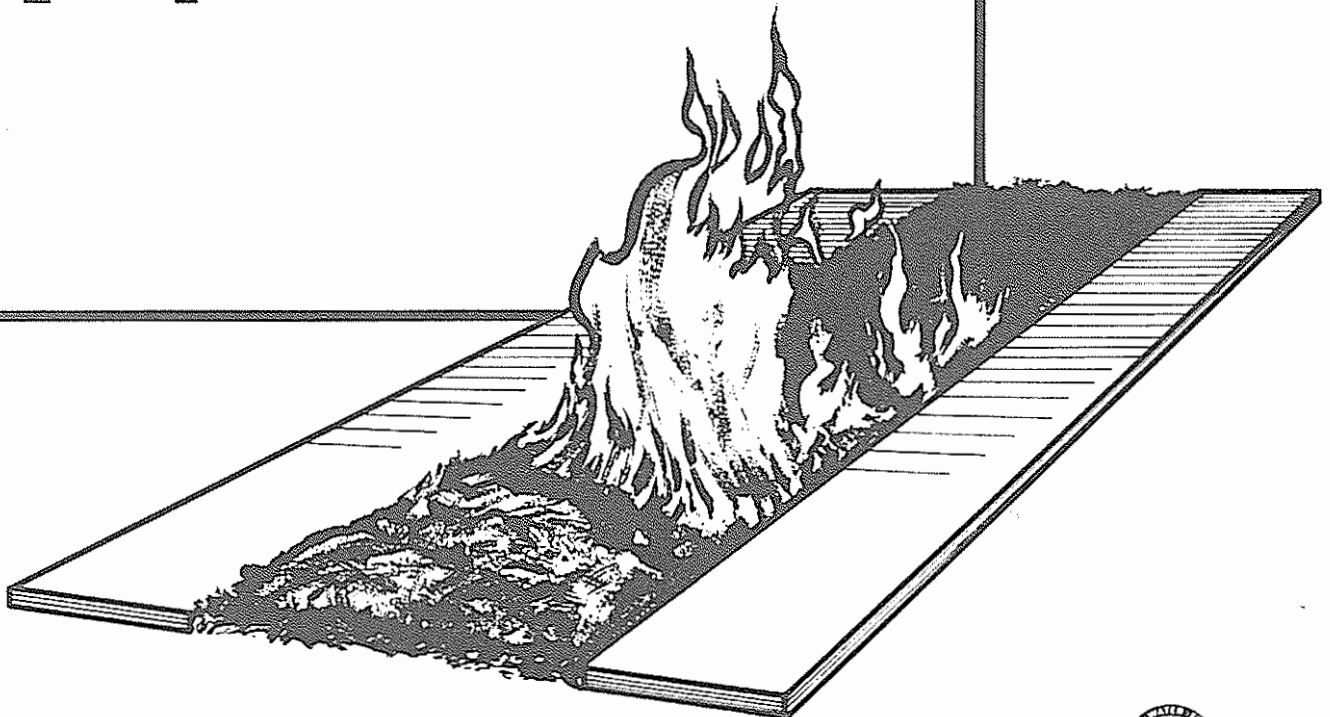
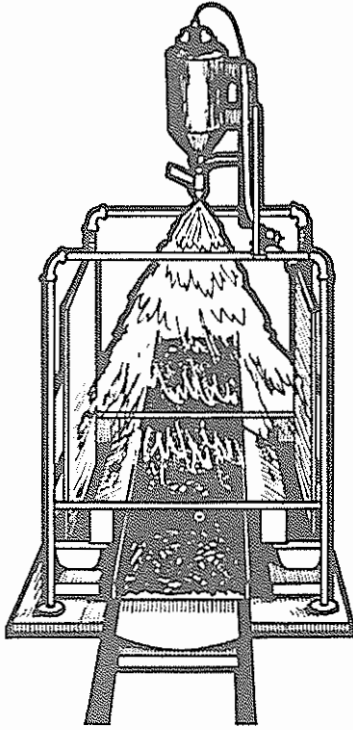


0024

Effects Of Ammonium Sulfate And Ammonium Phosphate On Flammability

CHARLES W. GEORGE AND AYLMER D. BLAKELY



GEORGE, CHARLES W., and AYLNER D. BLAKELY

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CHARLES W. GEORGE AND AYLMER D. BLAKELY

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U. S. Department of Agriculture
Ogden, Utah 84401
Robert W. Harris, Director

THE AUTHORS

CHARLES W. GEORGE was graduated from the University of Montana in 1964 in Forest Engineering. He received his master's degree at the University of Montana in 1969. In 1965, he joined the Northern Forest Fire Laboratory staff in Missoula, Montana, where he is now responsible for research dealing with forest fire retardant chemicals.

AYLMER D. BLAKELY was graduated from the University of Montana in 1960 in Forestry. He received his master's degree at the University of Montana in 1970. In 1967, he joined the Northern Forest Fire Laboratory Fire Management unit where he is involved in fire retardant chemical research.

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ABSTRACT

Ponderosa pine needle and aspen excelsior fuel beds, chosen because they exhibit different chemical fuel characteristics, were treated with various amounts of ammonium sulfate and ammonium phosphate and burned in a wind tunnel under controlled environmental conditions. The rate of fire spread, rate of weight loss (equivalent energy release rate), and the residue were measured to quantify the retardants' effects on flammability.

An increase in the amount of either fire retardant chemical caused a reduction in rate of fire spread and rate of weight loss while increasing the amount of residue. However, at all treatment levels, ammonium phosphate was more effective than ammonium sulfate. These two chemicals exhibit their primary difference in their effect on glowing combustion. The rate of weight loss and especially the residue are parameters that quantify glowing combustion.

Ammonium phosphate is much more effective in decreasing the rate of weight loss and increasing the residue than is ammonium sulfate, which has little effect on the residue. The superior effectiveness of ammonium phosphate is probably due to the difference in thermal behavior of the two fire retardants; total decomposition of ammonium sulfate occurs prior to 450° C., about 250° C. sooner than ammonium phosphate. Temperatures at the surface of the fuel bed probably are within the range of these total decomposition temperatures. Although ammonium sulfate is effective in retarding flaming combustion, the majority of the chemical may decompose prior to the glowing phase and thus not be available to alter reactions taking place during glowing combustion.

The study provides general relationships which can serve as standards for comparing the effects of other basic chemicals or forest fire retardant additives.

INTRODUCTION

The Problem

More than 80 million gallons of fire retardant have been used in the control of forest and rangeland fires by fire control agencies throughout the United States in the last 10 years. These fire retardants are specially formulated and usually contain: an active retardant chemical; coloring agent; corrosion inhibitor; thickening agent; and spoilage inhibitor, when necessary.

The most commonly used active retardant chemicals are ammonium sulfate $(\text{NH}_4)_2\text{SO}_4$ and ammonium phosphate $(\text{NH}_4)_2\text{HPO}_4$. These chemicals, when applied to cellulosic fuels, alter the combustion process to produce less flammable products while increasing the amount of nonflammable products. The most efficient use of these chemicals can only be made after thorough quantification of their effects on flammability.

Flammability has been defined as the interaction of ignitibility, sustainability, and combustibility (Anderson 1970). Ignitibility is the ease with which a fuel will ignite. Under given conditions, the most ignitable fuel will ignite with the least energy input. Sustainability is a measure of how well the fuel will continue to burn with or without the heat source after ignition. Combustibility is a measure of the rapidity with which energy is released from the fuel following ignition.

Fire retardant chemicals are often applied to reduce the overall flammability of fuels. In other instances these chemicals are used specifically to reduce the sustainability or combustibility. It is often thought that ignitibility is decreased by treating fuel with retardant chemicals such as ammonium sulfate and ammonium phosphate; however, recent empirical data indicate the reverse--i.e., less energy is necessary for ignition of treated fuel.¹ This fact is substantiated by more sophisticated thermal analysis data which indicate that treated cellulose undergoes pyrolysis and combustion at lower temperatures and with less energy inputs than does untreated cellulose (George and Susott 1971). (Pyrolysis is the thermal degradation of a material.)

¹Unpublished experimental data on file at the Northern Forest Fire Laboratory, USDA Forest Service, Missoula, Montana.

A study of the effects that ammonium sulfate and ammonium phosphate have on flammability must include quantification of several appropriate parameters. Many researchers have used rate of fire spread to assist in the evaluation of fire retardants (Hardy, Rothermel, and Davis 1962; Rothermel and Hardy 1965; Johansen 1967; Eickner and Schaffer 1967). The rate of spread is a measure of sustainability, or the ability of a fire to propagate itself. The combustibility, or rate at which energy is released from the fire, can be measured by monitoring the weight loss rate that occurs during the fire (Rothermel and Hardy 1965; Rothermel and Anderson 1966). Only recently has it been pointed out that retardant chemicals applied to open fuel bed fires may have similar effects on the rate of spread but different effects on the rate of energy release (George and Blakely 1970). Because fire retardants are used to reduce fire spread and combustion rate, it is necessary for both parameters to be quantified.

Although ignitibility and sustainability may be encompassed in rate of spread measurements, and combustibility in energy-release rate measurements, they do not entirely describe a fire retardant's effect on flammability. Combustion can be divided into two phases: flaming (associated mainly with the fire front); and glowing (associated with residual burning)--different rates of energy release apply for each of these. The retardant chemical, due to inherent decomposition characteristics, may only be available at given temperatures or for a given time during the fire, (George and Susott 1971) thus causing different effects on the flaming and glowing processes. The extent of combustion, both flaming and glowing, can be determined by measuring the amount of residue.

The quantification of the effects that fire retardants have on rate of spread, energy release rates, and residue should provide a basis for determining the chemical's overall effect on flammability.

Objectives

The major objective of this study was to determine the effects of ammonium sulfate and ammonium phosphate on the flammability of cellulosic fuels. The overall effects on flammability can be characterized by quantification of these effects on the following parameters:

1. Rate of spread (R_s)
2. Rate of weight loss (R_w)
3. Residue (R)

Standard curves were developed in this study for each parameter as a function of the amount of retardant chemical applied to the fuel.

The study was designed to provide general information which can be used to evaluate formulated ammonium sulfate and ammonium phosphate fire retardants. The curves will be used to evaluate the relative importance of additives, or impurities, and to determine whether they enhance or reduce the active chemicals' effectiveness. This information will be useful to potential suppliers for the formulation of more efficient fire retardants.

Also, this study will provide information which may eventually be used in the development of operational guidelines. The guidelines could assist fire control personnel in selecting the most efficient retardant chemical for a given job and help determine how much chemical is required for the specific situation.

THE METHOD

The development of a method to evaluate the effect of retardant chemicals on flammability required considerable attention to the following:

1. Type of fuel and fuel bed configuration;
2. Method of chemical application; and
3. Conditioning of fuel following chemical application and environmental conditions during burning.

Type of Fuel and Fuel Bed Configuration

Previous research on the effects of fire retardants (Hardy, Rothermel, and Davis 1962; Rothermel and Hardy 1965) demonstrated the usefulness of ponderosa pine needle fuel beds which were originally used because of their natural physical and chemical characteristics; whether or not this type of fuel is representative of most forest fuel was questioned.

Ponderosa pine needles alone are not representative because they contain a relatively high amount of ether extractives (approximately 10 percent) which apparently volatilize at low temperatures and support combustion. Furthermore, woody fuels make up a large portion of natural forest fuel and generally contain less extractives and a larger percentage of cellulose. Aspen excelsior (0.021 inch by 0.021 inch by 3 inches), is a representative woody fuel and also exhibits a high degree of reproducibility; thus, it has been used to successfully evaluate fire retardants (USDA Forest Service 1970; USDA Forest Service 1969). This excelsior contains less than 1 percent ether extractives but has nearly the same heat content as ponderosa pine needles. (A comparison of chemical characteristics is given in table 1.) By using both of these fuels the researcher was able to simulate the extremes of chemical fuel characteristics normally found in forest areas.

