EVALUATION OF FOREST FIRES WITH RESPECT TO REQUIREMENTS FOR AIRCRAFT

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PREFACE

If this report appears to be unduly lengthy in relation to the depth of the subject matter, and if a great deal of seemingly unnecessary effort has been devoted to discussing alternative solutions to problems which are subsequently rejected, the author can only offer his apologies. This report is an attempt to trace the development of solutions to many new problems, and some new solutions for old ones. The reasons for adopting a particular approach are often given the same emphasis as the description of the methodology itself. In some cases, the plodding step by step discussions may appear to be unduly elaborated, perhaps even painfully so. It was felt however, that the consequences of excessive elaboration in this report would be more acceptable than a debate on the validity of the conclusions at the completion of the study caused by the disagreements concerning the methodology used.

The thoughts and comments presented herein are a synthesis of discussions which have been held with numerous knowledgeable fire control individuals across the country and some personal opinions of the author. Before proceeding with the study, some feedback would be greatly appreciated in the form of comments on, and/or suggestions for, improvement of the material presented in this report. The reader should consider this report as being a suggested approach to the solution of the airtanker dispatch problem. Any worthwhile suggestions for alternative approaches will be given due consideration and will be incorporated if they show promise of more accurate results or increased efficiency. If no comments are received, it will be presumed that the approach proposed in the present paper is satisfactory to all concerned, and this portion of the study will proceed as outlined.

INTRODUCTION

This paper is the first of a series of progress reports on a study of the feasibility of a Canada-wide mobile airtanker fleet. The development and background of this project is covered in detail elsewhere (Anon. 1963, Anon. 1965, Williams, et. al. 1968, and Simard 1969), and will not be discussed here. The present paper concerns itself with the determination of a set of rules which can be used to select those fires which appear to have generated a demand for aircraft activity from the entire set of fires which have occurred. This is Box 3 (evaluate fires) of the simplified project schematic which is presented in Figure 1. It should be noted that the number of fires in which aircraft are required is less than the total demand for aircraft because in many circumstances, several aircraft will be required for use in a number of different roles on a single fire. The number and types of aircraft to be dispatched, or the use to which they should be put will be considered in subsequent papers.

Since "non-aircraft" fires do not directly affect the demand for aircraft, it is obvious that these fires should be eliminated from the sample at the beginning of the study. It should be pointed out, however, that an individual "non-aircraft" fire could generate a demand for aircraft if several such fires occurred simultaneously. Such a fire would therefore have to be considered as an "aircraft fire". Of the sixty-five thousand fires across Canada during the period 1958-1967 (Anon., 1967), it is estimated that about fifteen percent generated a demand for airtanker activity and that an additional five to fifteen percent required the use of aircraft for other roles*.

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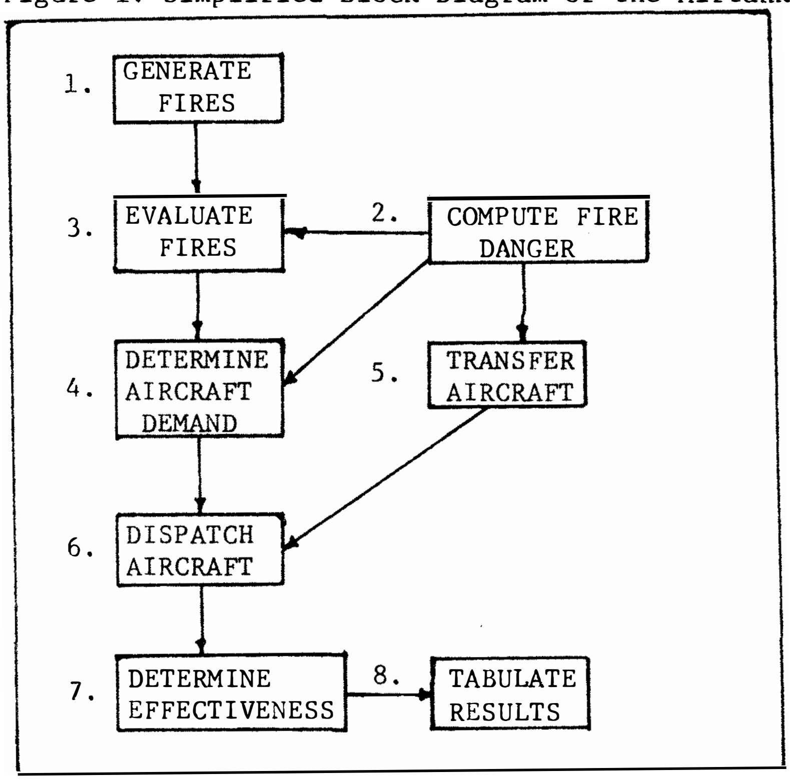
* Personal interviews with provincial officials across Canada.

Figure 1. Simplified Block Diagram of the Airtanker Project



There is no simple, yet reliable, method of separating "aircraft fires" from the entire set of fires which have occurred. Final fire size at the time of control is of little use because many small fires were so because airtankers were used for initial attack. The size at the time of detection is of little value without information about the expected growth rate and the expected travel delay. Many fire reports refer to the use of aircraft and it has been suggested that one might simply consider all fires on which local fire control officials used aircraft in the past. This approach also has inherent drawbacks, for example: aircraft may have been needed but not used due to unavailability or incorrect decisions may have been made. Furthermore, the number of aircraft available for fire control use has increased considerably during the ten-year period of the study and hence the use has increased also. Similar arguments can be presented for any individual factor which precludes it being used as a simple determinant of the need for aircraft dispatch. Therefore, a preliminary analysis of all fires which have occurred will have to be conducted. This analysis will have to consider all of the major factors which are thought to influence the dispatch of an aircraft to a fire.

The purpose of using aircraft, as with all other fire suppression tactics such as the dispatch of bulldozers, tankers, and hand crews, is to accomplish a predetermined strategy, such as controlling forest fires at as small a size as possible. The selection of specific tactics to employ is governed by the available forces and a quantitative definition of "as small as possible". Such a definition is achieved through the establishment of fire control objectives. Therefore, prior to a discussion of the use of specific tactics, the more basic question of fire control objectives will be considered.

The section on fire control objectives is a review of current thinking and practices in selected areas of the field of fire control and airtanker operations as well as relevant literature. This section serves as background material for subsequent discussions of aircraft requirements. The second section discusses specific approaches which will be used in the present study to solve the various problems which are encountered.

Forest Fire Control Objectives

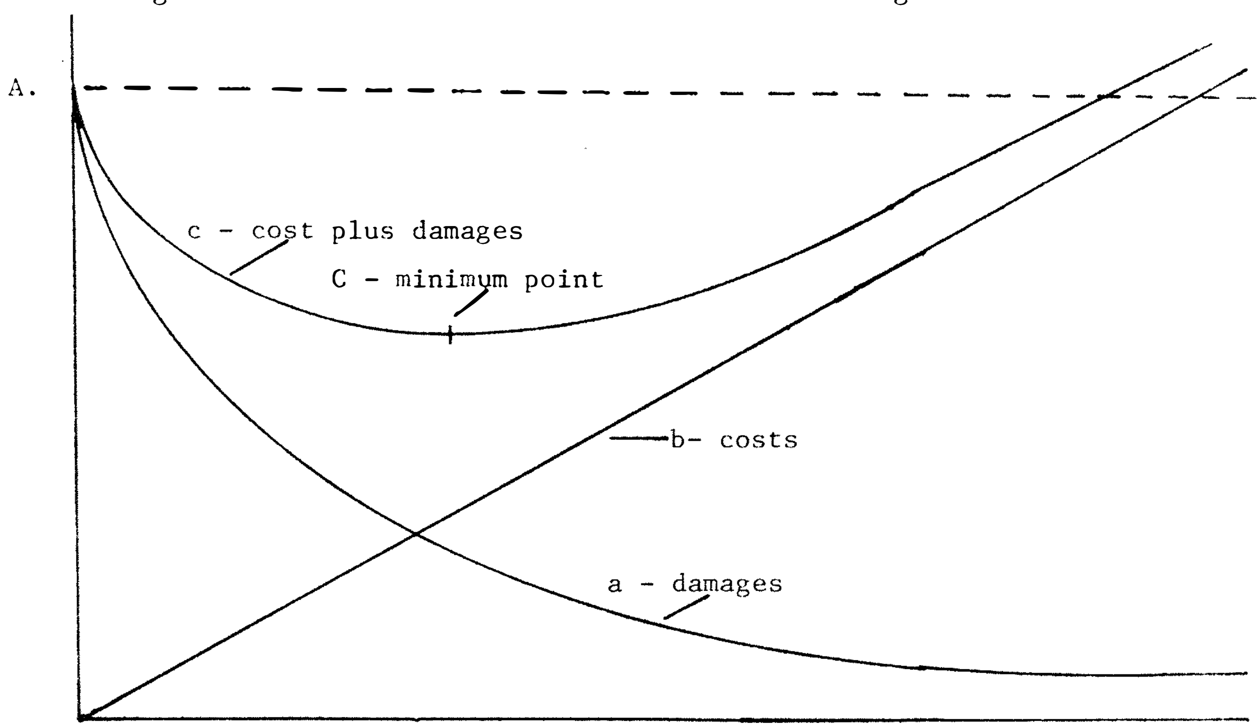
A. Economic Objectives

There are two limits to the intensity of fire control which can be applied to a forested area. At one end is the absence of protection which in turn incurs excessively high damages. It is obvious that this level of protection is not compatible with present day concepts of land use and conservation. At the other end of the scale is complete fire exclusion, which is defined by Davis (1959) as no fires larger than one-quarter acre. This definition assumes that despite all conceivable human efforts, there will be some damage incurred from forest fires. Because of the excessive costs of such an objective, it is normally attained only in relatively small areas of extremely high value.

Between the extremes is a full range of increasing intensities of protection which are assumed to cause corresponding decreases in damage incurred. The problem is therefore one of finding the optimum intensity of protection to employ.

Many attempts have been made to determine optimum intensities of fire control. The "least-cost-plus-damage" concept was stated as early as 1916 by Headley. The concept has been elaborated upon and discussed by numerous authors (Show and Kotok, 1923, Sparhawk, 1925, Loveridge, 1944, Beall, 1949, Arnold, 1950, Davis, 1959, and Schultz, 1966). Briefly, the relationship between damage incurred, and protection intensity, is shown as curve *a* in Figure 2. Although

Figure 2. Theoretical Least - Cost - Plus - Damages Curve



numerous analysis of historical forest fire loss data have confirmed the general shape of the curve , the exact shape cannot be defined due to variations in methods used to collect cost and damage data. Superimposed on the same figure is curve b which depicts the cost of providing the various levels of suppression. By adding the two curves, curve c is produced - the total cost plus damages. It can be seen that the curve decreases from point A which is a maximum value at no protection to a minimum value where the marginal reduction in damages equals the marginal increase in cost. Beyond this point, it increases indefinitely passing through the level where it equals the value at no protection. Any greater degree of protection would incur an economic loss, and is therefore not justifiable. The optimum degree of protection is considered to be the level corresponding to the minimum value on the cost-plus-damage curve.

While the theory is widely accepted as the ideal approach, it cannot be applied. As concluded by Beall (1949), and still true today: "unfortunately, our knowledge of the factors involved is not, and perhaps never will be, complete enough to permit the specification of practical fire control objectives in such terms". Some of the problems involved are:

1. Lack of standardization in the determination of fire control and total protection system costs. The decision as to which costs to attribute to fire control and which to other resource management activities is often affected by varying political or budget constraints in different regions across the country. For example, if a district ranger is required to be on standby because of high fire danger, does

his salary for that period come under the fire control budget, even though he could be developing timber management plans at the same time?

