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AN ANALYSIS OF THE USE OF AIRCRAFT FOR FOREST FIRE SUPPRESSION: MODEL DEVELOPMENT

by

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FOREST FIRE RESEARCH INSTITUTE
OTTAWA, ONTARIO
INTERNAL REPORT FF-15

CANADIAN FORESTRY SERVICE
DEPARTMENT OF THE ENVIRONMENT
JULY, 1971

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PREFACE

In the first progress report comments and suggestions concerning the analytical procedures to be used in the study were solicited from the reader. There were a significant number of replies, many of which contained valid points and well reasoned arguments in support of alternate approaches. The authors would like to take this opportunity to express their appreciation to all those who have taken time and effort to prepare comments. Many of the suggestions have been incorporated into the study, as the present report will indicate.

As with the first report the analytical procedures discussed in this paper are not necessarily the final ones to be used. Suggestions for alternative approaches will be given due consideration and will be incorporated in the study if they show promise of more accurate results or increased efficiency.

Readers who have suggestions to make are urged to do so as soon as possible. As the study progresses, decisions must be made, many of which are irreversible. Suggestions received on portions of the study which have already been completed cannot be assessed from the same viewpoint as those received on portions of the study which have yet to be completed.

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AN ANALYSIS OF THE USE OF AIRCRAFT

FOR

FOREST FIRE SUPPRESSION: MODEL DEVELOPMENT

by

A. J. Simard[1] and R. B. Forster[2]

OBJECTIVES

This paper is the second of a series of progress reports on an analysis of the use of aircraft for forest fire suppression. The development and background of the project to date is covered in detail in the first report (Simard, 1969), and will not be considered here. The purpose of this paper is a discussion of changes in objectives and procedures which have occurred since the first report was published, as well as new procedures which have been developed. In addition, those procedures which haven't been altered are summarized in this report so that it is complete by itself. As with the first report only general comments and procedures are presented. Detailed discussions and numerical results for specific topics will be presented in separate papers as the individual analyses are completed.

The overall objective of the study is the development of computer oriented simulation models which will permit detailed analyses of aircraft operations with respect to forest fire control. Some of the specific uses for which these analytical tools are being designed are:

1. The determination of the optimum aircraft and types of operation for any set of use conditions.
2. The optimization of an aircraft fire suppression system for any administrative or geographic region.
3. An analysis of the effects of changes to currently operating systems prior to the implementation of such changes.

Undoubtedly once the models become operational more uses will develop. For example the models could be adapted to:

1. A dispatch training simulator
2. An operational dispatch aid
3. Research and development, wherein the effectiveness of a proposed new aircraft design could be tested prior to actual engineering development.

The most important development since the previous report has been the definition of more precise objective functions to replace those which served during the early stages of the study. As a result of these new objective functions the study has been reorganized to include a more rigorous cost-effectiveness analysis. In its present configuration there are two objective functions:

1. minimize suppression expenditures, and
2. minimize area burned.

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Both of these objective functions are desirable goals. Unfortunately they are neither directly comparable or compatible. They are not comparable because units of measurement used in assessing the attainment of the first objective is monetary while the units used in assessing the attainment of the second objective is acres. Since forest land units cannot satisfactorily be measured in dollars at the present time, direct comparisons of results of the two approaches is not possible. This will continue to be the case until more precise and generally applicable methods of damage appraisal are developed.

Even if comparable units of measurements were available the objectives are not compatible because the attainment of one is achieved at the expense of the other. Reducing area burned generally requires increased expenditures, whereas reducing expenditures generally increases area burned. In this study the approach will be to develop systems which minimize each objective independently, and then attempt to resolve the differences to achieve a balanced result. In carrying out this dual approach each objective will be minimized within a reasonable constraint imposed by the other objective. This will eliminate the obvious but unsatisfactory solution to each approach, i.e., reduce expenditures to zero while suppressing no fires and increase expenditures indefinitely in an attempt to immediately extinguish all fires. The constraints to be used will be discussed under Economic Analysis.

In addition to modifying certain analytical procedures both the analysis of inputs to the study and the overall method of analysis have been reorganized along more functional lines. The new organizational structure is outlined in the Summary so that the reader can visualize the manner in which all of the various pieces fit together.

I. INPUT PARAMETER ANALYSIS

Prior to analyzing aircraft systems, detailed investigations of several input parameters must be completed. The input parameter analysis has been grouped into four broad classes, each of which contains a number of individual sub-projects. The four classes are:

1. fire behaviour and occurrence
2. effectiveness of the ground suppression system
3. economic analysis
4. analysis of input parameters related to aircraft operations.

1. Fire behaviour and occurrence

A basic requirement for the analysis of any fire suppression system is a thorough understanding of and the ability to predict within reasonable limits the occurrence and behaviour of forest fires. Since the recently developed Canadian Forest Fire Weather Index (1970) will be one of the major components of the fire occurrence and fire growth models, a thorough analysis of this index and it's relationship to fire behavior is necessary. This section is divided into four parts:

A. free burning fire growth
B. fire growth during suppression
C. probability of fire occurrence
D. fire weather index analysis.

A. Free burning fire growth

Fire growth can be analyzed in two different ways: rate of growth per unit of time (i.e., a rate of perimeter increase of 500 ft. per hour), or total growth during a time interval (i.e., a total increase in the perimeter of 650 ft. in 1.3 hours). Both approaches are equally valid and useful, in that given either value and the time interval, the other can be calculated. At the present time, it is not possible to determine which of the two variables will have the highest degree of predictability from the data contained in the individual fire reports. This section as well as the next describes the analysis using rate of growth per unit of time as the main variable. However, if total growth during a time interval is more predictable, it will be substituted for rate of growth. The same reasoning and arguments with respect to development of the regression equations apply equally well to both variables.

In the first report, a fire growth model was presented in which rate of area growth could be calculated from various input parameters. Rate of area growth is non-linear with time. Developing a model which reflected this non-linearity involved the use of complex mathematic relationships. It was felt at the time that the simplifications in data acquisition brought about by the use of area growth rate would justify the additional complexity. It was found however, that development of many of the models was greatly hindered by the use of a non-linear growth function. By using the area to perimeter relationship:

(1) $$P = a\sqrt{A}$$

Where: P = perimeter in feet,
A = area in acres, and

(2) $$a = 738 + (.245\, W^{2 \cdot 3} \times \frac{A}{10}) \ ; A \leq 10$$

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

which was derived in the first report, the data acquisition problem is eliminated, and computations in subsequent analyses relating to the suppression effort required to control the fire and rate of growth during suppression are greatly simplified.

Regression equations will be developed which relate perimeter growth to the Fire Weather Index (or the Initial Spread Index) and fuel type. In addition to the FWI, fire size will be included to account for the rate of growth between ignition and the attainment of an equilibrium rate. An attempt is being made therefore to analyze both the build-up period when perimeter growth rate is increasing, (a function of fire size) as well as the steady state period when it remains constant (a function of the FWI). The exact nature of the functions will be discussed in detail after the regression analysis has been completed.

Development of a model to predict average rate of growth during suppression (discussed in the next section) makes it possible to edit the rate of growth input data and eliminate those observations which are obviously in error. The procedure is as follows: the average observed rates of growth before the start of suppression and during the control period are calculated. Then the average FWI (or subsidiary index) is calculated for the same time intervals. Following this, the expected ratio of the rate of growth during suppression to the free burning rate of growth (RPG_s/RPG_f) is calculated using the models in the next section. This ratio is adjusted for the changes in FWI (or other index) during the two periods, using the assumption that the rate of growth is directly related to the index under consideration.

The final step involves the comparison of the observed ratio RPG_s/RPG_f to the expected ratio. If the two ratios were equal it would be coincidental, as the models used to calculate the expected ratio are quite general in nature. On the other hand, if all of the input data is reasonably accurate the two ratios should be at least within an order of magnitude of each other. That is either ratio should not be more than 10 times the other. If such a wide range of differences were accepted it would be fairly safe to assume that none of the normally high degree of variability in the data would be lost and that any relationships which were eventually derived would not be biased by the initial model used for editing. On the other hand it can also be assumed that much of the obviously erroneous data will be eliminated by this procedure.

B. Fire Growth During Suppression

In the previous report, an iterative procedure was outlined whereby the rate of growth during suppression, time required to control and fire size at control could be computed. Because the simulation will require many repeated trials with each fire, the iterative procedure would have been very time-consuming. Therefore, a more direct solution which could calculate all of the above in single steps was needed. A mathematical model has been developed in response to this requirement.

Assumptions of the model are:

1. A constant rate of line construction (RLC) during the control period.
2. No change in the forward rate of spread of the fire during the control period.
3. Either the fire is spreading equally in all directions or the attack takes place at a point on the perimeter where the rate of spread is an average for the entire perimeter (ie - not at the head or back of the fire).
4. The ratio of the growth rate at any specific time (t) during suppression to the free-burning growth rate (RPG_s/RPG_f) is proportional to the ratio:

$$\frac{LC - PG}{IP} \tag{3}$$

Where: LC = total line constructed
PG = total perimeter growth
IP = initial perimeter at the start of suppression.

This assumption is based on the following reasoning.

The line constructed during any interval must be greater than the perimeter growth during the same period in order to control a fire. Some of the line constructed during the period is offset by the growth during that period. Only that portion of the line constructed which is in excess of the growth can be applied towards reducing the uncontrolled portions of the initial perimeter (IP). If there is no excess of LC over PG, no progress is made and the fire grows until a change in the weather slows its progress.

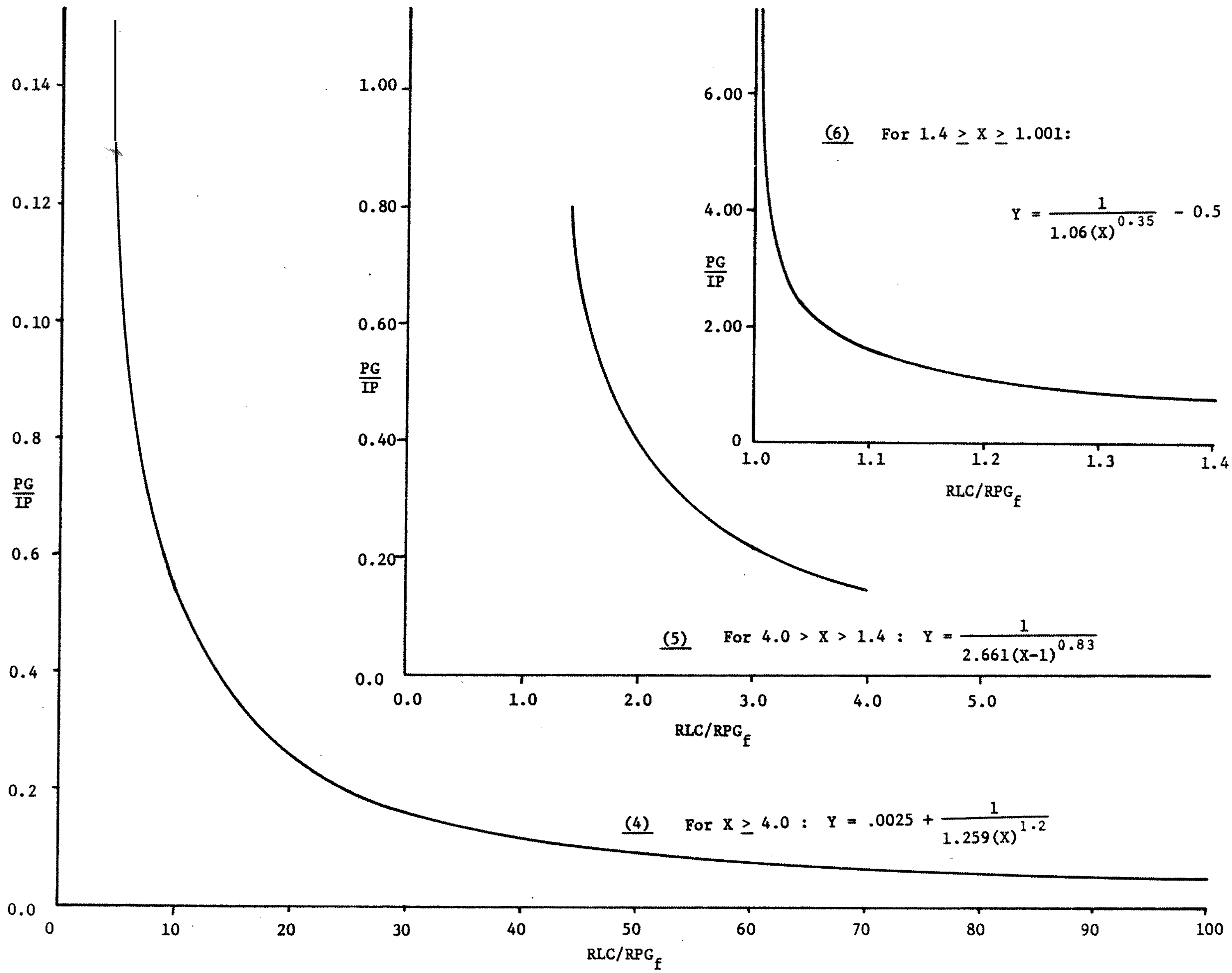
Perimeter growth is constant with respect to time only when it is related to forward rate of spread by a constant ratio. This will be the case for a fire of any unchanging geometrical shape which is burning freely. When a portion of the perimeter has been controlled, the ratio between forward rate of spread and PG is reduced because part of the perimeter can no longer spread. This reduction, at any instant of time is assumed to be proportional to the percent of the initial perimeter which had been controlled by that time (remembering that only the excess of LC over PG is applied towards the reduction of the uncontrolled portion of IP).

