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REDUCING FIRE SPREAD IN WILDLAND FUELS

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ABSTRACT

Increased emphasis on aerial attack of forest fires has brought to prominence the question of how to assess the amount of retardant to be dropped on a fire. This study was undertaken to look at one aspect of the problem: Can the amount of retardant on the fuel be related to the fire's ability to propagate itself?

A laboratory study was established that utilized our large combustion facilities. The retardant effect upon the fuel was evaluated in terms of the reduction of the propagating heat flux of the fire.

Three fuels were used in the experimental fires: ponderosa pine needles, poplar excelsior, and ponderosa pine sticks cut to $\frac{1}{4}$ - and $\frac{1}{2}$ -inch cross-sectional dimensions. Two retardants were used: diammonium phosphate and ammonium sulfate. No thickeners were used. The fuels were uniformly coated and completely dried before burning. Tests were conducted both with and without wind.

A maximum useful concentration criteria was developed from this study and applied to 11 fuel models representing many of the fuel types found in this country. Predictions of the maximum useful concentrations varied from 0.67 gpc for western range grass to 13 gpc for heavy logging slash. These quantities indicate that under severe burning conditions retardant aircraft would be very effective against light fuel concentrations, but would have difficulty stopping fires in heavy fuels.

Results of this study are a partial answer to retardant use. Additional modeling efforts are needed to consider not only the effect of retardant on fire propagation, but also the effect of concentration gradients, fuel moisture, retardant moisture, and drying rate.

DISCLAIMER STATEMENT

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INTRODUCTION

The need for predicting the effects of flame retardants on fire behavior has been longstanding. The 1968 Fire Retardant Chemical Conference resolved that an estimate of retardant effectiveness should be incorporated into predictive fire models (USDA Forest Service 1968). This is a very difficult problem because of the many interacting phenomena associated with retardants, fuels, and fire spread. Consequently, most of the work done in retardant effectiveness has really been retardant evaluation--determining and quantifying the effectiveness of one retardant by using standardized tests and procedures to compare it with another (Truax 1939; Truax, Harrison, and Baechler 1956; Tyner 1941). More recent studies have developed sophisticated methods and equipment to evaluate procedures and classify retardant effectiveness (Dibble, Richards, and Steck 1961; Hardy, Rothermel, and Davis 1962; Johansen 1967; and George and Blakely 1972).^{1/} But, there was still no basis for assessing the amount of retardant that would be needed for varying fuel situations.

^{1/} Muraro, S.J. A laboratory evaluation of aeri ally applied forest fire retardants. Masters Thesis on file at Univ. of Mont., School of For., Missoula, Mont. 1960.

An intense study of aerial attack methods has been underway since 1970 (Honeywell Inc. 1973a and 1973b; USDA For. Serv. 1973; Couvalt 1973; and Aerospace Corp. 1973).^{2/},^{3/} This intensified effort made the need for a quantitative method for estimating retardant effectiveness even more urgent. Our study uses mathematical modeling techniques in a form that can be applied to a wide variety of fuel types to estimate the maximum useful retardant concentration that would be useful in preventing fire spread.

^{2/} George, Charles W. Fire retardant ground distribution patterns from the CL-215. USDA For. Serv. INT Res. Pap. (In preparation for publication). 1974.

^{3/} Anderson, Hal E. Forest fire retardant: transmission through a tree crown. USDA For. Serv. INT Res. Pap. (In preparation for publication). 1974.

MODELING CONCEPT

The effect of inorganic salts in fire retardants upon cellulosic fuels is brought about by altering the pathway of pyrolysis. In the presence of a retardant, the cellulose molecule decomposes to form more char and fewer flammable volatiles. The effect upon the fire is an overall reduction in the intensity of flaming combustion. Some retardants also inhibit the glowing combustion of char, thus further reducing the heat available from the fire. This directly influences the fire's ability to spread by reducing the heat available to propagate the fire.

The rate at which a fire will spread through a uniform fuel bed can be expressed as a ratio between the heat-flux-that-impinges-on-the-fuel and the heat-required-to-bring-the-fuel-to-ignition (Frandsen 1972). The total heat that impinges on the fuel, the propagating flux, is directly related to a fire's capacity to spread and is an excellent measure of retardant chemical effectiveness. It would be desirable to evaluate the retardant's effect on the overall heat-release rate or the reaction intensity of the fire. However, to do so experimentally would require a knowledge of three poorly understood phenomena: (1) The fractions of the mass-loss rate that produce flammable gases, char, and nonflammable products; (2) the heat available in the pyrolysis products; and (3) the relative importance of the convective and radiant heat transfer in propagating the fire.

In contrast, the propagating flux can be evaluated by a relatively simple rate-of-spread experiment and a calculation of the heat required for igniting the fuel. Rothermel (1972) demonstrated this method of evaluating the propagating flux:

$$(I_p)_0 = R_0 \rho_b \epsilon Q_{ig} \quad (1)$$

where:

$(I_p)_0$	= no-wind propagating flux	btu/ft ² -min
R_0	= no-wind rate of spread	ft/min
ρ_b	= fuel array bulk density	lb/ft ³
ϵ	= effective heating number	
Q_{ig}	= heat of preignition	btu/lb

To be useful in this study, the heat of preignition, Q_{ig} , to be used in equation (1) must be adjusted to account for the presence of retardant salts. Q_{ig} is composed of three terms: (1) Heat required to bring fuel moisture to vaporization temperature; (2) heat of vaporization moisture in the fuel; and (3) heat necessary to ignite the dry fuel.

Frandsen (1973) evaluated these terms:

$$Q_{ig} = M_f c_w (212 - T_a) + M_f Q_w + [c_0 + c_1 (T_{ig} + T_a)/2] (T_{ig} - T_a) \quad (2)$$

where:

M_f	= fractional fuel-moisture content related to its oven-dry mass	
c_w	= specific heat of water	Btu/lb/°F
c_0 and c_1	are components of oven-dry fuel specific heat	
T_{ig}	= ignition temperature	°F
T_a	= ambient temperature	°F
Q_w	= heat of water vaporization	Btu/lb

Retardants alter the heat of preignition by imposing additional moisture to be evaporated and by altering the pathway to pyrolysis (Philpot 1971). Any additional moisture can be included in equation (2), however there are no accepted procedures for assessing the pathway to pyrolysis. Many have studied the effect of inorganic salts on cellulose pyrolysis (Shafizadeh 1968) and the alterations caused in heat production by promoting char formation rather than the release of flammable gases. The effect of retardants upon the heat of preignition is to lower the ignition temperature. This is a peculiar property for a fire retardant, but nonetheless a real one. The specific heat of the material may also be altered, but this is not now known. For our study, we assume that the only effect of a retardant on the heat required for ignition is the lowering of ignition temperature.

A method of approximating the effect of retardant on ignition temperature was developed for this study. We defined a dimensionless ignition temperature as the measured ignition temperature rise above ambient, divided by the ignition temperature rise above ambient for an ideal fuel containing no minerals or retardant.

$$\theta_i = \frac{T_{ig} - T_a}{(T_{ig} - T_a)_{S_{(e+r)=0}}} \quad (3)$$

where:

T_{ig} = ignition temperature

T_a = ambient temperature

$S_{(e+r)=0}$ = subscript indicates the absence of effective natural mineral or any retardant.