2. As pointed out by Schultz (1966) the least cost portion of the theory ignores the fact that a wide range of degrees of protection can be provided by a single budget level in a single area, depending on the management decisions which are made with reference to the type of system to employ. For example, for the cost of one aircraft, one could purchase a few bulldozers or tankers, or hire several crews for a fire season.

3. To date there is no completely satisfactory generally applicable method of determining the actual economic value of a stand of timber. Many considerations such as the value of providing employment or encouraging settlement in remote areas by the exploitation of marginal or sub-marginal stands have not been quantified.

4. No satisfactory method has been devised to quantify, even in broad categories, the non-forestry values of a stand of timber.

5. There is no reliable method for evaluating the loss incurred by the occurrence of a forest fire. This can range all the way from complete removal of all value from a parcel of land to an actual increase in value by preparing a seedbed in a logged-over area.

B. Practical Objectives

Lacking applicable economic objectives which would allow the comparison of fire control efforts with other resource management activities, many efforts have been made to establish specific, measurable fire control objectives which would at least make it possible to compare the effectiveness of various control organizations on a relative basis (Show and Kotok, 1930, Hornby, 1936, Loveridge, 1944, Beall, 1949). The general technique is to assume a standard level of protection for a particular area on the basis of assumed or estimated values. The objectives are stated in fire control terms such as:

(i) Acceptable percentage of the protected area burned annually

(ii) Maximum tolerable size for any individual fire

(iii) Control during the first work period

(iv) Lapsed time objectives:
- a) Between detection and control
- b) Between detection and commencement of fire fighting

The first objective is strategic, in that it refers to the total burned area for many fires during the entire year. The last three are tactical in that they apply to a particular fire. As with economic objectives, a gap exists between the statement of the above goals and their practical application. Use of any of the above objectives requires the availability of quantitative information about the behaviour of wild fires and the relative effectiveness of all possible tactics which could be employed in the suppression of these fires. In other words, knowledge is needed about the rate at which fires increase in size and the effort required to control them. Each of these problems will be discussed in some detail.

1. Fire Growth

For more than half a century researchers have been attempting to derive mathematical relationships between the rate of growth of a forest fire and the environmental parameters which are believed to influence fire growth. Historically, there have been two basically different approaches which have been used in an attempt to solve the problem.

The first approach - macro fire models, attempts to determine the effect of each variable by analyzing the behaviour of large natural fires. The final effect is known and this process attempts to separate the influence of each variable. From these studies have come numerous fire models of a mathematical nature (Parks, 1964, Stade, 1966); an empirical nature (Abell, 1940, Bates and Frazer, 1966); and combinations of the two (Newburger, 1966); all of which attempt to predict either the rate of area increase or the rate of forward spread of forest fires.

Most of the models make fairly gross simplifying assumptions such as: a uniform, homogeneous fuel type, level topography, standard fire shape (generally an ellipse or triangle), constant environmental conditions, and the availability of a mathematical relationship between all of the controlling environmental factors and fire growth. Because of the simplifing assumptions it is possible to observe general trends which are otherwise lost in masses of detail. Such models are useful for prevention and presuppression planning where one is looking for average values and probabilities. They are of little value for determining optimum tactics to employ in a specific fire control situation.

The second general approach - micro-fire models, has been in the form of laboratory or controlled field experiments where the individual variables are carefully regulated or measured and their effects are analyzed. The ultimate purpose is to synthesize a fire growth model from the individual environmental parameters and fire behaviour (Fons, 1946, Byram et al 1966, Rothermel & Anderson, 1966). While the relationships are precise, a number of problems preclude the use of these models in making decisions concerning fire suppression tactics:

(i) The number of variables required makes the calculations very cumbersome;

(ii) Much of the necessary information is simply not available for other than precisely measured samples;

(iii) The interaction between various individual factors which are assumed to occur in a natural environment are not completely understood;

(iv) It is not possible to extrapolate fire behaviour observed on a very small two dimensional scale to large fires which are often three dimensional phenomenon.

The gap between these approaches is still quite wide. What is needed for making tactical decisions in specific fire control situations is a fire model which can predict large scale growth of a particular fire with some reasonable degree of accuracy, yet not be cumbersome to apply due to excessive detail. Recently, both approaches have been coming closer to this type of model and at the same time to each other. At the macro end of the scale, efforts are being made to increase the detail available from fire reports (Chandler, et al 1963). At the micro end, larger control fires are being studied (Countryman 1964, Van Wagner 1968). More recently, a fire growth model for small natural fires has been developed for the purpose of analyzing alternative detection tactics (Kourtz and O'Regan, 1969). Unfortunately, the type of model which would be suitable for larger scale tactical decisions on fires some time after detection, is not presently available.

2. Fire Suppression Tactics

A literature review in the field of fire suppression reveals many similarities with the field of fire behaviour and one basic difference. There have been two basic approaches from opposite ends of the spectrum. The first approach is a large-scale analysis of fire reports to determine average rates of line construction for all tactics which have been employed in the past. Neuburger, 1966, used average values determined in this manner in an attack model for individual fires. It should be pointed out however, that since rates of line construction are related to the specific tactics employed, and since there is a considerable range of tactics which can be used, such average values are not applicable to specific fire control situations.

Their main values, as with macro-fire models, are as aids to presuppression planning.

The second approach, begun more recently, has been an analysis of the rates of line construction for each individual component of the fire control system. A great deal of work remains to be done with respect to these types of studies. Much of the presently available information is of a qualitative nature only. That quantitative data which has been acquired is highly variable, and no apparent reasons have been found which would explain the observed variability (Storey & Bower, 1968).

To date, investigations have dealt primarily with rates of line construction. However, anyone with fire control experience is well aware that many tactics which are employed do not directly increase the rate of line construction, although they do contribute significantly to the overall strategy of controlling the fire at as small a size as possible. The application of water, whether it be from back pack pumps, ground tankers or airtankers falls into this category, with the exception of the use of high pressure nozzles in certain areas as a digging tool for line construction.

The question of whether a fire is actually extinguished with the use of water has been vigorously argued for years. Although there is certainly enough evidence to support the claim that fires can be extinguished without building a line, many experienced fire control personnel consider the construction of at least a scratch line, a necessary pre-requisite for declaring a fire out. Where this would be prohibitive due to size of fire or other considerations, at least a ground patrol should be maintained for some reasonable period after the fire has been controlled. Throughout the study, any applications of water which are sufficient to extinguish a fire will be considered to have reduced the rate of spread to zero but not have put it out.

Rates of spread, fire intensities, and spotting are all reduced through the use of water, which in turn contribute to a smaller final fire size. Therefore prior to analyzing fire suppression tactics, the relative effectiveness of each tactic with respect to the utlimate strategy will have to be determined. The value of stopping fire spread will have to be compared to the value of constructing line, before a decision can be made as to the optimum combination of tactics to employ for any specific fire suppression situation.

There is one basic difference between investigations of fire behaviour phenomenon and suppression tactics. The former is a complex physical process which is related to natural and hence measurable parameters. Therefore, it is probable that the relationships will eventually be determined. The latter is a function of a complex decision-making process which is the result of years of individual experience and conditioning. Although it is often possible to classify decisions made in a number of similar fire control situations into broad categories, it is probable that due to the differences between individuals, the decision-making process will never be fully understood. Some insight to the complexity was gained by Schultz (1966) when the results of game simulation indicated that strategies are often altered during the course of fighting a fire. Whereas the initial goal was normally minimization of acreage burned by direct attack, this became secondary to safety of personnel and structural protection as the fire grew to major proportions. There were indications that minimization of acreage burned again becomes predominant as the behaviour of the fire becomes less severe.

Another interesting point was that -

"..... each fire management team consistently makes deployments which, if successful, would result in smaller acreages burned than those they are simultaneously predicting. Such evidence suggests that the decision-making model being used by actual fire managers is much more rich and complex than is suggested by recent models which do not allow such apparently "irrational" behaviour".*

In summary, a great deal of additional investigation will be needed before accurate quantitative information is available in the fields of fire behaviour and fire suppression. Therefore, at the present time, the only way to develop an optimal fire control system to meet specific practical objectives in a given area is by trial and error. There is no way in which an optimal system can be defined in the absence of field experience. Hopefully, with careful planning and consideration, the trials required and errors incurred will be few.

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* For example: Parks, 1964, McMasters, 1966, Parks, 1966, Newburger, 1966.

C. Objectives of Using Aircraft

As previously mentioned, there is a set of tactics which contribute to the minimization of area burned, but not directly to the construction of fire line. The various uses of aircraft fall into this category. There are a number of functions for which aircraft are particularly well suited. One of these uses - detection - is being studied in considerable detail elsewhere and will not be considered here (Kourtz and Townsend 1967). The objectives of each of the various suppression uses will now be discussed.

The first major use is for transportation of men and equipment. This could be either an initial attack crew, or reinforcements, and/or supplies on a major fire. It could also be for the purpose of transferring men and equipment from one sector of a major fire to another. The main objective in the first case is rapid initial attack. The plane can get ground forces to remote fires much faster than ground transportation.

There are many instances where aircraft are the only form of transportation available, in which case the high costs are of little consequence. The question of the value of land which is in fact, inaccessible for logging at the present time, and probably will be for at least a few years, will not be dealt with here. Where alternative means are available, it is believed that high aircraft costs are offset by the reduced costs and damages incurred by the reduction in final fire size achieved through early attack. In the case of reinforcements and supplies to a major fire, speed is perhaps not as paramount, especially if one is maintaining the status quo of a static force, as in the case of mop-up. In these cases, aircraft are normally used only if the costs of ground movement would be greater than by air. Again, in the absence of nearby roads, the choice is self-evident.

In order to determine the demand for air transportation when alternative methods are available, we must define the input to the fire suppression system which the aircraft generates and the effect of that input in terms of a production function on the overall fire suppression system. The input is travel time to the fire and the objective is to minimize this input. The effect is a reduction in suppression costs and damages incurred because of the early initiation of suppression. The methods which will be used to estimate the benefits of air transportation will not be discussed in the present paper.

The second major use is by far the most dramatic. That is dropping water or retardants on or in front of a fire. In terms of overall suppression strategy, the airtanker is simply another water delivery system. In terms of tactics however, the impact can be considerable. A few of the advantages are: large quantities of water or retardant can be delivered at once, relatively few areas are inaccessible, early initial attack is possible, and aircraft can be readily shifted from one fire to another. There is general agreement that the use of water dropping aircraft in the past few years has reduced fire losses below the levels which were attained prior to their use. It is also generally agreed amongst knowledgeable fire control personnel, that the use of airtankers has averted many potential conflagrations due solely to their ability to act early and effectively.

Unfortunately, our knowledge of aircraft effectiveness is almost entirely qualitative. Recently, efforts have been made to arrive at quantitative measurements of effectiveness, but much remains to be done, (Anon, 1968, Hodgson, 1968, MacPherson, 1969). Such effectiveness values would be useless however without corresponding information for other means of water delivery such as pumps and ground tankers.

Lack of knowledge of the relative effectiveness of the various delivery systems prevents a realistic determination of the optimal tactic or combination of tactics to employ. Therefore, the determination of airtanker demand will have to be accomplished through indirect means. It will be assumed that only ground forces will be used if they are capable of successfully controlling the fire before it causes excessive damage. It will be further assumed that the high costs of airtanker use are justifiable only if ground forces are incapable of performing the above mission. Specific definitions of ground forces, control, and excessive damage will be discussed in the next section.