Table 1.--Comparison of chemical characteristics of ponderosa pine needles and aspen excelsior

Item	Aspen excelsior	Ponderosa pine needles
Cellulose (percent dry weight)	42.0	18.0
Ash content (percent dry weight)	0.36	3.87
Silica-free ash (percent dry weight)	0.36	1.55
Ether extractives (percent dry weight)	<1.0	9.73
Heat content (B.t.u./lb.)	8,485	8,753

Ponderosa pine needles for fuel beds were collected and cleaned during the year prior to the tests. The needles were stored indoors until an equilibrium moisture content was reached, and aspen excelsior which had been cut to specifications was given similar treatment. Following this ambient indoor conditioning, moisture contents were between 5 and 8.5 percent (percent of oven-dry weight) for both types of fuel.

Fuel beds, fuel bed configuration, and a method of preparation similar to that used by Rothermel and Hardy (1965) was adopted for use in the study. A lighter fuel loading was necessary for aspen excelsior because of its higher surface area-to-volume ratio. Characteristics of the fuel bed are shown in table 2.

Method of Chemical Application

A method of application was developed and used to distribute the retardant solution uniformly over the surface of the fuel bed at a constant depth of penetration. This was accomplished by applying a constant volume of solution and varying only the concentration or amount of the chemical in solution. The solution was contained in a pressurized supply tank that had a calibrated flow. The calibration was established by

Table 2.--Fuel bed characteristics

Fuel bed (Inches)	Average equilibrium moisture content	Loading at EMC	Fuel surface-to- volume ratio	Fuel bed void volume-to-surface- to-area ratio	
	Percent	Lb./bed	Lb./ft. ²	σ ft. ² /ft. ³	λ ft. ³ /ft. ²
Aspen excelsior					
3 by 18 by 36 ¹	7.0	1.5	0.33	1,848	9.36 by 10 ⁻³
3 by 18 by 96	7.0	4.0	.33	1,848	9.36 by 10 ⁻³
Ponderosa pine needles					
3 by 18 by 36 ¹	7.5	2.25	.50	1,741	8.46 by 10 ⁻³
3 by 18 by 96	7.5	6.0	.50	1,741	8.46 by 10 ⁻³

¹Igniter tray.

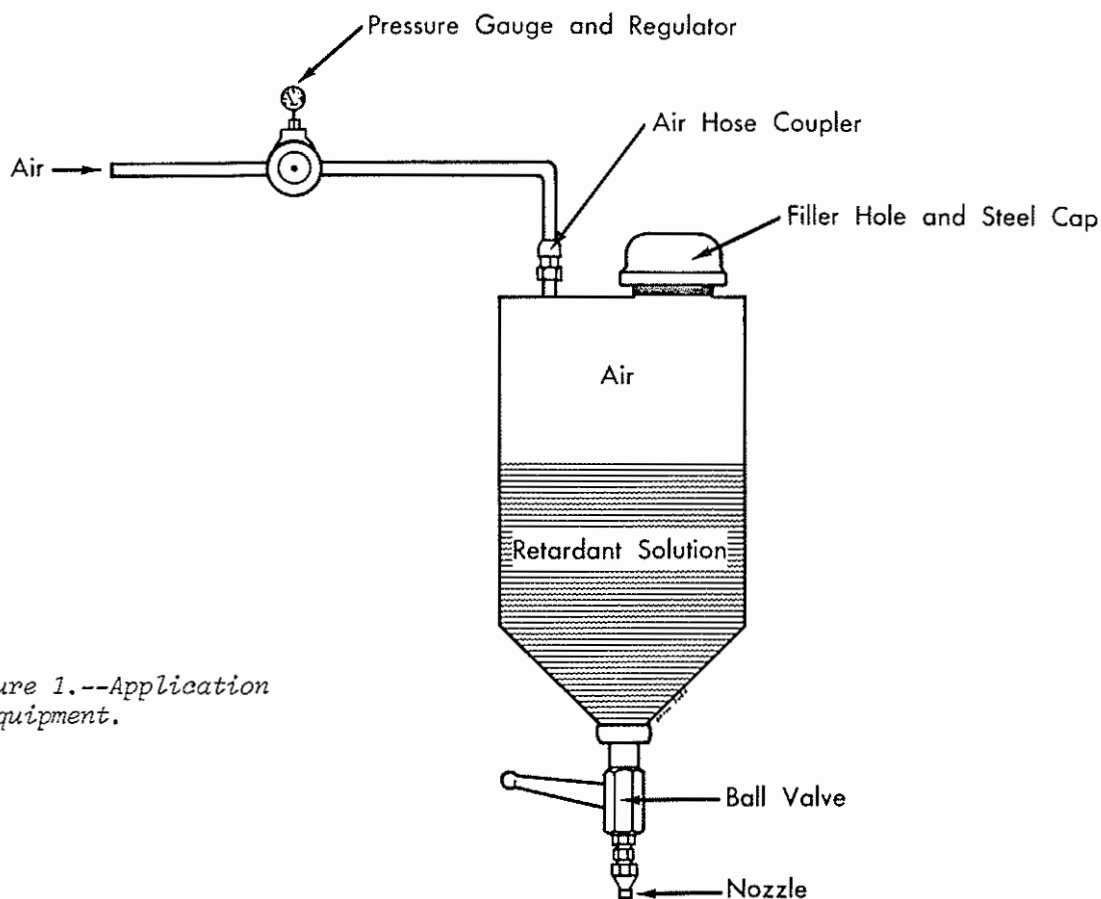


Figure 1.--Application equipment.

determining the volume rate through the nozzle at a given pressure while measuring the lateral spray pattern. A nozzle diameter, height, and tank pressure were selected that would provide a uniform lateral pattern over the fuel bed width. The fuel beds were then pushed under the nozzle at a constant predetermined speed to apply the desired amount of solution. The application equipment and spray system in operation are shown in figures 1 and 2.

The fuel beds were weighed prior to and following application of the retardant solution. The amount of solution per square foot of fuel bed and the percent of solution as a function of dry fuel weight were calculated.

Conditioning of Fuel and Environmental Conditions

Following application of the retardant solution, the fuel beds were allowed to reach an equilibrium moisture content in the combustion chamber under controlled environmental conditions. The combustion chamber air temperature was held at $90^{\circ} \pm 2^{\circ}$ F. and the relative humidity at 20 ± 2 percent. A new equilibrium moisture content of between 5.0 and 6.5 percent was reached. Equilibrium was determined by periodic weight checks of the fuel bed, and the moisture content was determined by using the xylene distillation method.

All burning tests were made in a large wind tunnel at an air velocity of 5 m.p.h. Fuel bed conditioning and the burning tests were conducted under similar temperature and relative humidity conditions. These conditions are equivalent to a Fine Fuel Spread Index of 36 (USDA Forest Service 1964).

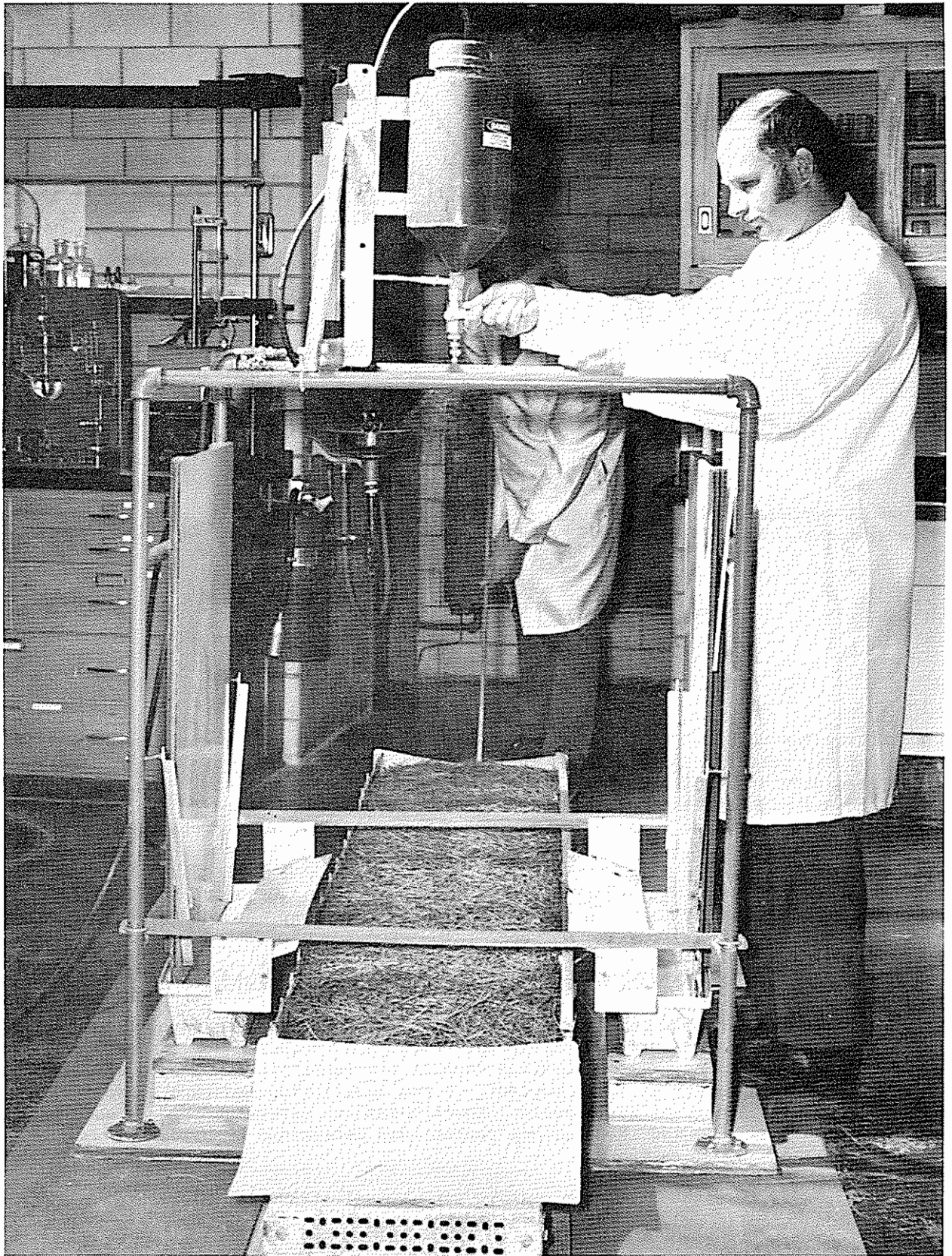


Figure 2.--Spray system in operation.

BURNING TEST

Burning Procedures

Treated and conditioned fuel beds were removed from the combustion chamber and placed on the weighing system in the wind tunnel. The weighing system, described by George and Blakely (1970), was a multiple point system capable of monitoring a weight loss from 0 to 6 pounds, depending on the fuel type and loading; sensitivity of the system was about ± 0.25 percent, or ± 0.001 pound. The weighing system utilized transducer-type elements and load cells manufactured by the Statham Instrument Company. The signal from these transducers was summed and averaged to produce a single direct measurable output and then recorded.

Aprons were placed on all sides of the treated fuel beds and the starter beds to produce uniform airflow over the fuel surfaces. A small tray of ethanol (approximately 25 ml.) at the bottom edge of the igniter tray gave uniform ignition at the leading edge. Just prior to test time, a remote controlled electric spark was produced to ignite the ethanol. The positioning of the beds and a schematic of the weighing system are shown in figure 3. The positioning of side aprons and fuel beds during burning is shown in figure 4.