Using these assumptions, a computer program was written which calculated rate of perimeter growth during suppression (RPG_s) and Total Perimeter (P) at one minute time intervals for numerous combinations of IP, RLC, and RPG until each fire was controlled. Examination of the results indicated that the Ratio PG/IP is constant when the ratio RLC/RPG is constant regardless of the values of IP, RLC, or RPG. The Ratio PG/IP is plotted as a function of RLC/RPG in Figure 1 along with regression equations for the function.

With this function, it is possible to calculate total perimeter growth during suppression in a single step. By adding the growth to IP, the total perimeter at the time of control is obtained. As an example, assuming RLC = 40 ft/min. RPG = 10 ft./min., and IP = 5,000 ft.. From Figure 1, PG/IP = .15 and the total growth (PG) (.15 x 5,000) = 750 ft. The total perimeter = 5,750 ft. The time to control is simply the total perimeter divided by the rate of line construction (5,750/40 = 144 min.).

In the last section brief mention was made of an editing procedure which is being used to delete obviously erroneous data from the sample used in the rate of growth analysis. The procedure involves comparing the observed ratio RPG_s/RPG_f with the

FIGURE 1. Perimeter growth during suppression as a function of RLC/RPG_f.



expected ratio. This procedure is made possible by an extension of the procedures just demonstrated. By dividing PG by the time to control, average RPG_s is obtained. Numerous trials indicated that the ratio RPG_s/RPG_f is constant for a constant RLC/RPG_f regardless of IP, RLC, or RPG. The function relating these two ratios and the equation for this function are shown in Figure 2. With this ratio, it is possible to calculate the expected RPG_s given RLC and RPG_f.

The behaviour of RPG during the control period was examined. RPG during the control period is plotted on two relative scales in Figure 3 for several ratios of RLC/RPG_f. Examination of the functions shows that in the limit where RLC/RPG_f = infinity, RPG_s will equal 0.5 RPG_f. On the other hand, where $RLC/RPG_f = 1.0$, $RPG_s = RPG_f$ (and control is not possible). Between these two limits RPG_s approaches RPG_f but there is very little change in the ratio of the two until RLC/RPG_f approaches 1.0.

As with all simplified solutions this one has its weaknesses. The model uses constant values for RLC and RPG. In actual fire control situations RLC is not constant with respect to time except for very brief periods. Even if only a single crew is dispatched RLC will reach a peak shortly after their arrival and then gradually decline with time as the crew becomes fatigued (Lindquist, 1969). Several crews or types of equipment arriving at the fire at random intervals, will cause random variations in RLC. On the other hand, it is not possible to extract the necessary detail from available records to allow the computation of actual values of RLC at any specific time during a fire's history. In addition, such a procedure even if it were available, would be over-precise with respect to the needs of the current study. It is expected that the use of an average of RLC will not measurably affect the accuracy of the final answers.

Unlike RLC, it would be possible to estimate RPG at any time during the fire's history using the expected diurnal variation of the FWI. There is a problem however with respect to calculating the average FWI during the control period. In simulating various control tactics, the time required to control a fire will vary with each tactic employed. Without knowing the time required to control a fire, it is not possible to calculate the average FWI during the interval, and without the average FWI, it is not possible to calculate RPG_s and hence, the time to control. Preliminary investigations indicate that the increased accuracy obtainable through use of the average FWI during the control period is marginal at best. The increased in accuracy does not justify the additional effort which would be required to solve the above dilema. Therefore, the FWI to be used in the suppression analysis will be an observation at a specific time. This time may be either 1600 (the simplest approach) or at the start of suppression, depending on which value proves to be most meaningful.

FIGURE 2. RPG_s/RPG_f as a function of RLC/RPG_f.

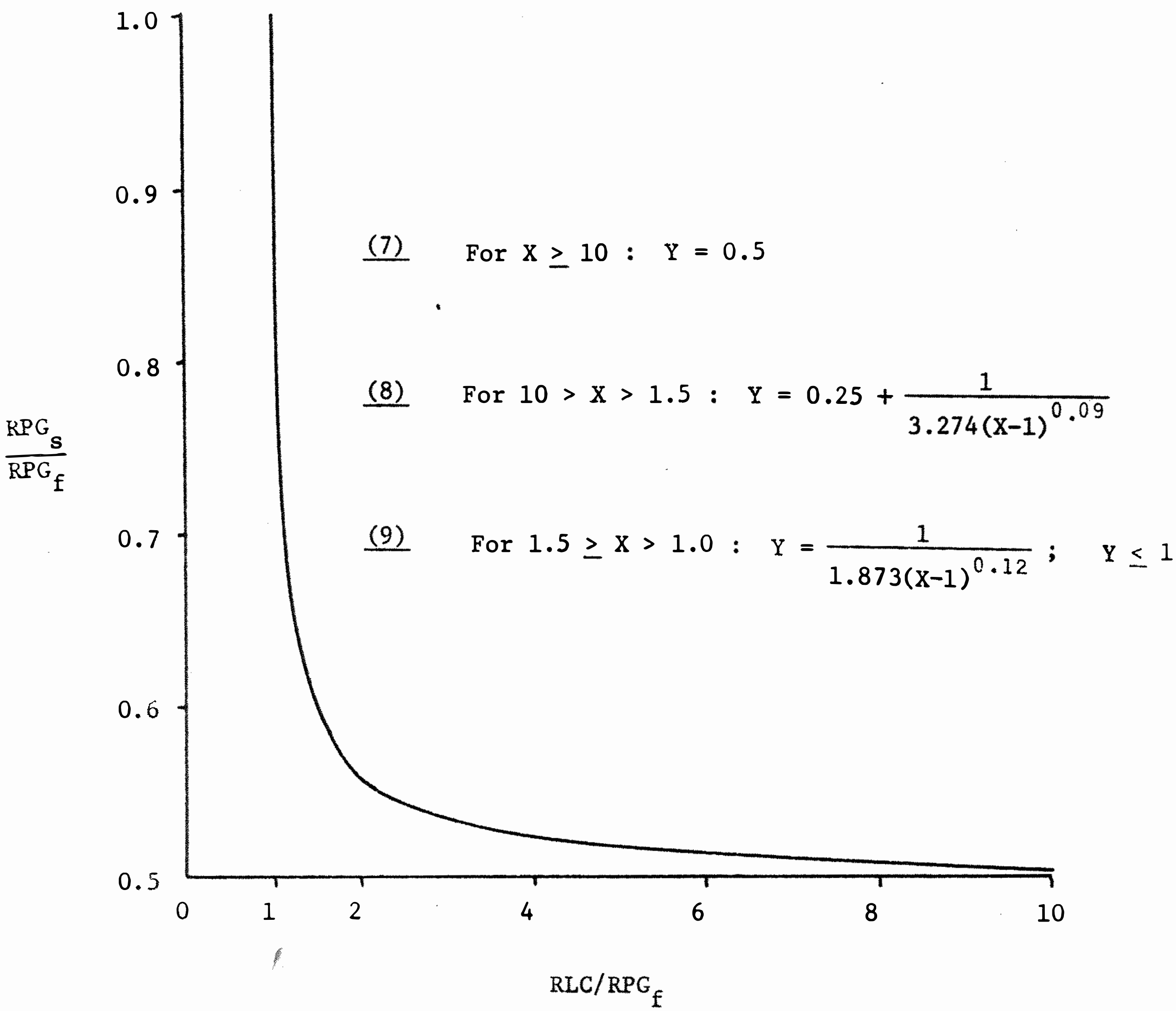
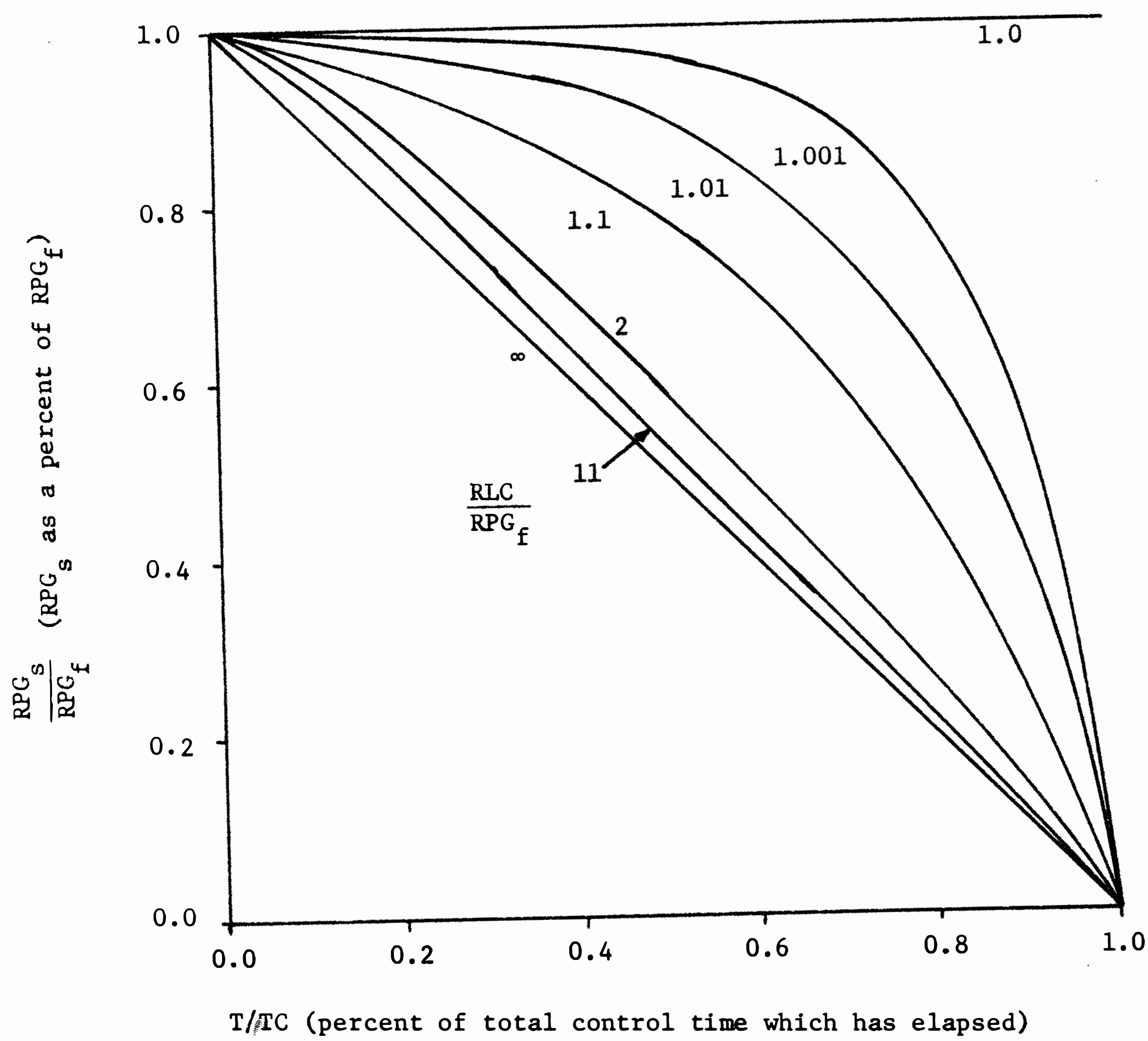


FIGURE 3. Changes in RPG_s during the control period.



