EFFECTIVENESS OF DIRECT AND INDIRECT ATTACK ON WILDFIRE WITH AIR-DELIVERED RETARDANTS

(WSCI 73-14)

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ABSTRACT

The use of aircraft for fire suppression has two legitimate and substantially different roles: 1) direct attack in which a suppressant is delivered against the fire itself, and 2) indirect attack in which a retardant is delivered to the fuels in advance of the fire front. This study, conducted under contract with the U. S. Forest Service, attempts to reconcile the two roles as broad guidelines for tank design. The core study was a computer characterization of the vertical fuel organization of Douglas Fir Crowns and a Chaparral Brush field. Using forest hydrological data on species and surface-related retention characteristics, the effects of retardant rains representing various thicknesses and salt concentrations are then calculated in terms of the retardant damping coefficient. Exercise of the model shows a limit to the amount of water (or salt) that can be applied. Thickeners increase the retention limit, but ultimately encroach on the ability to penetrate and cover the lower fuel substories. By comparing the reduction in spread rate afforded by fuel treatment with Canadian data on fire suppression in direct attack, the two missions can be compared across a wide fire spectrum. The most efficient tactical mission can then be assessed in terms of fire intensity and retardant application levels. The study further suggests that a sequential attack strategy might significantly increase the range of fires that can be successfully controlled by air tankers.

ACKNOWLEDGMENT

The authors wish to acknowledge A. Luedecke and P. Burmeister of Honeywell for their efforts in describing the fuels and programming the resulting models. We also acknowledge the assistance of R. Rothermel, H. Anderson, and C. George from the Northern Forest Fire Laboratory, Missoula, Montana, for their patience as tutors and for the information they supplied. And, of course, acknowledgement is also due to Messrs. Grah and Wilson and the Forest Hydrologists in general without whose work both conceptually and emperically the thesis could not have evolved.

INTRODUCTION

How do the two missions of direct attack and indirect attack affect the designs of an aircraft tank and gating system? This was the question we faced in conducting a study on High Altitude Retardant Delivery Systems under contract with the U.S. Forest Service. The mother of the following study was necessity. We needed reasonable (not necessarily rigorous) answers to this question to get on with the business at hand. There is a kind of desperate freedom in such necessity to strike out boldly across an analytically uncharted wilderness. The reconciliation of these two fundamentally different missions has not been previously treated analytically, nor has there been adequate experimental work to validate fully the results and conclusions. This study, then, represents a first attempt to organize and to deal with the information available on the subject. Even in this form, with the acceptance of uncertainties inherent in initial work of this nature, the study allows us to make reasonable conclusions regarding important factors in assessing the effectiveness of aerial attack.

The findings are not revolutionary in terms of important parameters. They do, however, provide some surprises on the details of operation and suggest potentially rewarding future investigations. It is offered not as a final word, but as a potential beginning for the characterization and understanding of an important factor in Wildfire Management and Control.

OVERVIEW: SUPPRESSION AND RETARDANT MISSIONS

Retardant delivery missions may be characterized by their intent in terms of the tactics employed over a wide range of potential fire situations. It is convenient to distinguish between two basic intents; i.e., direct attack, in which the retardant is delivered against the fire to reduce its intensity or to put it out, and indirect attack, in which the retardant is delivered ahead of the fire front to slow or, in some cases, to extinguish the fire by the action of long-term retardants on the fuels. This action is shown schematically in Figure 1.

