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

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**Daniel Madrzykowski  
David W. Stroup, Editors**

**July 1998**



**U.S. Department of Commerce  
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**Federal Emergency Management Agency  
U.S. Fire Administration  
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**U.S. Department of Commerce**  
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**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 prevent 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  $2.7 \pm 0.14$  kg ( $6 \pm 0.3$  lbs) or  $0.9 \pm 0.05$  kg/m<sup>2</sup> ( $0.1 \pm 0.01$  lbs/ft<sup>2</sup>) 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 ( $\pm$ ) 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 $\pm$ 3	A	Solution
5	11 $\pm$ 1	A	Solution
6	7 $\pm$ 1	A	Solution
7	10 $\pm$ 3	B	Solution
8	10 $\pm$ 1	B	Solution
9	8 $\pm$ 2	B	Solution
10	8 $\pm$ 1	C	Solution
11	6 $\pm$ 3	C	Solution
12	7 $\pm$ 1	C	Solution
13	8 $\pm$ 2	D	Solution
14	9 $\pm$ 1	D	Solution
15	8 $\pm$ 2	D	Solution
16	11 $\pm$ 1	A	CAF
17	12 $\pm$ 2	A	CAF
18	6 $\pm$ 1	A	CAF
19	<6	B	CAF
20	9 $\pm$ 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<sup>4</sup>.

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 ( $\pm$ ) 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<sup>2</sup> 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  $4.25 \pm 0.75$  was realized on the stained panels. The unstained panels maximum effectiveness was approximately  $2 \pm 0.3$ , 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  $2 \pm 0.25$ . 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  $6 \pm 2$  was realized on the stained panels. The unstained panels maximum effectiveness was approximately  $4 \pm 1$ , 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  $3 \pm 0.75$ . From this point it increases nearly linearly until reaching a maximum of  $6 \pm 2$  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  $23 \pm 3$  °C ( $73 \pm 5$  °F) and the relative humidity was  $50 \pm 5$  %. Under these conditions the equilibrium moisture content of the wood was approximately  $9 \pm 1$  %. 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  $97 \pm 14$  kPa ( $14 \pm 2$  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  $30 \text{ kW/m}^2$  (Figure 7). To gain perspective on the effects of a  $30 \text{ kW/m}^2$  heat flux, sunshine provides approximately  $1 \text{ kW/m}^2$  at the earth's surface, when skin is exposed to  $10.4 \text{ kW/m}^2$  pain is experienced after 3 seconds, and when skin is exposed to  $16 \text{ kW/m}^2$  it blisters after 5 seconds.  $12 \text{ kW/m}^2$  can be considered as a minimum for piloted ignition of most wood although  $27 \text{ kW/m}^2$  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].

$$\left[ q_r - (q_r)_{\min} \right] t_{ig}^{2/3} = 0.6 \left[ (\sqrt{k\rho c})^2 + 0.119 \times 10^6 \right]$$

where,  $q_r$  = the irradiance of the object ( $\text{W/m}^2$ ).  
 $(q_r)_{\min}$  = the minimum irradiance at which ignition is possible ( $\text{W/m}^2$ ).  
 $t_{ig}$  = the time to ignition (s).  
 $\sqrt{k\rho c}$  = the thermal absorptivity of wood ( $\text{J}/(\text{m}^2\text{s}^{1/2}\text{K})$ ).

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  $0.11$ - $0.15 \text{ W}/(\text{mK})$  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 ( $480 \text{ kg/m}^3$ ), is harder to ignite than wood with low density, say balsa ( $130 \text{ kg/m}^3$ ) [10,11]. The large range in wood density is the reason  $12 \text{ kW/m}^2$  is considered as the minimum heat flux for piloted ignition of most wood but  $27 \text{ kW/m}^2$  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<sup>2</sup>; 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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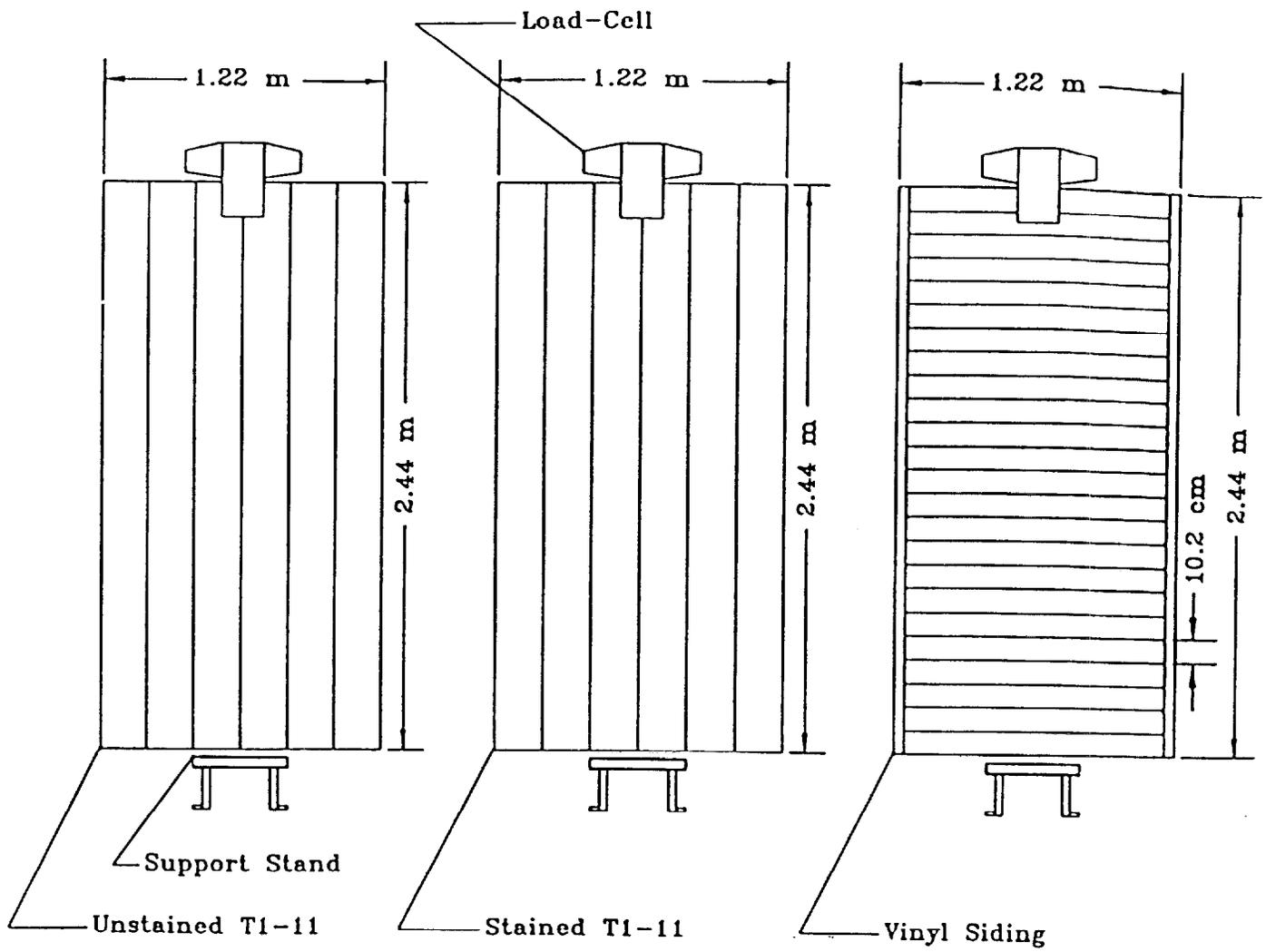