The dimensionless ignition temperature, θ_i , was evaluated as a function of retardant concentration from thermogravimetric data taken by George and Susott (1971). We assumed that the ignition temperature decrease would be proportional to the lowering of the decomposition temperatures as shown on thermograms when retardant was present. This thermoanalysis was done on dry cellulose treated with either diammonium phosphate (DAP) or ammonium sulfate (AS), in the presence of air. Thermogravimetric analysis (TGA) is commonly used to assess the thermal behavior of materials. The rate at which a material volatilizes as the temperature is raised in a controlled environment is measured by dynamic TGA. A small sample (usually <1 g) is placed in the pan of an electronic balance suspended in a heated tube. As the system is heated, the weight loss of the sample is continuously recorded against temperature.

Data taken by George^{4/} on dry excelsior treated with either AS or DAP in a thermogravimetric analyzer were also nondimensionalized and included with the cellulose data. The relationship between the dimensionless ignition temperature, θ_i , and the retardant-salt concentration, including the effective mineral content of the fuel, $S_{(e+r)}$, was determined.

^{4/} Unpublished data on file at the Northern Forest Fire Laboratory, Missoula, Montana.

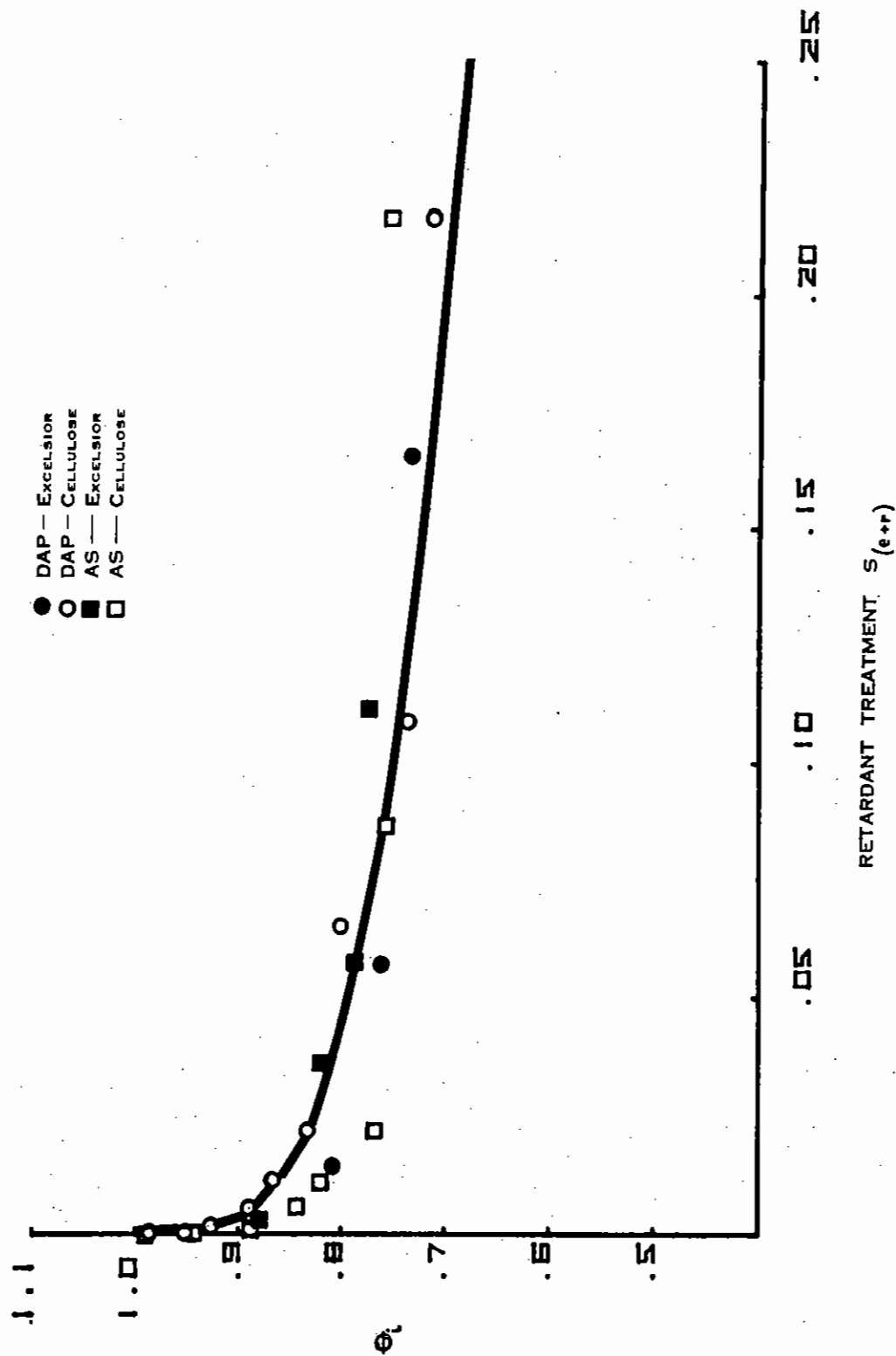


FIGURE 1.--EFFECT OF RETARDANT TREATMENT ON IGNITION TEMPERATURE.

A power function of the form,

$$\theta_i = 1 - 0.4567(S_{(e+r)})^{0.2655}, \quad (4)$$

was found to give a reasonable fit to the data (Fig. 1). The correlation coefficient was 0.855. Equations (3) and (4) were used to compute T_{ig} of equation (2) to account for the alteration of ignition temperature.

The propagating flux may be used to define a nondimensional parameter, η_r , which is the ratio of the propagating-flux-measured-from-retardant-treated-fuel to the propagating-flux-measured-from-untreated-fuel. After cancelling constant terms in equation (1), we obtain:

$$\eta_r = \frac{(RQ_{ig})_r}{(RQ_{ig})_{r=0}} \quad (5)$$

where, subscript r refers to retardant treated conditions. This new term may be used to evaluate retardant effectiveness from the experimental data. It may also be incorporated into fire spread models used to predict the reduction in spread rate that results from retardant application.

The rate-of-spread data needed to evaluate equation (5) are taken directly from fire spread experiments in identical fuel arrays with and without retardant.

METHODS

We built treated and untreated fuel beds, burned them in a controlled environment, and measured rate of spread for evaluation of equation (5).

Because reproducible fuel beds can be built from them, we used ponderosa pine needles, excelsior (shredded Populus spp. wood), and square ponderosa pine sticks (Schuette 1965; Anderson 1964; Rothermel and Hardy 1965)(Table 1). Our intent was to burn a wide variety of fuel configurations, and then determine if analytical efforts could resolve the results into a simple predictive model. If this could be done it would give confidence to our ability to apply the model to the wide variety of fuel configurations found in the field. If the important parameters such as fuel loading and particle size could be included, then an estimate of the effect of these parameters upon the amount of retardant required to suppress a wildland fire could be shown.

The needle and excelsior fuels were treated by controlled dipping into solutions of various concentrations of DAP or AS. The chemicals contained none of the thickeners, dyes, or corrosion inhibitors characteristic of operational retardants. Retardant treatment levels on the fuel ranged from about 0.5 to 18 percent dry weight for DAP and up to 23.5 percent for AS. Dipping the fuels assured an even distribution of retardant over all the fuel. This eliminates the problem of accounting for the effect of retardant concentration gradient on the experimental fires.