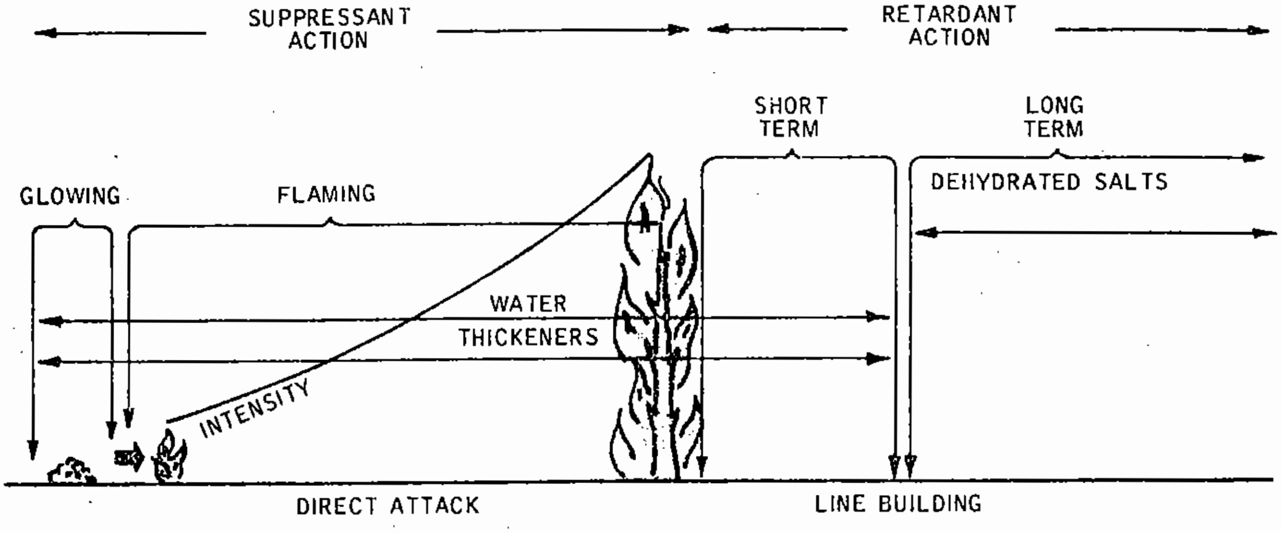

Figure 1. The Fire Spectrums – Two Basic Approaches are Possible – Direct Attack and Line Building

An advanced retardant system must maximize the ability to deal with both situations, although they pose substantially different implications for the air tanker.

Direct attack implies high concentrations of water and thickeners delivered with sufficient energy to penetrate the fire plumes. These concentrations require high accuracy and benefit from low altitude delivery. Treatment of the fuels in advance of the fire is enhanced by higher altitude delivery to generate wide, long patterns of relatively low density. These patterns require gross accuracy (the ability to overlap patterns) and rely primarily on the long-term retardant salts.

Direct attack, if successful, has obvious immediate benefits. Line building is more subtle in its use. Although fuel treatment alone can sometimes extinguish the fire, these fires are also suppressible in direct attack. The significance of line building is substantially against difficult-to-suppress fires as a closely coordinated element of the total suppression mission. Line building is seldom an end in itself, but it exerts considerable leverage on the fire in reducing its ability to cross a weak natural barrier, or in improving the ease with which ground or subsequent air attack can achieve suppression.

The objective of the following studies was to put the two missions in visible context so that preliminary decisions could be made as to their effects on tanker design. When the information is then ordered, it is also possible to make some qualitative observations on tactics and to suggest areas for improving the capability.

INDIRECT ATTACK

The indirect attack mode is the easier to characterize analytically since it is based on a singular rather than complex set of phenomena. Specifically, it requires the distribution of an initially wet, but subsequently dehydrated, salt concentration on the fuel surface area. The effect of salt concentration on the fuel is measurable in terms of the resulting fire spread rate. (The effect of moisture can also be assessed, although in the typical fire environment it ceases to contribute significantly if the line is much in advance of the fire). The primary effects of a retardant salt are to reduce the fire spread rate through the treated fuel, and the amount of retardant to achieve prescribed levels of effectiveness is determined primarily by the concentration on the fuels.

In most work on retardant delivery and effects, the measured values derive from planar factors: the retardant distribution on the ground, and the fire spread through a fuel bed. In the following study, we have attempted to extend these known factors by means of a computer simulation of the vertical fuel arrays. A Douglas Fir Stand and a Chaparral field were chosen to represent two critical and intuitively different fuel situations.

How a Tree Wets Out

The first problem encountered is to provide a general description of the wetting out process. Unfortunately, it cannot be represented by a singular phenomenon, and the dominant features change with different methods of application. The observation that aerially delivered retardants have the characteristics of a very heavy rainfall of extremely short duration leads to the contention that the phenomenon is most directly related to a relatively large volume of forest hydrology studies. (We are not dealing with sprays or fogs.)

Following the definitions of Hamilton and Rowe (Ref. 1), interception is the process in which rainfall is caught by the vegetative canopy and redistributed as throughfall, stemflow, absorption, and evaporation:

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[1] Hamilton, E. L. and Rowe, P. B., "Rainfall Interception by Chaparral in California," California State Board of Forestry, 1949.

- Throughfall is that portion that reaches the ground directly, or is dripped from leaves, twigs and stems. (This corresponds to the retardant that reaches litter of duff beneath an understory.)

- Interception loss is the portion retained in the aerial vegetation and is then either absorbed or evaporated. (This corresponds to the retardant retained in the vertical fuels.)

- Storage area is the surface area of leaves, twigs, branches, and stems that can retain water against gravity.

- Storage capacity is the depth of water on the projected area covered by the vegetation that can be stored or detained on the plant surfaces in still air.

The theoretical and experimental work of Grah and Wilson (Ref. 2) bridges a great many of the variables associated with the modeling problem. Conceptually, their work relates the retention characteristics of the vegetation to a film thickness assumed to be applied uniformly over the tree surface area. This value was obtained experimentally for two species in terms of three storage conditions:

- Transitory storage is that component never retained and which is lost by drip and evaporation

- Conditional storage is that component that can be retained by the vegetation in still air or can be lost under the influence of winds

- Residual storage is that always retained by the foliage.

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[2] Grah, R.F. and Wilson, Carl C., "Some Components of Rainfall Interception", Journal of Forestry, Vol. 42 p. 890-898, 1944.