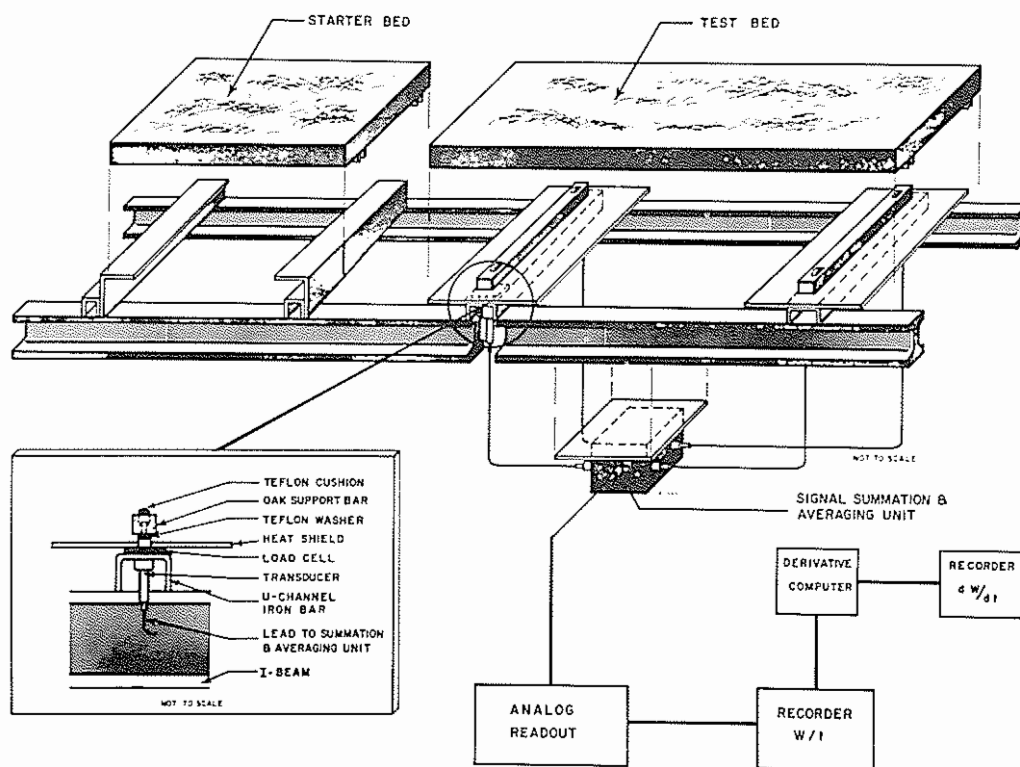


Figure 3.--Multiple strain gage transducer-type weighing system and positioning of starter and treated fuel beds.

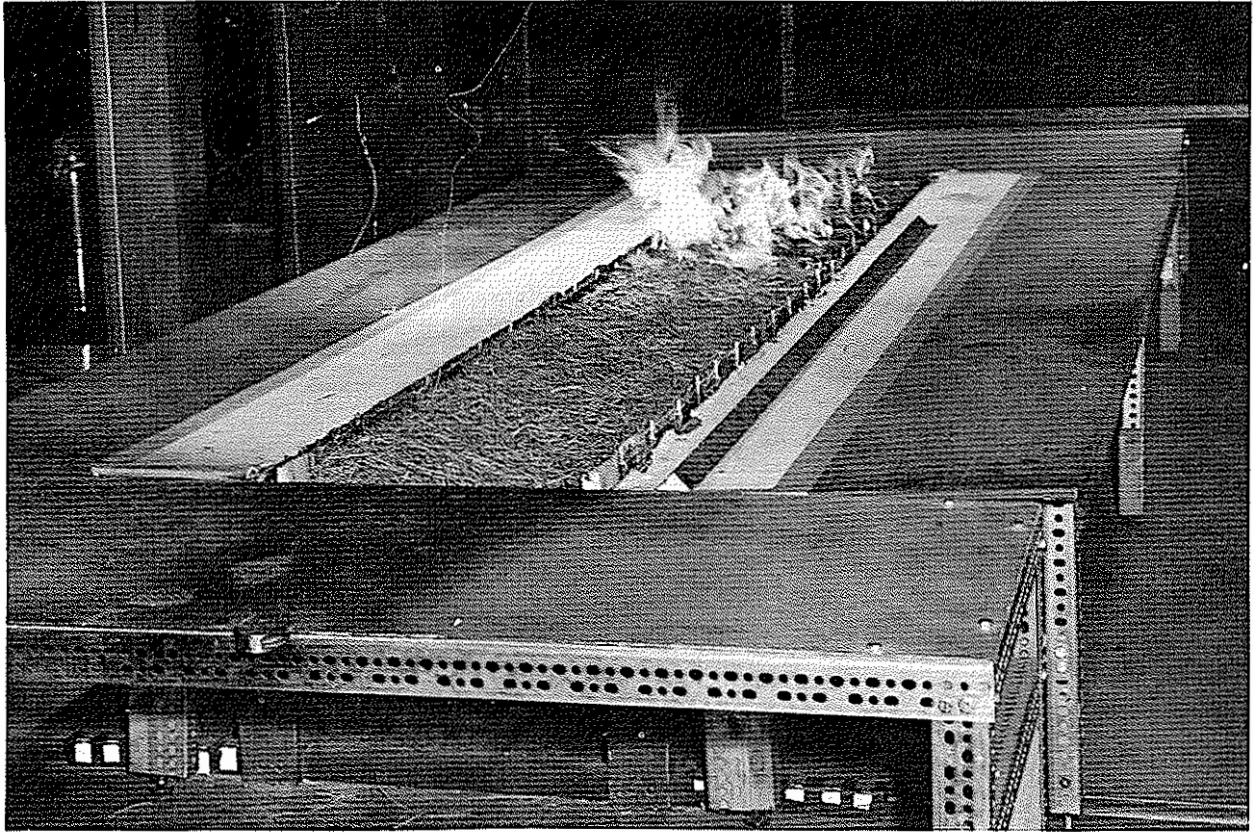


Figure 4.--Positioning of fuel beds and side aprons during test fire.

Measurements

Rate of Spread

The rate at which fire spread through the fuel was measured visually. An aluminum strip with marks at each half-foot interval lay alongside the treated bed. An observer, with a remote switch, activated an event marker which was attached to a recorder being used to record weight loss. The time required for the fire front to cover each half-foot interval was measured and the average steady-state rate of spread between the 3- and 7-foot mark calculated.

Weight Loss Rate

The weight of the treated fuel bed was monitored during the fire on a recorder which had previously been calibrated for a full scale deflection of 4.4 pounds (2,000 grams). The weight loss at the 3- and 7-foot intervals was determined. The time between these intervals was computed from the rate-of-spread event marks and then the steady-state rate of weight loss was calculated.

Residue

The fuel was allowed to burn until glowing combustion was completed; then the fuel bed was weighed and the residue determined.

Figure 5 shows a burning test in progress and the equipment being used for taking the required measurements.

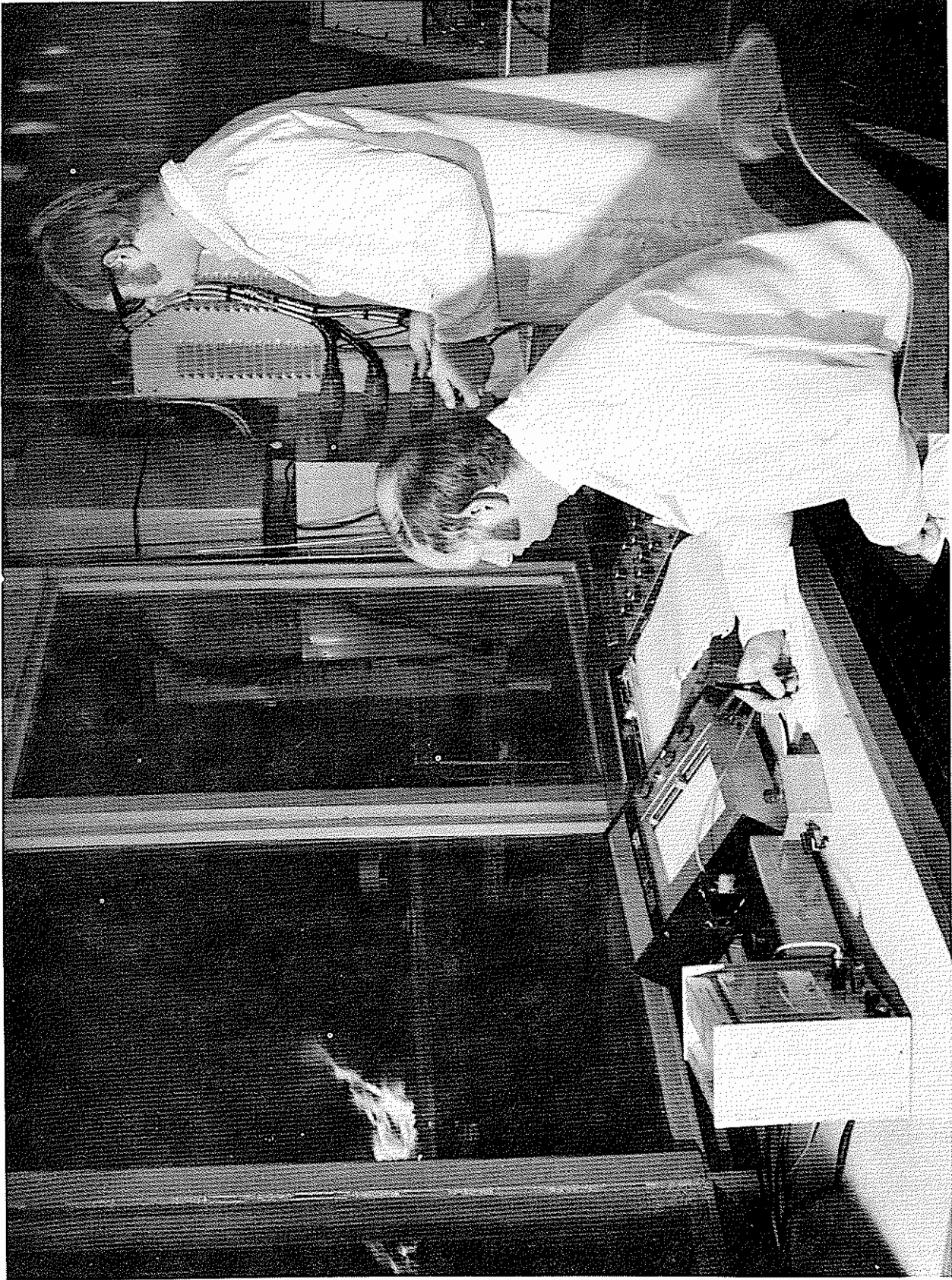


Figure 5.--Instrumentation and setup used during test fires.

RESULTS

A total of 133 treated and untreated fuel beds were burned during the study. Of these, 73 were composed of ponderosa pine needles and the remaining were aspen excelsior. The treated beds received applications of $(\text{NH}_4)_2\text{SO}_4$ or $(\text{NH}_4)_2\text{HPO}_4$. Data for the untreated fuel beds are given in table 4 of the appendix. A summary of the test data for $(\text{NH}_4)_2\text{HPO}_4$ and $(\text{NH}_4)_2\text{SO}_4$ treated ponderosa pine needle fuel beds is presented in tables 5 and 6 of the appendix. A summary of the test data for treated aspen excelsior fuel beds is given in tables 7 and 8 of the appendix.

The relationship between the amount of chemical applied per square foot of fuel bed and the rate of fire spread through the pine needle and excelsior fuel beds is shown in figures 6, 7, 8, and 9. The rate of weight loss and equivalent energy release rate (assuming the energy released is equal to heat content of the fuel times the weight loss rate) as a function of the amount of chemical for the two types of fuel beds are shown in figures 10, 11, and 12. The percent increase in residue over the average residue for untreated was calculated for each fire. This percent increase in residue as related to the amount of chemical applied is shown in figures 13 and 14.