Table 1.--Physical properties of fuels.

Fuel type	Silica-free mineral content S_e	Gross fats* F_g	Surface area-to-volume ratio σ	Heat content H	Density ρ
	-----Percent dry weight-----		Ft^{-1}	BTU/lb	Lb/ft ³
Pine needles	1.6	8.12	1,741	8,754	36.0
Excelsior	.3	.00	1,843	7,830	24.7
Pine sticks ½-inch	.3	2.05	192	8,836	27.5
Pine sticks ¼-inch	.3	2.05	96	8,836	27.5

*This component of the fuel material includes all nonpyrolytic volatile organic compounds, such as waxes, oils, terpenes.

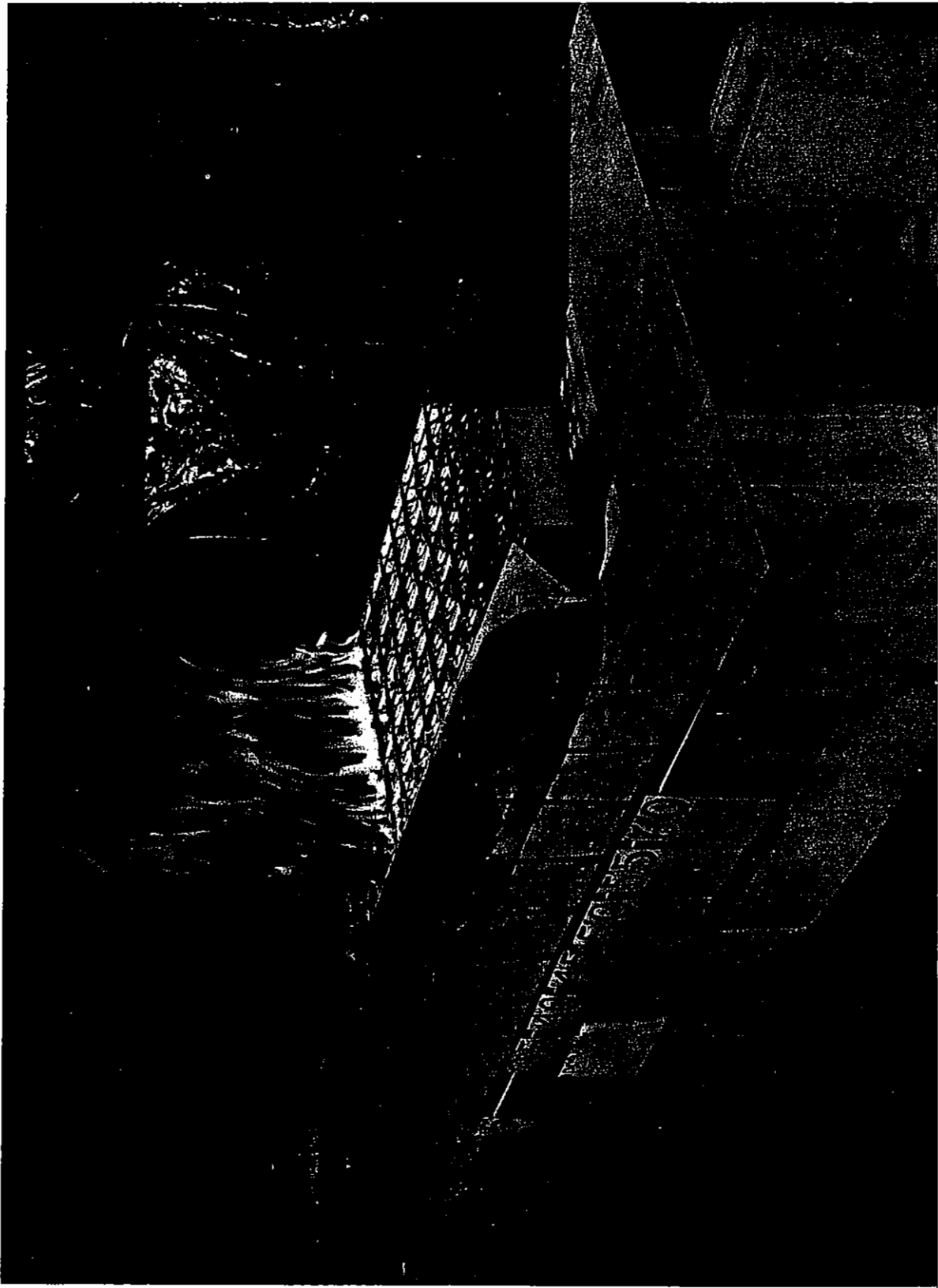


FIGURE 2.--CRIB FIRE (NO WIND).

The stick fuel beds (Fig. 2) were built using a "jig" arrangement and two kinds of glue--a water soluble glue that did not melt during the burning, and a hot glue that set up immediately upon cooling and did not dissolve when the cribs were dipped in the chemical solutions. The beds were submerged in retardant solutions for predetermined intervals. The length of the dipping time did not influence the retardant concentration on the fuel. The fuel treatment was varied by using different solution concentrations. The characteristics of the fuel beds are given in Table 2.

The fuel beds were allowed to dry to a nominal moisture content near 6 percent. Burning conditions were 18 to 27 percent relative humidity and 89° to 100°F. Just prior to ignition the fuels were subsampled for moisture and chemical treatment level. Moisture samples were taken from three different layers in the fuel beds. The sticks were sampled by cutting out small pieces. Xylene distillation was used for determining moisture content (Buck and Hughes 1939). Two independent visual measurements of the rate of spread were taken.

The chemical treatment level was determined by grinding subsamples of treated excelsior and pine needles to 20 to 40 mesh. DAP-treated samples were digested in ternary acid (4 perchloric, 1 sulfuric, and 10 nitric) and phosphorus was determined spectrophotometrically using ammonium molybdate. AS-treated samples were digested in sulfuric acid and ammonia was determined using standard nitrogen microkjeldahl analysis. The stick subsamples were digested without grinding.

Rate-of-spread data were determined under three wind conditions: 0, 2, and 5 mph. We concentrated on the no-wind condition to develop a retardant damping coefficient. A limited amount of wind-tunnel data were taken to test the computed coefficients η_r . The results of the no-wind and wind-tunnel tests are given in Tables 3 through 5 and shown in Figure 3. These data show the wide range of results retardants can have on rate of spread and that particle size is especially important.