Specimens of Monterey Pine and Kidneywort Baccharis were suspended from a balance and exposed to sprays that fell only with the force of gravity. The accumulated water, measured at one minute intervals, is shown in Figure 2.

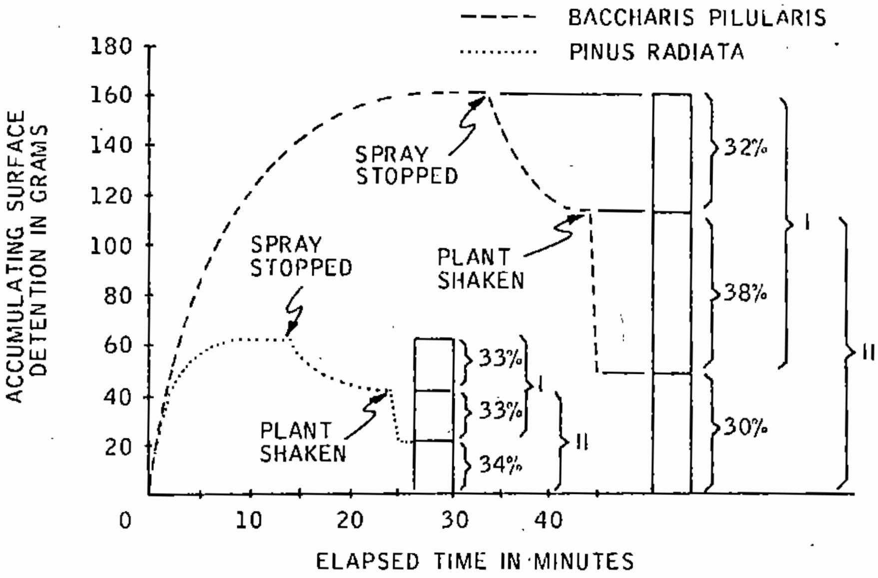

Figure 2. Grah-Wilson Experimental Data (Reference 2) Depicting the Rise and Fall of Surface Retention and its Subdivision into Storage Types

The weight of water for each storage condition is then changed into film thickness value from surface area determinations.

The equivalent film thickness, for purposes of our study, was taken at the retention level achieved after dripping, but before the tree was shaken. The values were 0.003 inch for the pine and 0.007 inch for the baccharis. These values were chosen to replicate by similarity the expected water film thicknesses retained by Douglas Fir and Chaparral fields, respectively. Use of this approximation (with many others) is not critical to the study, in that a range of film thickness values will be encountered in the real world situation, while the retardant can also be manipulated rheologically to change this value.

Retardant Film Thickness

To estimate the increase in retention afforded by typical retardants, a series of dip tests was conducted both by Honeywell and the U.S. Forest Service. The results, though far from definitive, suggested that retardant film thickness could be approximated by about four times the equivalent water film thickness. Consequently, the film thickness value for Douglas Fir was established at 0.012 inch and the Chaparral field at 0.028 inch.

ORGANIZATION OF THE VERTICAL FUELS

The next step in the process is to organize the fuels in a three-dimensional array so that retardant rains of various concentrations can be applied and the amount and organization of resultant fuels treatment estimated. We used the assessed characteristics of a Douglas Fir Stand and a Chaparral brush field supplied by Hal. E. Anderson of the Northern Forest Fire Laboratory. The data are for the Chaparral example appear in Table 1.

For purposes of computation, we organized the characteristics of the Chaparral field into a geometrical representation of a Chaparral bush, although no such species actually exists. The Douglas Fir was similarly represented by a single crown. Both assumptions are normative in that they give us a standard for comparing retardant effects without regard for extreme cases.

Table 1. Vertical Fuels Stand Data Chaparral Field

Representative Unit: One Square Foot Representing Average Brush Field Characteristics

Fuel Distribution: Uniform Using the Averaging Assumption

Loading: 0.598 lb/ft^2 (W_O)

Density: Foliage: 25 lb/ft^3 Wood: 40 lb/ft^4

Vertical Fuel Distribution: Variable (See below)

6.0'

	Surface Area Per Size Class, Aij (ft^2/ft^2)						Total Surface Area with 5th level	
Loading per Category	Foliage	0-1/4"	1/4-1/2"	1/2-1"	1-2"	2	Ai, ft^2/ft^2	Loading $(W_o)i$.
21.2%xWo	.904	.146	.044	.031	.026	.001	1.153	.1268
34.2%xWo	1.459	.235	.072	.051	.042	.001	1.859	.1483
19.1%xWo	.815	.131	.040	.028	.023	.001	1.038	.2781
25.5%xWo	1.088	.175	.053	.038	.031	.001	1.386	.1292
% of Total Weight	10.7	17.9	14.6	20.7	34.2	1.9	A_T = 5.436 (ft^2/ft^2)	

Our Chaparral bush is represented as a collection of areas of interception, as shown in Figure 3, which have surface areas derived from the fine fuels descriptions. It is assumed that the interception is proportional to surface area of the fine fuels until the film thickness limit is reached.