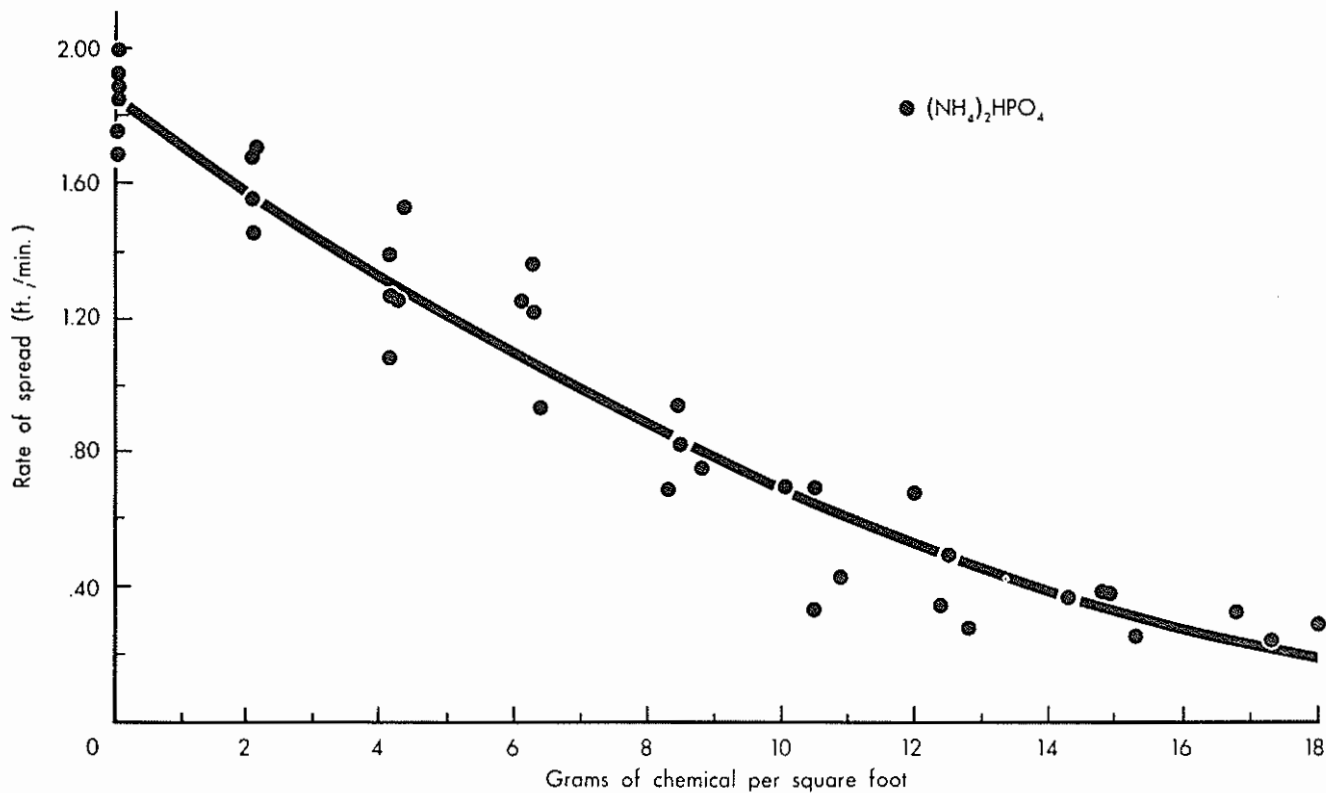


Figure 6.--Effect of $(\text{NH}_4)_2\text{HPO}_4$ on the rate of spread in pine needle fuel.

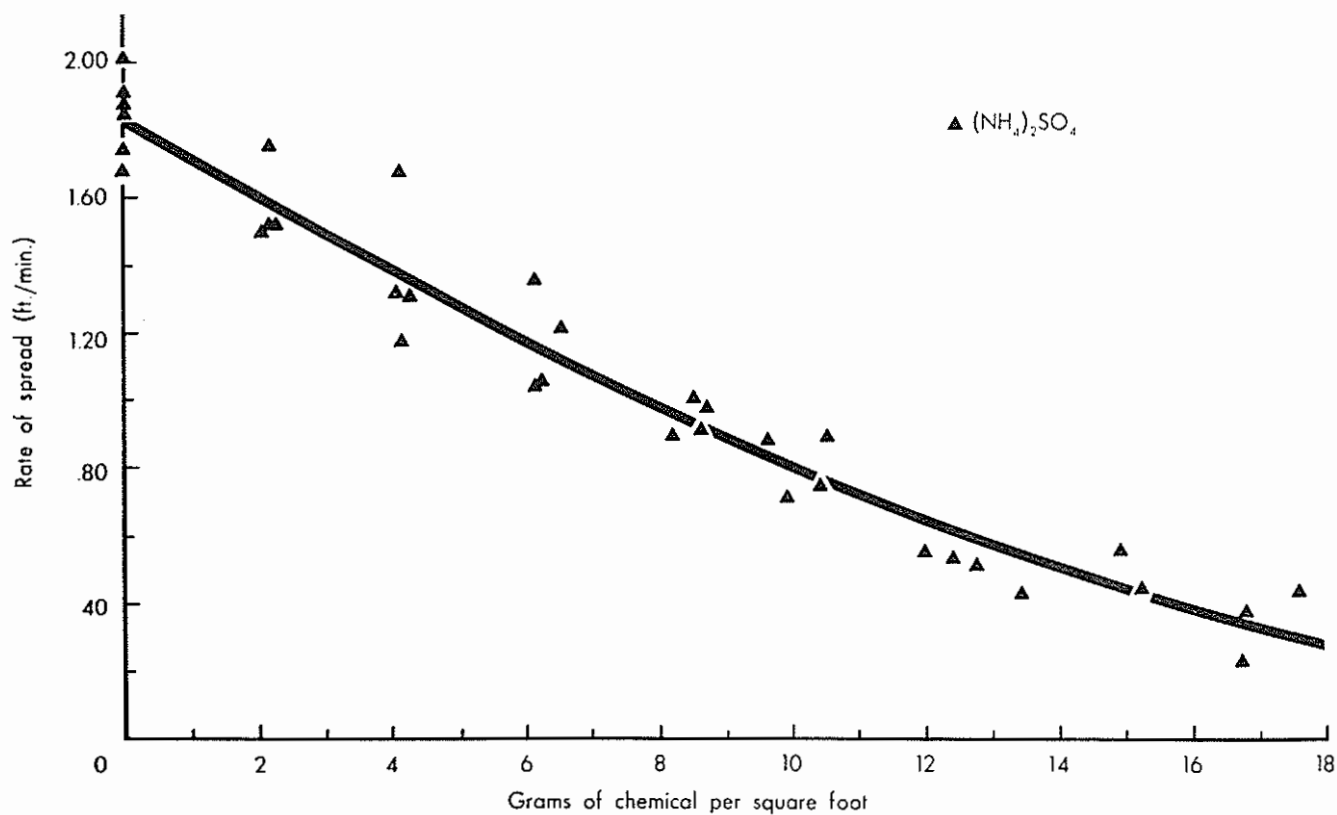


Figure 7.--Effect of $(\text{NH}_4)_2\text{SO}_4$ on the rate of spread in pine needle fuel.

Figure 8.--Effect of $(\text{NH}_4)_2\text{HPO}_4$ on the rate of spread in excelsior fuel.

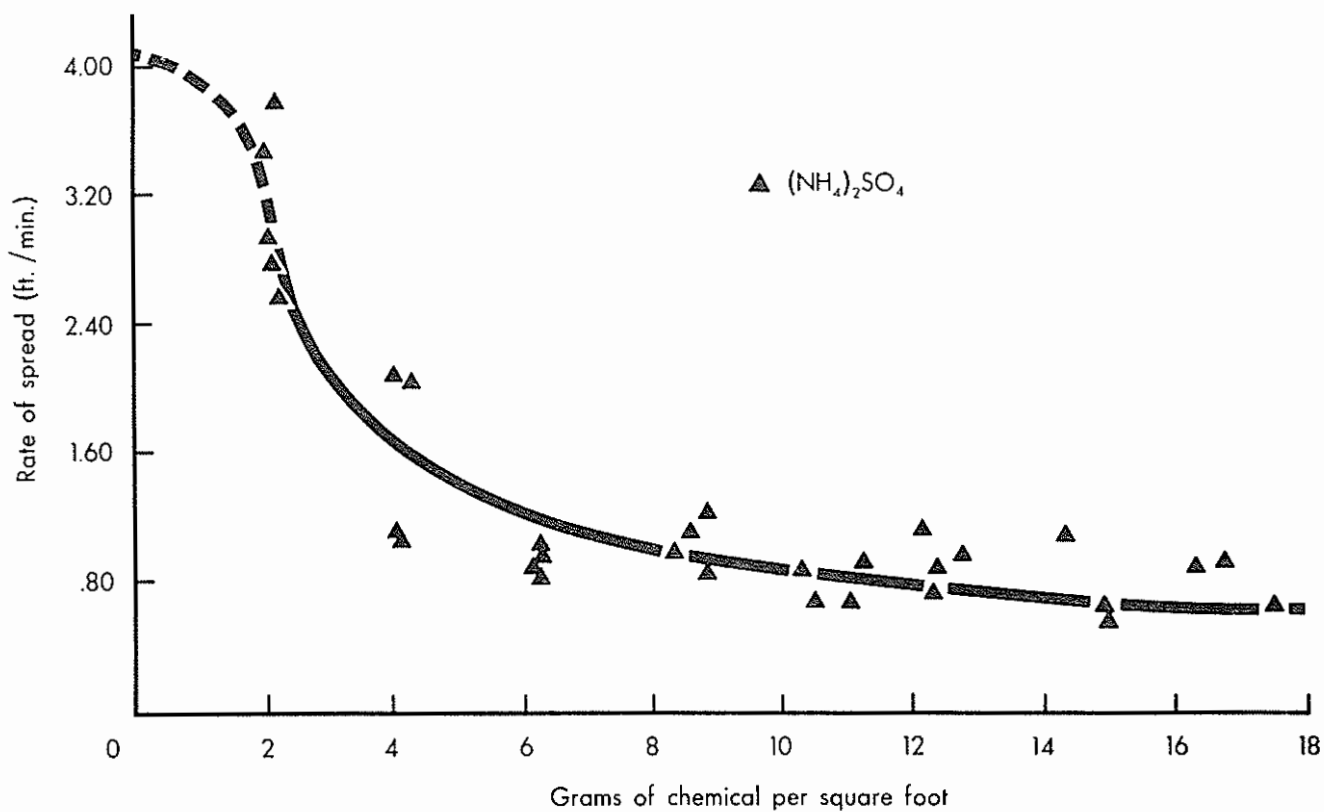
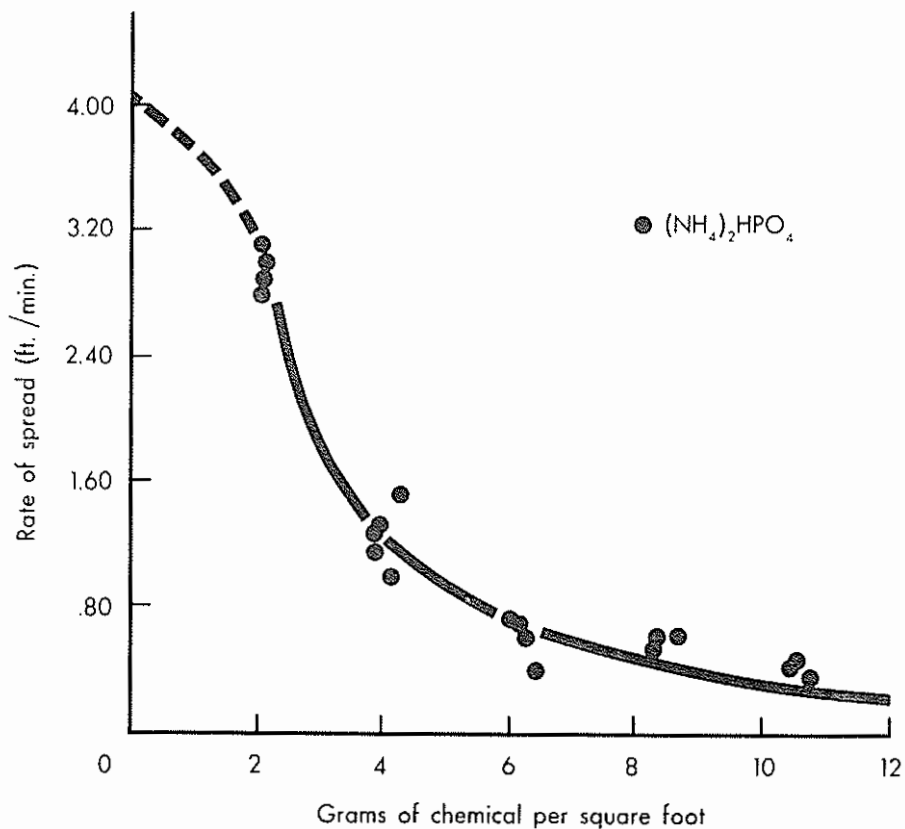


Figure 9.--Effect of $(\text{NH}_4)_2\text{SO}_4$ on the rate of spread in excelsior fuel.