C. Probability of Fire Occurrence

One of the primary inputs to the aircraft transfer model will be the probability of fire occurrence per unit area. In the model, the probability of fire occurrence is a function of the Fine Fuel Moisture Code (FFMC) of the FWI. This probability may also be stratified by fuel type, day of the week, and average density of fires if these factors prove to be significant. From these distributions regression equations will be developed which yield the expected probability of the occurrence of a fire per 1,000 square miles.

D. Fire-Weather Index Analysis

In order to make long range planning decisions such as the establishment of permanent bases and seasonal transfers it is necessary to know the expected distributions of the FWI. The distributions of the FWI and of all of the codes and indices of which it is composed are being determined separately for each weather station for each year (for the period 1957 to 1966); by month (for all years); and overall. The same yearly, monthly, and overall distributions will also be determined for each province.

In addition to seasonal variation, the diurnal variation of the FWI is also needed primarily for use in the fire growth model. The method of calculating the expected hourly FWI as a percentage of the 1600 (4 p.m.) value is described in detail in a separate report (Simard, 1970). In brief, it involves the use of average hourly values of temperature, relative humidity, and wind to calculate the hourly FFMC, using tables published by Muraro et al. (1969). An hourly ISI is also calculated. The Duff Moisture Code and Drought Code are assumed to remain constant.

The hourly FWI is then calculated assuming a 1600 value of approximately 85. The last step is to find the hourly value as a percentage of the 1600 value. With these percentages it is possible to estimate the average FWI during any interval in the day. This procedure is valid only when the fuels are not drying after a rain, as such a trend overshadows the diurnal variation. However, if the fuels are drying after a rain they will not, in all probability, sustain a fire of any significant consequence with respect to aircraft operations.

2. Effectiveness of the Ground Suppression System

An aircraft system is only part of a larger fire suppression organization. To evaluate the effectiveness of a system, there must be a standard with which to compare it. In this study the standard by which the use of aircraft is evaluated is the ground suppression system. Therefore, it is essential to know what the unaided ground system can do in order to determine the benefits derived through the use of aircraft. When the various elements of the ground suppression model are combined with the fire behaviour model, the size at which a fire can be controlled with ground forces only can be determined by simulation. This section of the study is divided into four parts:

A. travel time
B. suppression
C. mop-up
D. effect of multiple simultaneous fires

Each of these topics is discussed individually below.

A. Travel Time

A detailed discussion of the travel time analysis was presented in the first report. Essentially, it can be summarized as follows: each province is subdivided into a grid with each block having dimensions of 5 x 5 minutes of latitude and longitude. For large areas where this size proves too small to be practical the dimensions are increased appropriately. After eliminating invalid data, the average travel time to all fires within the blocks is computed. This average is further stratified to more than and less than 1/2 mile from a road. These averages will be used wherever data is missing, or if for some reason the available data is suspected of being erroneous, or lastly, if the data is invalid (i.e., travel time for simulation purpose based on aircraft transport).

B. Suppression

This was also discussed in detail in the first report. Since there have been no significant changes, this topic will only be summarized here. Essentially this analysis involves the determination of regression equations to calculate either rate of line construction or time required to control the fire. As was the case with fire growth, either variable can be used with equal validity. The variable with the highest degree of predictability will be used. To maintain consistency within this report, the discussion in this and the next section will be with reference to rate at which the operation takes place. Input variables to be used are: fire intensity (as a function of the FWI), resistance to control (as functions of fuel type and topography) and lastly, size of the attack force. The last parameter will be indirectly estimated on a relative basis for each station from the following variables: FWI, size at the time of discovery, travel time, and fuel type. By knowing the rate of line construction, it will be possible to determine the total time required to suppress a fire and hence total costs. It also becomes possible to calculate reductions in suppression time and costs as a result of reductions in fire size.

C. Mop-Up

Since airtankers are not normally used in mop-up, this phase of the suppression operation was omitted from the initial analysis. In subsequent analyses, however, it was found that mop-up expenditures can constitute as much as 25% of the total suppression costs. Since the study is now analyzing suppression costs it has become necessary to analyze the factors which affect the mop-up operation.

As with the rate of line construction, the total effort being expended on mop-up varies considerably with time. Initially, the entire suppression force is normally involved until the fire is completely secure. This level of activity normally lasts for only a relatively short period of time after the fire has been controlled. Secondly, a small force is left to complete the job. This normally takes somewhat longer than the first phase. Lastly, a patrol which may consist of only one man is maintained for an extended period.

During the interval between control of a fire and complete extinguishment, it can be seen from the above that a fairly wide variety of operations and rates of production prevail. In addition, the number of hours during each 24 hour period during which work is actually performed may vary considerably. For example, on a large fire there will probably be extensive night-time patrolling as well as daytime activity for the first day or two after the line is completed. By the third day mop-up activities will probably take place during an 8 to 12 hour day-time shift. Lastly, the patrol will probably only require one man hour or so per visit which may be on a daily basis initially with the intervals between visits being increased until the fire is declared out.

From the information available it is not possible to accurately determine what level of activity was taking place at any specific time during the mop-up and control period. Some individual fire reports differentiate between mop-up and patrol activities but many do not. Therefore in the interests of uniformity, the average rate of mop-up during the entire period between control and complete extinguishment will be used.

Although the average rate of mop-up is of little value in actual fire control situations, it is useful in a simulation model. Its usefulness stems from the following reasoning: to a first approximation, total mop-up effort is simply the product of the average rate of mop-up multiplied by the time interval during which this work took place. Therefore, if the expected average rate of mop-up can be computed, it should be possible to estimate the total time required to complete the job from the size of the fire at the time of control (total effort required). To continue, there should also be a positive correlation between total time and total costs for any specific average level of activity. If the total effort consisted of a constant proportion of each level of activity (intense mop-up, normal mop-up, and patrol) the relationship between total costs and total time would be fairly simple. But the proportions of each activity vary considerably on any individual fire, so that the relationship is quite complex. For example, for the smallest fires the entire suppression crew may mop-up for a brief period and the fire could be declared out immediately. On larger fires, all three levels of activity can be used in widely varying percentages.

Despite the fairly high degree of complexity of the mop-up function, preliminary analyses indicate that a positive correlation between total mop-up time and total suppression costs is sufficiently high to warrant the use of total mop-up time in the cost model. Furthermore since the mop-up component of the total suppression cost is generally not the major factor, even fairly large errors will not drastically alter the total suppression costs.

Many of the factors which affect RLC also affect the rate of mop-up (RMU). The most important factor is crew size and configuration. This will be determined indirectly in the same manner as for RLC, as was discussed in the first report. With respect to RMU, however, there is an additional indirect indicator of crew size which was not available for the calculation of RLC. Since the fire has been controlled and RLC has been determined, and since RLC is related to crew size, RLC itself may be used as one of the regression variables for the estimation of RMU.

In addition to crew size, the FWI or one of the drought codes within the FWI should be related to the amount of work which has to be done per unit area. Lastly, the size of the fire may have an effect on the average amount of work required per unit area. This effect could be the result of two different factors. The first factor is time. Unless water is available to extinguish the fire the main purpose of mop-up is to maintain a sufficiently large crew at the fire site to contain any potential reignition outside of the control line. The crew is kept at the fire site until the fire eventually goes out. While the crew remains at the fire site, however, they are actively scattering piles of large materials, mixing small burning materials with mineral soil, and exposing buried smouldering material to the atmosphere in an effort to speed up the process by which the fire goes out. This in turn reduces the total waiting time required. In the case of a large fire and small crew part of the fire may go out before the crew gets to it, thereby eliminating the need for some of the work. Similarly in the case of very large fires, a wide stip around the perimeter may be rendered safe, and the interior portion left to go out unattended. In such cases, lengthy patrols may be maintained. The effect in either case would be to reduce the average amount of work and hence time required per unit area. Whether or not such effects can be isolated from the available data remains to be seen.

D. Effect of Multiple Simultaneous Fires

When a single ranger district is confronted with several simultaneously-occurring fires, the previously discussed method of analysing factors relating to the ground suppression system must be modified. The models, as outlined to this point, are only applicable to situations where the manpower and equipment available are equal to or greater than the fire suppression requirements which they must satisfy. When several fires burning at the same time require more crews and/or equipment for their suppression than are available, one or more of the following occur:

(1) Initial attack dispatch may be made from a more distant base located in an adjacent region, thus lengthening travel time.
(2) Dispatch may be delayed for several hours or even days until a crew becomes available, thus lengthening the dispatch time.
(3) A smaller than normal force may be dispatched, thus reducing RLC below the expected value.
(4) Crews may be transferred from fires immediately after containment to attack new outbreaks, thus reducing the force remaining to control and mop-up the fire which in turn would decrease RMU below the expected value.

The number of simultaneous fires which would be necessary to cause any of the above to occur (critical fire load) would vary considerably from one administrative unit to another. A district which frequently experiences dry lightning storms would be organized to handle a large number of small fires at the same time. Another district where lightning is uncommon might be overtaxed by three or four simultaneous outbreaks. Therefore the analysis of the effect of simultaneously-occurring fires will have to be stratified by individual stations to determine the fire load which exceeds local suppression capabilities.

The scale of the study prevents the development of a simulator which keeps a continuous record of the status of every crew. Furthermore, since expected RLC is being used rather than values for specific configurations of crews on individual fires, such a record would be more detailed than the models to which it would apply. Therefore, the investigation of the effect of simultaneously-occurring fires will be made by using expected values. Mean travel time, RLC, and RMU will be computed for all days on which there were 1, 2, 3, etc. fires. If any significant trends in the mean values can be found, regression equations will be developed which yield the change in expected values as a function of the number of fires per day.

Whether this change should be applied uniformly to all fires on a given day or there should be no reduction applied until the critical fire load is reached is a difficult question to answer. On one hand, dispatch is normally made to fires in the order of detection. The reasoning is simple -- the occurrence of the detected fire is an established fact whereas the probability of the occurrence of subsequent fires is unknown but it is most probably less than 1. On the other hand, a district does not normally commit all of its resources to the first fire detected. Even though the probability of the occurrence of subsequent fires is unknown, the occurrence of certain events such as a dry lightning storm on the previous day may indicate to the dispatcher that the probability is very high. In other words, there is a certain amount of qualitative information on which to base an "educated guess" of what is likely to happen. The dispatch decision-making process involves the analysis of a complex combination of factors by an individual whose training, experience, abilities, and thought processes differ from every other individual. To attempt to quantify this process would be beyond the scope of this study.

To resolve the difference, the same approach will be used as has been used several times throughout the study in the absence of quantitative data. A method of applying the change has been developed which is a compromise between the two alternatives. If a significant difference in the expected values exists on a day with multiple fires, the difference will be applied in gradually increasing amounts to each subsequent fire in such a way that the change applied to the second fire is twice the first; the third fire is three times the first; and so on for all fires.

3. Economic Analysis

The purpose of the economic analysis is two-fold. The primary purpose is to provide the cost functions which are needed to minimize suppression costs within a maximum area burned constraint. The second purpose is to provide realistic constraints for that portion of the study which will minimize annual area burned. This section is divided into three parts;

A. ground suppression costs
B. relative land values
C. acceptable annual area burned.

A. Ground Suppression Costs

One of the benefits which can be directly attributed to airtanker suppression efforts is the reduction of costs which are expended on ground suppression efforts. In order to determine the magnitude of these savings, the costs of ground suppression supplemented by airtankers must be subtracted from the costs of ground suppression which would have been expended had not the airtankers been used.

Traditionally, analyses of suppression expenditures have centred around attempts to relate expenditures to area burned. These attempts have had only limited success however, because suppression expenditures are related to many variables in addition to area burned. Some of the more important additional parameters are: fuel type, travel time, fire-fighting time and mop-up time. While there are innumerably additional variables which influence total suppression costs, most of them are related either directly or indirectly to one or more of the above. Furthermore, data on each of the above are readily available whereas such is not the case for many other variables which could be considered.