RESULTS

The no-wind data (Fig. 3) for all fuels and all packing ratios were used to correlate the ratio of the nondimensional-propagating-flux, η_r , against the dry-retardant-salt-to-fuel ratio, S_r . To find a good correlation, it was necessary to account for the effect of fuel particle size. The small fuels have a much higher surface area-to-volume ratio. Hence for a given film thickness, the retardant will be more effective on the mass of the fine fuels. The problem may also be described by considering the heat absorbed by a fuel particle as it is brought to ignition. Small particles will have most of their mass raised in temperature by the time ignition occurs, whereas only the outer surface of larger fuels is so involved. Since we are considering the retardants' effect upon this ignition process, a method of accounting for the retardant treatment on the fuel involved in ignition is needed. Frandsen (1973) found a parameter which represents the fraction of the fuel involved in ignition. This parameter is a function of the surface area-to-volume ratio, σ , and is called the effective heating number:

$$\epsilon = e^{-138/\sigma}.$$

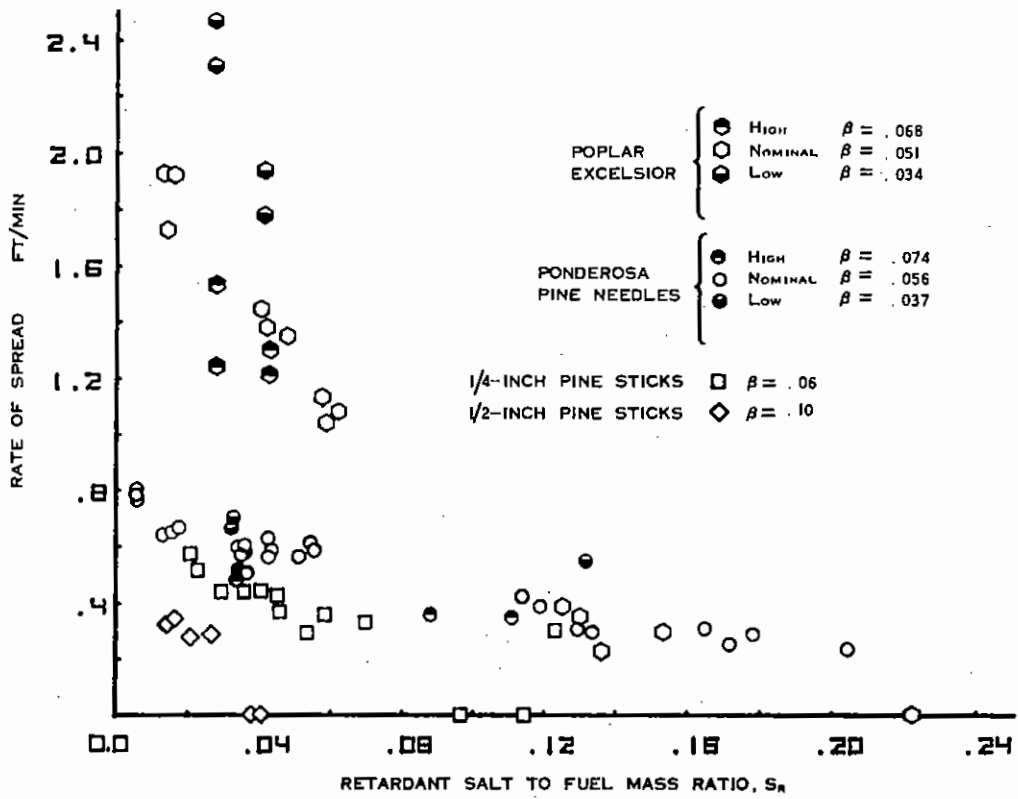


FIGURE 3.--(A) NO-WIND RATE-OF-SPREAD
RAW DATA FOR DAP TREATED FUELS.

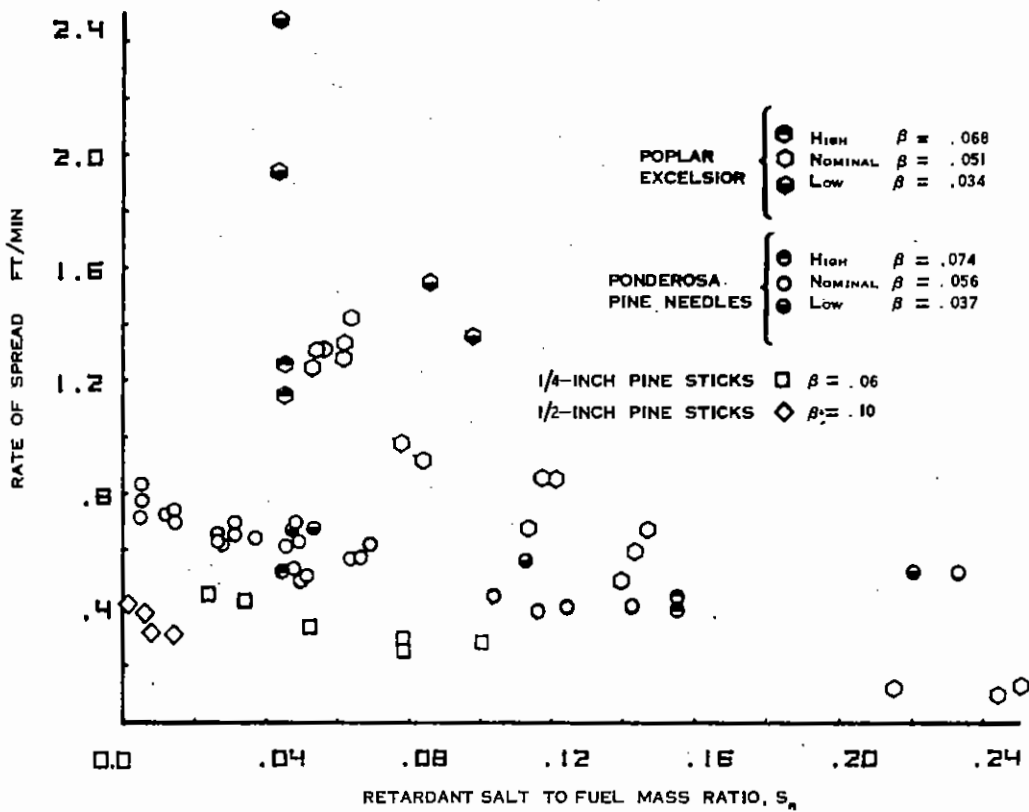


FIGURE 3.--(B) NO-WIND RATE-OF-SPREAD
RAW DATA FOR AS TREATED FUELS.

Table 2.--Characteristics of fuel beds.

Fuel type	Length	Width	Depth	Packing ratio	Loading
	-----Feet-----			β	<u>Lb/ft²</u>
Needles	8	1.5	0.2500	0.037	0.333
	8	1.5	.2500	.056	.500
	8	1.5	.2500	.074	.666
Excelsior	8	1.5	.2500	.034	.210
	8	1.5	.2500	.051	.315
	8	1.5	.2500	.068	.420
¼-inch sticks	5	1.5	.4375	.040	.457
	5	1.5	.4375	.060	.685
	5	1.5	.4375	.100	1.130
½-inch sticks	5	1.5	.5000	.060	.775
	5	1.5	.5000	.100	1.288

Table 3.--Results of fire experiments.

Retardant	Fuel	No wind				2-mph wind				5-mph wind			
		Packing ratio β	Fuel treatment S_T	Fuel moisture M_f	Rate of spread R	Packing ratio β	Fuel treatment S_T	Fuel moisture M_f	Rate of spread R	Packing ratio β	Fuel treatment S_T	Fuel moisture M_f	Rate of spread R
None	Ponderosa pine needles	0.037	--	0.057	0.930	--	--	--	--	0.037	--	0.052	3.489
		.056	--	.064	.813	0.056	--	0.055	1.356	.056	--	.054	3.150
		.074	--	.059	.703	--	--	--	--	.074	--	.054	2.348
None	Excelsior	.034	--	.036	2.124	--	--	--	--	.037	--	.042	6.300
		.051	--	.046	1.671	.051	--	.450	3.005	.051	--	.039	5.092
		.068	--	.038	1.432	--	--	--	--	.068	--	.400	5.596
None	1/4-inch sticks	--	--	--	--	--	--	--	--	--	--	--	--
		.060	--	.043	.624	.060	--	--	2.469	.040	--	--	.536
		--	--	--	--	--	--	--	--	.100	--	.040	3.372
None	1/4-inch sticks	.060	--	--	.311	--	--	--	--	--	--	--	--
		--	--	--	--	--	--	--	--	--	--	--	--
		.100	--	.060	.434	--	--	--	--	--	--	--	--

Values are fractions of oven-dry fuel weight.

