under the sponsorship of the United States Fire Administration has examined methods for demonstrating the suppression effectiveness of water based fire fighting agents. This report includes methods, as developed by the United States Department of Agriculture, for demonstrating environmental safety and toxicity of these agents. NIST investigated smoke generation during suppression and conducted a broad-based study on fire suppression effectiveness including laboratory scale experiments and large-scale fire suppression experiments. The following characteristics were investigated at laboratory scale: specific heat, drop size, cooling and penetration, contact angle, mass retention and ignition inhibition. Large-scale experiments were used to examine the suppression effectiveness of the agents on wood crib, tire, heptane, gasoline, magnesium and titanium fires.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

class A fires; class B fires; class D fires; compressed air foam; fire extinguishing agents; fire suppression; large scale fire tests, small

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