It was not assumed that any of these parameters were linearly related to cost. Thus, to account for possible non-linearity, the square and square root of each of these parameters were considered as independent variables in the regression analysis. It was noted however, that the differentiation between the fire-fighting and mop-up functions is not uniform in all provinces. Some provinces do not separate these two components of fire suppression in their records. Therefore, to account for this lack of uniformity, the total time for both fire-fighting and mop-up was considered as a single element and included in the model. It was believed that fire-fighting costs would vary with species or forest type. Therefore, the fires were stratified by species, or type and a regression equation was developed for each type for each of three provinces analyzed. Lastly, to insure that the models reflect ground suppression costs only, all fires on which aircraft were used are not included in this analysis.

The following generalized equation was developed to predict fire-fighting costs:

$$(10) \quad C = a + b_1 F + b_2 F^2 + b_3 \sqrt{F} + c_1 M + c_2 M^2 + d_1 (F + M) + d_2 (F + M)^2 + e_1 A + e_2 A^2 + e_3 \sqrt{A}$$

where: C = Total cost of fire suppression (dollars)
F = fire-fighting time plus travel time (hrs.)
M = mop-up time (hrs.)
A = area (acres)
a = constant
and b, c, d, e = coefficients of respective independent variables.

The square roots of M and (F + M) were deleted after a preliminary analysis indicated that they were not significant factors in any of the equations which were developed.

A step wise regression program was used to determine the coefficients of the independent variables. The results indicated that fire-fighting costs could be predicted with a high degree of accuracy. The highest R^2 for a specific forest type was .99 while the lowest was .63. Intermediate results indicated that from three to six of the variables in the generalized equation accounted for the majority of the predictable variation in the dependent variable. For simplicity's sake only the significant variables were included in the final equations. Each of these shortened equations was examined to insure that each variable behaved predictably throughout the range of the equation. These final equations will be included in the final airtanker simulation model to predict fire-fighting costs by ground crews alone.

B. Relative Land Values

It is generally conceded that fire protection efforts should be expended in proportion to the relative value of the area being protected. In some provinces this concept is formalized by a set of rules which states that the fires above a specific parallel will not be suppressed except where they threaten life or real property. In other provinces, where it is the stated policy that all land will be protected, the intensity of the protection effort is greatly diminished as one progresses towards the more remote northern areas of the province. Thus if the airtanker model is to reflect reality it must take into account the relative protection given a specific area which is a function of relative land value.

Value is a function of time, place and form. For example, a cord of pulpwood in eastern Canada has the highest per unit value when that cord is spruce, with a diameter greater than 12 inches, cut in four foot lengths, smooth and stacked in the yard of the highest bidder. Each of these qualifications add to the value. Spruce pulpwood yields 20 to 30 percent more pulp than Balsam fir (Frost, 1958). A cord of straight smooth softwood which has a diameter greater than 12 inches and is cut into four foot lengths has a solid content of 100 cubic feet. In contrast, cooked, rough and knotty softwood which has a diameter of less than 6 inches and is cut into eight foot lengths has a solid content of about 65 cubic feet (Flann, 1962).

The most advantageous location for a cord of pulpwood is at the point of utilization. Any other location necessitates the expense of transportation. Time also involves a cost. When pulpwood arrives at a yard prior to the time it is needed, the pulpmill not only incures the cost of idle capital tied up in inventory but also must provide for storage and absorb the risk that the pulp will deteriorate or be destroyed before it is used. Thus, the value of pulpwood, like any other commodity is a function of time, place, and form.

The value of land is also a function of time, place, and form. Time influences the demand for the products of the land, i.e., the need for white pine masts in the latter half of the 18th century has changed to demand for recreation in the latter half of the 20th century. At any given time, place is important because it determines the accessibility of the land and the distance over which the products of the land must be transported. Form determines the potential of the land to produce products. Desirable qualities in agricultural land are flatness and fertility, whereas a recreationist wants water and land with contrasts.

There are other factors associated with land which increase its value. Among these are: (1) land is often used as security against inflation and (2) individuals want to own land for its own sake. Although these other values are recognized, in this study the value of land is considered to be the present worth of the stream of products the land is capable of producing over time. To determine the present worth the value of each product has to be discounted from its time of use to the present. It should be pointed out that in discounting future costs and values the following assumptions are made: (1) knowledge of the future is perfect, (2) capital is unlimited at the rate at which costs and benefits are discounted, and (3) the motives of the land owner are purely profit maximization.

The products which are harvested from forest land can be divided into two groups; consumptive and non-consumptive. The consumptive products are those which are traditionally associated with forest land, i.e., pulpwood and sawlogs. Non-consumptive products are those non-quantifiable uses which have always been harvested by man in limited quantity but for which the demand has been recently rising dramatically. These uses are primarily recreation such as hunting, fishing, hiking, and camping, but also include the production of water, aesthetics, wildlife preservation, and the knowledge that wilderness still exists.

Evaluating the quantifiable consumptive products is relatively straightforward. It is assumed that the area to be evaluated is large enough to sustain a perpetual flow of forest products. The total volume per acre at the end of the rotation is divided by the number of years in the rotation and this volume is assumed to be available each year. The harvesting costs and the costs of transportation are substracted from the total value of these products at the nearest point of utilization. The remainder is the net value of the yearly per acre yield. The value of the acre is the net present worth of a perpetual flow of a value of this magnitude.

Evaluation of non-quantifiable values presents a far more challenging problem. Because the objective of the study is to develop guides for macro management decisions, the evaluation of non-quantifiable variables can be approached only in a general way. The model uses the following assumptions to reflect some of the non-quantifiable values of land:

(1) The recreational value of land decreases as the distance from population centers increases.
(2) The recreational value of land is directly proportional to the accessability of the land.

(3) The recreational value of land is increased by contrast and its location with respect to water.

A computer model was developed to calculate relative land values. The model considers five factors in calculating these values:

(1) The location of the land with respect to markets, i.e., wood using industrial complexes for consumptive markets and population centers for non-consumptive uses.
(2) The capacity of the land to produce consumptive and non-consumptive products.
(3) The value of the products. Consumptive products are valued at the point of utilization and non-consumptive products are valued at the site.
(4) The costs of transportation needed to bring forest products to the point of utilization.
(5) The accessibility of the land to the harvester and the public.

In the first step of the analysis a 5 x 5 minutes latitude and longitude grid is superimposed over the area under consideration. Then the computer program takes into consideration all of the above factors, and calculates a value for each element of the grid. Using the highest calculated value as a standard, all of the elements are ranked on a scale from one to nine. Iso-value contour lines are then drawn. These lines are then transferred to a map which can, in turn, be used in making macro land management decisions.

Because non-quantifiable values cannot be evaluated in absolute terms, the final solution is a relative indication of the value of the land. The sale value or the justification land management programs will have to be evaluated by other methods. The relative land values of this study will however enable an administrator with a fixed budget to allocate his efforts to the land under his administration in proportion to the quantity and quality of the values which will be produced by the land.

C. Acceptable Average Annual Burn

No matter how diligent protection efforts are, a certain amount of damage by fire is inevitable. It is physically impossible to totally eliminate fire. Additional efforts become economically unjustifiable long before the physical inputs cease to have a measurable effect. The reason is that response to additional expenditures in protection reach the point of diminishing returns, i.e., each additional dollar spent in protection yields less results than the dollar of expenditure which proceeded it. Faced with this type of function the point is soon reached where an additional expenditure exceeds the benefits which are the direct result of that expenditure. Ideally it would be desirable to determine the exact shape of the function and identify, not only the point where costs exceed benefits but also the point where the marginal net benefit was maximum. Unfortunately, because of the variability of the factors which are directly associated with the occurrence and final size of forest fires, it is impossible to identify this function with any degree of reliability. For this reason, administrators usually choose an acceptable average annual burn and increase their protection expenditures until the desired level of protection is met.

Choosing an acceptable annual burn is a decision which must be made on a multitude of factors including the allowable annual cut, the percent of the allowable annual cut which is presently being utilized or is expected to be utilized in the foreseeable future, the attitudes of the population of the area involved and the resulting directives of the incumbent political party, the total forestry budget and the amount which is allotted to protection, and last but not least, tradition which can be bent a bit but is difficult to break with completely. In choosing an acceptable annual burn for the purposes of the airtanker model, the above restrictions cannot be ignored but they are not as binding as they are in the real world. Therefore, before choosing an acceptable burn a simulation model was constructed to determine the effects of various average annual burns on the timber available for harvest. The results of this model will be used to choose the allowable average annual burn in the airtanker simulation model.

(1) The Model

The model simulates the effects of any predetermined average annual burn on the annual harvest in a hypothetical even age forest. The inputs needed to adapt this model to any specific forest management unit are: (1) merchantable and total growth functions typical of the species of the forest unit, and (2) the acceptable annual average burn or burns to be analyzed.

(2) Assumptions

A simulation model is constructed upon a number of simplifying assumptions. These assumptions discard the non-relevant complexities of real life so that the model can analyze the significant variables and assist in identifying the inter-relationship between these variables and the results. The assumptions upon which the allowable average annual burn model was constructed are:

(a) The area managed consists of one million acres of forest land divided into 200 five thousand acre blocks or cutting units. This forest is managed under a modified area management scheme in which the two units containing the greatest volume are cut each year.

Fires will modify the relative age patterns between units of the forest but because of the management scheme which chooses the units with the greatest volume to be harvested each year, deviations from normal tend to correct themselves. This management scheme also reduces radical fluctuations in the volume harvested each year.

The forest considered is a fully regulated or nearly regulated forest. This assumption is not valid for most areas under consideration in Canada, which have an over-representation in the immature and over-mature stands. But since a fully regulated stand is the goal of most forest land managers, and they are managing their land to meet this goal, conclusions based on this assumption will be valid when their goals are met.

This model, therefore, will not portray a valid picture of areas which are actually unregulated, but the distortion is no greater than that which would be obtained from applying other regulated land management models to unregulated land.

(b) Fires occur with equal probability in all age classes.

Although it has not been tested, the above assumption is based upon the hypothesis that in spite of differences which actually occur in the probability of fire occurrence in differing age classes, these differences are not great enough to invalidate conclusions drawn from a model based upon this assumption.

(c) Fires totally destroy stands that they burn.

This assumption is obviously not true. A light surface fire can destroy a young stand but it would take a very intense crown fire to destroy some of the older stands.

The effect of this assumption on the validity of the conclusions is that they will be conservative in their estimate of final volume. It is possible to take this factor into account in later studies and it is suggested that studies be initiated to describe this relationship.

(3) Structure of the Model

The model is based on generated stocastic variables which are used in functions constructed from available data. These functions generate the number, size and location of forest fires in the model within the allowable burn constraints supplied by the researcher.

The model is divided into six parts. The first constructs the even age fully managed forest. The second step adds a years' growth to the forest and harvests the two cutting units with the maximum volume. The third determines the number of fires in any single year. The forth determines the number of acres burnt in each fire. The fifth step activates the hypothetical burn described in steps two and three. Part six prints the results and returns the program to either step 2 or step 4 depending upon whether there are unactivated fires in the year under consideration, or whether there are additional years for which to compute values. A generalized flow chart of this model is presented in Figure 4.

(4) Application of the Model

The model was used to determine the effect of six acceptable average annual burn values ranging from 0.1 to 0.2 percent on the annual yield of white spruce and Douglas fir. For a third species, Red pine, the annual burn was varied from 0.05 to 0.5 in increments of 0.05 percent. The first two species represent major wood products of Canada, and the third is a classical species which lends itself easily to analysis because of the volumes of information written about it.