Figure 1. Exterior Siding Panels Set-up

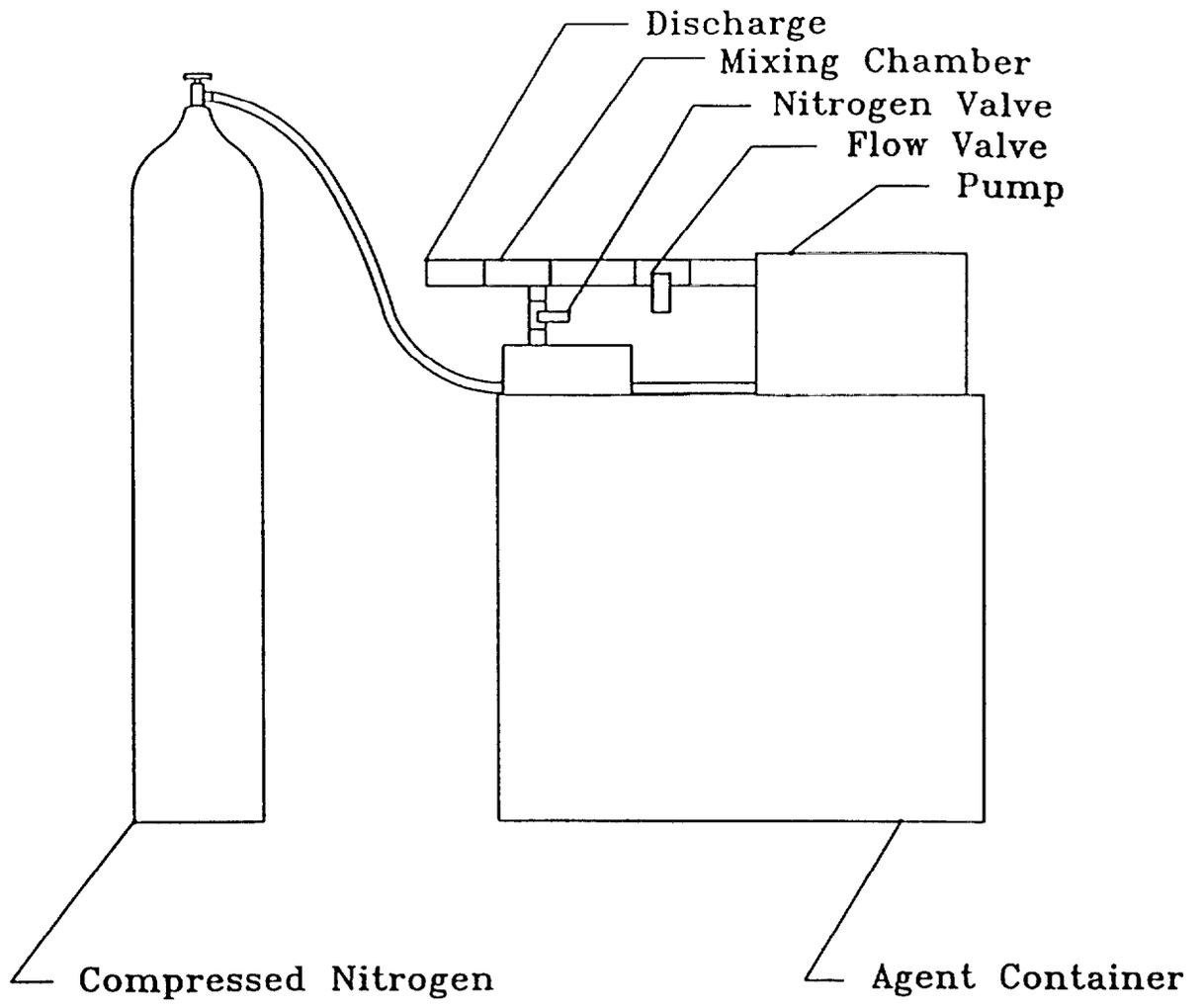


Figure 2. Agent Application (CAF) System

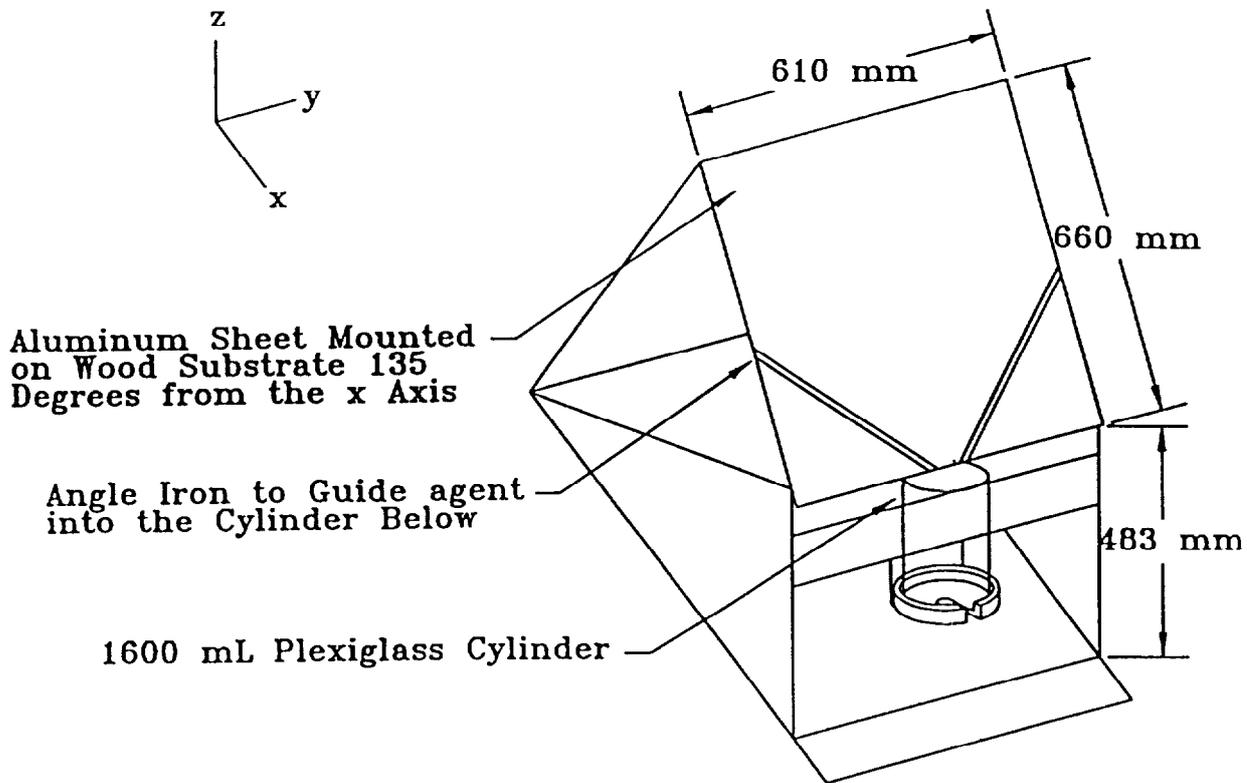


Figure 3. Foam Slider Board

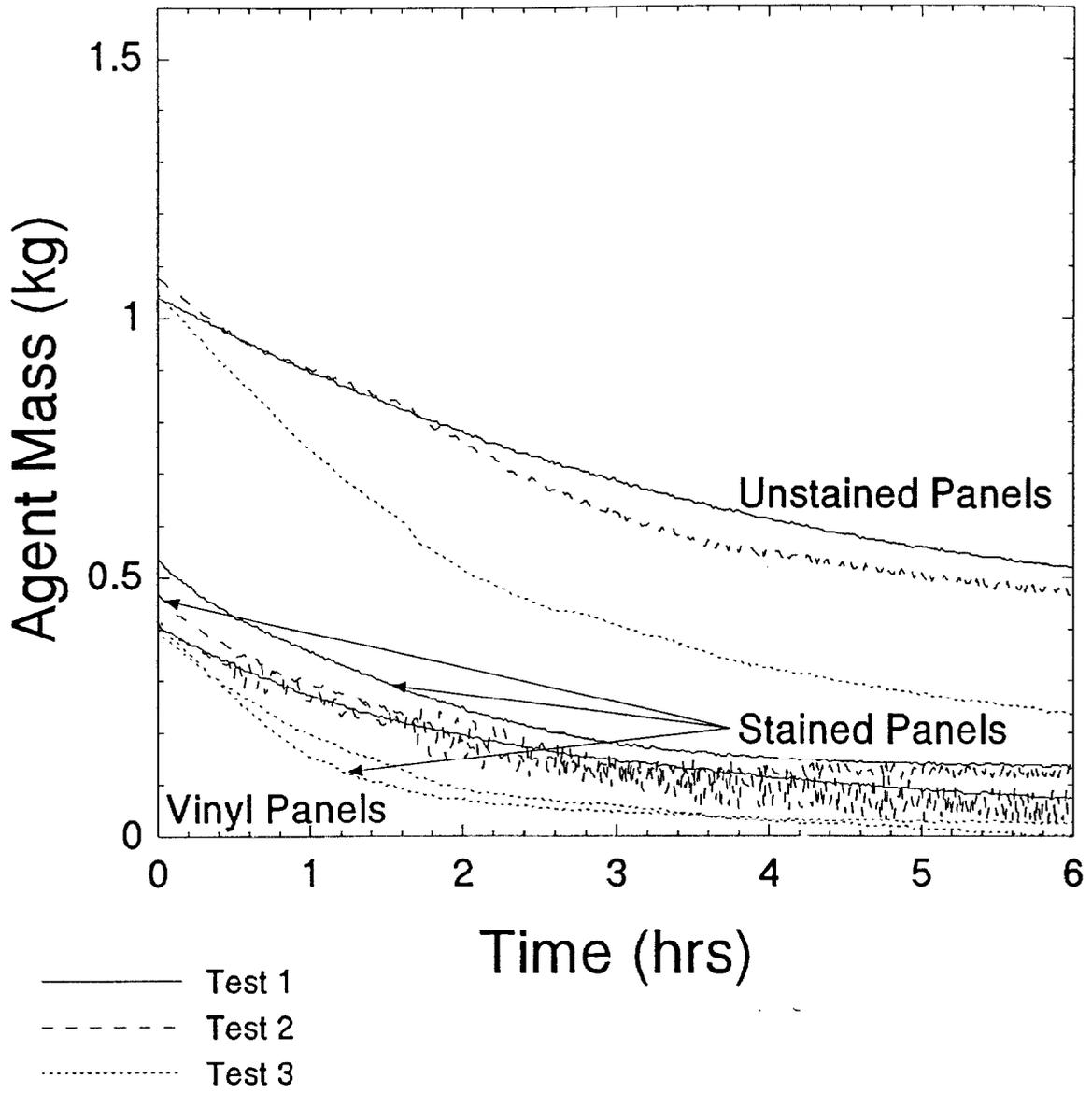