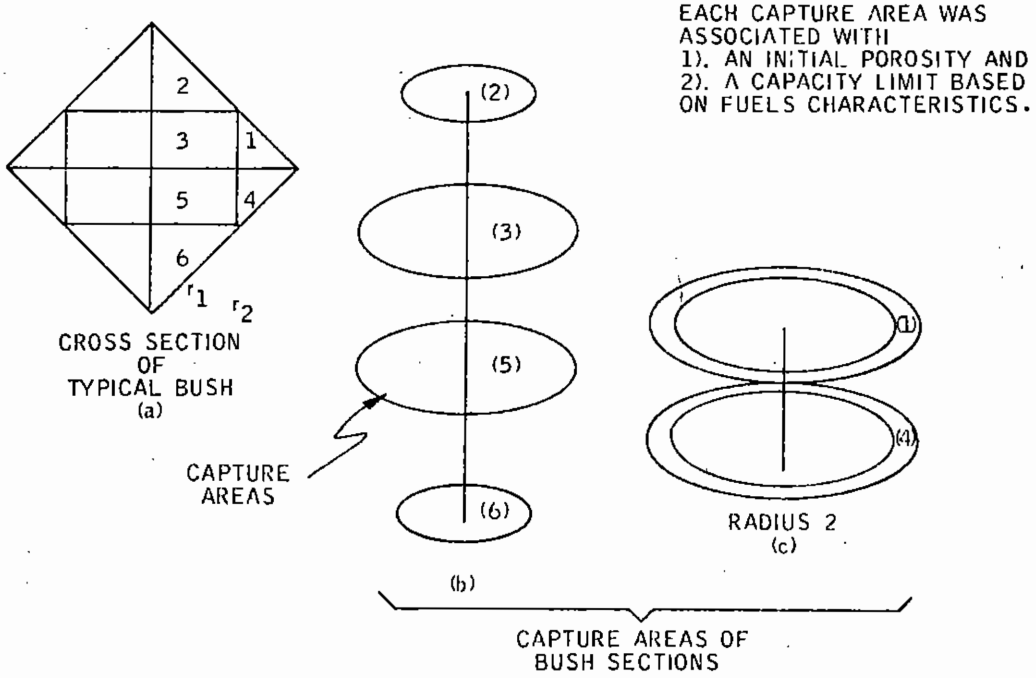

Figure 3. Abstract Chaparral Bush Used in Capture Model

The amount captured in ring 1, level 1, is the delivered quantity in gallons/ft^2 times the surface area of the fine fuels in this ring up to the film thickness limit that is part of the input. Only a fraction of the incident quantity is removed, with the remainder continuing to level 2 of that ring where the process is repeated.

Using this program we can watch the sectors of the vegetation move to saturation as a function of the retardant input measured in gallons per 100 ft^2, and assess the effects of species and retardant variables by means of the film thickness input (Figure 4).

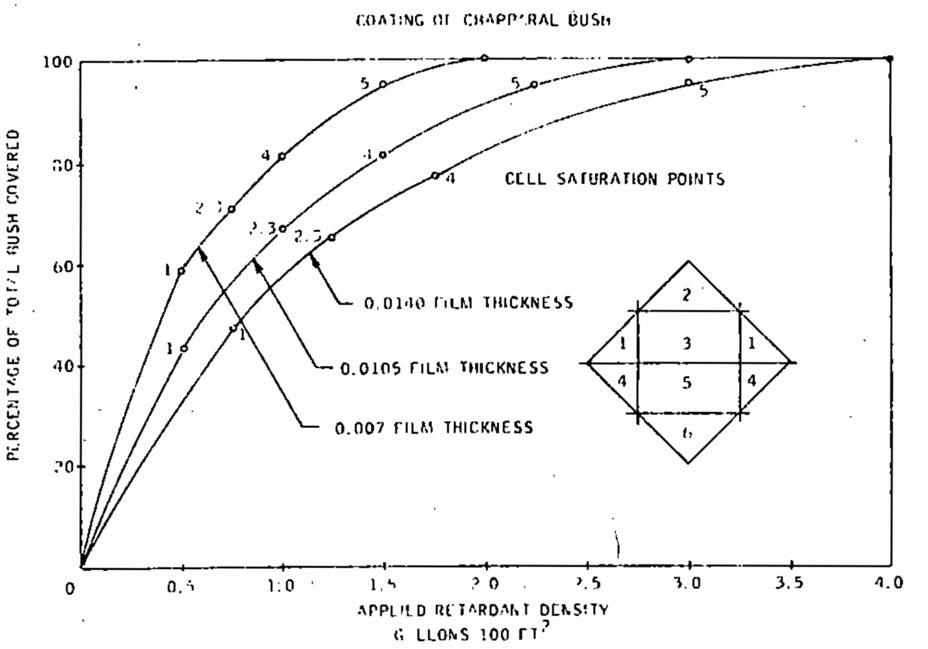

Figure 4. Coating of Chapparal Bush as a Function of Retardant Film Thickness – Data from Computer Model

Application of the Capture Model to Fire Spread

The next step in the program relates the effect of the captured retardant to the rate of spread through a homogeneous fuel array with the properties of the stand. This step is based on the application of the Rothermel model of fire spread (Ref. 3) which estimates the rate of spread, R, and the reaction intensity, I_R, using the geometrical properties of the fuels, their arrangement, the quantity of fuels, available heat energy, moisture and mineral properties, and the effects of wind and slope.