The last major use to which aircraft are well suited is the gathering of intelligence. In fact, unlike the other two uses, there is no alternative method which can perform this mission with anywhere near equal effectiveness. Few things are as valuable to a fire boss as a view from the air. It will therefore be assumed that all large fires generate a demand for aircraft for the purpose of gathering intelligence.

In summary, it can be seen that there are a number of fire suppression and support roles to which aircraft are particularly well suited. Their general place in the system structure is in the form of support of one form or another for ground forces. Because of high costs, aircraft are generally used only when one of two situations arises: There is no other means available to achieve the objectives, or aircraft costs are less than costs of using an alternative method. The next section will outline a procedure for separating those fires which require aircraft from those which do not appear to require aircraft. Also an attempt will be made to quantify many of the concepts discussed in this section.

Aircraft Requirements

A. Objectives

As discussed in the previous section, all considerations of tactics are dependant on the objectives which are established for the fire suppression system. Beall (1949), established a standard acceptable area burned for a particular area on the basis of personal interviews with knowledgeable foresters and calculated all other acceptable annual burns relative to it. The process is fairly involved and a complete description would be far too lengthy for inclusion in the present paper. A separate investigation into this phase of this study is currently being undertaken. Suffice it to say at this time that a similar type of economic analysis will be conducted using computer simulation and the latest available values. Some changes in methodology will be incorporated which will reflect current opinions on the subject.

If one could define strategic objectives such as acceptable annual burn, they would then have to be converted to tactical objectives which could be applied to a particular fire control situation. Unfortunately, as pointed out by Beall (1949) and still true today; "..... No universal rule, however desirable from the standpoint of clarity and simplicity could be applied to the enormously varied forest conditions of this country without leaving so much to the users discretion as to render it, in effect, no rule at all".

It may be possible however, to obtain sufficient indirect information to allow a reasonably accurate estimation of the optimal solution without establishing pre-determined control objectives. If the demand for aircraft could be determined, then the percentage of this demand which could be satisfied by using various levels of aircraft protection, could also be determined. The percentage of demand satisfied could then be compared with the cost of providing that level of protection. This could be considered as the cost portion of a cost-benefit analysis. The benefit portion is at present considered to be beyond the state of knowledge in this field.

The essential consideration of the above is the determination of aircraft demand. As previsouly discussed for the purpose of the present study, demand will be assumed to be related to the number of fires on which the use of aircraft appears to have been required or justified. Initially therefore, this study will determine the number of fires which appeared to have required the use of aircraft, and the number and types of aircraft apparently required, and then attempt to meet this demand in the most efficient manner possible. It should be emphasized that more than one aircraft will be required on most of the larger fires. The model will attempt to determine the actual number required, and will consider each aircraft requirement as a separate demand. The same will be true for multiple simultaneous outbreaks. Once aircraft are assigned to perform a task, they will be assumed to be providing a useful output in terms of helping to control the fire. During the latter stages of this study, an attempt will be made to measure and compare aircraft effectiveness with corresponding costs.

It is generally agreed that aircraft are most effective during the early stages of a fire when their output is significant in relation to the total effort required. For this reason, this study will concentrate on the first working period of the fire's existence.* When insufficient aircraft are available to meet the total demand, the primary objective will be to satisfy first work period demand whenever possible. All subsequent demand on large multi-period fires will be considered secondary or supplementary demand, and will be satisfied only if there is no first period demand outstanding. Furthermore, initial attack demand, or that demand which occurs between the time of detection and arrival of the ground crew will have a higher priority than support demand, or that demand generated after a crew arrives, even though both may occur during the first work period. Multiple fire outbreaks will be handled in order of occurrence. Any "aircraft" fires which do not receive aircraft service will be considered as unsatisfied demand.

One cannot simply use the total number of hours during which a fire burned to estimate aircraft demand (Maloney 1966), because presumably, an increase in the use of aircraft will reduce the total time required to control a fire. This is particularly true where a small fire is attacked quickly in simulation, when there was a considerable delay in real life. If there is no reduction in the total

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* The time between detection and 10 a.m. the following day.

time required to control a fire, there is probably no justification for aircraft use. Therefore we are directly confronted with the problem of determining "what would happen if...". By devoting the major consideration to the first working period only, the amount of effort involved is greatly reduced.

It is fully realized however, that the requirements for aircraft on the second and subsequent periods of a multi-period fire cannot simply be ignored. With respect to this supplementary requirement, some simplifications are justified. The fact that some fires will not be controlled during the first work period indicates that for these fires, all reasonable control efforts are not adequate, and in many cases probably ineffective, as was suggested by Miyagawa (1969) for the peak period of fires in Alberta during the spring of 1968. It is reasonable to assume therefore, that additional aircraft will probably have only limited effectiveness, and the total reduction in time will probably be small. As a result, the number of daylight hours during which a multi-period fire burned will be considered to be a reasonable estimate of supplementary aircraft demand, with the realization that it will be somewhat in excess of what would have occurred had additional aircraft been available.

The next two sections discuss the individual models and components which will be used to evaluate each fire. The entire procedure is outlined in a simplified block diagram which can be found at the end of Section C (Figure 10).

B. Rules for Aircraft Dispatch

Prior to establishing a set of rules to be used for aircraft dispatch, a number of terms require definition as they will be used in the present study:

(1) Aircraft requirements:

a) Not needed - dispatch will not take place

b) Optional - dispatch depends on a more detailed analysis of the specific situation (to be discussed subsequently)

c) Required - dispatch is automatic - note situations which over-ride the two previous categories:

(i) Multiple fires - a number of simultaneous fires occurring during the same period which are in excess of the ability of the control organization to simultaneously attack. This number will be determined separately for each administrative unit, and for various fire dangers.

(ii) Unusually high values - Timber values are of little consequence; the primary concern is the protection of a settlement, industrial complex or other specific development with a very high value per unit area.

(iii) Above average values - Timber values are secondary; other land values predominate such as: an important resort or fishing area, picnic or camping ground, a particularly important watershed, areas closed to centers of population, etc.

(2) Burning period: time interval during which fires are likely to spread at relatively rapid rates - 10 a.m. to sunset (Anon, 1963)

(3) Fire Class:

a) Initial attack fire - a fire which is easily and quickly controlled by a fairly small suppression force, reinforcements are not normally required.

b) Extended attack fire - Several crews are required, heavy equipment is probably also necessary.

(c) Major fire - Fire management organization and fire camp established multi-period effort, reinforcements from co-operative organizations required, hired equipment.

(d) Campaign fire - Fully developed management organization, decentralized operations, non-forestry personnel required.

(4) Fire size:

a) Actual (A_1, A_2, etc.) - in the form of data from fire reports (for example: fire size at detection, or initiation of suppression).

b) Expected (A_E) - the computed size at the end of a specified time interval, considering both free growth and suppression efforts.

c) Potential (A_P) - The potential size which a free burning fire would attain by the end of the first work period if no control action were applied.

(5) First work period - The time interval between detection and 10 a.m. the following day.

(6) Second work period - Time interval between 10 a.m. on the day following detection and 10 a.m. on the third day.

(7) Tactical objectives - A fire is:

a) Being held if - A control line has been constructed around or in front of the head of the fire only. This can also be considered as; stopping the forward rate of spread.

b) Contained if - a control line, or at least a cold trail has been completed around the entire perimeter.

c) Controlled if - In addition to "b)", sufficient mop-up has been done to insure that the fire is not likely to jump across any control lines or cold trails.

d) Extinguished or put out if - Mop-up has been completed to the point where no further effort is required.

The percentage of the perimeter which will be considered as the head will be discussed in the fire model.

A great deal of thought and consideration went into the derivation of the rules presented in Table 1. In fact, several entirely different approaches were used before the particular one was adopted as having the fewest number of faults, combined with the greatest degree of applicability. Admittedly, the rules are far from perfect and perhaps not applicable in all situations. However, it is hoped that they are reasonably applicable in the majority of situations which will be encountered.

Examination of the rules discloses that they are not intended to be tactical objectives. They do not state a limit for the final control of all fires either in terms of time or size. They merely state that if ground forces alone can't accomplish the stated objectives, it is probable that the use of aircraft is justifiable due to the potential damage which could occur. It can be noted that the objectives are presently stated in terms of potential fire size. It is recognized that economic values would be more appropriate but such values are not available. Since fire size is related to total damage, it is used, of necessity, as a second choice. Perhaps, during the course of the study, the separate investigations previously referred to will

RULES FOR AIRCRAFT DISPATCH

Potential Fire Class	For fires with a potential size at the end of the first work period of:	Aircraft dispatch is: Not needed if ground crews can:	Optional if ground crews can:	Required if:
Initial attack	$f \leq 1$ acre	Commence firefighting before the end of the first work period.	Commence firefighting before the end of the second work period.	Optional objectives cannot be attained.
Initial attack	1 acre $< f \leq 10$ acres	Stop forward rate of spread before the end of the first work period.	Commence firefighting before the end of the first work period.	Optional objectives can't be attained, or multiple fires, or unusually high land values.
Extended attack	10 acres $< f \leq 100$ acres	Contain fire before the end of the first work period.	Stop forward rate of spread by the end of the first work period.	Optional objectives can't be attained, or unusually high values, or multiple fires.
Major	100 acres $< f \leq 500$ acres	Contain fire before the end of the first burning period.	Contain fire before the end of the first work period.	Optional objectives can't be attained, or above average values, or multiple fires.
Campaign	$f > 500$ acres	---	Control fire before the end of the first burning period.	Optional objectives can't be attained, or above average values, or multiple fires.

derive economic values which can be used to replace potential size, in which case such a substitution will be made.

The objectives are more stringent and hence more difficult to achieve as the potential fire size increases. This simply means that as potential fire size increases, the probability of aircraft being required increases also. It also means that the strength of the initial attack force will have to be greater both because the objectives are more stringent and because the fire is spreading more rapidly.

The preceding discussion is in line with present operating procedures, in that as fire danger increases, the strength of the initial attack force is increased correspondingly. The reasoning is simply that the potential damage which could be caused by a small fire which required several periods to extinguish is generally several orders of magnitude less than that which could be caused by a large multi-period fire.

The intent in designing the rules was to automatically dispatch aircraft whenever the potential damage was considerable or the probability of controlling the fire by the end of the period immediately following the last period referred to in the optional use category would be in doubt. In addition, special circumstances such as multiple outbreaks or unusually high land values over-ride other considerations. On the other hand, those fires which could be quickly controlled by ground forces at a fairly small size, would not require the use of aircraft. The optional category is for those fires which apparently can be controlled by the subsequent period, but the total damage may be sufficient to justify the use of aircraft.

Some additional comments are required with respect to the optional use category. To a first approximation, the damage incurred as a result of a forest fire is a function of the size of that fire. Therefore, the maximum potential damage which could occur on the first day is related to the potential fire size (A_P). Note that in all cases where the optional category is used, little additional damage can be expected to occur during subsequent periods because either the rate of spread is low or the fire is under control or nearly so. This statement of course, assumes that no major weather changes occur during subsequent periods. It is felt that such would be the case for the majority of fires under consideration.

The minimum damage which could occur on the first day without the use of aircraft can be estimated by the expected fire size (A_E) which considers the modifications to free growth which are brought about by ground suppression efforts. To a first approximation, the larger the difference between the two (A_P-A_E) the more effective are the ground forces in controlling a particular fire. Where the differences are small or negligible, further suppression effort may be justified.