Figure 4. Mass-Retention of Water

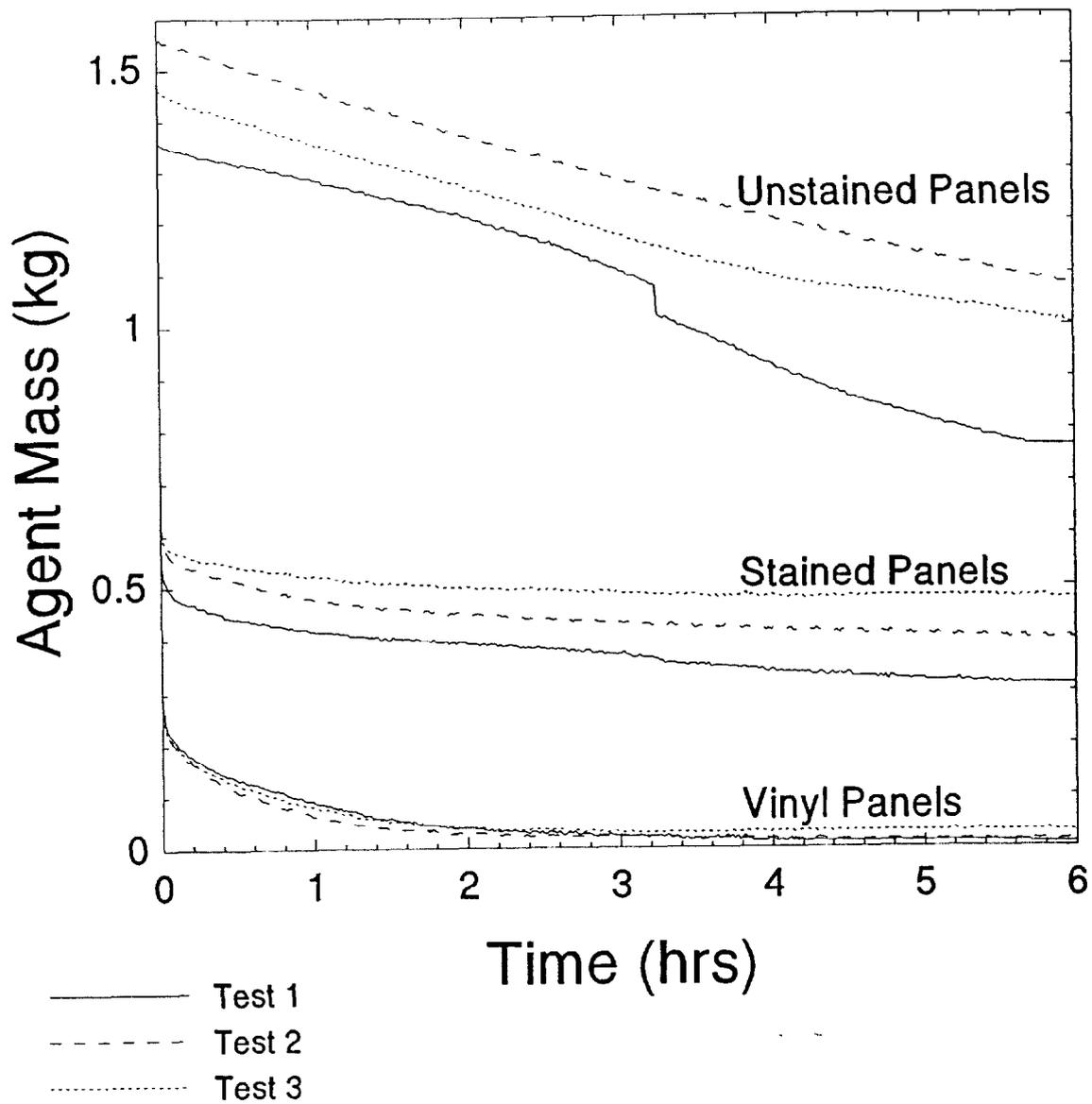


Figure 5. Mass-Retention of Solution A

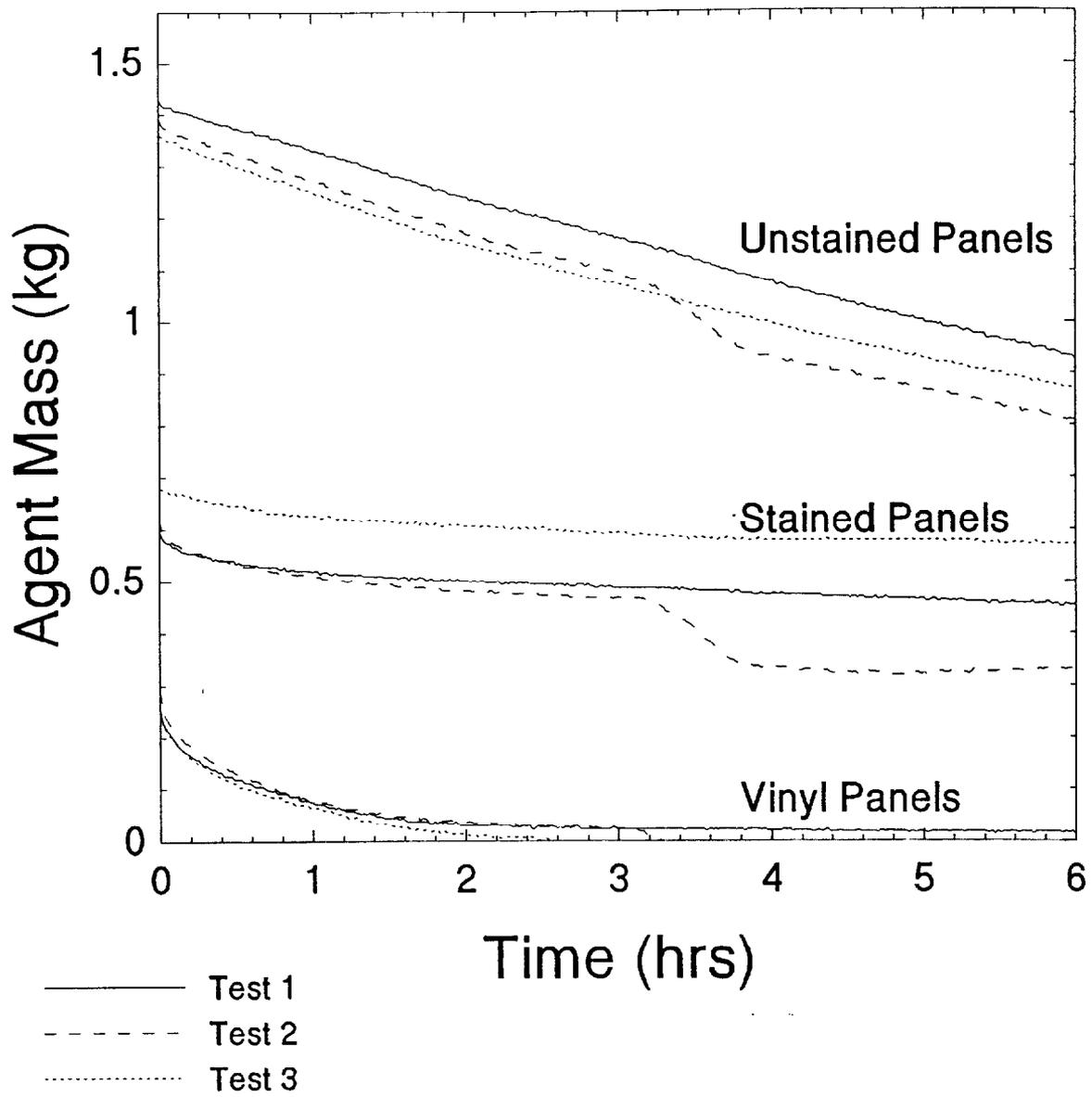


Figure 6. Mass-Retention of Solution B

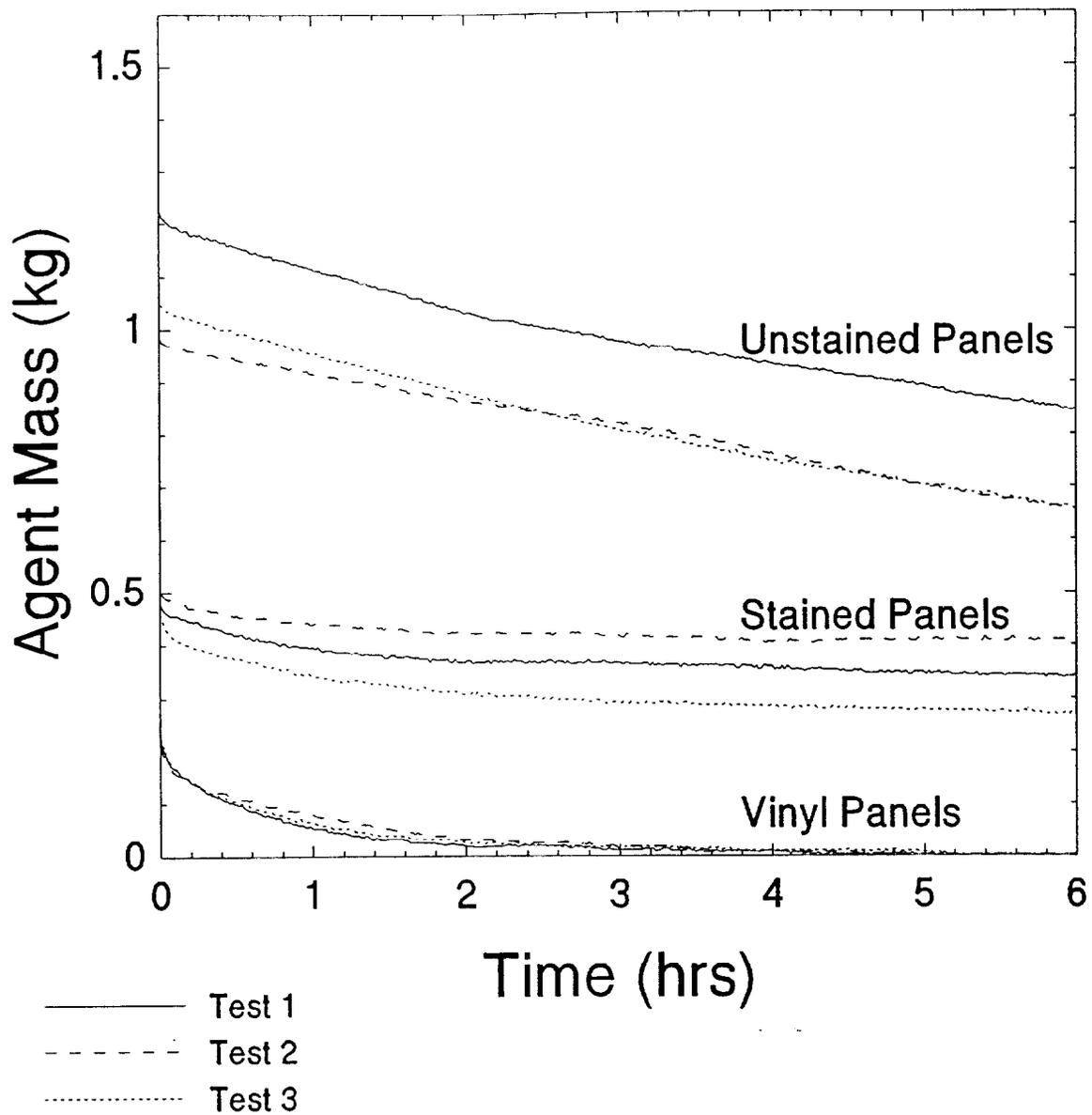