(5) Results

Preliminary analysis shows that the reduction of merchantable volume available for harvest on a sustained basis can be determined on an approximate basis by the following relationship:

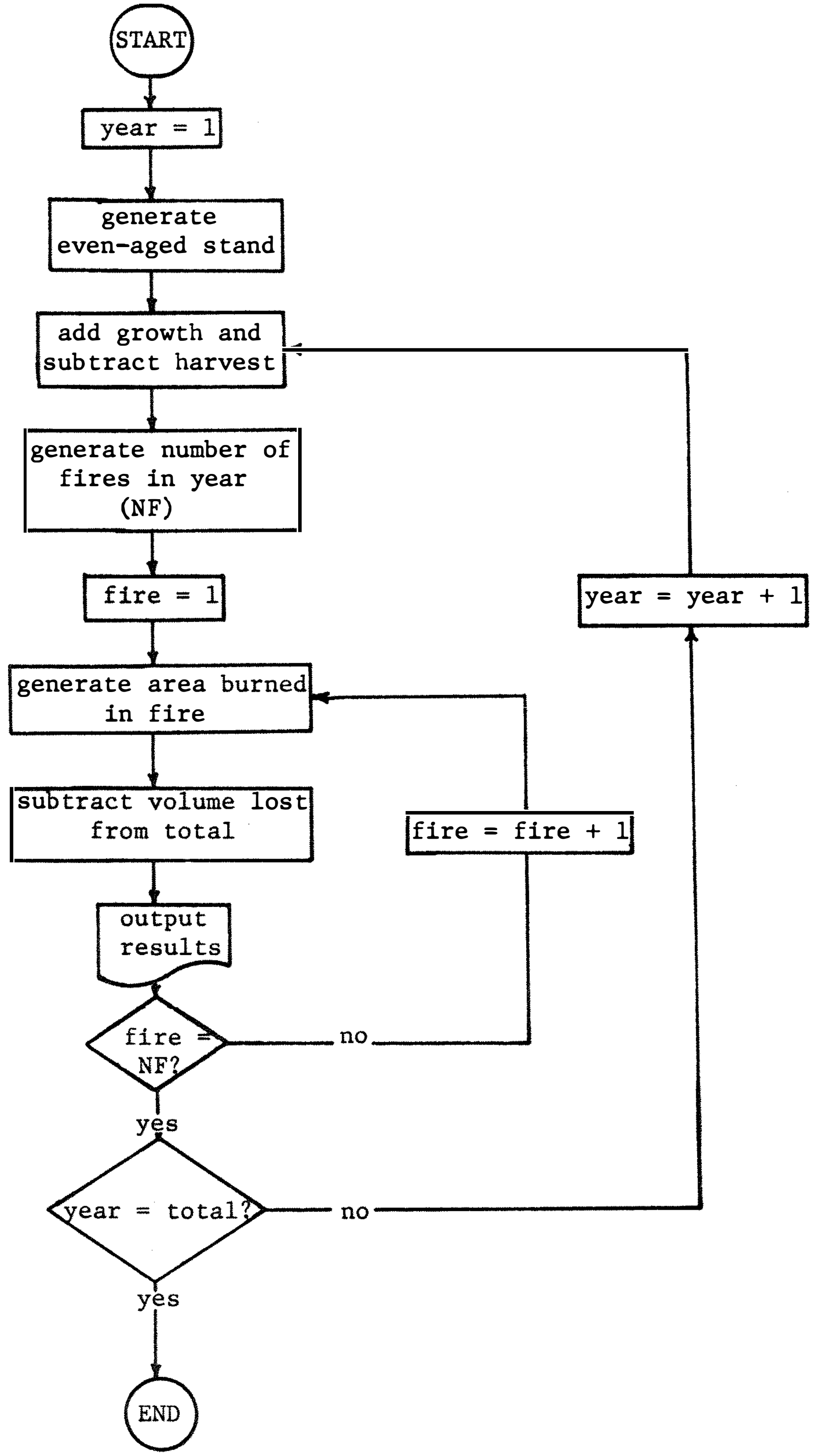
(11) $$R = 0.75\ (RO + AB)$$

where: R = reduction of merchantable volume (%).
RO = rotation in years
AB = acceptable annual burn in percent of total area

Thus, if the acceptable annual burn was .12 percent per year and the rotation was 100 years, the total potential annual yield would be reduced by about 9 percent.

This study should be completed shortly and the results available for use. These results will be used in the airtanker simulation model to assist in determining the optimum fleet size.

FIGURE 4. General flow chart of the allowable annual burn model.



4. Analysis of Parameters Related to Aircraft Operations

This section is divided into four parts;

A. fire to lake distance distribution
B. the amount of water or retardant required to control wildfires
C. water or retardant distribution patterns
D. aircraft performance characteristics

With acquisition of the above data it will be possible to compare the efficiency of aircraft operations with ground operations. It will also be possible to compare the various aircraft with each other. Each of these parts are discussed in detail below.

A. Fire to Lake Distance Distribution

One of the first attempts at determining distributions of distances between fires and lakes was undertaken by Newburger (1968). Based on his results, a more detailed analysis of fire to lake distance distributions was undertaken for this study. The most significant changes between the work of Newburger and the present study are:

(1) The area in each analysis has been considerably reduced.

Visual examination of numerous maps indicated that the lake distribution in a single ranger district might be considerably different from the average of the larger region within which it lies.

(2) The spatial distribution of fire occurrence was determined from actual data rather than on a random basis.

Only lightning fires can be considered randomly distributed. The majority of man-caused fires tend to be clustered around population centers, along roads, and in the case of recreation fires, close to water sources. Since lake density is not uniform over a large area, the areas of high fire occurrence may not coincide with areas of average lake density.

(3) The suitability of a lake for water pick-up was determined for each individual lake by local forestry personnel rather than by size alone.

All lakes of specified minimum dimensions or greater are not necessarily usable by aircraft. A lake may be too shallow, have rock outcrops, it may be surrounded by steep hills, it may contain pulpwood and so on.

The procedure used in the analysis was as follows:

(a) Obtain from each province a list of all lakes which are either usable or not usable, whichever list is smaller.
(b) From a complete list of fires, randomly select a sample of between five and ten percent of the total. Plot these fires and measure the distance to usable lakes of 0.5, 1.0, 1.5, 2.0, and 3.0 miles in length or longer.
(c) Obtain distributions of distances and mean values by region and province.

The results of a preliminary analysis (in New Brunswick) indicated that the histograms were very similar in general shape to those obtained by Newburger. It was also found, however, that the mean distances for New Brunswick were about twice those obtained by Newburger for Quebec and that the mean distances of the regions within the province varied by a factor of about 2.5. A similar range of variation may be encountered in some of the remaining provinces which are currently being analyzed.

B. The Amount of Water or Retardant Required to Control Wildfires

A detailed report of investigations in this field of study has been published by Stechishen (1970). Briefly his procedure involved the preparation of fuel beds of various species and of predetermined depth and moisture content. One end of the bed was ignited and burning was allowed to progress approximately two-thirds of the fuel bed length. At this time a predetermined amount of water was applied and its effects recorded. This research has been continued for a second season and it is anticipated that similar investigations will be undertaken using retardants.

C. Water or Retardant Distribution Patterns on the Ground

Hodgson (1967) and MacPherson (1967 and 1968) have done extensive work in this field. Their procedure involved the establishment of a large grid of paper cups on the ground. The aircraft being tested flew over the grid as close as possible to a predetermined height and ground speed and dropped a load of water[1]. The amount of water in each cup was determined by weight. A computer program was developed which interpolated the amounts of water at each grid point and produced contour patterns of uniform depths.

More recently, Grigel has carried out similar investigations with different types of aircraft[2]. His work differs from that of the previous two investigators in that the majority of his drops were made with thickened retardant. Also, he investigated the reduction in recovery and pattern lengths while dropping through typical forest canopies. As a result of the work of these investigators there is now sufficient data on hand to allow quantitative comparisons of the drop patterns of various aircraft.

D. Aircraft Characteristics

In order to compare the operating cost and effectiveness of various aircraft, all of the performance characteristics pertinent to fire suppression operations must be known. Every attempt is made to obtain the data from an unbiased source whenever possible. When this cannot be done the data is obtained from brochures published by the individual manufacturer.

The following statistics must be obtained for every aircraft to be considered:

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[1]Three drops were made with thickened water or chemicals but this was only a very minor part of the experiment.

[2]Data on file at the Forest Fire Research Institute.

(1) Cost Data

(a) purchase price with 15% spares -- new or completely rebuilt
(b) crew per year
(c) insurance -- 9% for landbased, 15% for amphibious
(d) depreciation -- straightline, 15 years to 20% residual
(e) gas and oil per hour of flying
(f) maintenance per hour of flying

(2) General Characteristics

(a) empty weight
(b) maximum take-off weight
(c) maximum landing weight
(d) minimum take-off distance (full load)
(e) maximum cruising speed
(f) economy cruising speed
(g) fuel capacity
(h) fuel consumption
(i) maximum range -- ferrying
(j) maximum range -- fully loaded
(k) maximum endurance

(3) Characteristics as an Airtanker

(a) maximum load capacity
(b) maximum load capacity with full fuel load
(c) maneuver load factor (G's of stress)
(d) minimum turning radius
(e) minimum length of lake for pick-up (water based only)
(f) time required for pick-up or loading
(g) load distribution patterns on the ground

Some of the characteristics in Section C are calculated by using various combinations of pertinent statistics from the previous section as well as additional statistics not mentioned here. The detailed calculations will be discussed in a subsequent report.

II. AIRCRAFT SYSTEMS ANALYSIS

Aircraft Systems Analysis is divided into seven sections:

1. General
2. Determination of the optimum aircraft and methods of operation
   (1) for each fire and
   (2) by geographical configuration
3. Establishment of the demand for aircraft assistance
4. Determination of a preliminary fleet mixture and distribution
5. Estimation of the optimum fleet size
6. Analysis of aircraft transfer and final fleet optimization
7. Determination of the potential effectiveness of the hypothetically optimum fleet.

Aircraft have become an integral part of all fire suppression systems in Canada. Since aircraft are part of a larger system their maximum potential is realized only when they are properly integrated into the overall system. However, due to the magnitude of such an undertaking, the aircraft subsystem will be optimized as a separate entity to determine what constitutes an ideal aircraft system and how it can best be deployed to realize maximum benefits.

1. General

A number of researchers and groups have conducted investigations of fire control operations using operations research techniques. Parks (1964) was one of the earliest workers in the field. His mathematical models described the entire fire suppression operation on a fairly broad scale. The models concentrated on the efficient deployment of ground forces, which limits their applicability with respect to the current study. Davis (1968) and his associates are currently developing and expanding the use of operations research techniques to optimize the deployment and use of ground forces.

More closely related to the present study, Greulich (1967) and Maloney (1968) analyzed air operations in northern California. Their objective was maximization of the satisfaction of demand for aircraft at least cost in the region. This concept forms a basic part of the current analysis. Their analysis considered only land based operations however. In addition, few of the aircraft currently operating in Canada were analyzed. Lastly, their procedures were specifically adapted to the region and would not be readily adaptable to significantly different areas.

Analysis of aircraft operations in Canada have been undertaken by Stade (1966) and Newburger (1968). Stade analyzed the use of the CL-215 for fire suppression. Newburger investigated the use of rotary winged aircraft for fire suppression. Both of these studies had more limited objectives than have been stated for the current analysis.

In addition to different objectives, the procedures used in the current analysis differ significantly from those employed by previous researchers in several respects:

1. the use of fire growth models based on perimeter rather than area

2. the use of deterministic rather than stochastic input data wherever possible
3. a greater emphasis on the use of simulation rather than mathematical modelling
4. no assumptions are made as to optimum types of operations, tactics or policies

As a result, most of the work which has been previously undertaken cannot be adapted to the purposes of the current analysis. Therefore, most of the techniques used in this analysis are entirely new, or in some cases new adaptations of concepts expressed by previous investigators.

To date, there has not been a rigorous general analysis of the optimum operating procedures, tactics or equipment with respect to aircraft for all fire control situations. The presently operating airtanker systems have evolved over a number of years of trial and error. Considering the large number of possible combinations of procedures, tactics and equipment, it cannot be said with any degree of certainty that any current system is optimum for any set of use conditions. Therefore, prior to determining the effectiveness of any presently operating system, the determination of the hypothetically optimum system for each set of use conditions is necessary.

The computed effectiveness of the hypothetically optimum system will be used as a standard with which all actual systems can be compared. While the effectiveness of the optimum system is unlikely to be attained in practice, actual systems can be compared with each other on the basis of the percentage of the optimum effectiveness which each system attains.

The hypothetically optimum aircraft system will be compared with the suppression efforts of ground crews, using the ground suppression model described previously in this paper. In other words, on each fire, ground forces alone will be used to suppress the fire by simulation. Then all combinations of aircraft and tactics of interest will be dispatched to the same fire from the nearest usable airport and it will again be suppressed by simulation. The best combination for the specific fire (which could be no aircraft dispatch at all) will be indicated by the solution which has either the least total suppression cost or the least area burned depending on the specific objective function being used.