The retardant damping coefficient, η_r , was correlated with the S_r normalized by the effective heating number. The results are shown in Figure 4 for all fuels and all packing ratios.

The data fell into two groups: One for the ponderosa pine needles, and one for the excelsior and pine sticks. The grouping is attributed to the difference in concentration of gross fats (waxes, terpenes, and oils)--8 percent in the pine needles, less than 0.5 percent in the excelsior, and 2 percent in the pine sticks. These are nonpyrolytic volatiles that are not expected to be affected by retardant salts.

Correlation between η_r and S_r/ϵ produces these equations:

$$\text{DAP} \quad \eta_r = 1 - (5.435 - 43F_g)(S_r/\epsilon)^{(1 - 5.5F_g)} \quad (6)$$

$$\text{AS} \quad \eta_r = 1 - (2.6 - 13.7F_g)(S_r/\epsilon)^{(0.69 - 2.5F_g)} \quad (7)$$

where:

F_g = ratio of gross-fat-weight to oven-dry-fuel-weight.

Equations (6) and (7) contain the important features sought that will enable the effect of the retardant on wildland fuels to be quantified. The effect of retardant-salt to fuel-mass is encompassed in the S_r parameter; the effect of fuel particle size is accounted for by ϵ ; the effect of gross fats is accounted for by F_g . By itself, η_r quantifies the reduction in propagating flux caused by the retardant. If a more detailed examination of rate of spread is needed, equation (5) can be utilized to substitute η_r directly into Rothermel's fire spread equation (1972):

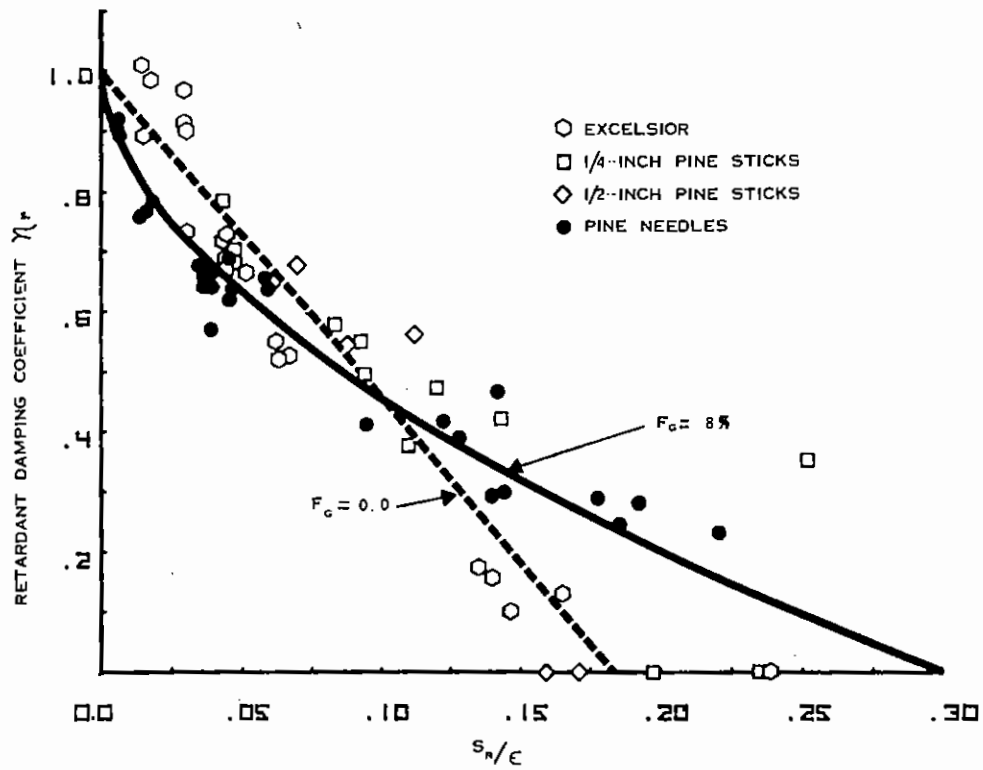


FIGURE 4.--(A) CORRELATION OF RETARDANT DAMPING COEFFICIENT WITH EFFECTIVE RETARDANT TREATMENT FOR DAP.

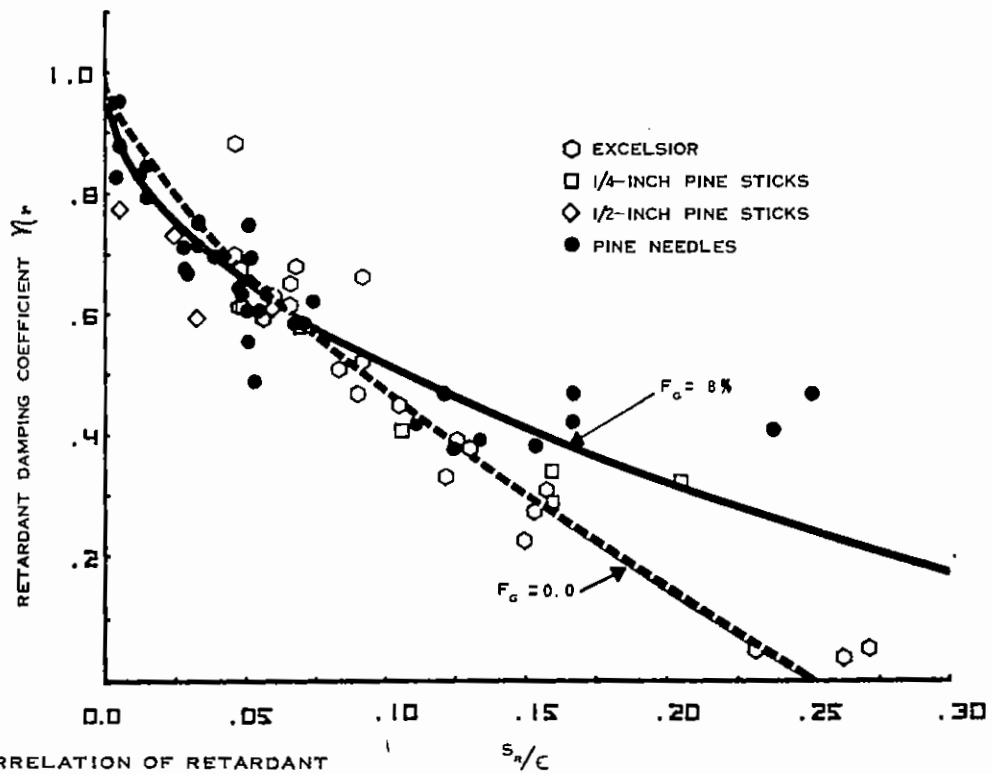


FIGURE 4.--(B) CORRELATION OF RETARDANT DAMPING COEFFICIENT WITH EFFECTIVE RETARDANT TREATMENT FOR AS.

$$R_r = \frac{\Gamma_w \rho_o h \eta_m \eta_s \eta_r \xi}{\rho_b \epsilon (Q_{ig})_r} \quad (8)$$

The extent to which equation (8) is applicable in wildland fuels has not been determined. It is expected to give a first approximation of the rate of spread for the no-wind condition in fuels that have previously been used with the fire spread model. Additional inputs needed are the retardant-to-fuel concentration and the amount of gross fats in the fuel.