Figure 10.--Effect of $(\text{NH}_4)_2\text{HPO}_4$ on the rate of weight loss or equivalent energy release rate in pine needle fuel.

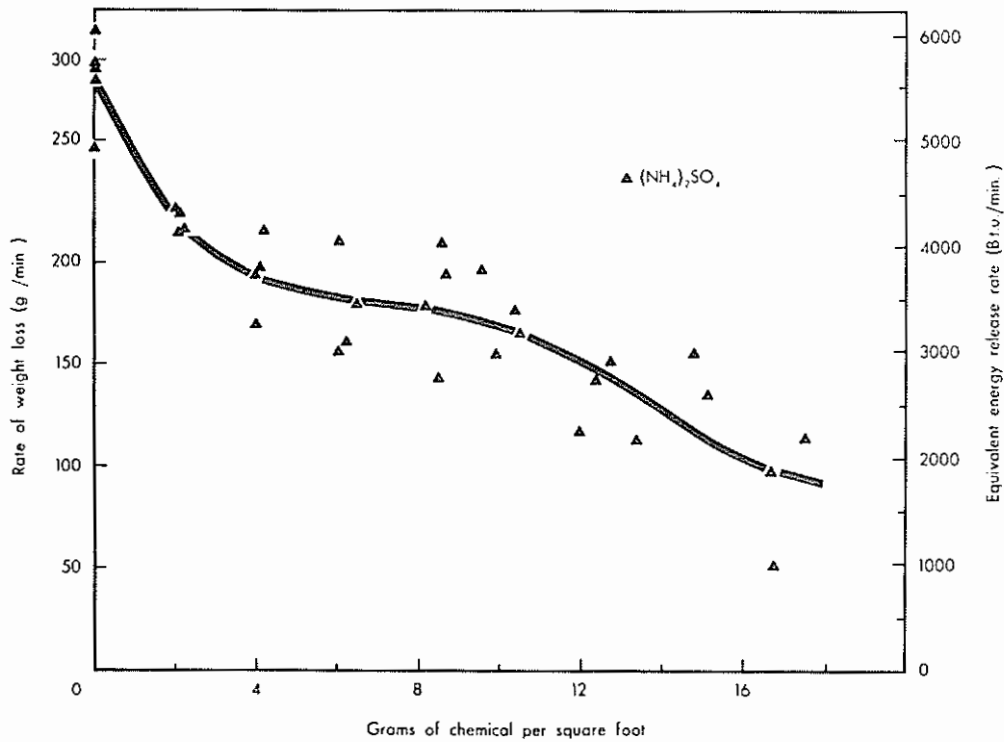
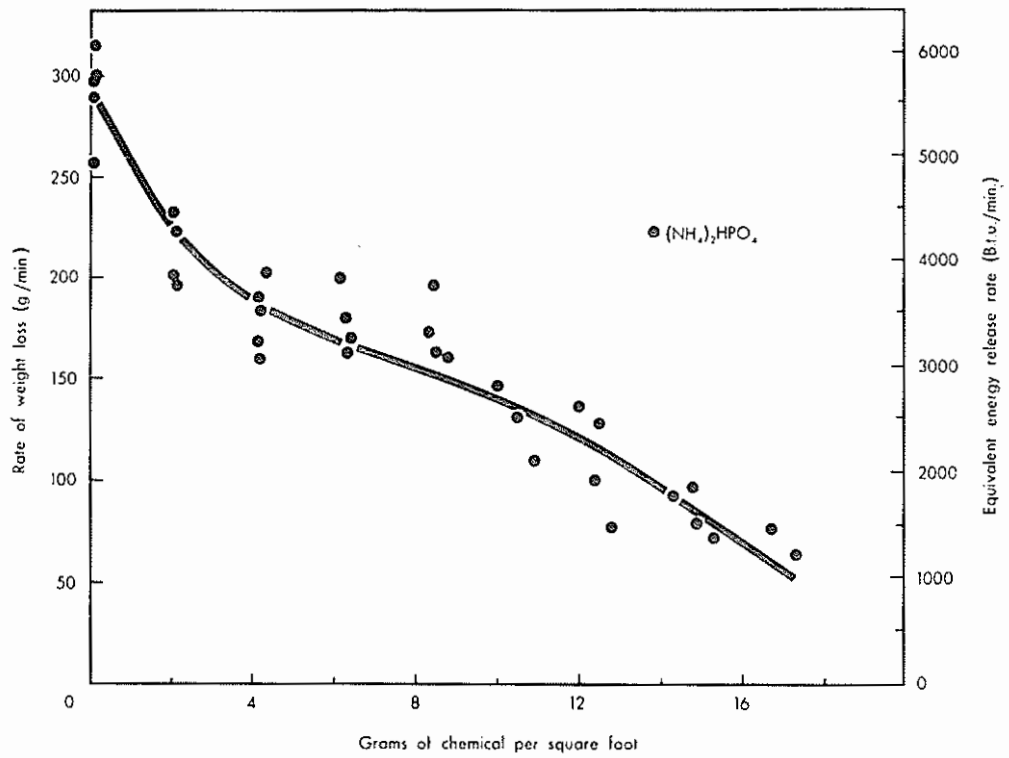


Figure 11.--Effect of $(\text{NH}_4)_2\text{SO}_4$ on the rate of weight loss or equivalent energy release rate in pine needle fuel.

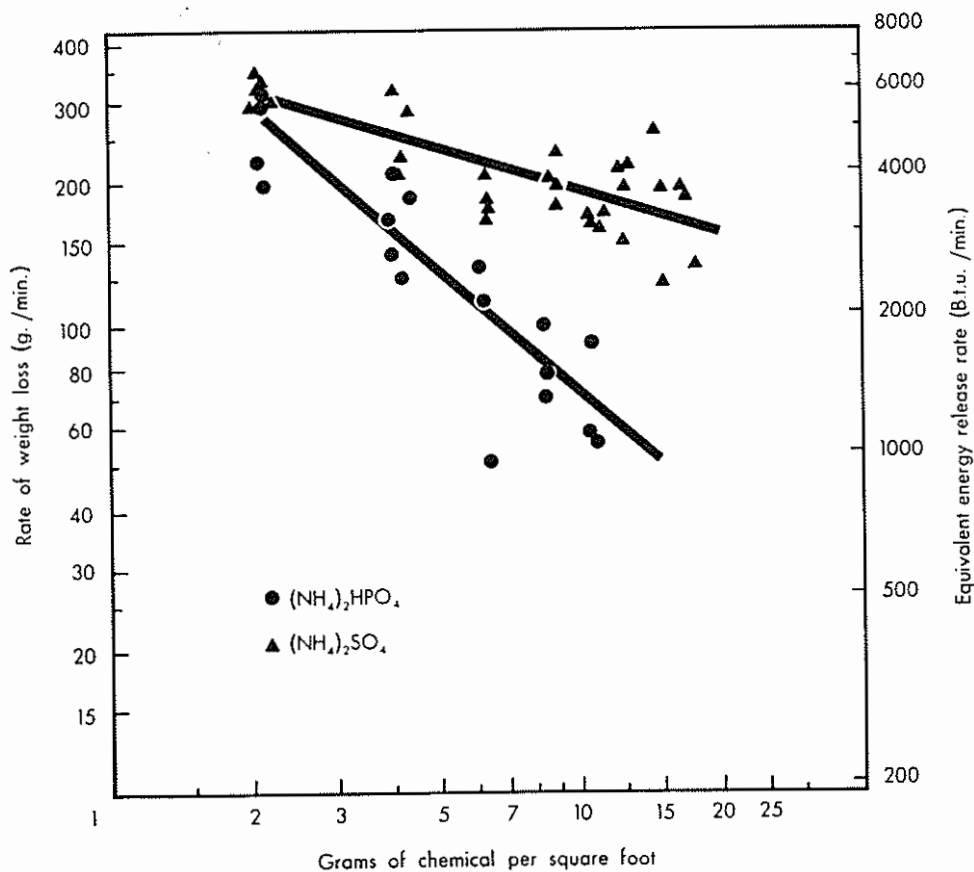


Figure 12.--Effect of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ on the rate of weight loss or equivalent energy release rate in excelsior fuel.

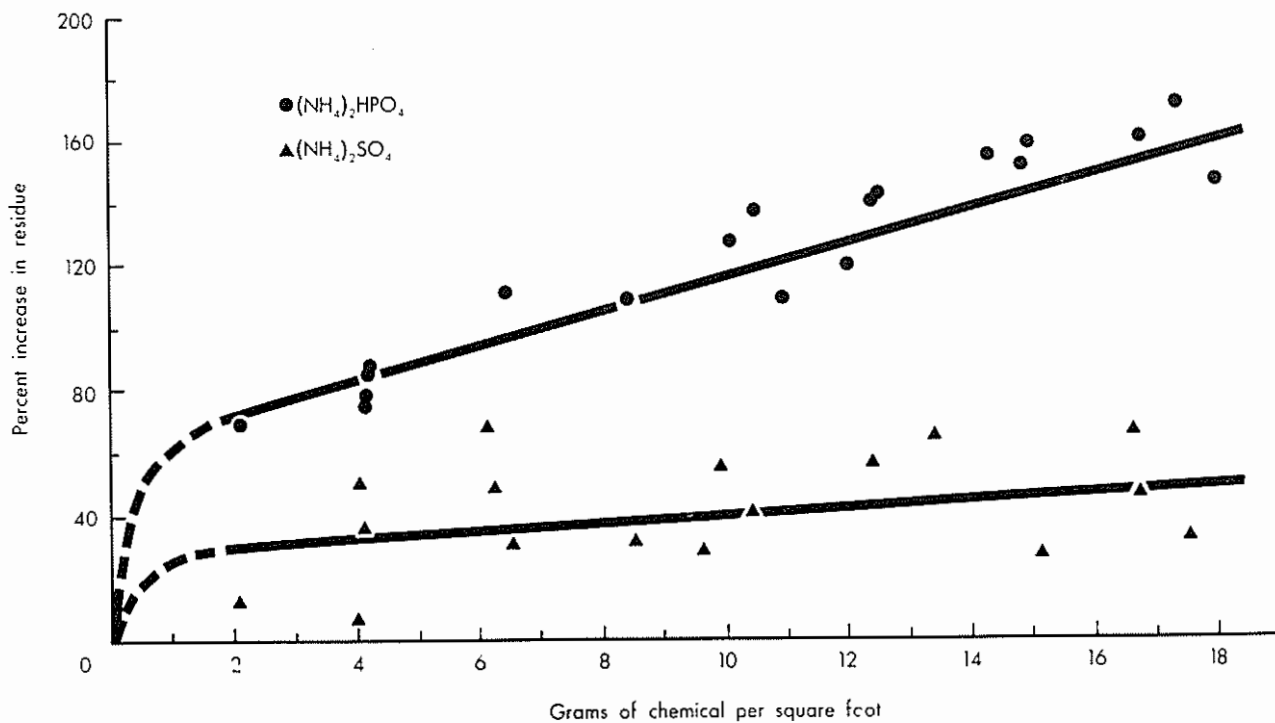


Figure 13.--Effect of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ on the residue in pine needle fuel.