To apply this concept to the vertical fuels simulation, we assume that the fire response of each sector of the tree is similar to an equivalent fuel bed treated uniformly to the level predicted by the capture model. The response of the

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[3] Rothermel, R. C., "A Mathematical Model for Predicting Fire Spread in Wildland Fuels," USDA Forest Service Research Paper INT-115, 1972

fuel to various treatment levels is then calculated using the retardant damping coefficient, η_r, defined by Rothermel and Philpot (Ref. 4). The performance of the array is calculated as an average of the fuel cells, that is not particularly sensitive to various weighting schemes.

Byram's Intensity

It will be convenient in comparing results against suppression data to relate the changes in rate of spread and reaction intensity to Byram's intensity, which is also capable of giving us some intuitive feel for real world fires.

Rothermel has shown (Ref. 5) that Byram's Intensity (BTU/ft. min) can be expressed in reaction intensity, I_R, and rate of spread, R, if the residence time, t_r, can be approximated.

He has further shown that t_r can be calculated from data generated by Anderson, using a weighted surface area to volume ratio, $\tilde{\sigma}$, for the stand. His formula is:

$$I_B = \frac{6.4\ R\ I_R}{\tilde{\sigma}}$$

Using this formula, it can be shown directly that the ratios of Byram's Intensity for treated and untreated fuels varies as the square of the retardant damping coefficient, η_r.

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[4] Rothermel, R. C. and Philpot, C. W., "A Retardant Effectivness Parameter," Northern Forest Fire Laboratory, Preliminary Draft, 1972

[5] Rothermel, R. C. Private Communication, Northern Forest Fire Laboratory Memorandum, 9-6-72.

Let us now display the results of the capture model exercise against a scale of Byram's Intensity as it is modified by application of various retardant coverage levels (Figure 5). It will be recognized that the bands represent envelopes covering a wide range of variables. There is no point solution to fires in general. Although the bands shown here were estimated for a fixed retardant, species, and fire condition with various dry salt content in pounds per gallon, similar variability can be attributed to species, film thickness, wind conditions and the like. The curves for grass and litter are simple approximations, exploring the consequences of applying the same reasoning to planar fuels. Note also that the intensity scale does not go to zero.

The forms of the curves and the retardant coverage values are nonetheless significant. They suggest that the low density crowns with a limited retention capability reach a distinct limit in the knockdown afforded by fuel treatment. Although the limit can theoretically be decreased by rheological manipulation of the retardant toward thicker films, other considerations such as penetration to the understory in more dense vegetation begins to take effect.

Figure 6 shows, for example, indications of such a tradeoff. When three thickness assumptions are applied to the dense Chaparral representation, a potential optimum film thickness is suggested. It is interesting to note that the intermediate thickness value, the best of the three, corresponds to the estimated film thickness value of current retardants.

DIRECT ATTACK

Direct attack on the fire is considerably more complex phenomenologically than indirect attack. Little data have been generated on the quantities of material required to suppress a fire from the air, nor is there agreement on the characteristics of the fire that determine this value.