Fewer burns were made in the presence of wind. If the ratio of rate-of-spread-with-retardant to rate-of-spread-without-retardant were the same in the presence of wind as it was in the absence of wind, then equations (6) and (7) would apply in both cases. Measured values did not correlate well with the predicted values except for the needles and DAP (Fig. 5).

Although equations (6) and (7) may not be useful for predicting actual rate-of-spread-values versus retardant-concentration, they appear to be useful for predicting the maximum useful concentration (MUC). To test this concept, the results of similar tests (George and Blakely 1972) were used. They also used ponderosa pine needles and excelsior for fuel and DAP and AS for retardant, but their retardant was mixed with standard thickening agents and sprayed over the top of the fuel beds to simulate retardant applied in the field. All tests were conducted in a 5 mph wind. Since the retardant was applied from above, a vertical concentration gradient would be expected with more retardant on the upper fuel than near the bottom.

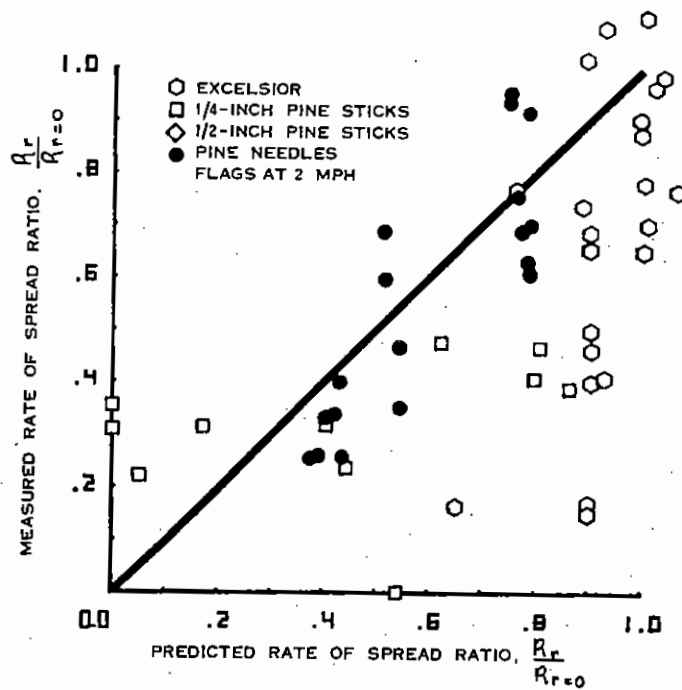


FIGURE 5.--(A) RATE OF SPREAD WITH 5 AND 2 MPH WIND COMPARED WITH PREDICTION BASED ON NO-WIND DATA, DAP.

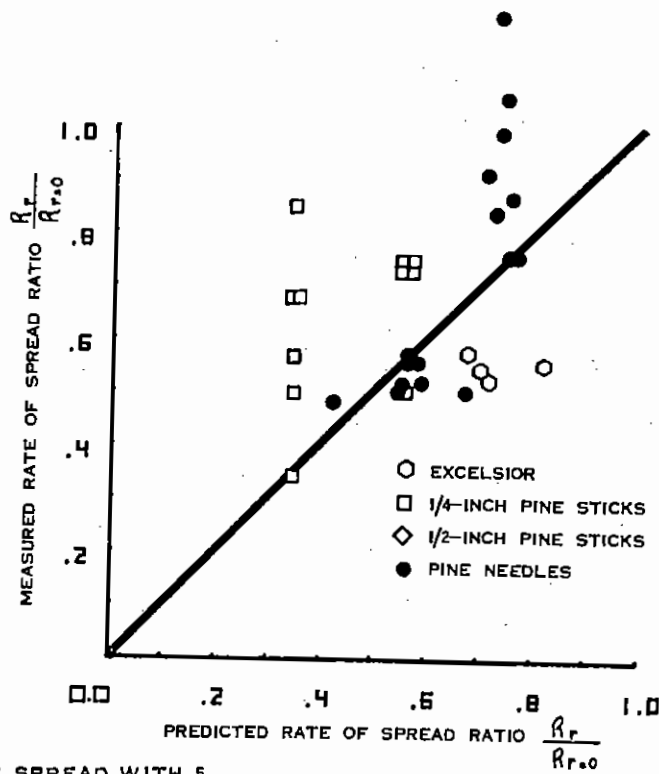
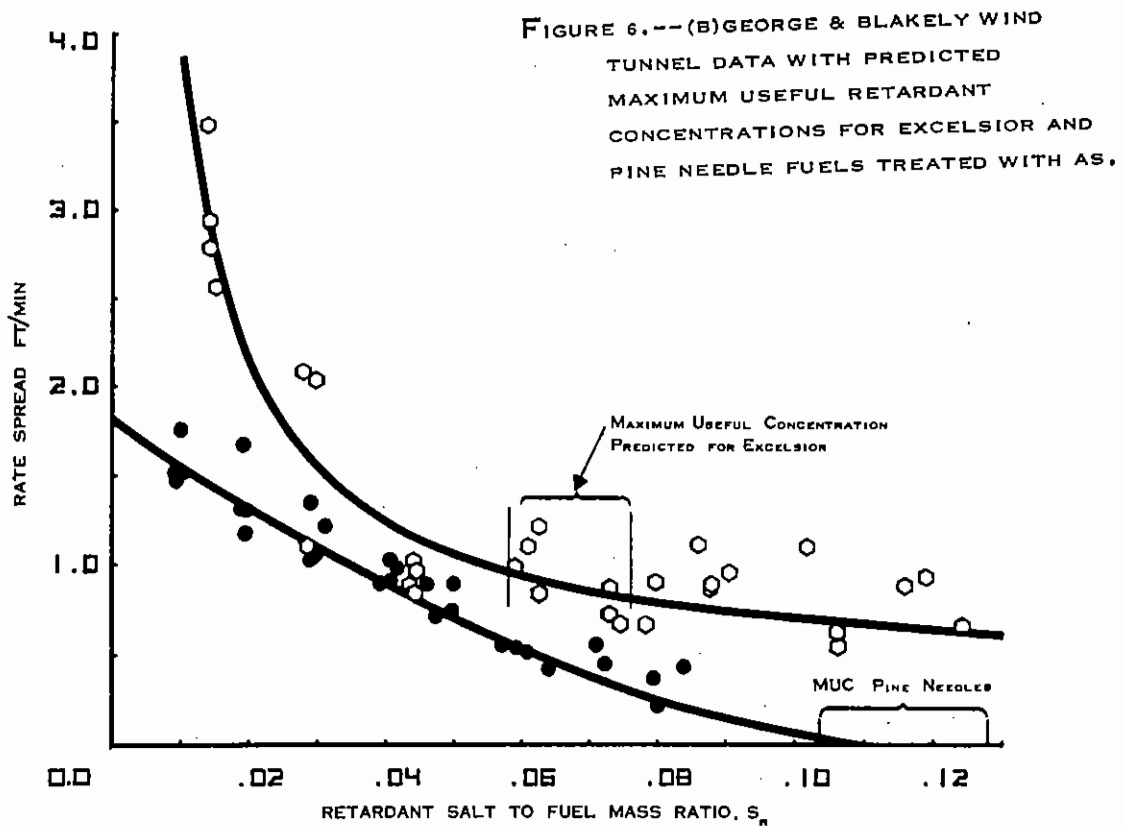
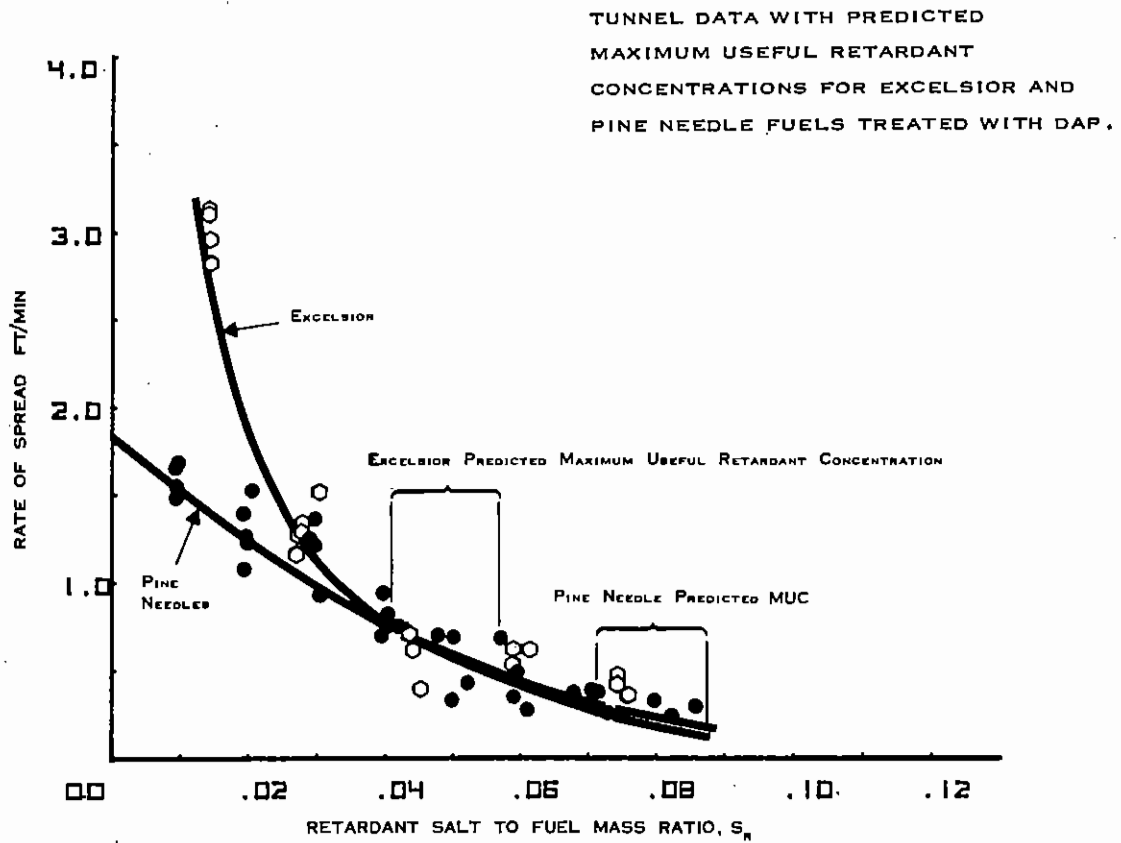