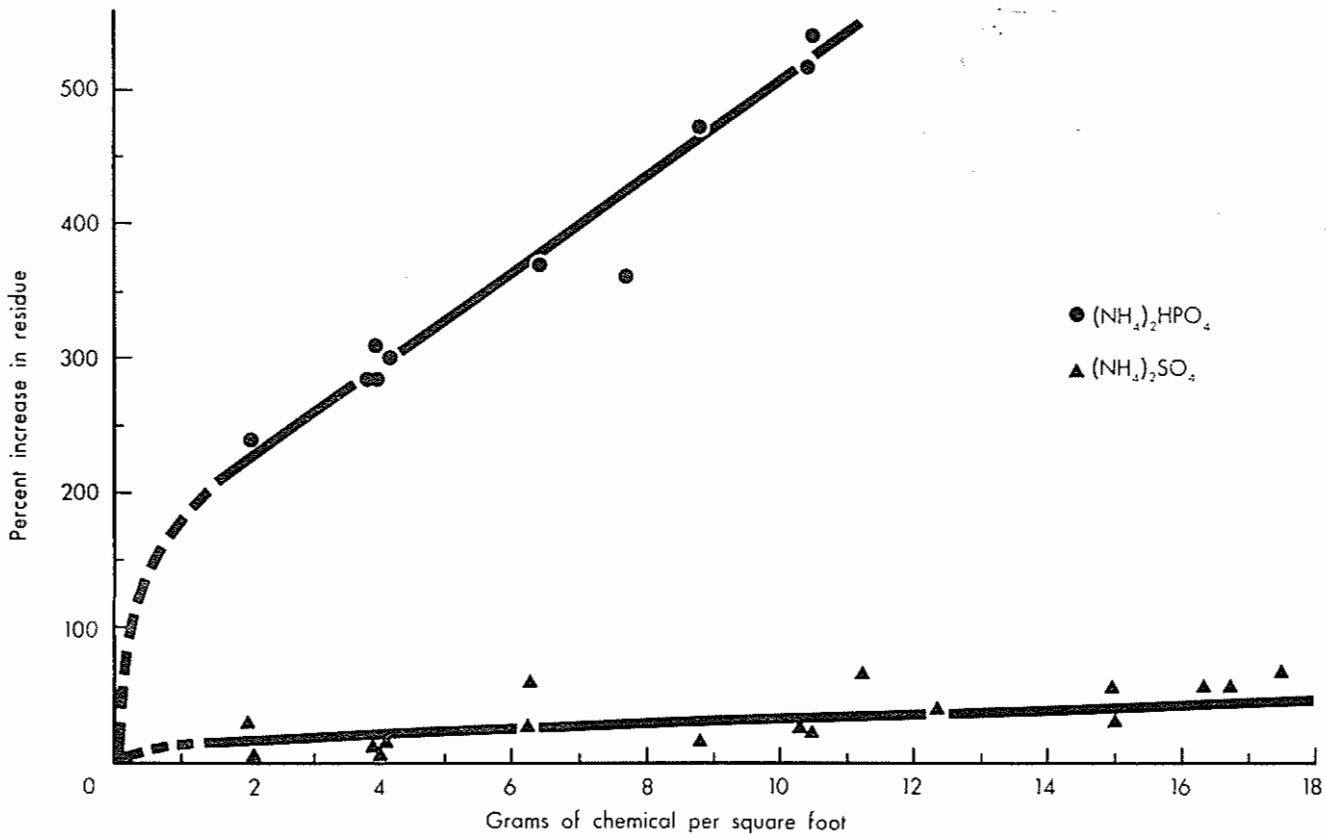


Figure 14.--Effect of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ on the residue in excelsior fuel.

Regression equations were determined for each relationship. The data for both chemical treatments of the same fuel type were then pooled and an analysis of covariance completed. A measure of how well each regression equation fits the sample data is shown by the coefficient of determination, r^2 . The r^2 for each relationship and the r^2 and the F (variance ratio) for the pooled data are given in table 3.

The statistical data indicate that for all parameters measured and for both ponderosa pine needle and aspen excelsior fuel, ammonium phosphate and ammonium sulfate have significantly different effects. The rate of spread in pine needles as a function of the amount of chemical, for both treatments, was the only dependent variable that was not significantly different at the 99 percent level (see table 3).

The regression equations in table 3 (also appendix tables 4 through 8) show that ammonium phosphate reduces the rate of fire spread and rate of weight loss (or equivalent energy release rate) to a greater degree than ammonium sulfate in both the excelsior and pine needle fuel beds. Ammonium phosphate also caused a greater increase in residue, thus decreasing the total energy released.

Ammonium phosphate is more effective than ammonium sulfate in reducing all parameters measured in the study; the largest difference occurs in the greater ability of ammonium phosphate to decrease the rate of weight loss or energy release rate and increase the amount of char or residue formed. Residue in pine needle fuel beds treated with ammonium phosphate showed an 80 to 160 percent increase over residue formed in untreated beds. Ammonium sulfate used under the same conditions did not increase the amount of residue beyond 50 percent. Excelsior fuel beds treated with ammonium phosphate showed an increase in residue of 200 to 500 percent, depending on the treatment level; ammonium sulfate increased the residue only about 50 percent. Figures 15 and 16 show the effects of ammonium sulfate and ammonium phosphate on the residue of combustion occurring in ponderosa pine needle and aspen excelsior fuel beds.

Parameter	Treatment	n	Equation	r ²	F (variance ratio) ^{1/}	Significance percent ^{2/}
<u>Ponderosa Pine needles</u>						
Rate of spread (R _S)	(NH ₄) ₂ HPO ₄ (DAP)	44	$y = 1.83 - 0.143(x) + 0.00289(x^2)$	.95		
	(NH ₄) ₂ SO ₄ (AS)	41	$y = 1.81 - 0.119(x) + 0.00184(x^2)$	.96		
	Pooled	85	$y = 1.82 - 0.131(x) + 0.00234(x^2)$	.95	3.15 (f = 3, 72)	95
Rate of weight loss (R _W)	(NH ₄) ₂ HPO ₄ (DAP)	43	$y = 292 - 43.7(x) + 5.98(x^2) - 0.399(x^3) + 0.00883(x^4)$	.94		
	(NH ₄) ₂ SO ₄ (AS)	40	$y = 294 - 48.7(x) + 8.05(x^2) - 0.583(x^3) + 0.0140(x^4)$	.91		
	Pooled	83	$y = 292 - 43.3(x) + 6.05(x^2) - 0.394(x^3) + 0.00848(x^4)$	.91	4.13 (f = 5, 73)	99
Residue (R)	(NH ₄) ₂ HPO ₄ (DAP)	19	$y = 50.4 + 6.06(x)$	.91		
	(NH ₄) ₂ SO ₄ (AS)	17	$y = 29.5 + 1.18(x)$	.11		
	Pooled	36	$y = 40.0 + 4.43(x)$	.20	165.4 (f = 2, 32)	99
<u>Aspen excelsior fuel beds</u>						
Rate of spread (R _S)	(NH ₄) ₂ HPO ₄ (DAP)	19	$y = -0.332 + 6.67(x^{-1})$	.97		
	(NH ₄) ₂ SO ₄ (AS)	31	$y = 0.330 + 5.50(x^{-1})$	.87		
	Pooled	50	$y = 0.147 + 5.68(x^{-1})$	.86	15.0 (f = 2, 46)	99
Rate of weight loss (R _W)	(NH ₄) ₂ HPO ₄ (DAP)	19	$\ln y = 6.19 - 0.841 \ln x$	.79		
	(NH ₄) ₂ SO ₄ (AS)	31	$\ln y = 5.95 - 0.295 \ln x$	.60		
	Pooled	50	$\ln y = 5.75 - 0.321 \ln x$	.21	46.7 (f = 2, 46)	99
Residue (R)	(NH ₄) ₂ HPO ₄ (DAP)	9	$y = 158 + 35.0x$	.99		
	(NH ₄) ₂ SO ₄ (AS)	17	$y = 7.32 + 2.81x$	.49		
	Pooled	26	$y = 189 - 4.73x$	.02	1726 (f = 2, 22)	99

^{1/} Test for the reduction in variance between the pooled and unpoled models.

^{2/} All regressions significant at the 5 percent level or better.

Table 3.--Regression equations for rate of spread, rate of weight loss, and residue

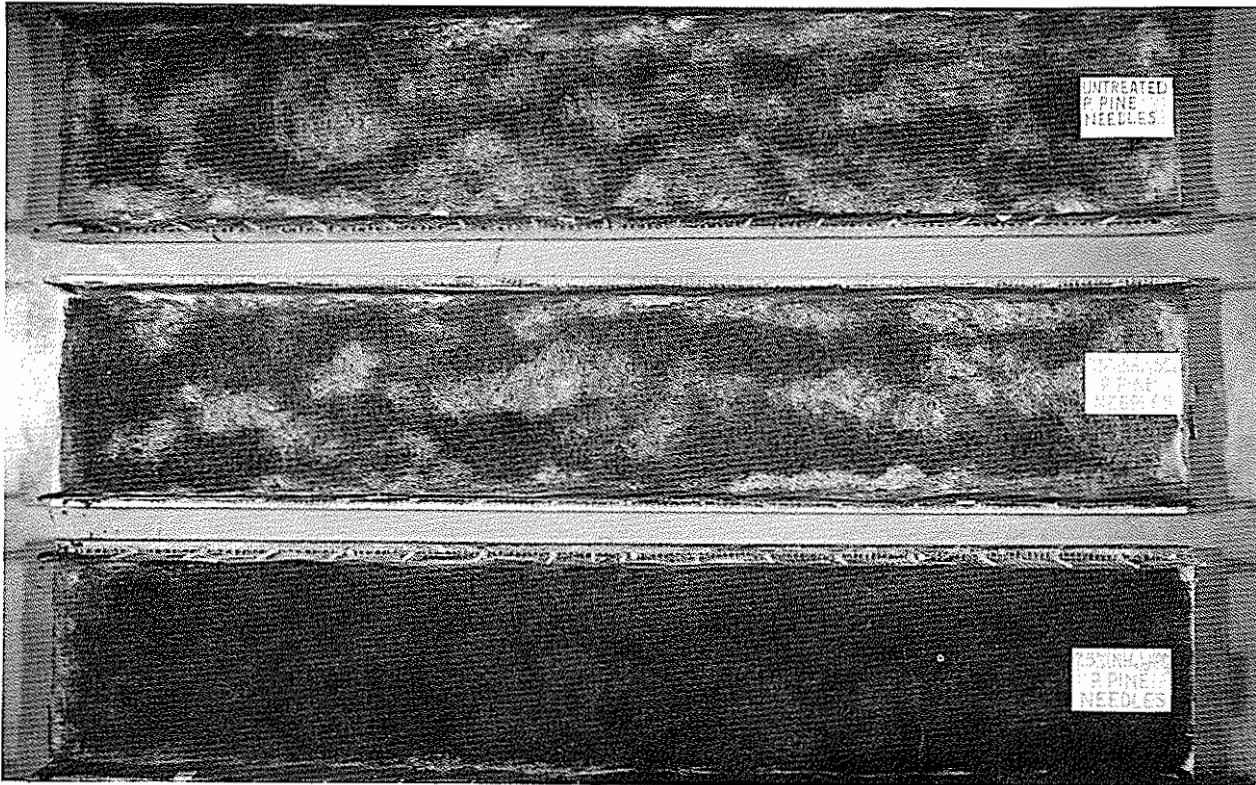


Figure 15.--Ponderosa pine residue for (top or bottom) untreated, 7.5 percent $(\text{NH}_4)_2\text{SO}_4$, and 7.5 percent $(\text{NH}_4)_2\text{HPO}_4$ treated fuel beds.