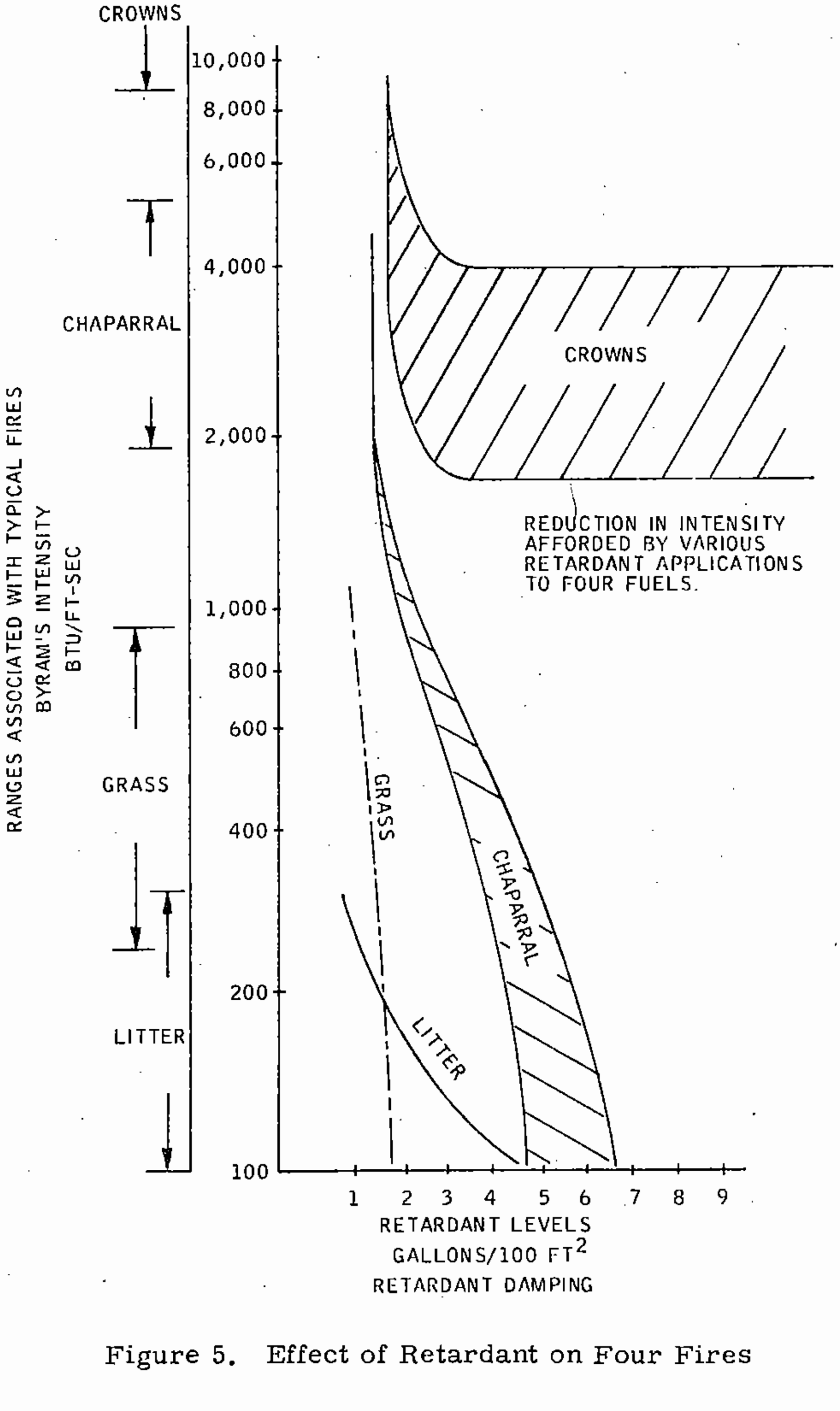

Figure 5. Effect of Retardant on Four Fires

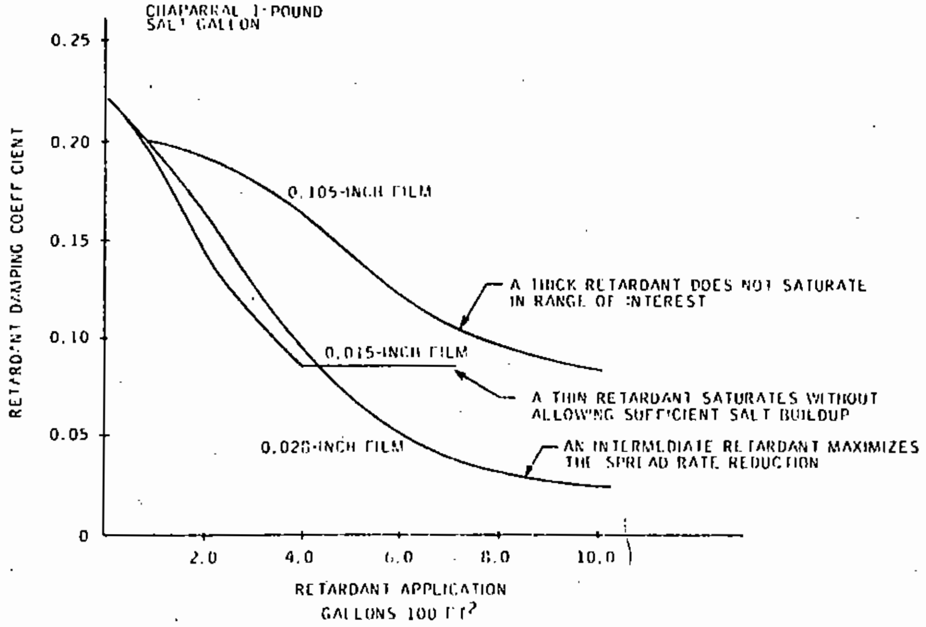

Figure 6. Effect of Film Thickness on Achievable Retardant Coverage Levels

Considering the wealth of data on suppression by conventional techniques, this situation is intuitively surprising. It is due to an important difference between conventional fire fighting and aircraft attack. Conventional fire fighting is primarily concerned with the continuous application of a suppressant, i.e., application of a cooling flux. In aircraft attack,the time of application seldom exceeds 30 seconds; the application is impulsive.