The maximum reduction in damage which could be brought about through the use of aircraft is clearly the difference between A_E for ground suppression and the size of the fire when the aircraft could start suppression (A_S). The maximum reduction could be achieved only if the aircraft was able to instantly reduce the rate of spread to zero.

With the exception of spot fires, the actual reduction will be somewhat less than the maximum possible. Since the purpose of the initial analysis is only to eliminate those fires which to not appear to have required the use of aircraft, it is considered sufficient for the present time to simply eliminate those fires where the maximum possible reduction in area burned does not justify the expense of using aircraft. It would be more appropriate if the value of the saved areas could be compared with aircraft costs. This may in fact, be attempted in the later stages of the study. Those fires where the maximum possible reduction in damage appears to justify the use of aircraft, will be included in the final sample, to be analysed in greater detail, subsequently to determine the expected reduction. This will require the development of aircraft attack models which will not be considered in the present paper.

It should be pointed out that the acreages listed in the dispatch rules are intended to be illustrative rather than applicable to a particular situation. The actual acreage used on any particular administrative unit will be adjusted according to the relative acceptable area burned values which will be determined for each unit. The relative acceptable area burned values include some consideration of the economic values of the land at least from the forest industries standpoint. The acreages used in the examples are size class boundaries presently used on most fire report forms, with the exception of the boundary between the first and second class. Since the acreages refer to potential growth over several hours rather than size at control, it was felt that one acre would be more appropriate than one-quarter acre.

C. Fire Growth

1. Free Burning Growth Model

In order to apply the aircraft dispatch rules in a manner which simulates reality, a fire growth model is needed which can predict the potential area of a free burning fire at any time, given the area at the time of detection and other pertinent parameters. Since it is known that the area of a fire when detected is in many cases little more than a guess, present plans provide for updating the prediction based on area at the start of suppression, which is perhaps somewhat more reliable. Since fire area is the parameter which is most often found on individual fire reports, it was decided that in order to simplify the data acquisition problems the model would be based on this variable directly. Also to be included are: fuel type, the new Canadian Fire Weather Index (Anon., 1969) and duirnal weather variations*.

As with many other natural phenomena, if all controlling variables remain constant, the rate of increase of the area of a fire is related to its size. From fire reports, the following relevant parameters are generally available:

a) A_1 - area at the time of detection.

b) A_2 - area at the time of initiation of suppression.

c) T_1 - Time of detection.

d) T_2 - Time of initiation of suppression.

The average area between detection and the start of suppression is given by:

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* See Appendix 1 for a discussion on the influence of topography.

(1) $$\bar{A} = \frac{A_1 + A_2}{2}$$

And the average rate of increase between detection and the start of suppression is:

(2) $$\frac{\partial \bar{A}}{\partial t} = \frac{A_2 - A_1}{T_2 - T_1}$$

From the mean value theorem, there is a point on the curve where $\frac{\partial \bar{A}}{\partial t}$ equals the actual rate of increase. Since the degree of curvature for the curves under consideration is assumed to be small (see Figure 3), the error incurred by assuming that this point is at $\bar{A}$ should be slight. Applying this assumption to equations 1 and 2, we get:

(3) $$\frac{\partial \bar{A}}{\partial t} = \frac{\bar{A}}{T_2 - T_1}$$

An analysis of fire records (Newburger, 1966) indicated that the general function $\frac{\partial A_t}{\partial t}$ was of the form:

(4) $$\frac{\partial A_t}{\partial t} = \frac{\partial A_1}{\partial t} \left[\frac{A_t}{A_1} \right]^k$$

where: $\frac{\partial A_t}{\partial t}$ = the rate of area increase at time T

$\frac{\partial A_1}{\partial t}$ = the rate of area increase at the time of detection

k = slope of the line obtained by plotting $\frac{\partial \bar{A}}{\partial t}$ as a function of $\bar{A}$ (see Figure 4)

Figure 3. $\frac{\partial A}{\partial t}$ as a function of A

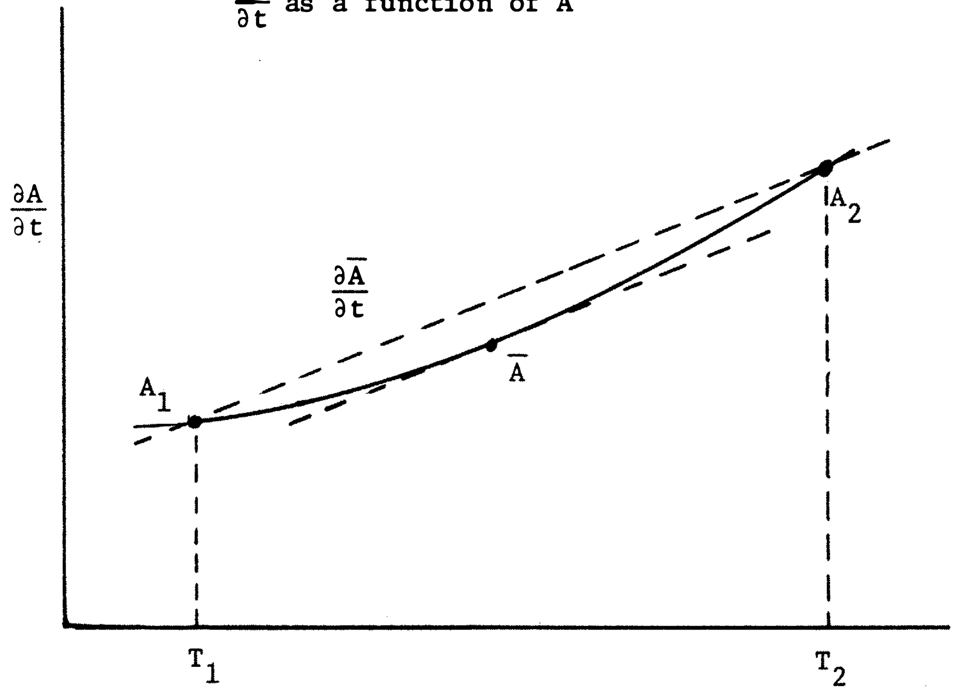


Figure 4. $\frac{\partial \bar{A}}{\partial t}$ as a function of $\bar{A}$

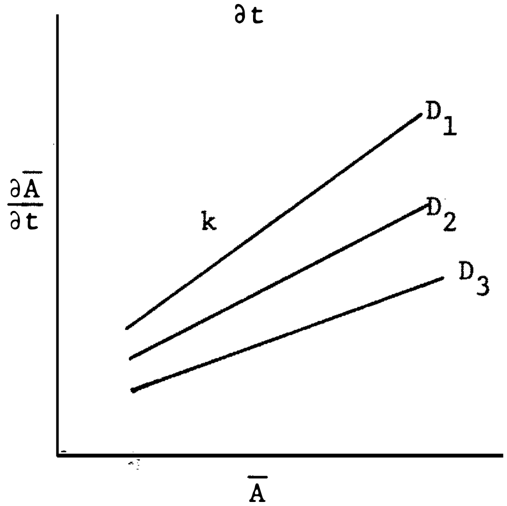
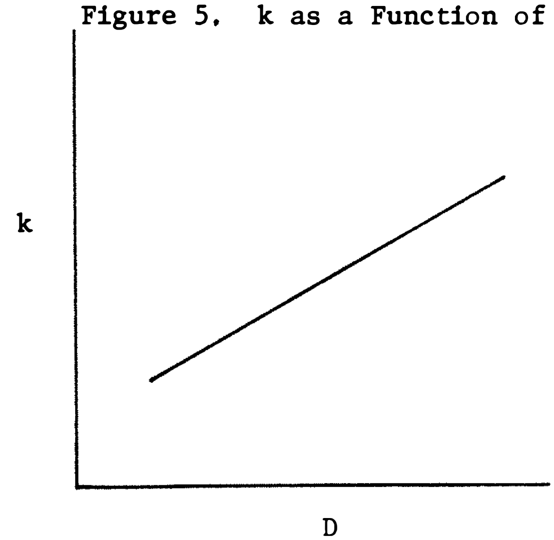


Figure 5. k as a Function of D



Integration gives;

$$(5) \qquad A_t = A_1 \left[1 + \frac{(1 - k)\,(\partial A_1 / \partial t)}{A_1} . t \right] \frac{1}{1 - k}$$

We now have to determine values for k and $\frac{\partial A_1}{\partial t}$. At any specific place and point in time, k is a function of fire danger. Whether it is linear or not cannot be determined until an analysis of past fires and fire danger records is completed. For the purpose of this paper the assumption will be made that:

$$(6) \qquad k = a + bD$$

where: a & b = constants

D = fire danger

This function is plotted in <u>Figure 5</u>, and is of course subject to verification. The actual form however, does not affect the remainder of the discussion.

Examination of <u>Figure 3</u> discloses that Equation (3) can be rewritten as:

$$(7) \qquad \frac{\partial \bar{A}}{\partial t} = CD + k\bar{A}$$

if we substitute A_1 for $\bar{A}$ and combine with equation 6 we have:

$$(8) \qquad \frac{\partial A_1}{\partial t} = CD + A_1 \ (a + bD)$$

With the preceding series of equations, it is possible to compute the rate of growth and size of a fire at any subsequent time t, given the size at detection, and fire danger, assuming that all other factors remain constant.

The most essential and difficult variable to quantify will be k. Further discussions of the procedure involved are necessary. A separate distribution of the expected values of k, will be determined for a number of classes of fire danger. The number of classes involved will be governed by the sensitivity of k and the smallest danger class which contains a sufficient number of observations for a meaningful analysis. A distribution will be used because it is anticipated that even with an accurate fire weather index at a particular weather station, the aerial variability of rainfall (Webb, 1968) will induce considerable variations in fuel moisture and hence fire behaviour in the general area surrounding the weather stations.

This procedure alone is not sufficient however as meteorological parameters, and hence fire danger, are constantly changing throughout the day. However, the amount of work involved in obtaining a complete weather history for every fire is far too formidable to even be considered. This can be approximated however, if one assumes that the normal diurnal cycle will prevail. In fact, this probably will be the case for the majority of fires. Therefore, A_t will be computed on an hourly basis from the time of detection and revised if necessary at the start of suppression to the end of the work period. A revised hourly fire danger will be used, based on the normal diurnal cycle. This procedure should yield greatly improved results over simply assuming a constant fire danger, as has often been done with previous large scale models.

The fires will be further stratified into major fuel type classes where possible. The determination of the distribution of k will be done independently for each class. In this way it is hoped that the final distribution of the expected values of k which are obtained will be sufficiently accurate to allow meaningful results to be obtained with the fire growth model.

2. Fire Growth During Suppression

Since the dispatch rules require some knowledge of the effectiveness of ground forces, the fire growth model has to be extended to the period after suppression commences. The basic approach to be used will be to reduce the potential free growth rate based on the ratio of line constructed to total perimeter. The reasoning is as follows;
If a control line is constructed around a portion of the perimeter of a fire, that portion can no longer expand, assuming that the fire does not jump the line. The fire can expand only at the uncontrolled portions of the perimeter. At this point a simplifying assumption is required: the reduction in free growth rate is directly proportional to the percent of the total perimeter which is controlled. That is, a ten-acre fire with a free growth rate of four acres per hour which has a line half way around it will increase in size at a rate of two acres per hour.