Figure 7. Mass-Retention of Solution C

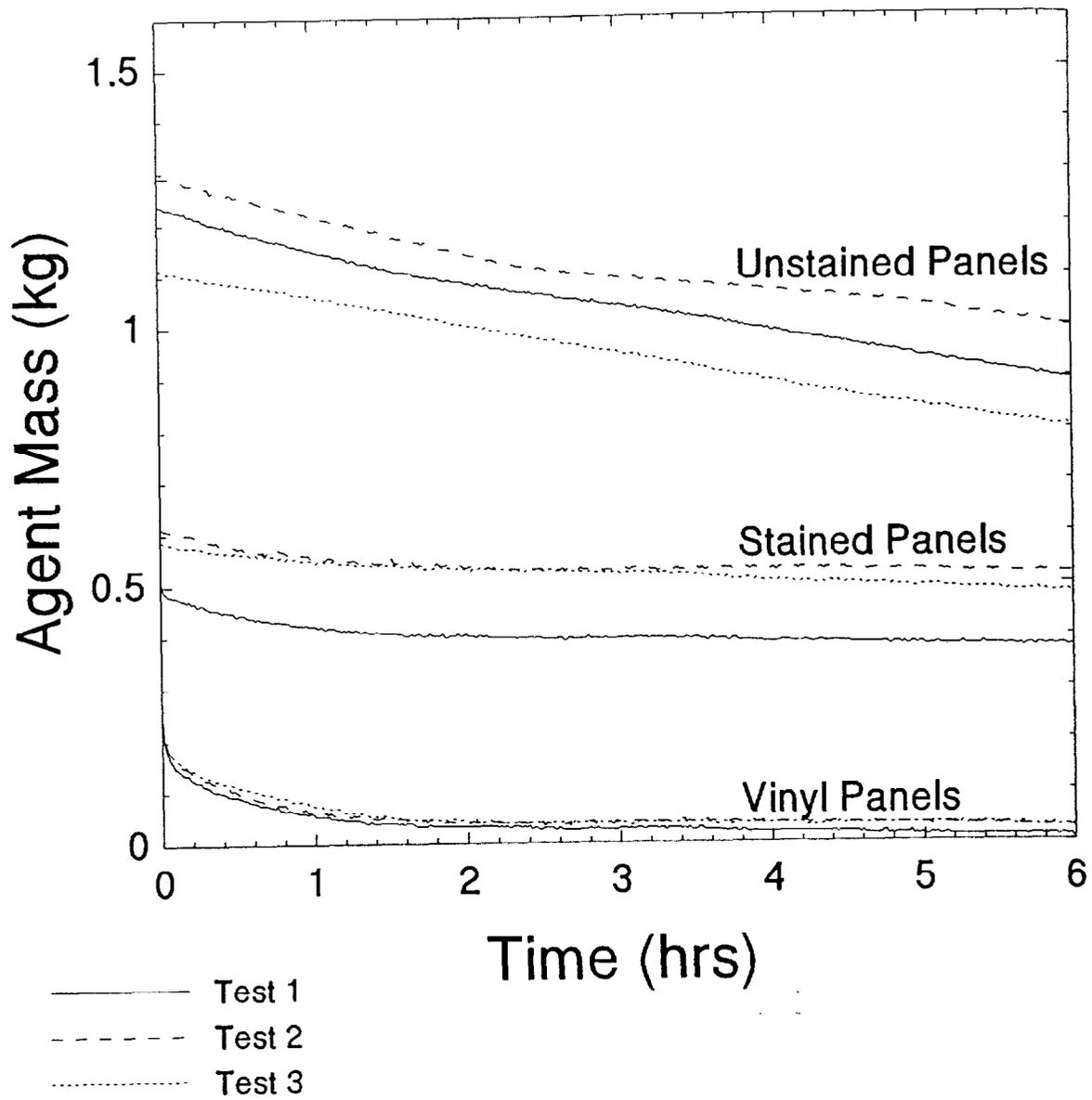


Figure 8. Mass-Retention of Solution D

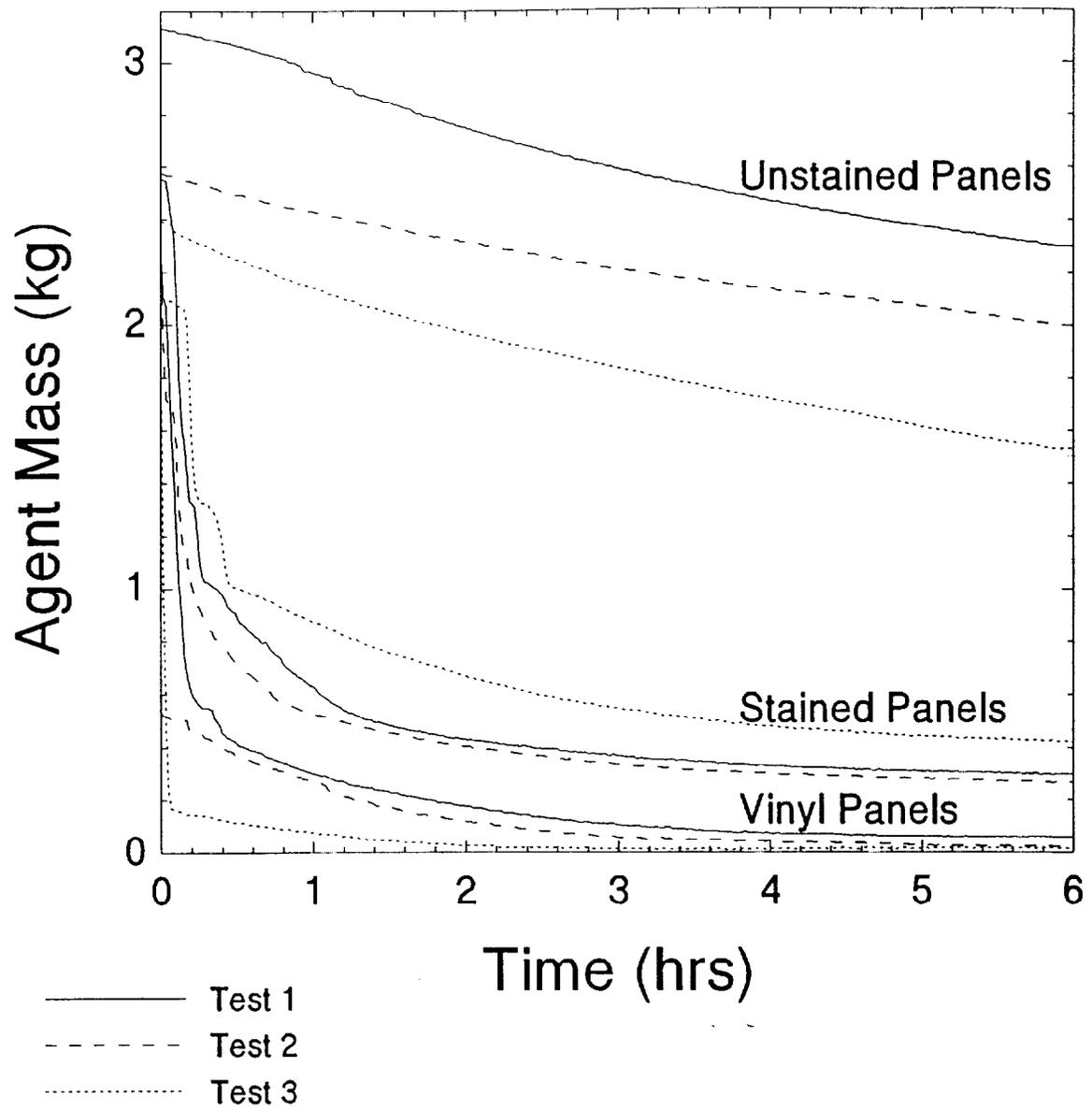


Figure 9. Mass-Retention of CAF A

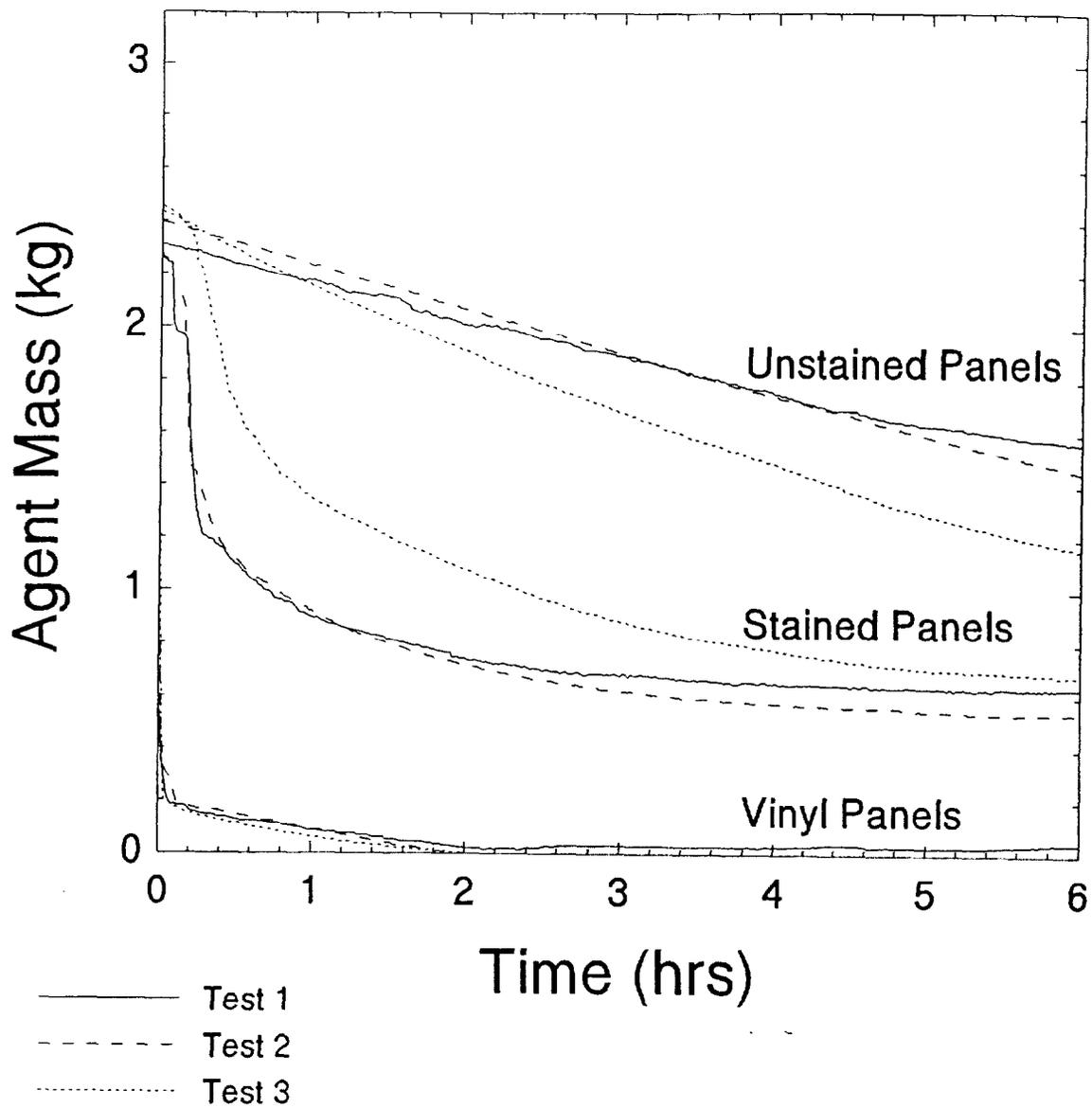