These two parameters are the limits of the effectiveness of any airtanker system. Thus, to justify the use of aircraft on an economic basis, the total suppression costs with aircraft must be less than the total cost without aircraft. Likewise, a fire on which aircraft use is justified must burn less area than the same fire would if ground forces alone are used. Therefore, whenever costs or area savings are referred to in the remainder of this report, it will be relative to the unaided ground suppression system.

The method of aircraft cost accounting to be used in the study differs somewhat from the system presently employed by many agencies in that only variable costs will be considered when an aircraft is used on a specific fire. A common practice has been to apply the fixed as well as variable expenses to a specific fire on a dollar per hour basis. This procedure is difficult to apply because the total number of hours flown must be known in advance in order to determine the per hour fixed cost component of the total cost. This value is normally estimated from previous experience, but due to the variability of aircraft demand, these estimates may be considerably in error.

The main reason for not considering fixed costs when dispatching to individual fires, is that short term decisions should be based on variable costs only. For example, if an aircraft is rented, the total cost is variable and the aircraft is dispatched if anticipated savings exceed costs. On the other hand, if the aircraft is owned, fixed costs do not enter into the dispatch decision because if savings on any specific mission exceed the variable costs, the net return, no matter how small, helps to reduce the total yearly fixed cost deficit. The optimum self supporting system will be the one in which the total yearly savings just equal or perhaps slightly exceed the total yearly fixed cost, when several years are averaged together. By considering fixed costs as capital expenditures, fleet size can be dealt with separately from aircraft dispatch on individual fires. Therefore, only variable costs will be considered when dispatching aircraft to specific fires.

2. Determination of the Optimum Aircraft and Methods of Operation

This section is divided into 5 parts:

A. The optimum aircraft type for each fire
B. The optimum number of aircraft for each fire
C. The optimum tactics for each fire
D. The optimum type of operation for each fire
E. Distributions of results by geographical configuration.

A. The Optimum Aircraft Type for each Fire

The following aircraft are being included in the study:

	LAND	WATER	AMPHIBIOUS
A-26 (Mitchell)	X		
Canso (Consolidated)			X
CL-215 (Canadair)			X
Otter (de Havilland)	X		
Snow Commander (Aero-Commander)	X		
Stearman (Boeing)	X		
T.B.M. Avenger (Grumman)	X		
Tracker (Grumman)	X		
Turbo Beaver (de Havilland)	X	X	
Twin Otter (de Havilland)	X	X	

The analysis has been designed in such a way that other aircraft can be added at any time.

In the current analysis only fixed wing aircraft are being considered. Rotary wing aircraft can and do play a vital role in fire control but in general the two types of aircraft are best suited to different roles. Since their best uses tend to be supplementary rather than competitive, it is felt that non-consideration of rotary wing aircraft at this time will not significantly reduce the validity of the conclusions drawn concerning fixed wing aircraft. When drawing conclusions concerning the overall system, however, the influence of rotary wing aircraft will have to be considered. It is anticipated that a detailed analysis of the uses and benefits of rotary wing aircraft will be undertaken at the conclusion of the present study.

B. The Optimum Number of Aircraft for Each Fire

The optimum number of aircraft varies from zero (if aircraft costs are greater than savings) to the number which is limited by the maximum possible drop rate per hour. The maximum rate can vary as follows:

(1) for a single aircraft -- 12 per hour. The pilot assesses each drop himself but he has no requirements for "stacking", selecting a particular route away from the fire or other air traffic control problems.
(2) for multiple aircraft on easy targets using "tag on" drops only -- 20 per hour. This assumes the presence of a bird-dog officer to direct traffic, assess each drop, and select targets. This rate is not likely to be achieved in practice.
(3) for multiple aircraft -- 16 per hour. This assumes the presence of a bird-dog officer, and it also assumes that out of every three drops, two will be "tag on" and one will require a demonstration run by the bird-dog plane.
(4) for difficult targets -- as few as 6 per hour -- both the bird-dog and the tanker may require more than one pass at the target.

For purposes of the study, a maximum rate of 10 drops per hour will be used for single aircraft and 14 per hour will be used for multiple aircraft since it is not possible to determine target accessibility and difficulty from the available data. These limits refer only to the time required for the approach, drop and assessment. For single aircraft 5 minutes is simply added to the time required to fly to and from the pick-up point and reland. For multiple aircraft, since one can be reloading while another is dropping, the limit of 14 drops per hour is imposed only when the total drop rate of all aircraft combined would exceed this limit. In the latter case the additional aircraft would simply spend more time waiting.

It should be mentioned that if aircraft are used at all, the minimum mission will be 3 tank loads regardless of fire size. This may consist of 3 single tank drops in a triangular pattern or 2 double tank drops in a square pattern (assuming that each of the double tanks can be released independently).

C. The Optimum Tactics For Each Fire

Each of the tactics mentioned below will be tested on every fire.

(1) Air Transport -- This may reduce ground crew travel time and therefore allow suppression to start sooner. It may also reduce the expected RLC because one can carry much less equipment in an aircraft than is possible with surface transport.
(2) Drop Retardants -- This will reduce the rate of perimeter growth and thus the fire size, which in turn reduces the amount of work that the ground crew must perform. It does not affect RLC.
(3) A combination of air transport and retardant drops.

D. The Optimum Type of Operation For Each Fire

There are two basic types of operation which will be tested on each fire:

(1) Types of Retardant

(a) Water -- While this is the most readily available and least expensive retardant, it is also the least effective. If used in areas with light canopies and on light intensity fires, it may be expected to hold the fire for up to one hour.

(b) Short Term -- Additives are added to the water to increase its viscosity and reduce evaporation, which prolongs the retarding effect. Short term retardants are not as readily available as water, in that only a limited number of loads can be dropped before the plane must reload the chemical. It is also restricted in that the chemical is most effective only within a limited range of water temperature and salt and mineral content. The purchase price of the chemical adds to the cost of airtanker operations, but, because of the small quantities used, the cost is low. If used in areas with light to moderate canopies and light to moderate intensity fires, it will probably hold the fire for from two to four hours.

(c) Long Term Retardants -- These are the most limited in availability in that a plane must land at a base and reload for each drop. They are also the most expensive due to the quantities required. On the other hand, long term retardants are by far the most effective in that they are effective even on fairly hot fires, and can be expected to hold a fire for 12 to 24 hours.

It should be pointed out that the figures given above for effectiveness of the various retardants are rule of thumb figures based upon observations of field operations. The actual effectiveness values to be used in the study will be based on the results of separate investigations which are currently being undertaken. Generally speaking, the actual effectiveness of each of the retardants varies directly with the amount of the retardant applied and inversly with the intensity of the fire to which it is being applied.

(2) Operating Concepts

(a) The "One Strike" Concept -- A number of aircraft are dispatched immediately in the hope that one drop from each aircraft will be sufficient to hold the fire, thus releasing the aircraft for further action on other targets. This is most useful where the fire is small, the delayed time is expected to be long, and lakes are not numerous.

(b) The "Continuous Operation" Concept -- One or more planes are dispatched to a fire on which they are expected to be operating for a fairly lengthy period -- quite often holding until the arrival of a ground crew. This is most useful where there are numerous lakes, delay time is not expected to be long, and the fire is small to moderate in size.

The calculation of a deterministic solution of the optimum aircraft operation on each fire would require an exceedingly complex analysis of the interaction between all of the factors involved. Because of this complexity simulation appears to be the best method for finding the solution at the present time. If a simulation model is used, a very large number of alternatives can be examined and compared. One of the major problems with simulation is the large number of solutions (many of which are of little or no interest) which can be examined. In this analysis, approximately 2,300 individual solutions could be calculated for each of the 40,000 fires in the sample. Even with high speed computers, the time requirements would be considerable. A few simplifying assumptions are used which substantially reduce the actual number of trials on each fire. The assumptions are:

(1) If the cost of flying to and from the fire with a single aircraft is greater than the total suppression cost no further calculations are necessary as dispatch is not justifiable on economic grounds. Similar limitations will be developed for the area burned objective.

(2) Land based aircraft will use long term retardants only. Since they have to land

to load and since circuit time is expected to be fairly long, the load should be as effective as possible.

(3) Only long term retardants will be used with the "one strike" concept.

(4) Water-based aircraft will use short term retardants only. It is felt that the increased effectiveness relative to water offsets the requirements for periodic reloading, and chemicals can be flown to landable lakes near the fire.

(5) The first load with a water based aircraft will be long term retardants whenever feasible.

(6) Land based airtankers cannot be used for air transport.

(7) The number of aircraft will be increased only as long as the total cost is reduced. When the addition of an aircraft increases total costs, calculations cease for that particular combination of factors.

All of the above assumptions are reasonable considering present operating practices. With them it is possible to reduce the number of solutions which must be calculated to about one-tenth of the total possible number. It is also expected that one-fourth to one-third of the fires can be immediately eliminated by use of the first assumption.

The analysis will proceed generally as follows. After the simulation model has been developed, a separate computer run is made for each type of aircraft. Within each run, the effectiveness of all combinations of interest are calculated for each fire subject to the above assumptions, and the most effective combination for that aircraft type is selected. All pertinent data for the optimum combination for each aircraft is permanently stored. The results for all other combinations for that aircraft type are discarded. If the optimum combination of the aircraft under consideration has a greater effectiveness than all previously-considered aircraft, the results of that run are substituted in the fire record in place of the previously most effective aircraft. Sufficient descriptive information is also added to the record so that it is possible to determine the exact optimum combination which was determined for every fire.

E. Distribution of results by Geographical Configuration

When all fires have been analyzed for a single aircraft type, distributions of the effectiveness of the specific aircraft type are calculated. Using the most effective combinations on each fire (regardless of whether or not that aircraft type was more effective than all other types), the following distributions and totals by region and the province as a whole are determined, using the results from individual fires:

(1) savings in suppression expenditures
(2) savings in area burned
(3) savings in suppression time
(4) number of hours flown
(5) the number of times that each of zero through the maximum number of aircraft were used on individual fires
(6) the number of times that each tactic was used
(7) the number of times that each method of operation was used
(8) for each tactic and method of operation, determine the distribution of each of the following:

  (a) fire to lake distance
  (b) fire to base distance
  (c) rate of perimeter growth

(d) rate of line construction
(e) ground travel time
(f) fire size at the time of detection

Using the first four distributions, the effectiveness of each aircraft type relative to all others can be determined. Using the last four, the best method of operation for the aircraft type can be determined for each geographical configuration.

When all aircraft types have been considered, distributions of parameters for the best aircraft on each fire are determined. All of the distributions discussed above are stratified by aircraft type. In addition, the number of times that each aircraft type is best suited is tabulated. By analysis of the distributions thus obtained it is possible to determine the optimum aircraft and method of operation for each administrative region and geographical configuration.

3. Establishment of the Demand for Aircraft Assistance

The sample selection procedures have been completely revised since the first report. The present procedure uses the results of the simulation model which was described in the previous section. As described, this model determines the potential cost and area savings attainable through the use of the hypothetically most efficient aircraft and tactics.

In the previous analyses the maximum potential benefits accruable through the use of aircraft have been calculated for each fire. This benefit can only be achieved in practice if the correct number of the best aircraft are available at the airport closest to the fire and they are used in the most efficient manner. For the majority of fires, one or more of the above conditions will not be met by any system which could be practically implemented. Therefore, the total benefit accrued from the use of any aircraft system will be somewhat less than the maximum potential benefit.

The above discussion leads to the consideration of three types of missions. They are:

A. missions with potentially positive benefits
B. missions with negative benefits
C. supporting missions.

A. Missions With Potentially Positive Benefits

There are two subclasses of fires under this heading. A discussion of the justification of dispatch is not necessary for those fires on which the benefits remain positive after dispatch is made from the available resources, since the justification is obvious. The justification is not obvious, however, in the case of marginal fires where the benefits are positive under ideal conditions, but become negative when the available resources must be used. It might be argued that it would be better not to include these fires as part of the demand since they constitute an expense rather than a benefit. On the other hand, the benefits accruable under ideal conditions were determined through the use of a number of very complex computer programs which use complete information gathered after the fact. A dispatcher has neither the computational facility nor hindsight available to him. He generally makes his decisions on the basis of estimates and incomplete information. As a result a dispatcher cannot make the fine distinctions which are being made in this analysis.