This assumption requires some elaboration. The actual reduction in growth rate is highly dependent on the location of the line. A line built in front of the head of a fire will have a considerably greater effect on growth rate than its length would indicate. Conversely, a line around the rear portions would reduce the rate of spread relatively little. This poses a problem in that each fire is attacked differently, depending on a great number of circumstances. There is no data available which can be used to determine which portion of a fire should have been attacked first. Therefore, for the purpose of the model, there is no choice but to use an average reduction based on the ratio of line built to total perimeter.

The effects of such an assumption on the results of the present study are not necessarily as great as one might think them to be. On smaller fires a crew is most likely to attack the head directly causing a considerable reduction in the rate of area increased. However, it is very likely that the majority of such fires will not require the use of aircraft, regardless of what reduction is used. Therefore, any errors associated with these fires are of little consequence as the fires will not be in the final sample, on which the airtanker study will be based. On large fires the intensity of the head is often such that it cannot be attacked directly by ground crews. They are forced to work on the flanks and rear, often attempting to pinch off the head. The reductions in rate of area increase in these cases will approximate average values, and therefore the errors should be small. Furthermore, the actual rate of construction at the head will probably be somewhat less than the average because the line has to be wider in order to contain the fire. Conversely, the actual rate of construction at the rear will probably be greater. The decrease in rate of line construction at the head partially offsets the increased effectiveness of that line. Lastly, the method used to determine rates of line construction which will be discussed subsequently, also helps to alleviate this difficulty.

Since tactics are normally determined on the basis of causing the greatest possible reduction in rate of growth, the average values used in the study will probably tend to be somewhat low. This is not considered to be necessarily undesirable, in that it would be better to select some fires which do not quite justify the need for aircraft, than to overlook some which did.

In reality, the reduction is a continuous process. Each foot of line which is built reduces the area rate of growth commencing at the time of completion. Only when the time interval between any two area measurements is zero can it be said that the actual reduction during that interval is equal to the ratio of line built to total perimeter. For all intervals greater than zero the above relationship will not be valid.

Because of this difficulty, a procedure to estimate the reduction in growth rate over periods of one hour has been developed, which will it is hoped, give sufficient accuracy for the purposes of the present study. This period has been chosen to coincide with the hourly revisions of fire danger. The procedure is illustrated in Figure 6 and described mathematically below.

From the size of the fire at the start of suppression (A_2) compute the potential size at the end of one hour (A_h). Determine the fire perimeters which correspond to each of these areas (P_2 and P_h) respectively. This procedure will be discussed in detail in the next section. The

Figure 6. Illustration of the Suppression Model

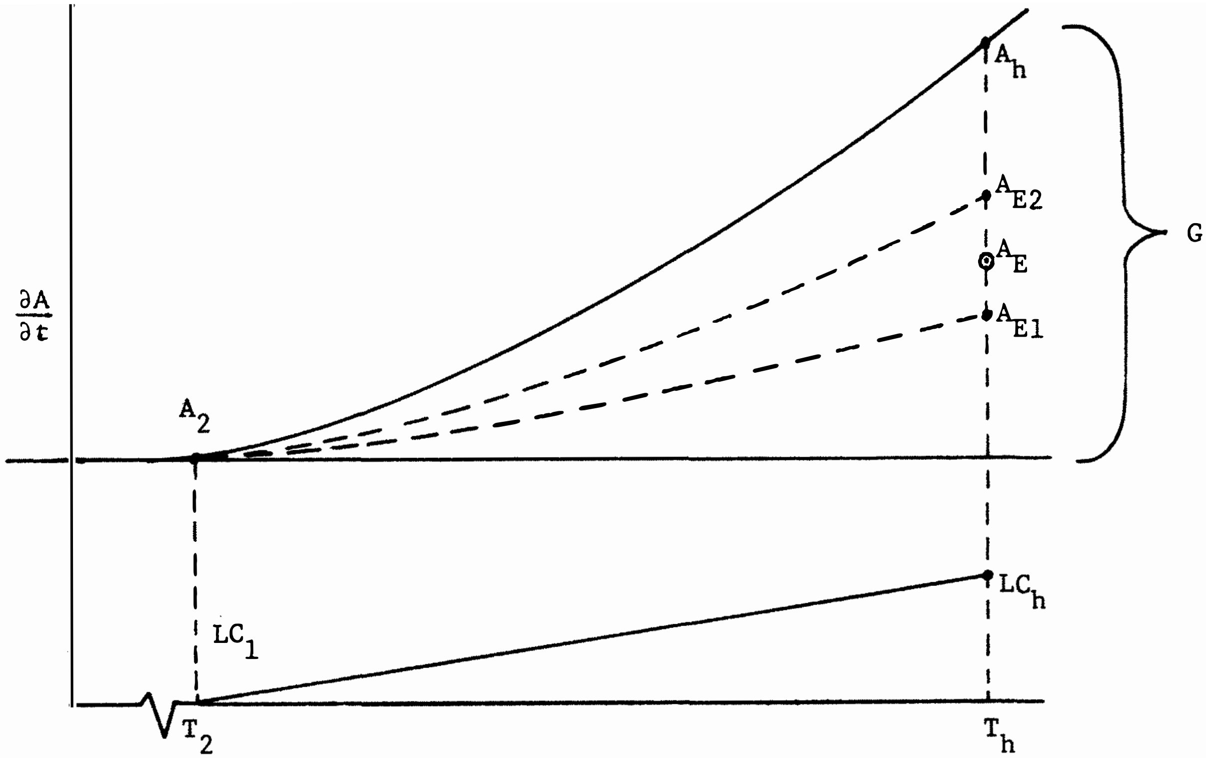
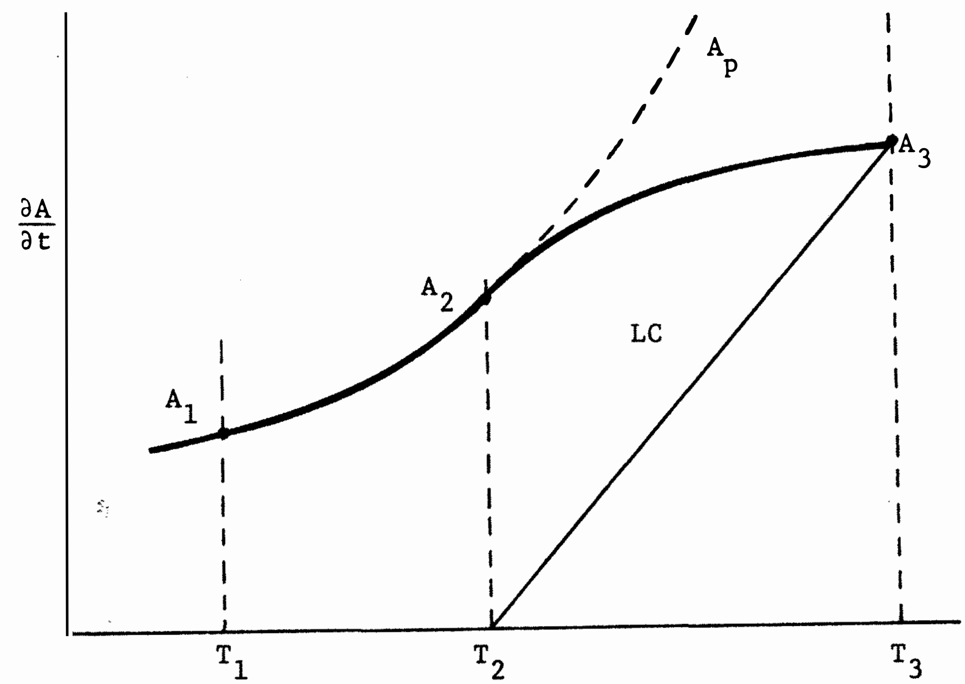


Figure 7. Complete Fire History from Detection to Suppression



potential growth (G) of the area and perimeter during the period is:

(9a) $$G_A = A_h - A_2$$

(9b) $$G_p - P_h - P_2$$

The expected area at the end of one hour is A_h minus a function of G_A which is proportional to the ratio of the amount of line constructed to the total perimeter. The most logical choice of variables would be the amount of line which had been constructed by the mid-point of the hour and the perimeter at that time. Unfortunately, the only two perimeters which are available are P_2 and P_h.

The use of P_2:

(10) $$A_{E1} = A_h - G \left(\frac{LC_1 + LC_h}{2P_2}\right)$$

where LC = length of line constructed,

would yield an area which is lower than the true value, (A_{E1}) because if the fire grows at all, the actual perimeter halfway through the hour will be greater than P_2. Therefore, the computed ratio will be greater than the true value and the reduction of G will be excessive.

Conversely, use of P_h:

(11) $$A_{E2} = A_h - G \left(\frac{LC_1 + LC_h}{2P_h}\right)$$

yields an overestimate of the true value of A_E because the actual perimeter halfway through the hour will be less than P_h. A_{E1} and A_{E2}

are the limits of A_E, as the former assumes zero growth and the latter assumes no line construction. Due to the absence of information which would support any particular method of calculating the actual value of A_E, the most logical choice is a simple average:

$$(12) \qquad A_E = \frac{A_{E1} + A_{E2}}{2}$$

For the second and subsequent hours, the procedure is reiterated by substituting A_E for A_1, and by adjusting $\frac{\partial A_E}{\partial t}$. Since a portion of the fire is now under control, the free growth rate is no longer what it would be for a fire of the same size before suppression. Only that portion of the fire which has not been controlled can expand. Therefore, $\frac{\partial A_E}{\partial t}$ should be reduced by the ratio of line constructed (LC_h) to the total perimeter (P_{AE}):

$$(13) \qquad \frac{\partial_{AE}}{\partial t}\ (adj.) = \frac{\partial_{AE}}{\partial t} \left\{\frac{LC_h}{P_{AE}}\right\}$$

Use of this procedure causes the growth rate to approach zero as the fire line approaches completion, which is the case for fires on which direct attack is used. The total fire history is portrayed in Figure 7.

It will be noticed that this growth model is applicable for direct attack only. The problems associated with indirect attack are so complicated that it was decided not to develop such a model for this study. Furthermore, there is no way to determine from fire reports which type of attack was used, or which would have been better. This means that on larger fires, where the probability that indirect attack actually was used, the model will exaggerate the reduction in rate of growth. For indirect attack, the rate of growth is greater than zero when control is achieved, because the fire burns towards the control line at the free burning rate, and then is instantly reduced to zero as it reaches the line. This problem was considered when the dispatch rules were developed. The stringent requirements for no dispatch on a potentially large fire should ensure that all questionable fires will at least fall into the optional category, where they will be analyzed in greater detail. Borderline cases will always be decided in favour of dispatch.

3. Relationship Between Fire Area and Perimeter

The relationship between the area of a fire and it's perimeter is a complex function which depends on the shape of the fire, the length to width ratio and fire size. To date, most attempts at relating the two variables have assumed either an elliptical or triangular shape of varying ratio between length and width (Hornby, 1936, Pirsko, 1961, Van Wagner, 1969). Stade (1966)assumed the somewhat more complex shape of a lemniscate. These relationships are of limited usefulness in a tactical situation however, where a fire can assume almost an infinite variety of shapes and sizes. For this reason an analysis of the area to perimeter ratio was undertaken as a function of a number of shapes, sizes and length to width ratios. Also, the probability of the occurrence of each shape was considered.