What is known can be quickly summarized. Canadian studies[6] have evaluated the amount of water to suppress test fires of low intensity (measured on the Byram Intensity scale), while the effects of viscous water and retardant salts have been evaluated in conventional fire fighting. Sprinkler studies in which the fire fighting fluid is delivered from above generally concede that if the fire is well started the primary effects are cooling of the adjacent fuels and

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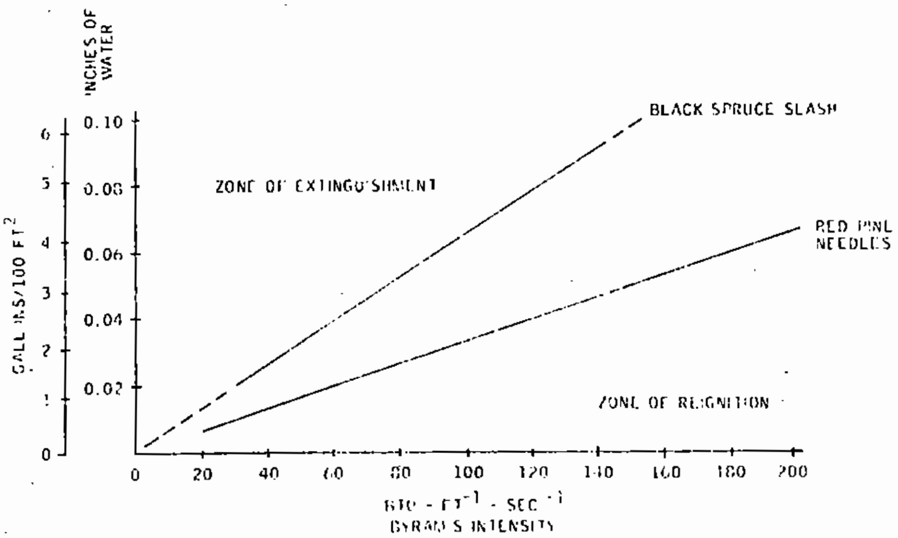
6 "Water Application Depths Required for Extinguishment of Low Intensity Fires in Forest Fuels," E. Stechisen and E.C. Little, Forest Fire Research Institute, Ottawa, Ontario. Information Report FF-X-29, May 1971.

the air above the flame rather than the fire itself. Since the controlling force must be applied at or near the base of the flame; i.e., in advance of or within the reaction zone, any force delivered from the top of the flame must penetrate the plume (or the thermal updraft), and only that which survives can produce a significant effect on combustion.

We can obtain a qualitative indication of fire suppressibility by modifying the Canadian data to apply to retardants delivered against the vertical fuels of interest. Figure 7 shows Canadian results of two fuels in a relatively low intensity range. Although considerable differences in these curves were noted in the three fuel types evaluated, we will let these fuels represent a range of interest.

Retardants are generally conceded to be better suppressants than water. Therefore, it is necessary to make some reasonable adjustment in the Canadian data before we apply it to our fire spectrum display.



REFERENCE WATER APPLICATION DEPTHS REQUIRED FOR EXTINGUISHMENT OF LOW INTENSITY FIRES IN FOREST FUELS

Figure 7. Water Application Depths Required for Extinguishment of Low Intensity Fires in Forest Fuels (Reference 6)

The effect of viscous water in fire fighting was reported in "Improving the Effectiveness of Water for Fire Fighting," C.S. Grove, Jr., et al, Fire Research Abstracts 4 (1 & 2): 54 1962, pp 54-66.

If we assume that the volume of application is the critical value, then the ratios of the times to achieve control with viscous materials and water (established in the above report) can be used to estimate volume reductions in the aircraft delivery mode that may be associated with retardants. This is not necessarily a valid assumption in that the times are large compared to those achieved in air drops, but it should yield a limit condition.

The Grove data show that the effects of viscous water are relatively constant above 20 centipoise. The improvement in time was equivalent to a 28 percent reduction in the delivered volume to achieve suppression. For this adjustment, a zone of suppression can be estimated in terms of Byram's Intensity and the required retardant application rates (Figure 8).

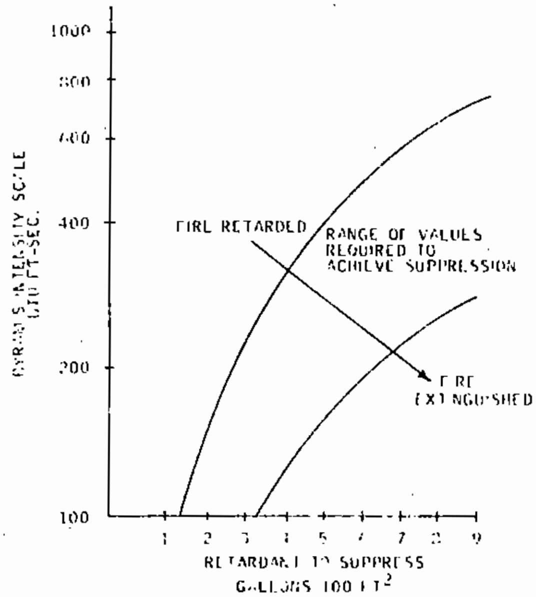


Figure 8. Quantities of Retardant Required to Suppress Low-Intensity Fires

A UNIFIED HYPOTHESIS

Figure 9 relates the predicted reduction in intensity afforded by indirect attack to the quantity of retardant needed to suppress the fire in terms of Byram's Intensity and retardant application levels.