As has been previously mentioned one of the objectives of the simulation is the greatest possible realism. In real life there is a general tendency to dispatch a slightly larger suppression force than might actually be necessary whenever possible. This is based on the reasoning that on the average, it is less costly to spend a little more than necessary on several fires than to lose a single fire due to an insufficient initial attack force. Therefore, all marginal fires will be included in the demand schedule.

B. Missions with Negative Benefits

If the simulation were attempting to measure the maximum theoretical benefit which an aircraft system would provide, missions with negative benefits would be excluded during the selection process. The purpose, however, is to measure the actual benefit which a practical system could realize. This requires that certain fires, on which the use of aircraft is not quite justifiable be included as part of the demand, because there are practical reasons why aircraft are sent to fires even though their dispatch increases the total suppression costs. Two of the most frequently encountered reasons are discussed below.

(1) Lack of information about the fire at the time of dispatch. This reason for dispatch is not the same as was discussed under part A of this section. In the former case the dispatcher had fairly good information about the fire but was unable to make a sufficiently fine distinction as to the need for aircraft. In the present case it often happens that very little is known other than the fact that a fire has been reported. The dispatcher knows that if he waits for more complete information to make his decision, it may be received too late. The amount of time that he is willing to wait should be inversely related to the F.W.I. Under high or extreme conditions he may act immediately, dispatching a predetermined minimum crew and holding additional forces in a state of readiness until more complete information is received. Under these circumstances, some of the aircraft dispatch decisions cannot be justified on an economic basis. As long as detection systems are such that only incomplete information is relayed to the dispatcher, this type of excess expenditure will be part of any aircraft system, and therefore it has to be included in this analysis.

In the model, these fires will be selected on a random basis. The probability of dispatch will be inversely related to the F.W.I. It will also be influenced by the detection source. For example, it will be assumed that detection aircraft under the employ of the protection agency are capable of relaying complete information in sufficient detail for the dispatcher's use. Therefore, there will be no economically unjustified dispatch to fires detected by these aircraft. Towers and non-airborne forestry personnel provide some information about fires but it is more limited than information provided by detection aircraft. Thus, some fires detected by towers will be included in this category. Lastly, information about fires detected by the general public has the lowest reliability. Therefore, this group of fires will have the highest probability of dispatch without information. It should be noted that our initial sample contains only real fires. The problem of weeding out false alarms reported by the general public is not a factor in this simulation, but does of course have to be taken into account in the real world.

(2) In-season training flights. The efficiency and accuracy of airtanker crews is related to the amount of practice they receive. Because of this, it is common practice to dispatch crews to fires at least once every 10 days. If fires requiring airtanker action do not occur for that length of time, or longer, crews are often dispatched on training missions. Therefore the selection procedure will include the necessity that each airtanker flies to at least one target at

least once every 10 days regardless of the economic justification of the fire itself. When tabulating system benefits, if dispatch to a fire with negative benefits does not occur due to lack of aircraft availability it will be treated as a cost which did not occur. In other words, it will not be included in the benefit calculation.

C. Support Missions

While the use of aircraft in support of ground forces is not an uncommon occurrence, measurement of the benefits derived therefrom is much more complex than measurement of the benefits derived through initial attack; i.e., it is more difficult to determine what would have happened if aircraft had not been used.

With initial attack the answer is often relatively simple -- the fire would have continued to grow until ground forces arrived on the fire. In a study of airtanker use conducted by the Division of Fire Control, U.S. Forest Service (1965) an average of 84% of the on target drops which could be classified as initial attack were rated as being of definite help compared with 66% of on target drops in a supporting role[1]. A further problem remains concerning the "definite help" drops for support purposes -- that is the determination of the additional area that would have burned, or the additional expense that would have been incurred had the airtankers not been employed. For most fires, solutions to these problems cannot be determined with any degree of accuracy. Results of the above study also indicated that drops on class E fires had the lowest probability of being useful (about 37%) as compared to class A fires (the second lowest) of 52%. The greatest probability of effectiveness (70%) was on the class B and C fires.

For the above reasons it is common practice to transfer airtankers from a supporting role to an initial attack role whenever the two occur simultaneously. In fact, some organizations do not dispatch airtankers to large fires unless they are requested for specific and limited targets. The model will attempt to simulate this practice in allocating demand in a support capacity. For all fires which are beyond the extended attack category, a random selection process will generate support missions which are similar in requirements and duration to randomly selected initial attack missions. The selection process will also generate the number of missions for each fire (including the possibility of no missions at all).

The result of the selection process will be a list of fires which require action by aircraft and the amount of action required. The potential savings in suppression costs and/or area burned for all of the fires on this list will be used as a demand schedule which all systems will attempt to satisfy. Although no practical system can possibly satisfy all of the demand, that percent of the demand which is satisfied can be used as a valid measure of the effectiveness of any system. With this measure of effectiveness systems can be readily compared with each other and the best system to employ under various sets of circumstances can be determined.

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1 Initial attack is classified for the purpose of this report as: direct and indirect line building and delaying. Support is classified as: cooling to hold a line, cooling a spot fire and reinforcing a weak line.

4. Preliminary Selection and Allocation of Aircraft

A. General

The selection and deployment of a fleet of aircraft is a considerably more complex problem than dispatching the optimum aircraft type to an individual fire. The greatest difficulty results from the interdependence that exists not only between two aircraft, whether they are of the same or of differing types, but also between two airports, in that an aircraft can be sent to fires which are closer to other airports if aircraft are not available at the closest airport. Aircraft dispatched to fires nearer to an airport other than the one at which the aircraft is assigned may be able to service the fire at only a slight reduction in effectiveness due to the longer initial travel time. Thus, when calculating the potential savings which can be attributed to the assignment of an aircraft to an airport, a percentage of the savings that would be realized if the aircraft were assigned to each of the surrounding airports must be added to the total benefits. The percentage of savings which cannot be realized is proportional to the increased initial travel time and the probability of the non-availability of the aircraft.

The interdependence of aircraft and airports requires that a substantial number of assignment combinations be tested to insure the determination of an optimum solution. The testing of numerous combinations would be prohibitively time consuming and expensive if done by accumulating totals for individual fires. For this reason the aircraft selection and assignment algorithim must be based on the expected values of the relevant fire behavior and control parameters within the sphere of influence of each airport. The use of expected values necessitates the acquisition of data on probabilities of simultaneous fire occurrence and aircraft availability at all airport combinations. For example if, when a fire occurs at an airport other than the one to which an aircraft has been assigned, a fire is also burning at the base airport, the aircraft cannot service both fires simultaneously. If, on the other hand, there is no fire at the base airport the aircraft can be dispatched to the more distant fire. This can be further complicated by the fact that the number of aircraft required for each simultaneously occurring fire may not be the same, thus possibly permitting dispatch of some but not all aircraft from one airport to the fires at another. Solutions to each of these specific problems will be discussed subsequently in this section.

When comparing the possible assignment of several aircraft types, the costs of making each assignment have to be considered as well as the total savings. Therefore, the net benefit of each of the possible assignments have to be compared with each other before a decision can be made as to which is best. The net benefit derived from an aircraft assignment is simply:

$$NB = \sum_{k=1}^{K} (TS_k - VC_k) - FC \qquad (12)$$

Where: NB = Net Benefit
TS = Total Savings
VC = Variable Costs
FC = Fixed Costs
k = Airport Number

The aircraft-airport combination with the greatest NB will be chosen.

One solution to the problem of assigning aircraft to a base airport would be to determine the net benefit of each aircraft at each airport and assign the aircraft to the airport with the highest net benefit. After the first aircraft had been assigned to an airport, the demand[1] at that airport and the surrounding airports is reduced to account for that demand which has been satisfied by the newly-assigned aircraft. The model is then rerun to determine which of the remaining aircraft-airport assignments will result in the greatest net benefit given the previous assignment. This assignment procedure continues until all aircraft have been assigned to an airport. Given a sufficient number of aircraft, it is quite possible that the net benefit of assigning a second aircraft to an airport will exceed the net benefit of assigning a first aircraft to another airport. Thus, in the final solution airports may have none, one, or several aircraft assigned to them.

The major disadvantage of this assignment procedure is that the final solution may not be optimum. That is, considering aircraft in combinations may provide a better solution than considering each aircraft individually. The simplest method for avoiding this problem would be to determine the solution for all possible combinations of aircraft and airports. This procedure would be very time consuming, however, because of the exceedingly large number of combinations which are possible, even when considering a small fleet and a limited number of airports (more than 5,000 alternatives have to be examined if only four aircraft and 20 airports are considered). Thus, a more efficient method of aircraft allocation was sought.

Other analytical approaches were considered in an attempt to find the best one. Queuing theory[2] was thought to be promising but the mathematics which are required for solving a problem with a hyper-exponential arrival distribution and several interdependent multi-channel facilities proved to be too cumbersome. If only a single airport and aircraft type were being considered queueing theory might be very useful.

The possibility of using network analysis[2] was also considered. In a standard network analysis approach all nodes (airports) are connected to all other nodes by arcs. The airtanker allocation problem could be solved by satisfying the demand at all nodes with a minimum transfer cost. The procedure generally involves trying all possible combinations to achieve the minimum. This is generally made possible by the prior definition of supply and receiving nodes which are often limited in number. If one considers that all airports may be both a supply and a receiving node, and the large number of possible combinations of aircraft allocation such a procedure also becomes cumbersome.

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[1]For this study, demand is defined as the potential benefit which could be realized from an assignment, whereas net benefit is realized as a result of an assignment (the satisfaction of demand). In other words, demand exists before assignment and benefit is realized after the assignment.

[2]References which discuss these procedures in detail are given at the end of the paper.

Having encountered similar difficulties with all of the standard approaches which were considered, it became evident that a unique algorithm would have to be developed to solve the problem. The algorithm which was developed uses the concept of convergence and examines in increasing detail an ever decreasing number of alternatives which appear to have the greatest probability of becoming the optimum solution. In utilizing this algorithm there remains the possibility of sub-optimization but the probability of such an occurrence is quite low. The advantages of the enormous reduction of alternatives to consider and in calculations to be made far outweigh the consequences of any such possibility.

B. The Model

In discussing the solution that has been developed and the ramifications of the procedures involved, the algorithm will be generally described in this section and the details will be dealt with subsequently. The best way to describe the algorithm is by means of an example. Assume that there are 12 aircraft, four of each of three types, and 20 airports. Because there are 12 aircraft, the program will loop 12 times, and each time a single aircraft will be assigned to that airport at which it contributes the greatest net benefit.

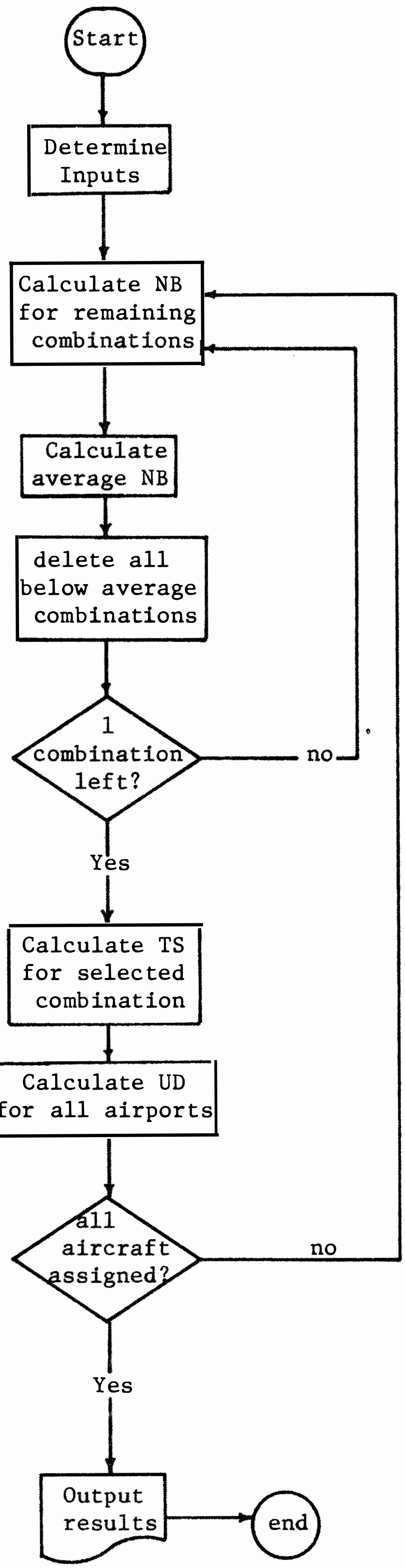
The first step in each loop is to calculate the net benefit for every aircraft-airport combination, considering only those fires which are closest to the airport of assignment. In the example there would be 60 aircraft-airport combinations which have to be considered. (20 airports times 3 aircraft types at each). Next, the average net benefit for all combinations is calculated. All combinations which have less than the average benefit are eliminated, since it is highly unlikely that the best combination will eventually emerge, starting with an assignment which is initially inferior to about half of the sample. This leaves about 30 combinations for the next step.