There are two limits to the area to perimeter ratio of any plane surface. The lowest limit occurs when the shape is a circle. The theoretical upper limit is infinity for a triangle whose width approaches zero, as the area is also approaching zero. This shape, is in fact, approaching a straight line. Since the latter condition never occurs in nature, a more practical upper limit has to be defined. A theoretical analysis of the expected fire shape which would result from expected variations in wind speed and directions only, proved to be unsuccessful. It is felt that the main reason is due to the lack of data on response times required for a fire to reach equilibrium. Therefore, the following somewhat more deductive approach was used.

To determine the minimum relative width which a fire is likely to have, the expected ratio of the forward spread to the rear and flank spread must be determined. To a first approximation, the rate of spread of fire backing into a wind or moving at right angles to it is independent of wind speed. The rate of advance is essentially the same as for no wind conditions. The length to width ratio of a fire can therefore be assumed to be the same as the ratio of the rate of spread at the prevailing wind speed to the rate of spread at zero wind respectively. From the initial spread tables presented in the Canadian Fire Weather Index, the maximum spread at a wind speed of 25 m.p.h. is 7.6 times the maximum spread at a wind speed of 0 m.p.h. The fact that the initial spread index considers fine surface fuels only, should not significantly affect the ratio between the two relative rates of spread.

By dividing the total wind speed range into ten 2.5 m.p.h. classes, the ratio of forward spread to lateral spread at the center point of the upper class is 7 to 1. If one assumes a relative spread of 1 laterally and back from the origin, and a relative forward spread of 7, the ratio of the fire length to width at the widest point is 4 to 1. The limits are therefore between a shape with a length to width ratio of 1 to 1 and 4 to 1.

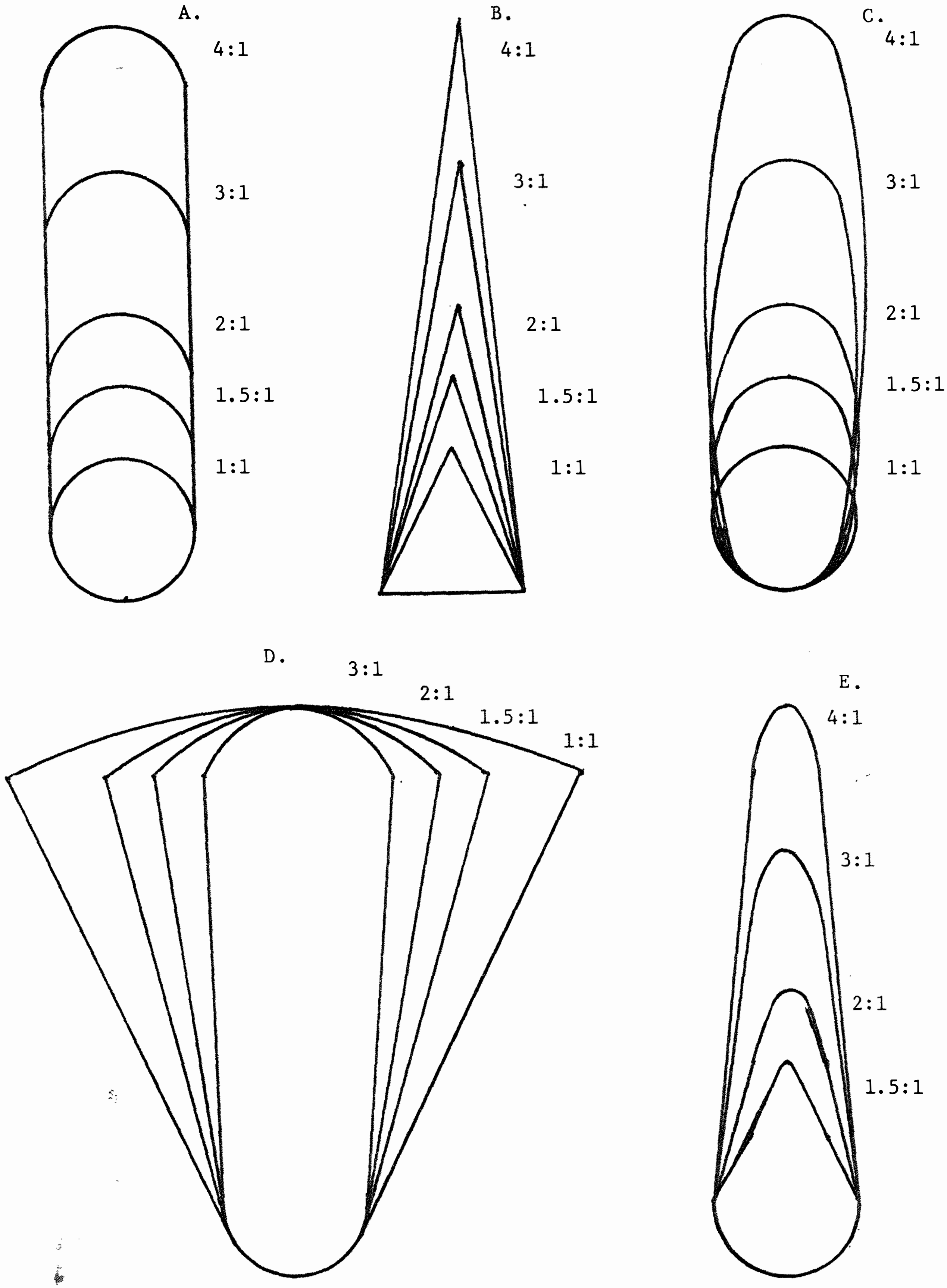
A series of constants (α) relating perimeter to the square root of the area of a fire are presented in Table 2. A number of different shapes were analyzed. The first two are respectively the lowest and highest values which the constant can have. These shapes are: a rectangle with semi-circular ends (a) and a triangle (b) of varying length to width ratios. The shapes are illustrated in Figure 8. The actual constant will have to lie between these two values. Also listed are the wind speeds which correspond to the specific length to width ratios.

Table 2: Values of (α) for $P = \alpha\sqrt{A}$

Length to Width Ratios	a	b	c	d	e	Windspeed m.p.h.*
1:1	738	953	738	845	---	1.2
1.5:1	749	1003	761	855	843	8.6
2:1	794	1068	809	880	897	13.6
3:1	889	1206	907	932	989	20.0
4:1	982	1339	1012	---	1105	24.1

* As measured at a "standard" forestry station.

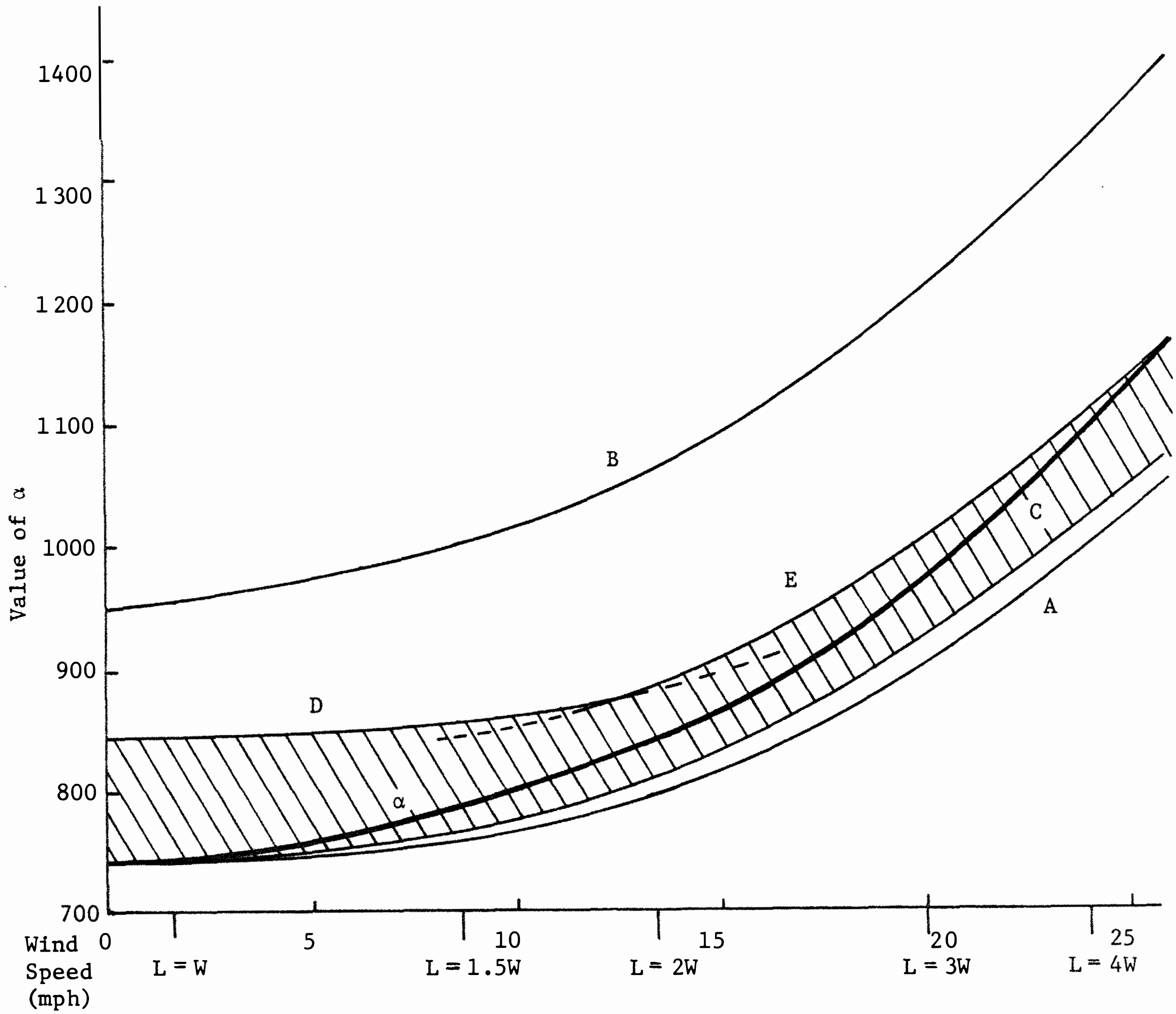
Figure 8. Fire Shapes



As with the straight line, a fire is not likely to be rectangular with semi-circular ends. Therefore, the values of α for an ellipse (c) have been determined. This is perhaps the most common fire shape which occurs at low to moderate wind speeds. Similarly, a true triangular shape does not occur in nature. The perimeter on the back edge of the fire will probably be semi-circular. There will also be a certain amount of curvature at the head of the fire. For this reason, the values of α for modified triangles were determined. The modified triangles assume a semi-circular back edge and an arc at the head. Two modified triangles had to be considered: One in which the width at the head of the fire is greater than at the origin (d) and one in which the opposite is true.(e). Note that if the width at the head equals that at the origin, shape (a) is produced rather than a modified triangle. For the diverging triangles (d) the width at the point of origin was assumed to be one-fourth L, the length was held constant, and the width at the head varied. For the converging triangle (e) the width at the origin was held constant, as was the width at the head which was set equal to one-half that of the origin, and the length varied. While inumerable other shapes and combinations of dimensions could have been analyzed, it was felt that sufficient information can be obtained from the data which is presented in Table 2.

The data presented in Table 2 have been plotted in Figure 9. The theoretical limit of the value of α as a function of wind speed lies in the region between curves a and b. A somewhat more realistic set of limits would be within the region between curve c and the greater of either d or e. Note that both of these last two curves do not extend

Figure 9. Value of α as a Function of Wind Speed for Selected Shapes



far beyond the point where they cross. This is because both of the functions either do not exist or have no meaning, as the ends of the wind speed range are approached, in the regions where the other curve is greater.