Although the actual values in Figure 9 must be regarded as speculative, the order of effects shown is believed valid. Specifically, as the fire grows in intensity, the volume demands for suppression soon exceed the capability of the air tankers. At this point, treatment of the fuels in advance of the fire front becomes the only practical option. Subsequent direct attack, when the fire enters and is knocked down in the treated region, can then potentially extinguish the flame front.

Such sequential attack should be effective for most fires, and indeed, more effective than single passes with larger pattern concentrations. This results because there is a limit to the amount of retardant that a vertical fuel can contain. In the case of crown fires, it appears that the retardant damping action can only reduce the fire to some extent.

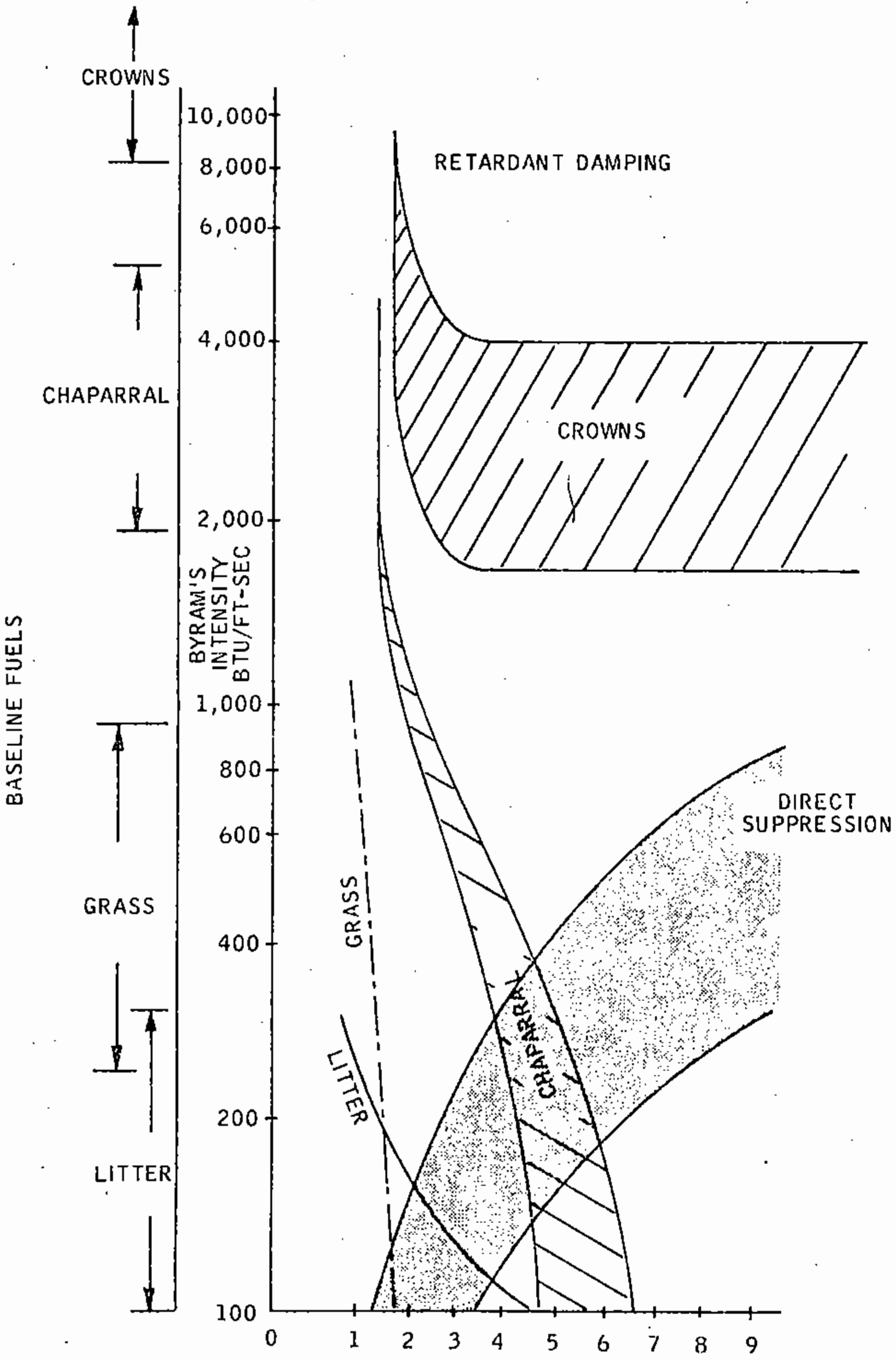


Figure 9. Comparison of Quantities of Retardant Needed to Retard or Suppress a Fire