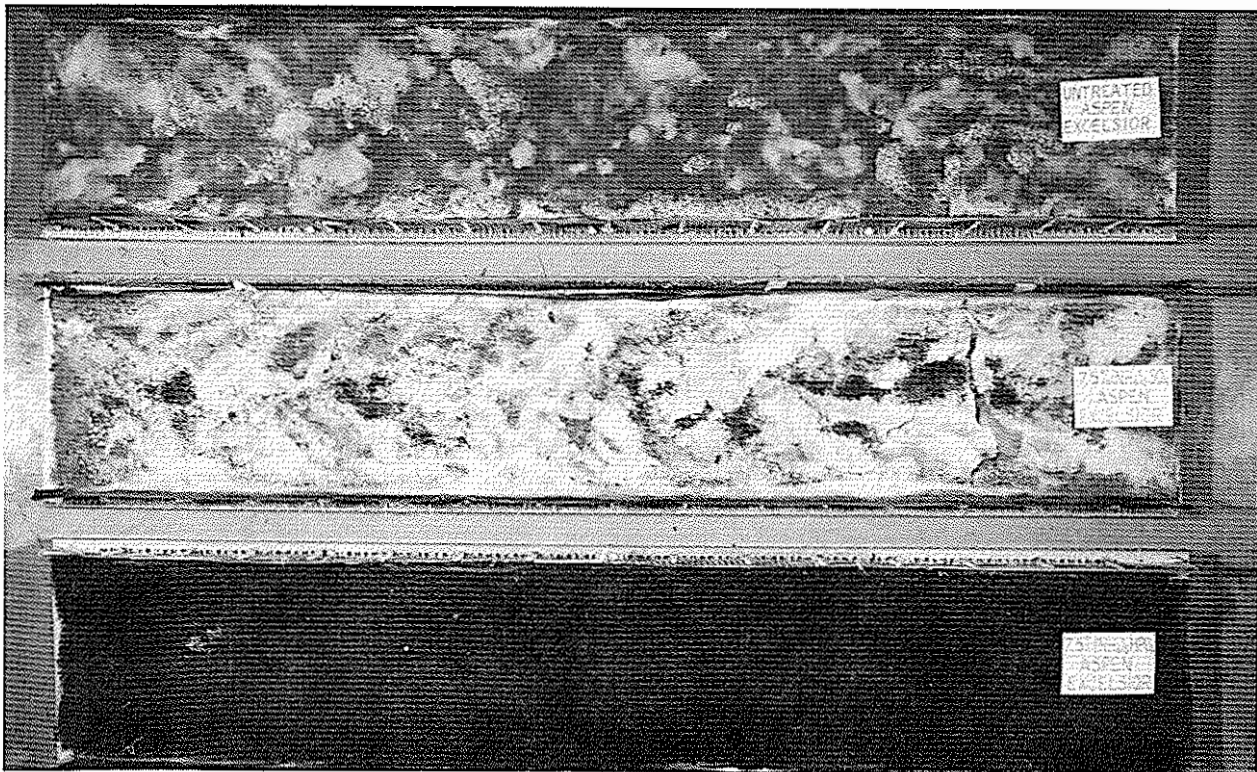


Figure 16.--Aspen excelsior residue for (top to bottom) untreated, 7.5 percent $(\text{NH}_4)_2\text{SO}_4$, and 7.5 percent $(\text{NH}_4)_2\text{HPO}_4$ treated fuel beds.

DISCUSSION

When attempting to characterize the effects of retardant chemicals on flammability, the measurement of three parameters provides a more complete picture than does the use of a single parameter. For example, the study has shown that chemicals can have similar effects on the rate of fire spread while having greatly different effects on the energy release rate and residue. Since retardant chemicals are used primarily to reduce both the combustion rate and the ability of the fire to propagate itself, it is necessary that these parameters be quantified to completely evaluate a retardant's effects on flammability.

For purposes of discussion, the effects a chemical has on flammability can be grouped under two primary considerations:

1. The effect the chemical has on flaming combustion, and
2. The effect the chemical has on glowing combustion.

Previous studies (George and Susott 1971) have indicated that the different effects ammonium phosphate and sulfate have on pyrolysis and combustion of cellulose are due to availability of the inorganic fraction involved in the reaction or to a different mechanism by which these chemicals alter pyrolysis and combustion. The results of this study indicate that although there are significant differences in the effects ammonium sulfate and phosphate have on flaming combustion, the differences in their effects on glowing combustion are much greater. It is theorized that the difference in the effects these chemicals have on glowing combustion is due to a difference in the availability of the inorganic fraction or retardant chemical. Figure 17 shows thermal decomposition curves for ammonium sulfate and ammonium phosphate.² The curves show that ammonium sulfate has completely decomposed by about 425° C. while ammonium phosphate decomposition is not complete until about 675° C. This suggests that by the time the fire has spread through an ammonium sulfate treated bed, and prior to the majority of the glowing combustion process, the ammonium sulfate may have decomposed. If this were true, the

²Figure 17 is taken from the paper by George and Susott (1971).

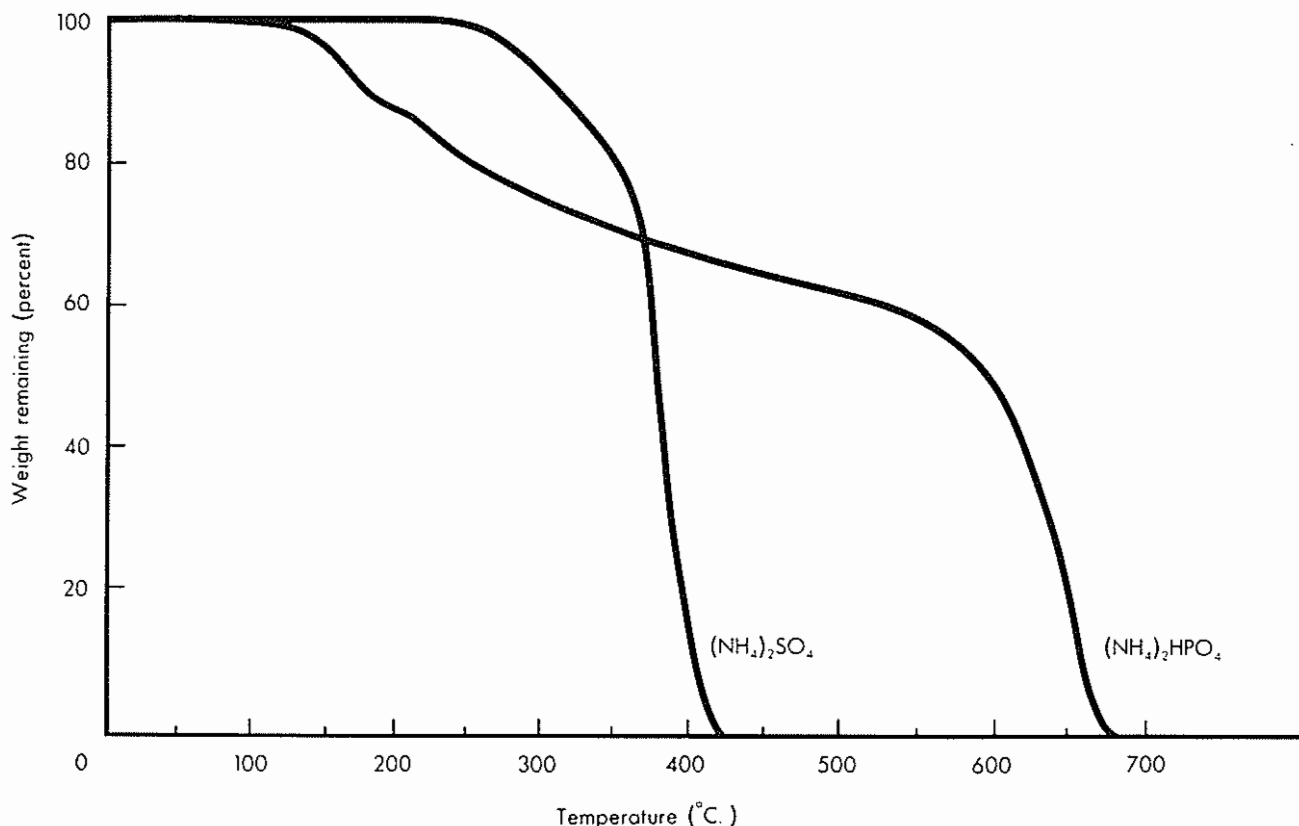


Figure 17.--Thermal decomposition curves for $(\text{NH}_4)_2\text{HPO}_4$ and $(\text{NH}_4)_2\text{SO}_4$ heated at 25°C./min. in a flow of 1 liter/min. air.

ammonium sulfate would affect the glowing combustion process very little. Ammonium phosphate, on the other hand, might still be present, altering glowing combustion as well as flaming combustion. This would explain why these two chemicals affect glowing combustion in different ways. This does not mean that the chemicals' effects are necessarily different because of physical degradation differences. The difference may be a chemical difference and still depend on the amount of chemical available to enter into the reaction.

Anderson (1969), using ponderosa pine needle fuel beds, similar to those of this study, found the average temperature within the combustion zone to be 867°C. Considering a reduction in these temperatures because of treatment and durational differences between temperatures measured in the combustion zone and those determined during thermal analysis, it is likely that most of the ammonium sulfate would decompose during passage of the flame front.

The effects other chemicals have on flammability can be evaluated by using the regression equations which quantify the effects of ammonium phosphate and sulfate on flammability. These relationships can be used as standards by which the effect of typical forest fire retardant additives such as thickening agents, coloring agents, and corrosion and spoilage inhibitors, can be judged.

These data can also provide the basis for linking some of the more basic pyrolysis and combustion data concerning the effects of fire retardant chemicals with actual controlled open combustion laboratory tests.

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APPENDIX

Table 4.--*Summary of test data for untreated ponderosa pine needle and aspen excelsior fuel beds*

Fire number	Rate of spread R_s (ft./min.)	Rate of weight loss R_w (g./min.)	Energy release rate E (B.t.u./min.)	Residue R (g.)
<u>Ponderosa pine needle fuel beds</u>				
1-PP	1.70	291	5,610	
2-PP	1.71	330	6,362	
3-PP	1.77	276	5,321	
4-PP	1.81	299	5,765	
5-PP	1.70	290	5,591	
6-PP	1.75	257	4,955	
7-PP	2.02	296	5,707	321
8-PP	1.85	290	5,591	295
9-PP	1.89	315	6,073	300
10-PP	1.92			315
11-PP	1.89	299	5,765	285
12-PP	1.68	290	5,591	
	$\bar{R}_s = 1.81$ $S_m = \pm 0.03$	$\bar{R}_w = 294$ $S_m = \pm 3.3$	$\bar{E} = 5,668$ $S_m = \pm 64$	$\bar{R} = 303$ $S_m = \pm 6.6$
<u>Aspen excelsior fuel beds</u>				
1-E	4.44	462	8,635	0
2-E	3.51	474	8,859	0
3-E	3.70	467	8,728	0
4-E	4.31	463	8,653	0
5-E	4.44	450	8,411	0
6-E	3.70	486	9,083	0
7-E	4.71	441	8,242	0
8-E	3.74	424	7,925	2
9-E	3.81	462	8,635	20
	$\bar{R}_s = 4.04$ $S_m = \pm 0.14$	$\bar{R}_w = 459$ $S_m = \pm 6.1$	$\bar{E} = 8,579$ $S_m = \pm 114$	$\bar{R} = 2$ $S_m = 0$

$\frac{1}{S_m}$ = standard error of the mean (S_m = standard deviation/ \sqrt{n} .)