FIGURE 5.--(B) RATE OF SPREAD WITH 5 AND 2 MPH WIND COMPARED WITH PREDICTION BASED ON NO-WIND DATA, AS.

To check the extinction, or nonspread condition, equations (6) and (7) were set equal to zero and solved for S_r . Since the fire in litter fuels with high packing ratios burns through the upper strata of fuel where the retardant concentration is heaviest, we assumed that the fuel involved in the fire was one-fourth to one-third of the total fuel. The retardant-concentration range for nonspread is shown with George and Blakely data in Figure 6. The predictions are consistent with the behavior of the fire in the experiments. When concentration levels became too high on the upper surface fuels, the fire crept through the lower level with an almost constant rate of spread. This condition is apparent in the excelsior data where a knee appears in the curve that appears to mark the transition between surface burning and subsurface burning. The concentration gradient caused by tightly packed litter fuel beds would probably prevent the retardant from being effective at lower levels, even with extremely high application levels. To prevent spread beneath the surface requires some other method of fire inhibition such as high moisture levels or a fuel discontinuity.

The results indicate that equations (6) and (7) can be used to predict a maximum useful concentration of retardant over a wide range of fuel conditions. This concept was checked by developing an equation for the amount of applied retardant in gallons per 100 ft² necessary to achieve the desired value of S_r for a given fuel complex. Since commercial retardants are mixed with varying quantities of salt per gallon, this consideration is included.



Retardant-to-fuel concentration can be calculated in terms of initial conditions:

$$S_r = \frac{(S_{pg})(gpc)}{w_o 100} \quad (9)$$

where:

S_{pg} = retardant salt per gallon

gpc = gallons per 100 ft²

w_o = dry fuel loading lb/ft²

To solve for the value of S_r at η_r equal to zero in equations (6) and (7) requires a value for F_g . Typical values of F_g are:

Aspen excelsior	0.0 percent
Larch wood	.6 percent
Douglas-fir punky wood	3.3 percent
Chamise stems	2.2 percent
Chamise foliage	5.1 percent
Ponderosa pine needles, dead	8.2 percent
Douglas-fir needles, live	8.5 percent
Aspen foliage	11.6 percent.

A nominal value for F_g of 5 percent was selected to illustrate the effect of fuel loading.

For DAP at $\eta_r = 0$ and $F_g = 0.05$, equation (6) predicts a value of $S_r = 0.194\epsilon$. (10)

For AS at $\eta_r = 0$ and $F_g = 0.05$, equation (7) predicts a value of $S_r = 0.317\epsilon$. (11)

These formulations of S_r represented the maximum useful ratio of retardant-salt-to-fuel for any fuel size. To apply this to actual retardant, it is necessary to account for the amount of retardant salt per gallon of mixed slurry. Two widely used commercial retardants are Phos Check, which uses DAP at a concentration of 0.94 lb/gal, and Fire Trol, which uses AS at a concentration of 1.47 lb/gal. Substituting these values and equations (10) and (11) into equation (9) produces formulations for predicting the maximum useful concentration delivered on the fuel:

$$(\text{gpc})_{\text{MUC}} = 20.6 w_o \epsilon \quad \text{Phos Check} \quad (12)$$

$$(\text{gpc})_{\text{MUC}} = 21.6 w_o \epsilon \quad \text{Fire Trol} \quad (13)$$

A mean value of the maximum useful concentration for inhibiting propagating flux and hence rate of spread is:

$$(\text{gpc})_{\text{MUC}} = 21 w_o \epsilon \quad (14)$$

The similarity of the constants in equations (12) and (13) is due to the higher concentration of retardant salt in Fire Trol. This does not imply that the overall effectiveness of the two retardants is the same. Their thickening materials are quite different--one a gum, the other a clay. Hence, the free-fall droplet size and fuel-coating characteristics are different. There is also a considerable difference in the residue and smoke production (Philpot and others 1972).