Figure 10. Mass-Retention of CAF B

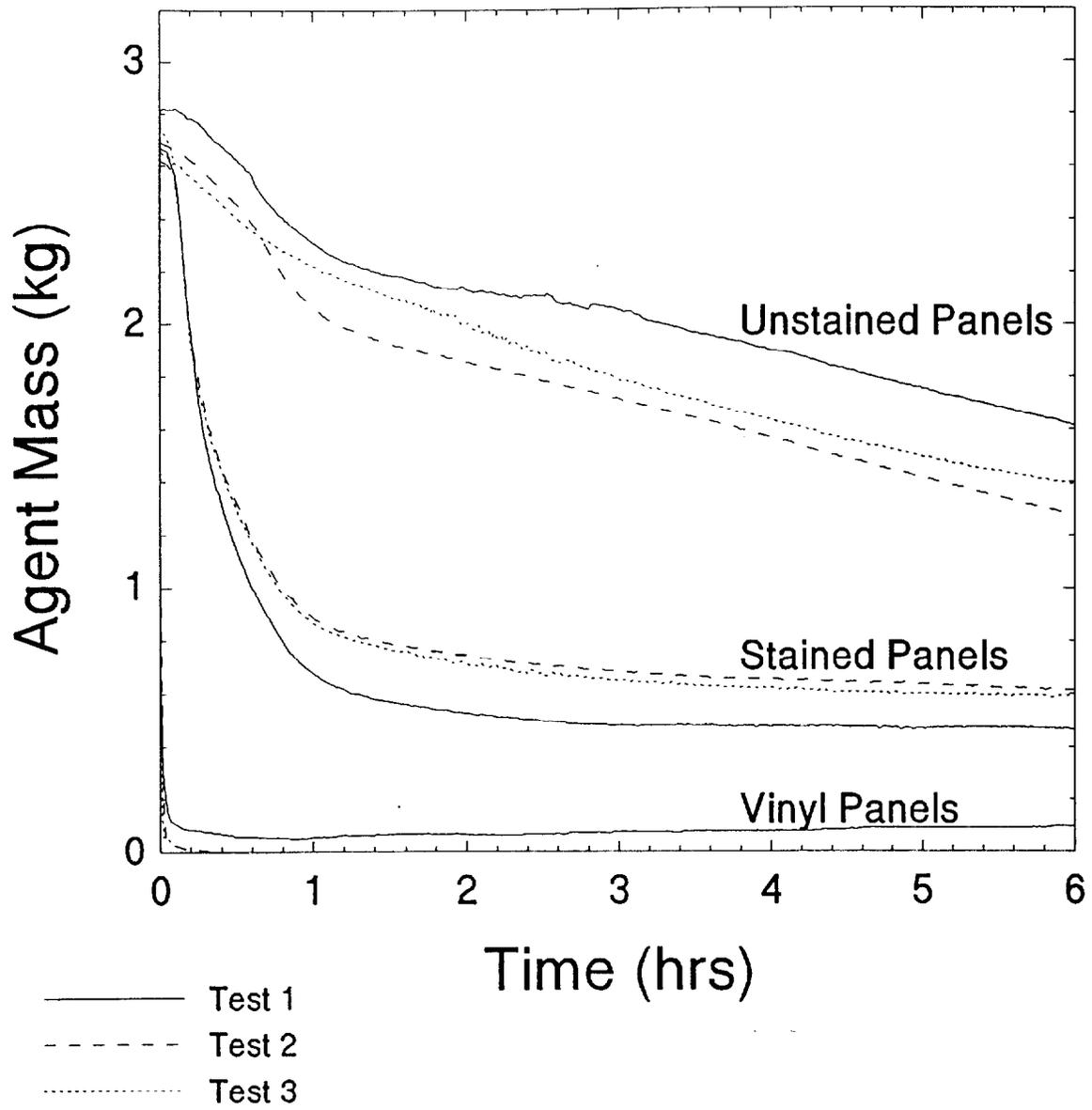


Figure 11. Mass-Retention of CAF C

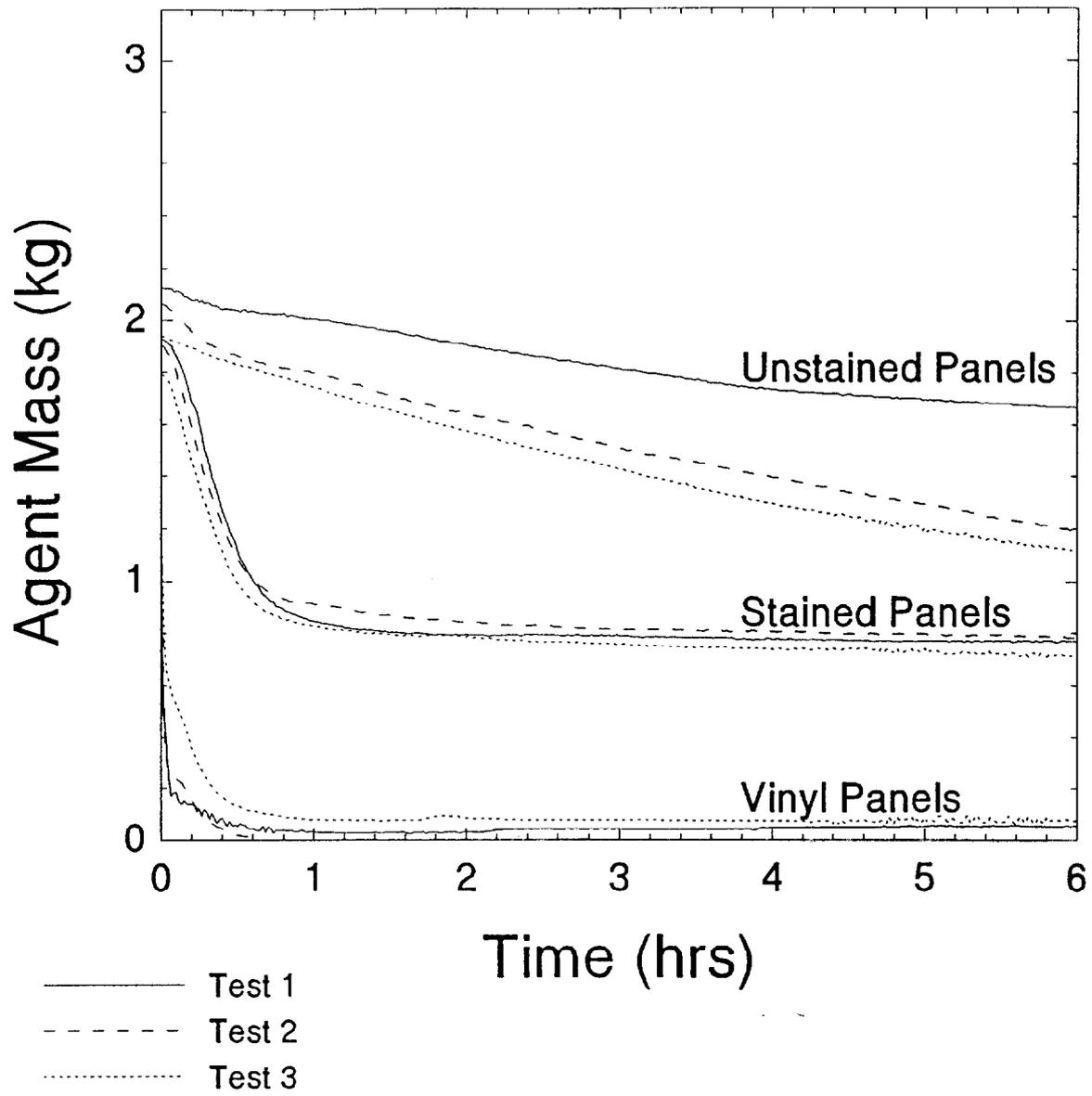


Figure 12. Mass-Retention of CAF D

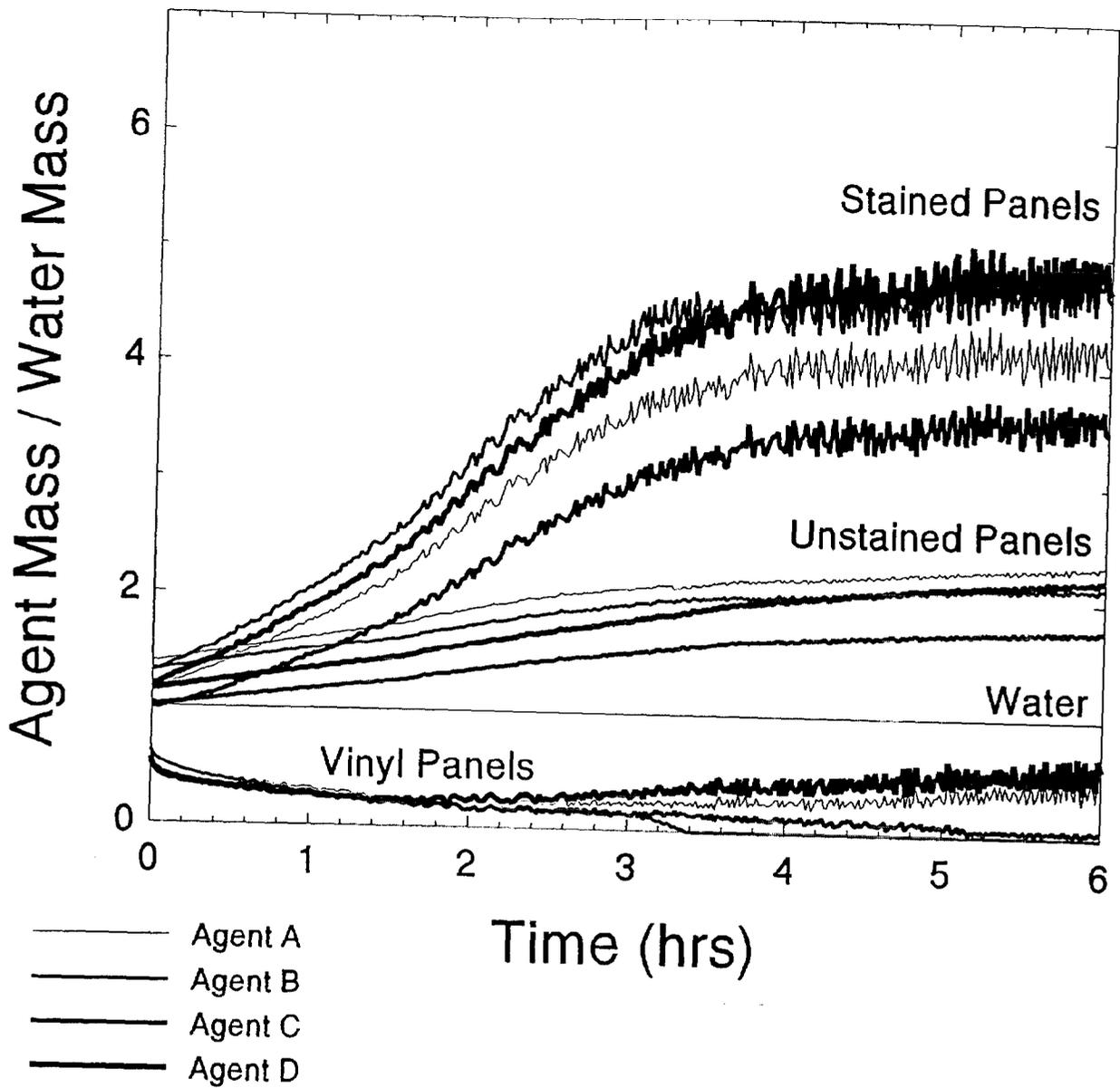