Table 5.--Summary of test data for $(NH_4)_2HPO_4$ treated ponderosa pine needle fuel beds

Fire number	Treatment solution (chemical by weight) Percent	Chemical applied				Fire characteristics				Residue Percent increase over untreated
		Solution Grams	Anhydrous chemical Grams	Anhydrous chemical/ft. ² Grams/ft. ²	Dry fuel weight Percent	Rate of spread R_S (ft./min.)	Rate of weight loss R_W (g./min.)	Energy release rate E (B.t.u./min.)	Grams	
2.5 A	2.5	975	24.4	2.03	0.97	1.46	223	4,299		
2.5 B	2.5	965	24.1	2.01	0.96	1.68	233	4,492		
2.5 C	2.5	955	23.9	1.99	0.95	1.55	202	3,895		
2.5 D	2.5	1,000	25.0	2.08	0.99	1.70	196	3,779	510	70.0
5.0 A	5.0	1,035	51.8	4.31	2.05	1.53	205	3,952		
5.0 B	5.0	995	49.8	4.15	1.98	1.27	160	3,085	560	86.7
5.0 C	5.0	980	49.5	4.12	1.96	1.08	169	3,258	540	80.0
5.0 D	5.0	1,000	50.0	4.17	1.99	1.26	184	3,548	565	88.3
5.0 E	5.0	980	49.0	4.08	1.94	1.39	191	3,682	530	76.7
7.5 A	7.5	1,000	75.0	6.25	2.98	1.36	180	3,470		
7.5 B	7.5	1,010	75.8	6.31	3.00	1.21	164	3,162		
7.5 C	7.5	975	73.1	6.09	2.90	1.25	200	3,856		
7.5 D	7.5	1,025	76.9	6.41	3.05	0.93	170	3,278	635	112.0
10.0 A	10.0	1,020	102.0	8.50	4.05	0.82	163	3,143		
10.0 B	10.0	995	99.5	8.29	3.95	0.69	174	3,355		
10.0 C	10.0	1,055	105.5	8.79	4.19	0.75	161	3,104		
10.0 D	10.0	1,010	101.0	8.42	4.00	0.94	196	3,779	630	110.0
12.5 A	12.5	1,010	126.2	10.52	5.01	0.69	131	2,526		
12.5 B	12.5	965	120.5	10.05	4.79	0.70	147	2,834	685	128.3
12.5 C	12.5	1,050	131.2	10.94	5.21	0.43	111	2,140	630	110.0
12.5 D	12.5	1,005	125.6	10.47	4.99	0.33	79	1,523	685	128.3
15.0 A	15.0	1,025	153.8	12.81	6.10	0.28	77	1,485		
15.0 B	15.0	960	144.0	12.00	5.71	0.68	137	2,641	660	120.0
15.0 C	15.0	1,000	150.0	12.50	5.95	0.50	129	2,487	730	143.3
15.0 D	15.0	990	148.5	12.38	5.90	0.35	101	1,947	725	141.7
17.5 A	17.5	1,050	163.8	15.31	7.29	0.26	71	1,369		
17.5 B	17.5	980	171.5	14.29	6.80	0.37	94	1,812	770	156.7
17.5 C	17.5	1,015	177.5	14.80	7.05	0.39	97	1,870	760	153.3
17.5 D	17.5	1,025	179.4	14.94	7.11	0.38	79	1,523	779	159.7
20.0 A	20.0	1,005	201.0	16.75	7.98	0.33	76	1,465	785	161.7
20.0 B	20.0	1,038	207.6	17.30	8.24	0.24	63	1,215	809	169.7
20.0 C	20.0	1,081	216.2	18.02	8.58	0.29	97	1,870	742	147.3

Table 6.--Summary of test data for $(NH_4)_2SO_4$ treated ponderosa pine fuel beds

Fire number	Treatment solution (chemical by weight) Percent	Chemical applied				Fire characteristics				Residue	
		Anhydrous		Dry fuel		Rate spread R_s (ft./min.)	Rate of weight loss R_w (g./min.)	Energy release rate E (B.t.u./min.)	Grams over untreated	Percent increase	
		Solution Grams	chemical Grams/ft. ²	weight Percent	Grams/ft. ²						
2.5 A	2.5	1,050	26.3	2.19	1.04	1.52	217	4,184			
2.5 B	2.5	970	24.3	2.02	.96	1.50	228	4,396			
2.5 C	2.5	985	24.6	2.05	.98	1.52	225	4,338			
2.5 D	2.5	995	24.8	2.07	.99	1.76	217	4,184	340	13.3	
5.0 A	5.0	1,015	50.8	4.23	2.01	1.31	218	4,203			
5.0 B	5.0	986	49.3	4.11	1.96	1.18	198	3,817	410	36.7	
5.0 C	5.0	965	48.3	4.02	1.91	1.32	170	3,278	320	6.7	
5.0 D	5.0	968	48.4	4.03	1.92	1.68	196	3,779	450	50.0	
7.5 A	7.5	970	72.8	6.06	2.89	1.36	212	4,087			
7.5 B	7.5	980	73.5	6.13	2.92	1.05	158	3,046	505	68.3	
7.5 C	7.5	1,000	75.0	6.25	2.98	1.06	162	3,123	442	47.3	
7.5 D	7.5	1,045	78.4	6.53	3.11	1.22	160	3,470	391	30.3	
10.0 A	10.0	1,030	103.0	8.58	4.09	0.92	210	4,049			
10.0 B	10.0	985	98.5	8.21	3.91	0.90	179	3,451			
10.0 C	10.0	1,045	104.5	8.71	4.15	0.98	195	3,760			
10.0 D	10.0	1,025	102.5	8.54	4.07	1.03	143	2,757	395	31.7	
12.5 A	12.5	1,000	125.0	10.42	4.96	0.75	167	3,220			
12.5 B	12.5	953	119.1	9.93	4.73	0.72	156	3,008	465	55.0	
12.5 C	12.5	925	115.6	9.64	4.59	0.72	197	3,798	385	28.3	
12.5 D	12.5	1,005	125.6	10.47	4.99	0.90	165	3,181	422	40.7	
15.0 A	15.0	958	143.7	11.98	5.70	0.56	118	2,275			
15.0 B	15.0	1,020	153.0	12.75	6.07	0.52	151	2,911			
15.0 C	15.0	995	149.3	12.44	5.92	0.54	143	2,757	468	56.0	
17.5 A	17.5	1,020	178.5	14.88	7.09	0.56	156	3,008			
17.5 B	17.5	922	161.4	13.45	6.40	0.45	113	2,179	487	62.3	
17.5 C	17.5	1,039	181.8	15.15	7.21	0.45	135	2,603	381	27.0	
20.0 A	20.0	1,053	210.6	17.55	8.36	0.44	114	2,198	395	32.0	
20.0 B	20.0	1,000	200.0	16.67	7.94	0.38	98	1,889	490	63.3	
20.0 C	20.0	1,005	201.0	16.75	7.98	0.23	51	983	439	46.3	

Table 7.--Summary of test data for $(NH_4)_2HPO_4$ treated aspen excelsior fuel beds

Fire number	Treatment solution (chemical by weight) Percent	Chemical applied				Fire characteristics					Residue Percent increase over untreated
		Solution		Anhydrous chemical/ft. ³		Rate of spread R_g (ft./min.)	Rate of weight loss R_w (E./min.)	Energy release rate E (B.t.u./min.)	Grams		
		Grams	Percent	Grams	Grams/ft. ³						
2.5 A	2.5	1,000	25.0	2.08	1.48	3.01	200	3,738			
2.5 B	2.5	990	24.8	2.06	1.46	2.96	320	5,981			
2.5 C	2.5	970	24.3	2.02	1.43	3.12	225	4,205			
2.5 D	2.5	985	24.6	2.05	1.45	2.82	296	5,532	240	240	
5.0 A	5.0	1,030	51.5	4.29	3.04	1.51	188	3,514			
5.0 B	5.0	950	47.5	3.96	2.81	1.33	213	3,981	285	285	
5.0 C	5.0	990	49.5	4.12	2.92	1.01	126	2,355	300	300	
5.0 D	5.0	936	46.8	3.90	2.77	1.27	143	2,673	310	310	
5.0 E	5.0	917	45.9	3.82	2.71	1.16	170	3,177	285	285	
7.5 A	7.5	1,000	75.0	6.25	4.43	0.61	114	2,131			
7.5 B	7.5	980	73.5	6.13	4.35	0.70	114	2,131			
7.5 C	7.5	970	72.8	6.06	4.30	0.72	133	2,486			
7.5 D	7.5	1,025	76.9	6.40	4.54	0.39	51	953	370	370	
10.0 A	10.0	1,000	100.0	8.33	5.91	0.61	71	1,327			
10.0 B	10.0	995	99.5	8.29	5.88	0.53	102	1,906			
10.0 C	10.0	1,040	104.0	8.67	6.15	0.61	79	1,477			
10.0 D	10.0	1,055	105.5	8.79	6.23				470	470	
12.5 A	12.5	1,030	128.8	10.73	7.61	0.35	56	1,047			
12.5 B	12.5	1,010	126.3	10.52	7.46	0.46	92	1,719	540	540	
12.5 C	12.5	1,005	125.6	10.47	7.43	0.41	59	1,103	515	515	

Table 8.--Summary of test data for $(NH_4)_2SO_4$ treated aspen excelsior fuel beds

Fire number	Treatment solution (chemical by weight)		Chemical applied		Fire characteristics				Residue	
	Percent	Solution Grams	Anhydrous Grams	Anhydrous chemical/ft. ³ Grams/ft. ³	Dry fuel weight Percent	Rate of spread R_s (ft./min.)	Rate of weight loss R_w (g./min.)	Energy release rate E (B.t.u./min.)	Grams over untreated	Percent increase
2.5 A	2.5	995	24.9	2.07	1.47	3.78	340	6,355		
2.5 B	2.5	960	24.0	2.00	1.42	2.94	352	6,579		
2.5 C	2.5	940	23.5	1.96	1.39	3.48	296	5,532		
2.5 D	2.5	1,035	25.9	2.16	1.53	2.56	307	5,738	5	5
2.5 E	2.5	975	24.4	2.03	1.44	2.78	323	6,037	30	30
5.0 A	5.0	1,010	50.5	4.21	2.99	2.03	293	5,476		
5.0 B	5.0	985	49.3	4.10	2.91	1.04	233	4,355	15	15
5.0 C	5.0	950	47.5	3.96	2.81	2.08	321	5,999	10	10
5.0 D	5.0	970	48.5	4.04	2.87	1.10	222	4,149	5	5
7.5 A	7.5	995	74.6	6.22	4.41	1.02	211	3,944		
7.5 B	7.5	1,000	75.0	6.25	4.43	0.84	170	3,177	28	28
7.5 C	7.5	1,005	75.4	6.28	4.45	0.96	180	3,364	60	60
7.5 D	7.5	980	73.5	6.13	4.35	0.88	188	3,514		
10.0 A	10.0	1,060	106.0	8.83	6.25	0.84	182	3,402		
10.0 B	10.0	1,000	100.0	8.33	5.91	0.98	204	3,813		
10.0 C	10.0	1,030	103.0	8.58	6.09	1.10	219	4,093		
10.0 D	10.0	1,060	106.0	8.83	6.25	1.21	247	4,616	15	15
12.5 A	12.5	1,060	132.5	11.04	7.83	0.67	163	3,046		
12.5 B	12.5	1,080	135.0	11.25	7.98	0.90	177	3,308	65	65
12.5 C	12.5	990	123.8	10.31	7.31	0.87	175	3,271	25	25
12.5 D	12.5	1,008	126.0	10.50	7.45	0.67	167	3,121	22	22
15.0 A	15.0	985	147.8	12.31	7.31	0.72	152	2,841		
15.0 B	15.0	1,020	153.0	12.75	9.04	0.95	222	4,149		
15.0 C	15.0	970	145.5	12.13	8.60	1.11	218	4,074		
15.0 D	15.0	990	148.5	12.38	8.78	0.88	200	3,738	40	40
17.5 A	17.5	985	172.4	14.36	10.18	1.09	260	4,859		
17.5 B	17.5	1,028	179.9	14.99	10.63	0.55	125	2,336	28	28
17.5 C	17.5	1,026	179.6	14.96	10.61	0.62	199	3,719	56	56
20.0 A	20.0	1,050	210.0	17.50	12.41	0.62	135	2,523	65	65
20.0 B	20.0	1,005	201.0	16.75	11.88	0.92	190	3,551	57	57
20.0 C	20.0	980	195.0	16.33	11.58	0.88	200	3,738	55	55

Headquarters for the Intermountain Forest and
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State University)

Missoula, Montana (in cooperation with
University of Montana)

Moscow, Idaho (in cooperation with the
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