To calculate the maximum useful concentration of delivered slurry with equation (14), fuel loading by particle size is needed. Fuel loading by particle size for a number of fuel models is given in Table 1 of Rothermel's "A Mathematical Model for Predicting Fire Spread in Wildland Fuels" (1972). For this exercise the only retarding effect is attributed to the retardant salt; the slurry moisture is assumed to have evaporated; and the fuel moisture is assumed to be a constant low value. The retardant required for three size classes of dead fuel and the fine-live fuel is shown along with the sum for all size classes (Table 6). No adjustment is made for concentration gradients. The fuel is assumed to be evenly coated. The results range from 0.69 gpc for short grass, to 10 gpc for chaparral, to 13 gpc for heavy logging slash. It should be reemphasized that we neglect the damping effect of both fuel moisture greater than a nominal value of ~6 percent, and we have not accounted for retardant slurry moisture. The condition is not entirely unrealistic because Rothermel and Hardy (1965) showed that slurry moisture can quickly evaporate under severe fire conditions. If taken as realistic worst-case values under severe burning conditions, it is not surprising that retardant aircraft have difficulty controlling fires in such fuels as heavy logging slash and thick chaparral. Retardant aircraft can produce large areas of 2 gpc, but the areas of 4 gpc or more are relatively small.^{5/} To achieve the necessary concentrations would require more than one drop on the same target fuels.

^{5/} George, Charles W., Op.cit.

Table 6.--Maximum useful retardant concentration

Fuel	Fuel loading <3-inch diameter	Total gpc
	<u>Tons/acre</u>	
Short grass	0.75	0.69
Tall grass	3.00	2.60
Brush	3.50	1.80
Chaparral	16.00	10.00
Timber, Grass & Understory	4.00	2.60
Timber litter	5.00	1.60
Timber litter & Understory	12.00	5.00
Hardwood litter	3.50	2.80
Logging slash, light	7.60	2.60
Logging slash, medium	34.50	7.50
Logging slash, heavy	58.00	13.00

CONCLUSIONS

The ability of fire retardants to prevent fire spread can be related to the reduction of the fire's propagating flux. This reduction was formulated into a nondimensional retardant-damping coefficient. In the absence of wind the retardant-damping coefficient is related to the ratio of the mass-of-retardant-salt to the mass-of-fuel, the size of the fuel particle, and the gross fat content of the fuel.

In the presence of wind, the retardant-damping coefficient does not accurately model rate-of-spread reduction for all fuels, but does not conflict with the concept of a maximum useful retardant concentration.

For fully dry retardant and low moisture content fuel, the maximum useful retardant concentration can vary from 0.6 gallons per 100 square feet for arid western grass to 13 gallons per 100 square feet for heavy logging slash.

To completely define retardant effectiveness, the effects of retardant moisture, fuel moisture, concentration gradient, and drying time should be included in the calculation of the extinction condition.

LITERATURE CITED

1. Aerospace Corporation
1973. Aerial delivery systems program, final report. INT Grant No. 4, El Segundo, Calif.
2. Anderson, Hal E.
1964. Mechanisms of fire spread, research progress report No. 1. U.S. For. Serv. Res. Pap. INT-8, 20 p., illus.
3. Buck, C.C., and J.E. Hughes
1939. The solvent distillation method for determining the moisture content of forest litter. J. For. 38(8): 645-65.
4. Covault, Craig
1973. C-130 adapted for fire fighting. Aviat. Week & Space Technol. March, 3 p., illus.
5. Dibble, D.L., S.S. Richard, and L.V. Steck
1961. Testing and evaluating chemical fire retardants in the laboratory. U.S. For. Serv. PSW Misc. Pap. 59.
6. Frandsen, William H.
1973. Effective heating of fuel ahead of a spreading fire. USDA For. Serv. Res. Pap. INT-140, 16 p., illus.
7. Frandsen, William H.
1972. Measuring the energy-release rate of a spreading fire. Combust. & Flame 19:17-24.
8. George, Charles W., and Aylmer D. Blakely
1972. Effects of ammonium sulfate and ammonium phosphate on flammability. USDA For. Serv. Res. Pap. INT-121, 26 p., illus.
9. George, Charles W., and Ronald A. Susott
1971. Effects of ammonium phosphate and sulfate on the pyrolysis and combustion of cellulose. USDA For. Serv. Res. Pap. INT-90, 27 p., illus.
10. Hardy, C.E., R.C. Rothermel, and J.B. Davis
1962. Evaluation of forest fire retardants: a test of chemicals on laboratory fires. USDA For. Serv. Res. Pap. INT-64, 34 p., illus.
11. Honeywell Inc.
1973a. High altitude retardant drop mechanization study final report. Vol. I and II, 319 p., illus.
12. Honeywell Inc.
1973b. Extended high altitude retardant drop mechanization study final report, 151 p., illus.

13. Johansen, R.W.
1967. A reproducible system for evaluating forest fire retardants.
USDA For. Serv. Res. Pap. SE-26.
14. Philpot, C.W., C.W. George, A.D. Blakely, G.M. Johnson, and
W.H. Wallace, Jr.
1972. The effect of two flame retardants on particulate and
residue production. USDA For. Serv. Res. Pap. INT-117,
14 p., illus.
15. Philpot, Charles W.
1971. The pyrolysis products and thermal characteristics of
cottonwood and its components. USDA For. Serv. Res.
Pap. INT-107, 31 p., illus.
16. Rothermel, Richard C.
1972. A mathematical model for predicting fire spread in wildland
fuels. USDA For. Serv. Res. Pap. INT-115, 40 p., illus.
17. Rothermel, R.C., and C.E. Hardy
1965. Influence of moisture on effectiveness of fire retardants.
U.S. For. Serv. Res. Pap. INT-18, 32 p., illus.
18. Schuette, Robert D.
1965. Preparing reproducible pine needles fuel beds. U.S. For.
Serv. Res. Note INT-36, 7 p., illus.
19. Shafizadeh, F.
1968. Pyrolysis and combustion of cellulosic materials. P. 419-474.
In Advances in Carbohydrate Chemistry. R. Stuart Tipson,
Ed., Vol. 23. Academic Press: New York and London.
20. Truax, T.R., C.A. Harrison, and R.H. Baechler
1956. Experiments in fireproofing wood. Fifth Progress Report.
USDA For. Serv. Rep. 1118, 23 p., illus. For. Prod. Lab.,
Madison, Wisc.
21. Truax, T.R.
1939. The use of chemicals in forest fire control. J. For. 37:
674-7.
22. Tyner, Howard D.
1941. Fire-extinguishing effectiveness of chemicals in water
solution. Ind. & Eng. Chem. 33: 60-65.
23. USDA Forest Service
1973. The CL-215: summary of its performance as an air tanker,
57 p., illus. Nor. For. Fire Lab., Missoula, Mont.
24. USDA Forest Service
1968. Fire retardant chemical conference, Sept. 24-27. Equip.
Dev. Cent., San Dimas, Calif.