Figure 13. Solution Mass-Retention Effectiveness

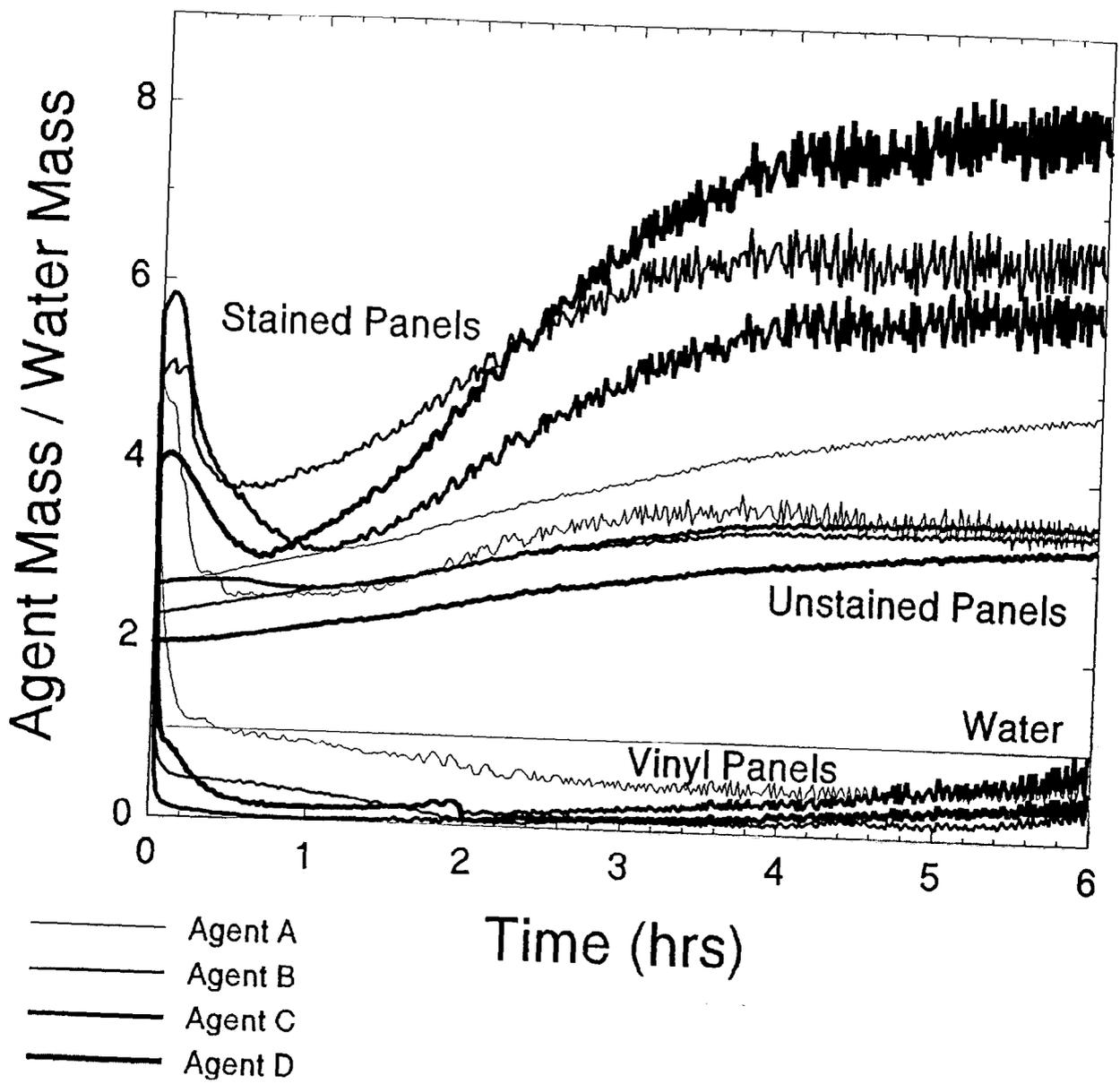


Figure 14. CAF Mass-Retention Effectiveness

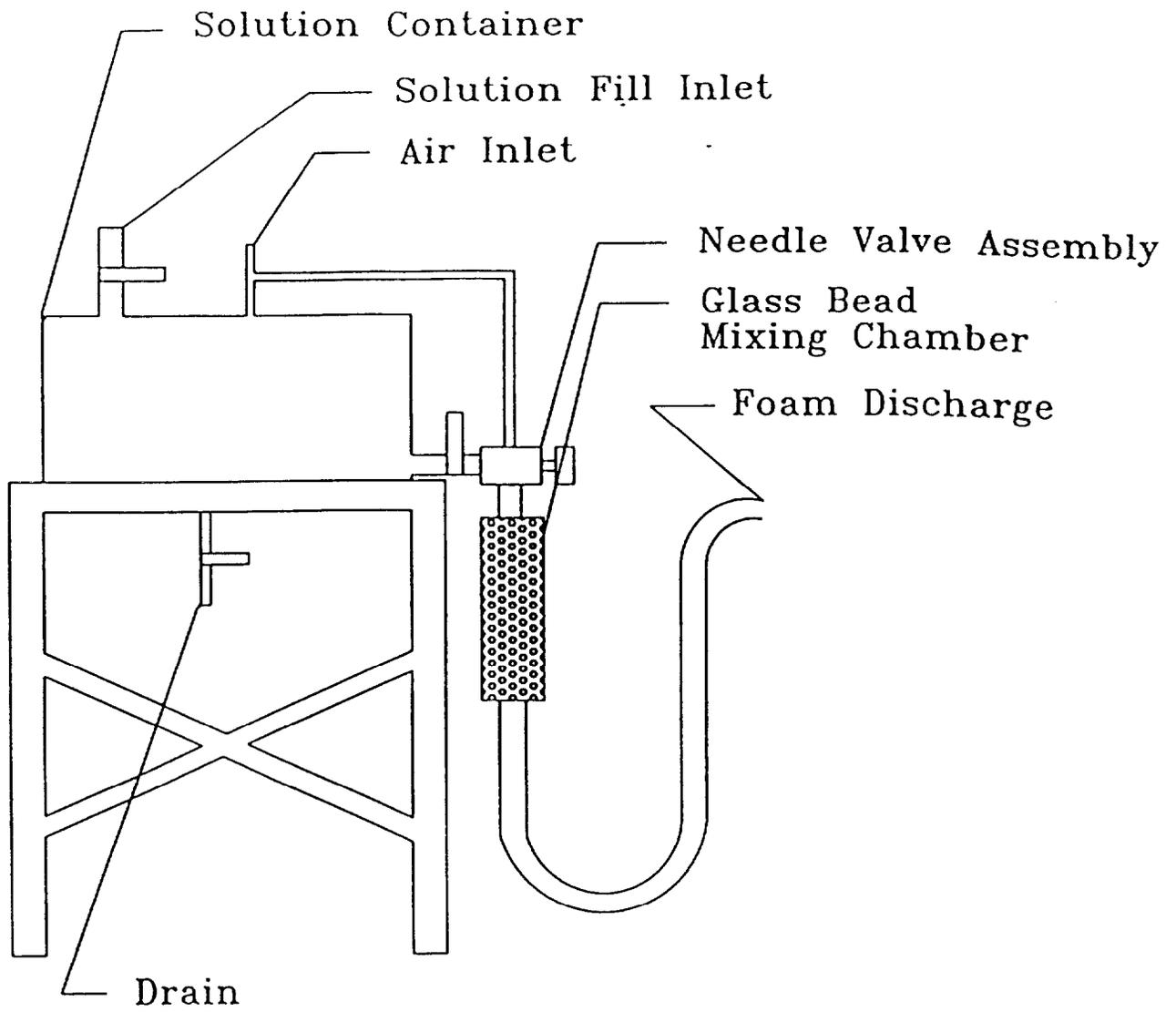


Figure 15. Foam Application System

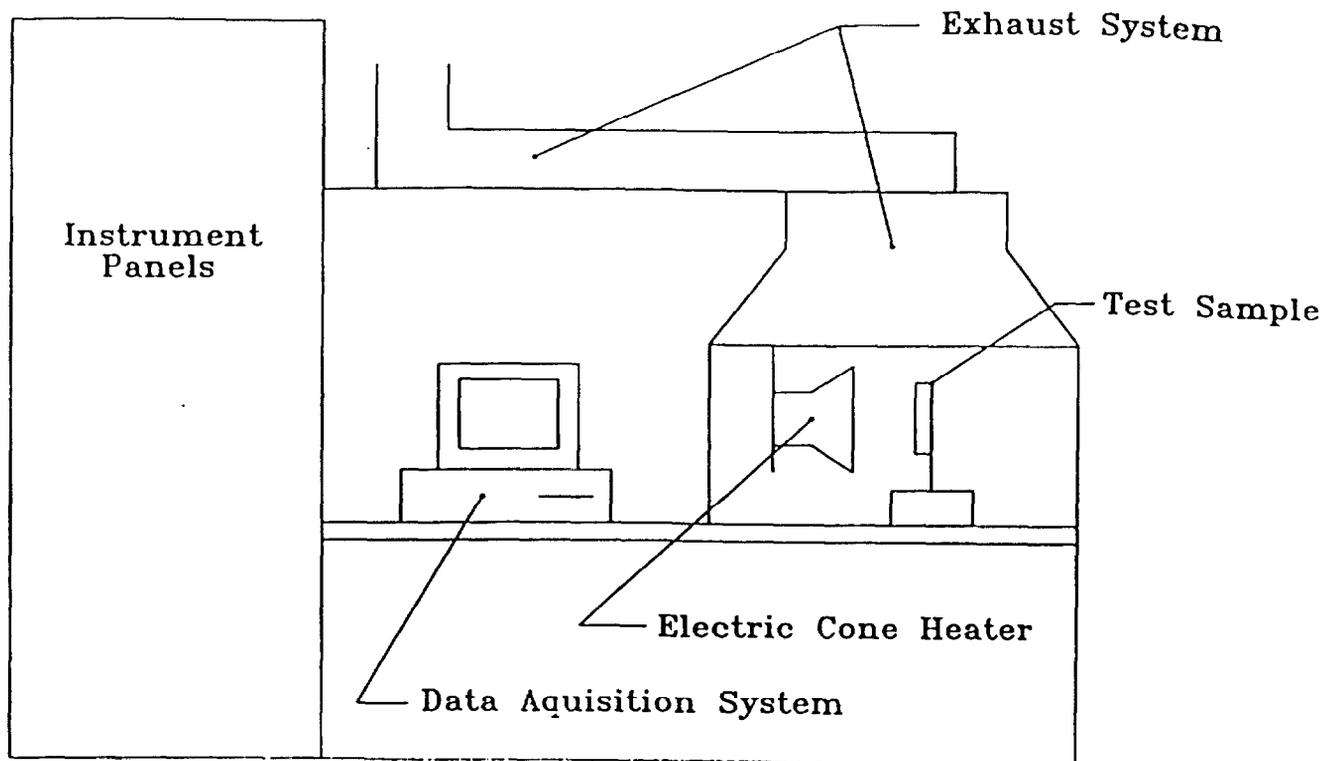