The simplest method of selecting a specific function from all those which could exist in the above-mentioned region would be to select a curve which lies approximately halfway between the limits. A bit of thought permits a somewhat more realistic choice however. Whenever the winds are light or nil, the fire shape is most likely to be circular or nearly circular. Whenever the winds are very strong, the fire will be very long, and in fact, probably relatively narrower at the head than near the point of origin. On the basis of this reasoning, a smooth curve for α (heavy line in Figure 9) was selected so that the end points approached the minimum limit in the absence of wind and the maximum limit at maximum wind speeds. This function is:

$$(15) \qquad \alpha = 738 + .245\, W^{2\cdot 3} \qquad (W \leq 25)$$

Where: W = wind speed in m.p.h.

The last point to consider is the fact that a fire does not assume the final shape that it will take until it has attained a certain size. The ultimate example is a spot fire which is always approximately circular. Therefore, the value of α for small fires should be somewhat lower than the value which would be determined by using wind speed alone, except where the wind speed is zero. In the absence of data, it was assumed that a fire of 100 acres or more will have attained it's final shape. The reduction of α for all smaller fires is assumed to be proportional to the ratio A/100. Therefore, the final equation for α is:

$$(16) \qquad \alpha = 738 + (.245\, W^{2.3} \cdot \frac{A}{100}) \qquad , \qquad A \leq 100$$

With equation (16) it is now possible to relate fire perimeter to fire area as a function of wind speed. While it may be argued that quite a number of assumptions have gone into the derivation of the above-mentioned relationship, when one considers the total possible relative error, it is not very large. It varies from slightly less than 15% of the actual value at no wind to slightly less than 10% of the actual value at maximum wind speeds.

One last point with reference to perimeter is what portion of the perimeter to consider as the head of the fire for the purpose of stopping the rate of spread. Again, looking at the lower limit, it can be assumed that even under no wind conditions, a circular fire will have some sort of a definable head, due to topography, fuel type differences, etc. Therefore, half of the perimeter of a circular fire will be assumed to be the head. At the extreme end of the wind scale, the converging modified triangle has a head which is .14 of the entire perimeter. The ratio of head to perimeter is a linear or almost linear function of wind speed for all shapes. In the same manner as for the derivation of α, a line was chosen which passed through the appropriate maximum and minimum values of h:

(17) $h = .5 - .0152\ W$

Where: h = ratio of head to total perimeter (%)

W = wind speed in m.p.h.

It should be pointed out that the relationship presented in Equation 17 is such that the amount of head for a large, fast spreading fire will be a smaller proportion of the total perimeter than for a slow moving circular fire.

4. Suppression Model for Ground Forces

The rate of line construction on a particular fire has classically been considered to be a function of the intensity of the fire (related to the width of line required); the resistance to control offered by a particular fuel type and ~~for~~ terrain; and the strength of the attack force. More recently, other factors such as physical conditions of the crew, leadership skills, and crew activity prior to arrival at the fire, are thought to be of equal or perhaps even greater importance than the previous factors. (Davis, 1969). These latter factors are generally not predictable or even measurable. For this reason, a distribution of expected rates of line construction will have to be determined. Lindquist (1969) indicates that the probability distribution can best be described by a Gamma probability function. This hypothesis will be tested in the current study.

In addition to the above, fires may or may not be fought during the night, depending on administrative policy and the urgency of a particular situation. Furthermore, all of the above variables are interrelated. The strength of the attack force is normally based on expected rate of spread, intensity, and resistance to control. In addition, for larger fires, the strength of the attack force is often limited by the amount of available resources. Furthermore, as discussed previously, the wide variety of tactics which can be employed, and lack of knowledge of the relative effectiveness of each, precludes the determination of a model which considers each tactic individually.

Due to the above-mentioned difficulties, the decision was made to attempt to obtain the necessary rate of line construction data from the individual fire reports. If one divides the perimeter of a fire (P_3) by the elapsed time between the start of suppression and control ($T_3 - T_2$), the average rate of line construction during that interval can be determined. If parts of a fire were cold trailed or patrolled only, this will be reflected as an increased average rate of line construction for a particular fire. Strictly speaking therefore, the above-mentioned rates would be more correctly referred to as: average rate of control of the fire. Since rate of control is a rather nebulous term, rate of line construction will be used, with the understanding that it integrates all control factors.

To make the average rate applicable for ground forces only, all fires on which aircraft were used will be eliminated. If one considers only those fires which are controlled during the first working period, many of the difficulties associated with the random arrival of reinforcements are eliminated. Furthermore, if one further stratifies the sub sample by separating fires controlled during the first burning period from those controlled during the first working period, the reduction in the rate of line construction at night can be estimated.

The overall average value thus obtained is for all combinations of equipment and tactics which have been used in the past. Because a crew can vary from a single patrolman to a number of bulldozers, tankers and several hand crews, the total range in average rates of line constructions is expected to be considerable. For this reason, an overall average of all of the above would be of little use in a specific fire control situation. To obtain more meaningful values, the averages should be for crews of similar sizes and configurations.

It is possible to indirectly stratify the full set of fires by expected relative strength of attack crew, without actually having knowledge of what in fact was used and without developing a complex attack model. Since the availability of co-operating as well as regular suppression forces varies between administrative units, it is necessary to consider each unit as a separate sample. In fact, the area protected by a single ground station should be considered separately. While reinforcements from adjacent units might often be required, their availability with respect to a particular unit would also be fairly constant. The use of manpower and equipment from co-operative agencies would be reflected in increased average rates of line construction for a particular unit. This is important, as co-operative agencies often play a significant role in fire suppression activities, yet they are not listed as part of the major organization, and hence would otherwise be overlooked by the attack model as a potential source of manpower and equipment.

With a reasonably uniform available force, it is necessary to determine the proportion of that force which will be dispatched. One of the major governing factors is the potential fire size. More men and equipment are dispatched to a potentially bad fire than to a small one. Therefore, each class of potential fire size will be considered as a separate sample. Multiple fire situations will have to be considered separately, as the forces available for the second and subsequent fires will always be less than prior to the first one. To a first approximation, if the protected area for each sample is sufficiently small, the range in strength of attacking forces which are dispatched to individual fires within a size class should be fairly small.

The above is only a fairly gross estimate however, because expected travel time and difficulty of control also affect the strength of the crew which is dispatched. With respect to the first variable, fires will be further stratified by travel time classes. The second variable has a twofold effect on the rate of line construction. Initially, it may affect the decision as to the size of crew to dispatch, in that more men are sent to a fire where the rate of line construction is expected to be low. Conversely, the degree of resistance to control will affect the rate of line construction of whatever forces are used. Each of these last two effects tends to offset the other. Therefore, the sample will also have to be stratified by major fuel types.

Upon completion of the stratification, the expected rate of line construction will be computed for all samples where the sample size is sufficient to allow a certain degree of confidence to be placed in the results. The results will then be extrapolated to all similar areas which have an insufficient sample size. Through this procedure it is hoped that reliable expected rates of line construction for a particular fire can be determined without having to solve problems of dispatching various sizes of crews and types of equipment and determining the relative effectiveness of each.

5. Travel Time

In order to apply many of the previously discussed models, the time required to travel to a fire must be known. The times given in the individual fire reports are not necessarily optimal travel times for ground transport. In all cases where aircraft transport was used, the expected ground travel time will have to be computed before a comparison can be made. An analysis of travel times (Newburger, 1966) indicates that for many fires, there is often a delay of several hours or even days. When a slowly spreading fire is detected late in the day, it is quite common to dispatch crews only at the first light on the next day. Therefore, the travel times listed on the fire reports will, in many cases, be far in excess of the actual time required to travel to a fire by surface transport.

Because of the above-mentioned difficulties, it was necessary to develop a procedure for computing expected travel time. The possibility of using an iso-travel time map (Maloney, 1966) for each station was discarded due to the amount of work which would be involved for a study of this scope. The procedure which will be used is as follows. Each province will be divided into a grid system with each block within the grid having dimensions of 5 X 5 minutes of latitude and longitude. This is an approximately rectangular shape with dimensions of about 4 X 5 miles at 45° north latitude. For some areas such a block size might prove to be too small to be practical. It is anticipated that block sizes might have to be expanded to anywhere from 10 to 20 minutes on a side for some areas. The total set of fires will be edited and the following will be deleted:

(a) All fires which have missing data;

(b) All fires for which aircraft transport was used;

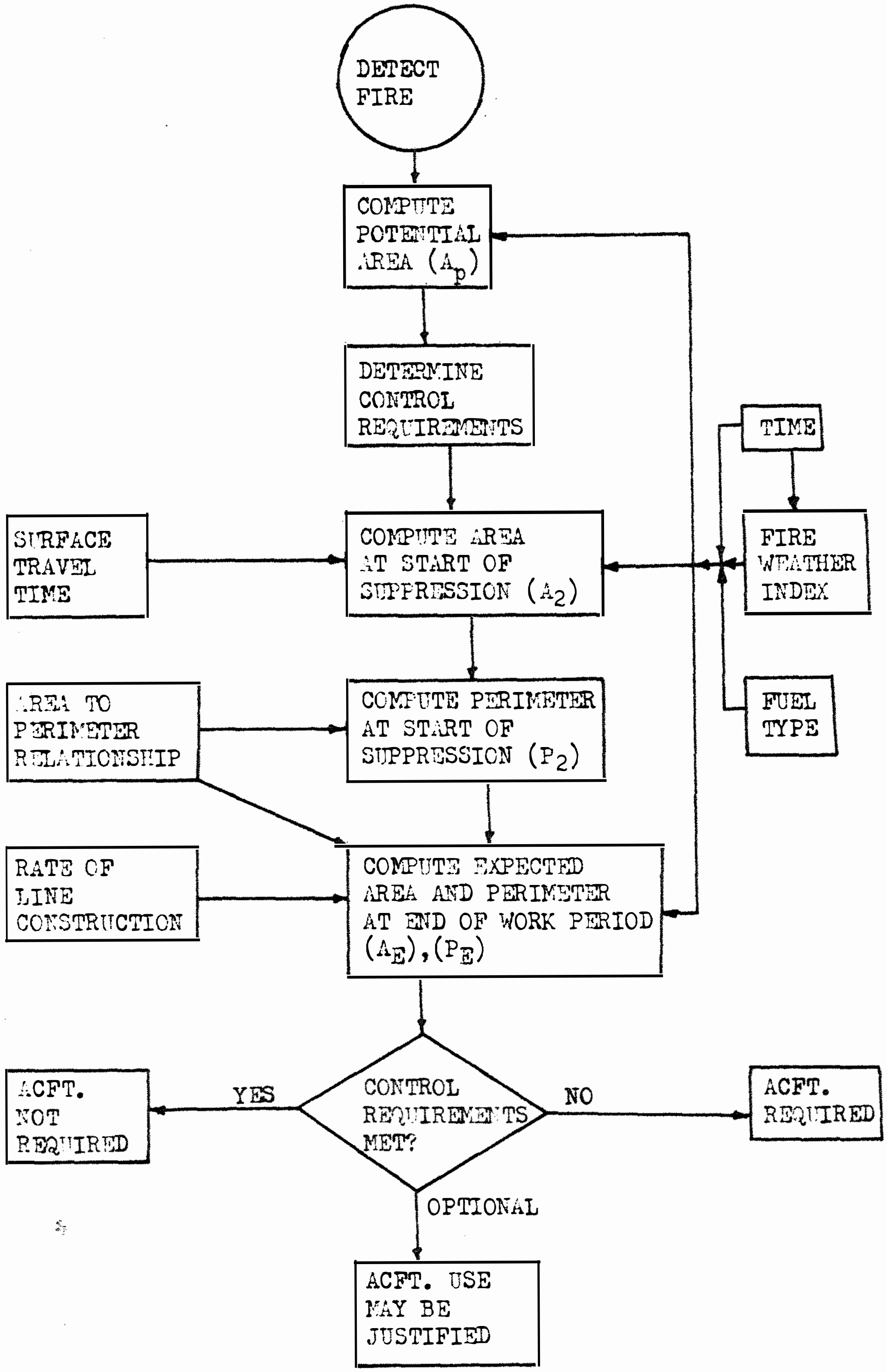
(c) All fires which had a travel time more than 20% greater than the maximum expected travel time to the most remote section for which a particular ground station is responsible.