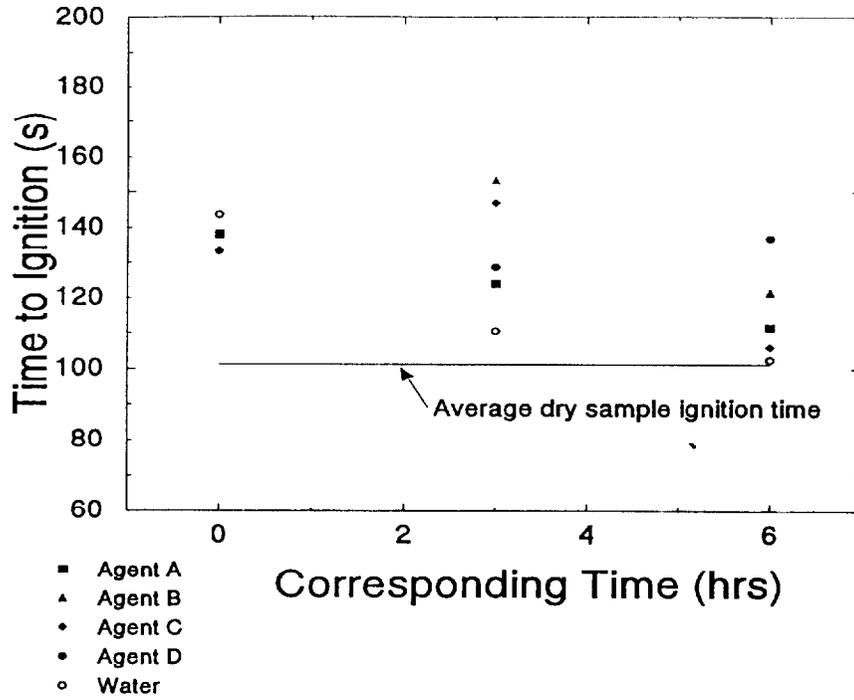
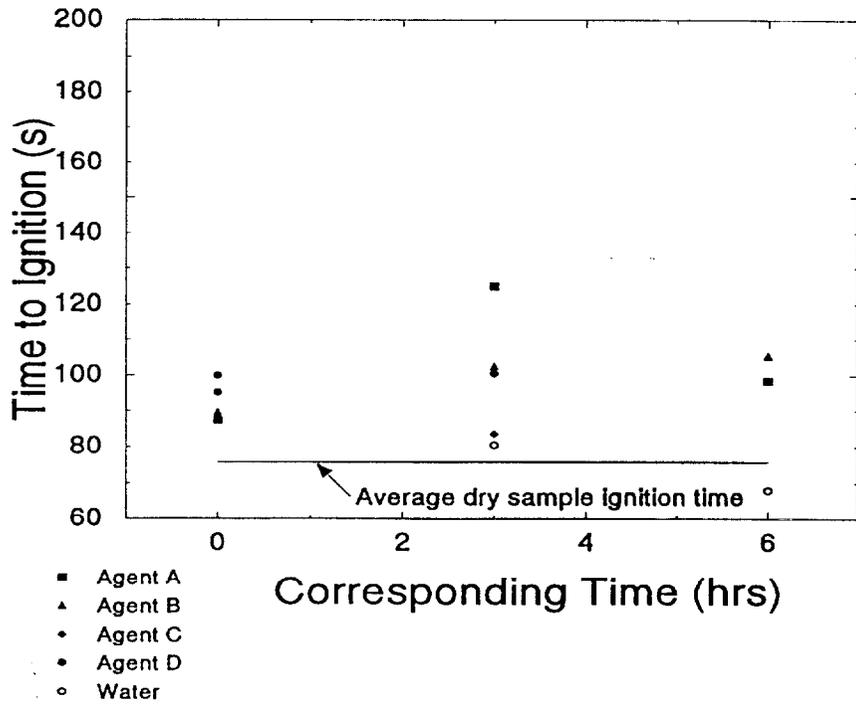


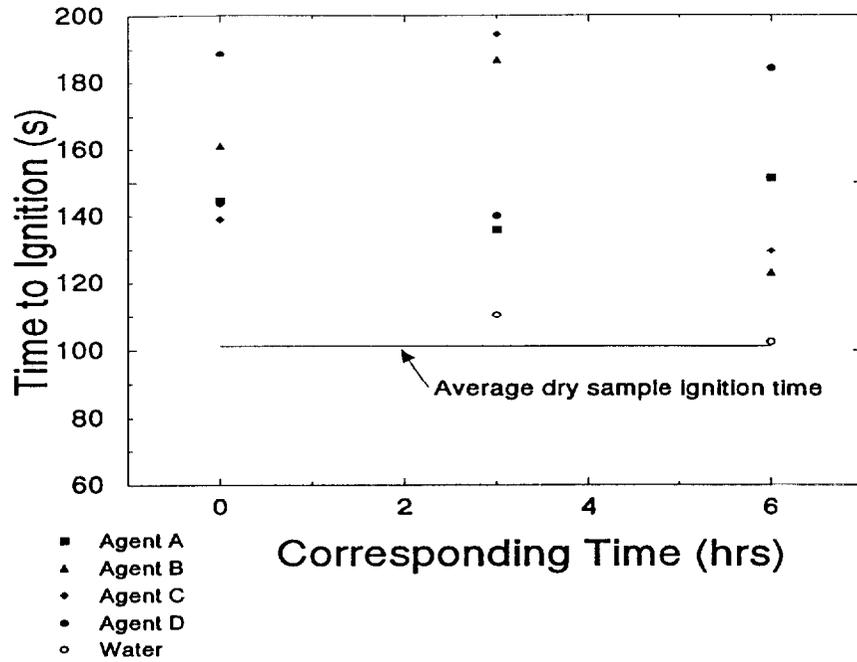
Figure 16. Cone Calorimeter Ignition-Inhibition Set-up



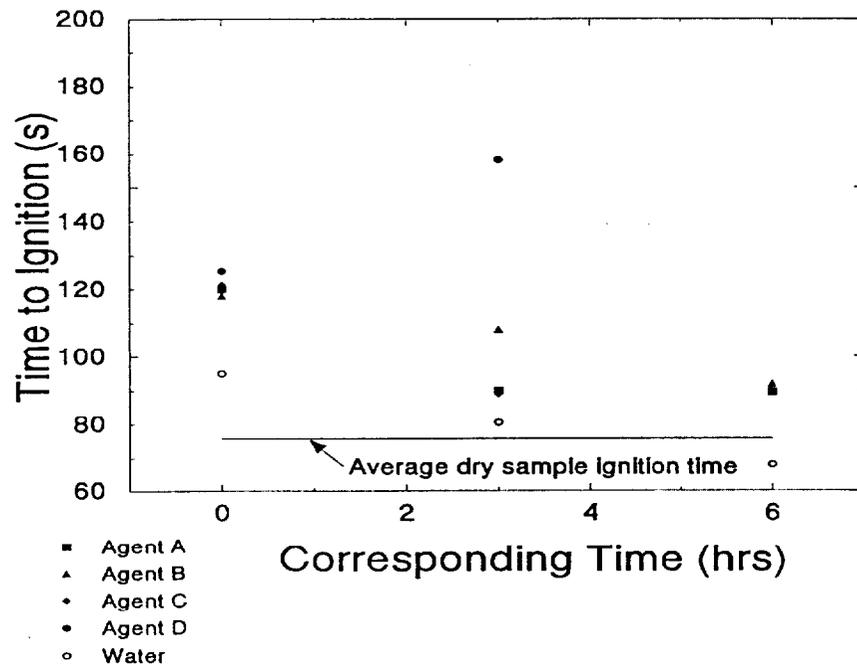
**Figure 17** - Ignition times for solution on unstained samples subject to 30 kW/m<sup>2</sup> heat flux



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



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



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