The average travel time to the remaining fires which have occurred within each block will be computed and the minimum travel time to a particular block will also be recorded.

If there is a good road network in a particular block, it is expected that the difference between the average and minimum travel times for that block will be fairly small. If there are no roads, or only a single road in one corner of a block, the difference in travel times could be great. Therefore, average travel times will be determined separately for fires within one-half mile of a road, and for fires which are more than one-half mile from a road. This will permit the use of more accurate expected values for individual fires.

With this procedure, all of the local topographical factors which affect the rate of travel will be integrated into the final expected travel time for a particular block. This avoids the necessity of having to develop a travel time model which would incorporate all of the individual factors. In the analysis, the expected travel time for a particular block will be used rather than the recorded value. This should eliminate the difficultires which would be associated with delays which were experienced in the past. It will also allow a comparison of aircraft travel times with surface transport times. Since this paper is concerned with ground forces only, the procedure for determining aircraft travel time will be discussed in another paper.

Figure 10. Simplified Block Diagram of the Fire Evaluation Procedure



D. Input Data

Since the model is empirical in nature, some comments on the validity of the input data would be in order at this point. For some of the data (fuel type and slope) there is no reason to suspect any significant errors other than missing observations. For T_1 and T_2 the measurement is quite straightforward and there should be no errors except those which result from bias. Examples of bias would be early reporting on initiation of suppression for payroll or administrative purposes, or in an attempt to conceal errors in dispatching. If the errors induced by bias are sufficient to significantly affect the final outcome, they will probably be noticeable. If such errors are small, their effect on the final outcome will probably be minor.

Potentially significant sources of error are A_1 and A_2, with A_2 possibly somewhat more reliable. A_2 is, at best, an ocular estimate made by a knowledgeable individual upon arriving on the scene of a fire. The pressure of other duties and an often confused situation serve to increase the difficulty of accurately estimating fire size. No doubt, in many cases, the estimate is made after control has been effected or sometime, (even weeks) after the person making the report returns to the office. The procedure is normally to determine the final fire size and use this to estimate the fire sizes at other times.

Estimates of A_1 on the other hand are normally made from considerable distances, except for those fires detected by patrol aircraft. The amount of smoke and width of the smoke column is often the only indicator of fire size which is available to a lookout tower. Fire sizes estimated by untrained members of the general public are of particularly dubious reliability. As with A_2, it is presumed that in many cases, A_1 is estimated from the final fire size or from memory sometime after the fire is controlled.

While the methods of determining A_1 and A_2 are a long way from being scientifically accurate, it is hoped that with a large enough sample and a thorough editing of the data, some useful relationships can be extracted. With slow growing fires or fires whose final size is small, the difference between final fire size and A_1 and between A_1 and A_2 will be small and the estimated values will therefore be fairly accurate. With fast growing and/or large fires the difference between final size and A_2 and between A_2 and A_1 will probably be large, and any errors in the two values will not cause significant changes in the final outcome. This is especially true if the amount of error is the same for both A_1 and A_2. The greatest difficulty is expected to be associated with medium sized fires which are growing at average rates.

All fires where A_1 is greater than A_2 or where one value is missing will be eliminated as being obviously in error. All fires where A_1 equals A_2 will also be eliminated, but a probability of occurrence distribution of zero growth will be determined as a function of $T_2 - T_1$ and fire danger. Finally, all fires whose growth is significantly greater or less than the average for the class will be analyzed in depth to determine if there are any errors in either A_1 or A_2. Hopefully, as a result of this editing procedure, the data which remains will be sufficiently accurate to permit the derivation of valid distribution of the expected values of k.

The last major input for the fire growth model is fire danger. Since the Canadian Fire Weather Index has only recently been published on a provisional basis, index values for the 10-year period under consideration will have to be computed from basic weather data. A preliminary network of approximately 300 stations across the protected areas of Canada has been selected. The objective in the selection was to have no area more than 50 miles from the nearest weather station. While a maximum distance of 25 miles would have provided somewhat more accurate local index values, twice as many stations would have been required, thereby doubling an already huge data processing task. Furthermore, the more stringent objective would have not been met in many areas simply due to a lack of stations. As it is, there are some areas which are more than 100 miles from the nearest weather station which have 10 years of data.

For the analysis of fire records, all fires more than 50 miles distance from a weather station will not be considered. If the variability remains too great, the allowable distance will be reduced to 25 miles. It is only because of the large initial sample size that this will be possible.

Of the 300 stations selected, approximately 200 are climatic stations only. This means that the only information available from these stations is daily rainfall and possibly maximum and minimum temperatures. This necessitates a transfer of some data from the nearest synoptic (hourly reporting) station. Such a procedure will no doubt increase the errors encountered in the local fire weather index values, but there is no alternative as the network of synoptic stations isn't sufficiently dense.

A preliminary analysis indicates that this error will be small. The possibility of obtaining meteorological data from the fire reports was rejected, because the index requires a continuous record for the entire season -- not simply the observations on the day of the fire. If meteorological data is available for a particular fire and it differs significantly from the nearest "network" station, the fine fuel and initial spread indices* will be adjusted accordingly.

When considering all the difficulties and potential sources of error in the various sources of data, one justifiably wonders whether any useful relationships can be derived. For the purposes of a national study, general trends and broad overall relationships are perhaps of greater use than precise mathematical relationships which are generally applicable only in very specific circumstances. It is very easy to become mired in a mass of complex detail. Although the simulation will endeavour to make tactical decisions on each fire individually, the only measure of success or failure to be used will be final average values at the end of a year. If the errors are consistent through each reiteration of the simulation, the final values will be biased in relation to real life, but the relative differences between the effects of the various trials will remain. Since only the relative effects of various tactics are of concern, it is felt that errors in the data will not serve to reduce the validity of any conclusions which are drawn on the basis of these relative differences.

* The remainder of the index changes slowly and no adjustment can be made without several consecutive days of data.

S U M M A R Y

This paper discusses the procedures which will be used to select from the total set of fires which have occurred, those fires which appear to have required the use of aircraft. To determine this, there has to be a set of objectives which a fire control organization is attempting to attain. The merits and faults of various types of fire control objectives which have been used in the past are discussed. In order to determine the intensity of protection which is necessary to attain the objectives, fire control and fire suppression models are needed. A brief review of the models which have been developed in the past is presented. Historically, the basic approach has either been through the application of general averages, or precise laboratory measurements. None of the presently available models are applicable to the present study as they are either too broad or too narrow in scope. The ideal model would be at a scale appropriate to the decision-making process for a specific fire control situation.

The second half of the paper discusses a proposed method of determining the requirements for aircraft. The requirement is assumed to be proportional to the number of fires on which the use of aircraft appears to have been necessary. Future investigations will determine the optimal number and types of aircraft required for each fire. A set of dispatch rules is presented which relate aircraft requirements to potential fire size. The assumption is made that the greater the potential fire area, the greater will be the probability that the use of aircraft will be justifiable. The difficulty of defining meaningful strategic or tactical objectives

which can be applied across the entire country is avoided by assuming that if a fire cannot be controlled by ground forces before excessive damage is incurred, the use of aircraft to aid the suppression effort is justified. No limit of either time or area is defined within which all fires must be controlled. The model assumes that many fires will not be controlled within the limits set by the dispatch rules.

A fire growth model is presented which can be used to determine the potential area of a free burning fire at any time after detection. The variables included are: fire size, fire danger, time of day and fuel type and possibly slope. A second model is presented whereby the growth rate during suppression can be computed. Suppression growth rate is assumed to be proportional to the free burning rate and the percentage of the total perimeter which is uncontrolled. In order to apply the above two models, the relationship between the area of a fire and it's perimeter must be known. This relationship is discussed in some detail, and a function is presented which relates the two variables on the basis of wind speed and fire area.

The procedure which will be used to determine expected rates of line construction is presented. Basically, the fires will be stratified into a number of individual samples where the expected strength of the attacking force is relatively uniform. Finally, a similar stratification procedure is described whereby the expected travel time to any specific area will be determined.

The source of data for all of the above will either be individual fire reports or Meteorological Branch, Department of Transport records. Some of the anticipated errors and potential difficulties associated with the data are discussed.

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APPENDIX I

THE INFLUENCE OF TOPOGRAPHY ON FIRE GROWTH

Fires are expected to spread faster up a slope than down due to the increased opportunity for flame contact with the fuel and convective heating. In contrast, fires are expected to travel more slowly when moving downslope. On the other hand loose burning material may roll down the hill and accelerate the downslope rate of spread beyond what is normally expected, in a manner similar to spotting, except that the distances involved are generally considerably less than for spotting.

The accelerating effect of slope on fire spread has been determined experimentally in the laboratory (Byram et. al. 1966). In a recent study pairs of spread rate measurements with identical environmental and fuel parameters and different slopes were compared (Anon. 1965C). It was found that half of the fires analyzed behaved as expected in response to slope conditions, and half behaved in a manner opposite to that expected. This led to the conclusion that within the accuracy of their rate of spread measurements, the effect of topography is insignificant. They, therefore, ignored slope and slope distribution in their models.

For the present study, a great deal more accuracy is required, however. As a result one would expect slope to play a significant role in the computations. There are several valid reasons why its elimination might not incur too large an error. In the first place, slope information is not given on the fire report forms for many areas. This necessitates plotting the fires on detailed topographic maps and computing the average slope from the contour intervals. This would be a very cumbersome procedure considering the number of fires involved.

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A second argument against considering slope is that fires do not spread upslope indefinitely. There is always a top of the hill or crest of a ridge, after which time fires are moving downslope. Therefore, for a generalized free burning fire growth model, it is not too unrealistic to assume that the duration of upslope spread will be balanced by the duration of downslope spread (although the distances covered will of course be considerably different). In this case average spread values applied to the entire burning period would be appropriate. Furthermore, much of Canada east of the Rocky Mountains is relatively flat, and slope is of little consequence.

One final argument is particularly applicable to the present study and stems from the procedure by which it is being carried out. Since fire growth is being measured by ~~the~~ area rather than linear rate of spread, the increase in forward rate of spread up a slope is partially compensated for by the reduced rearward rate of spread down the slope. This could be particularly noticeable if the wind was blowing downslope. The rate of area increase would be a function of all of these factors, and therefore would not show the effects of slope ~~as~~ nearly as much as if linear rate of spread were being considered.

For all of the above reasons, it has been tentatively decided that slope will not be included in the fire growth model at the present time. This point is still open to question, however, and it is possible that this decision might be changed in certain areas if it can be determined that the inclusion of a slope factor provides a significant improvement in the fire growth model.