Following this, the aircraft's effectiveness in servicing fires nearer bases other than that to which the aircraft is assigned is considered for each of the remaining combinations. The benefits of dispatching the airtanker to fires which surround the nearest neighbouring bases are computed and added to the original set of benefits. In the example, the benefits of the approximately 30 remaining aircraft-airport combinations are increased by the benefits which would occur if the new aircraft is allowed to service fires within the sphere of influence of the airport nearest the base at which it would be stationed. A new average benefit is then computed and those combinations which have a smaller benefit than the new average are discarded. Thus, in our example 30 combinations now become approximately 15.

The airport second nearest to the base airport is now considered and benefits which would accrue from servicing fires surrounding this base are now computed and added to the original alternatives. A third average is determined and alternatives which are less than the average are again discarded. This process is carried out until exactly two alternatives remain. One more airport further removed from each of the two remaining combinations is considered and the alternative having the greatest benefit indicates the airport at which the first aircraft is allocated.

In the final step, the total benefit which can be attributed to allocating this aircraft is determined. The method of calculating this total will be described in detail subsequently. The unsatisfied demand at each airport is then reduced by the amount which is satisfied by allocating the most beneficial aircraft to its corresponding airport. The process then returns to the starting point and the second aircraft is allocated to an airport in like manner. This reiterative process is carried out until all aircraft are allocated, each to an airport. Figure 5 is a general flow chart which portrays this allocation algorithm.

Figure 5: General Flow Chart for the aircraft allocation model



C. Determination of Input Data

In order to simplify the relationships encountered in this problem, several expected value and probability matricies are computed. They are:

(1) The Demand/Benefit Matrix -- This is the total potential savings for each aircraft of each type at each airport.
(2) The Aircraft Substitution Matrix -- This is the percentage of the savings of every airtanker type which every other airtanker type can account for at each airport.
(3) The Expected Values -- These are the expected values for all fire behavior and suppression parameters of interest with respect to each airport.
(4) The Airport Distance Matrix -- This is the distance between all airports of interest.
(5) The Airport Priority of Selection Matrix -- This is the order of selection of neighbouring airports from a predetermined base location.
(6) The Probability of non-simultaneous Fire Occurrence Matrix -- This is the probability that a fire requiring aircraft is not burning at the two airports or sets of airports under consideration of the same time.

(1) Calculation of the demand/benefit matrix

The total potential savings (TS) for the jth airtanker (j = 1, J) of the i^{th} type (i = 1, I) at the kth airport (k = 1, K), is simply:

(13) $$TS_{i,j,k} = \sum_{n=1}^{N} S_{i,j,k,n}$$

Where: K = the total number of airports of interest in the province
J = the maximum number of aircraft of any single type used on any single fire in the province
I = the number of aircraft types which were optimum on one or more fires in the province
S = the savings for aircraft i, j, k on fire n
N = the number of fires serviced by airtanker i, j, k.

Only the optimum aircraft and type of operation for each fire are considered. The output tape from the previous analysis contains all of the necessary information required for this analysis. The output of this step is a 3-dimensional matrix with dimensions I x J x K. The k^{th} plane[1] of this matrix is illustrated below:

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[1] A two-dimensional surface not an aircraft.

Airport k

Airtanker Type (i)	Aircraft No. (j) 1	2	3	→	J
1	S	—	—	—	—
2	1/2S	1/2S	—	—	—
3	1/3S	1/3S	1/3S	—	—
↓					
I					

Computationally, the procedure is as follows:

If, at airport k, one aircraft of type 1 is optimum on a fire, all of the savings for that fire (S) are entered in location (k, 1, 1). If on another fire, 2 aircraft of type 2 are optimum, 1/2 of the total savings are entered in locations (k, 2, 1) and (k, 2, 2). If, on another fire 3 aircraft of type 3 are optimum, 1/3 of the total savings are entered in the appropriate locations. When a second entry is made to an individual location in the matrix, the savings are added to the previous subtotals. A similar 2 dimensional matrix is tabulated for each airport. The totals in each location after fire N is tabulated are the values of TS which will be used.

(2) Calculation of the Aircraft Substitution Matrix

The percentage of the savings of an airtanker type (a) that another airtanker type (b) can satisfy ($PS_{a,b}$) is given by the relationship:

(14)
$$PS_{a,b} = \frac{\sum_{n=1}^{N} S_{nb}}{\sum_{n=1}^{N} SO_{na}}$$

Where: SO_{na} = Savings on fire n for aircraft type a where aircraft type a is optimum.
S_{nb} = Savings for aircraft type b on the same fire as above.

This operation requires the creation of a tape file after each run in the analysis described in Part A of this section, since only the savings for the optimum operation are permanently retained as part of the fire record. The output for this operation is in the form of a 3-dimensional matrix with dimensions K x I x I. The k^{th} plane of the matrix is illustrated below.

Airport k

Airtanker type	Airtanker Type a	b	c	→	I
a	x	–	–		–
b	–	x	–		–
c	–	–	x		
↓					
I	–	–	–		x

The computational procedure is as follows: if, on a fire, at airport k, airtanker type a is best, the savings for type a are entered in location (k, a, a) and the savings for the optimum combination of every other type on the same fire are entered in rows b through I in column a. If on another fire, airtanker type b is best, the savings for type b are entered in (k, b, b) and all other savings are entered in their appropriate rows in column b. This procedure continues until all fires have been considered. The savings for subsequent encounters of the same airtanker types are added to preceding subtotals. Finally, for each airport k all subtotals in column a are divided by the total in (k, a, a), those in column b by the total in (k, b, b) etc.

(3) Calculation of the Expected Values

There are six parameters of interest:

(a) ground crew dispatch and travel time (ETT_k)
(b) perimeter of fire at the time of detection (EPD_k)
(c) rate of perimeter growth ($ERPG_k$)
(d) rate of line construction (ground crew) ($ERLC_k$)
(e) rate of mop-up ($ERMU_k$)
(f) the percent of fires which require each of 1 through J aircraft at each airport.

(4) Calculation of the Airport Distance Matrix

A computer program (Valenzuela, 1971) is used to calculate distances between points where the location of each point is given in terms of longitude and latitude. Accuracy of the program is 0.04 percent up to 600 miles. Output is in the form of a two dimensional matrix similar to a standard distance table found on gas company road maps.

(5) Calculation of the Airport Priority of Selection Matrix

Using each airport (k) as a base, a priority of selection for all other airports relative to the k^{th} airport is determined. The priority is based on order of increasing distance from the base airport (k). The output is in the form of a two dimensional matrix with dimensions k x k-1. A hypothetical example is shown below:

Airport	1st	2nd	3rd	→ (k-1)
1	12	3	4	
2	4	5	10	
3	9	1	8	
↓				
K				

in which the number of the airport which is closest, second closest, etc. to every airport in the system is listed.

This table can be computed directly from the results of the previous analysis by simply sorting all stations on the basis of increasing distance from each airport k under consideration.

(6) Calculation of the Probability of Non-simultaneous Occurrence Matrix

Determine the probability that when a relevant fire[1] is burning uncontrolled at each airport k (k = 1, K) in each of the sequences determined in 5 above that there is no similar fire burning at any one of the preceding airports in the sequence ($PSF_{a,b}$). For example, if in the previous table, a fire is burning at airport 12 what is the probability that a fire is not burning at airport 1? If a relevant fire is burning at airport 4 what is the probability that relevant fires are not burning at either airports 1 or 12 or 3?

These probabilities have to be determined from the basic fire occurrence data, as the simultaneous occurrence of fires at any airport is not entirely independant of the occurrence at other airports since both are under the influence of similar weather patterns.

D. Calculation of Total Savings for the Selected Combination

The procedure for accumulating total savings for each aircraft assigned to the system depends on whether the aircraft is:

(1) the first one in the system or,
(2) the first one at an airport or,
(3) the second or subsequent aircraft at an airport.

Each of the above will be considered seperately.

(1) For the first aircraft assigned in the system:

(a) <u>at base airport (k=1)</u>
First, the assigned aircraft (i,j) accounts for all of the savings attributable to it at the base airport (1) ($TS_{i,j,1}$). In addition, the assigned airtanker can account for some of the savings attributable to other airtanker types at that airport. It cannot account for all of the savings of any other aircraft type however, since by definition only those aircraft which were best on at least one fire are being considered. An aircraft type is best only if it saves more than any other aircraft type on one or more fires. The percentage of each of the savings of other airtanker types which the assigned aircraft (i) can satisfy ($PS_{i,b}$) multiplied by the savings attributable to each airtanker type yields ($TS_{b,j,k}$) which is the savings which the assigned airtanker can account for by airtanker type. The sum of the individual savings:

$$(\underline{15}) \qquad PTS_{i,j,1} = \sum_{b=1}^{I} TS_{b,j,1} \times PS_{i,b} \; ; \; b \neq i$$

yields the total savings for all other aircraft types which the assigned aircraft can account for at the base airport (1). Total savings for the assigned aircraft at the base airport are given the sum:

$$(\underline{16}) \qquad TS_{j,1} = TS_{i,j,1} + PTS_{i,j,1}$$

---

[1]A relevant fire is one which requires aircraft action.

The unsatisfied demand ($UD_{i,j,1}$) is calculated by subtracting $PTS_{i,j}$ from $TS_{i,j,k}$ for each aircraft. UD for the assigned aircraft equals 0. The original values of $TS_{i,j,1}$ are replaced by $UD_{i,j,1}$.

(b) <u>at neighboring airports</u>
The calculation of $TS_{j,k}$ for each of the neighboring airports proceeds in the same manner as at the base airport except that the assigned aircraft cannot account for all of $TS_{i,j,k}$ at the neighboring airport. The reduced total savings (RTS) for the assigned aircraft type which can be accounted for are given by:

(17) $$RTS_{i,j,k} = TS_{i,j,k} \times PSF_{1,k} - n \left[RS(1,k)_{i,j} + TC(1,k)_{i,j}\right]$$

Where:
- $RTS_{i,j,k}$ = Reduced total savings at airport k which can be accounted for by an assignment at another base airport.
- $TS_{i,j,k}$ = Total savings at airport k.
- $PSF_{1,k}$ = Probability of non-simultaneous fire occurrence at airports 1 and k.
- $RS_{i,j}$ = Reduced savings at the airport due to the increased travel time from airport 1 to k.
- $TC_{i,j}$ = Transfer costs from airport 1 to k.
- n = Number of aircraft fires at airport k which the aircraft at another airport would fly to, which is given by:

(18) $$n = N_k \times PSF_{1,k}$$

Where: N_k = Total number of fires at airport k.

$RTS_{i,j,k}$ is calculated in the same manner as $TS_{i,j,k}$ at the base airport. By substituting the former for the latter in equation (15), $PTS_{i,j,k}$ can be calculated. Finally, total savings for the aircraft is simply the sum:

(19) $$TS_j = TS_{j,1} + \sum_{k=2}^{K} (RTS_{i,j,k} + PTS_{i,j,k})$$

(2) For the first aircraft assigned to each airport:

(a) at the base airport:
There is now one more aircraft in the system than there was formerly. In the previous case, only aircraft type (i) and airport (k) were considered. Now more than one aircraft at a single airport is introduced, thereby causing j to vary also. Previously, j was always equal to 1. Whereas an aircraft from one or more airports accounted for part of the first aircraft's savings, these savings will now be completely accounted for by the newly assigned aircraft. However, only those savings not previously accounted for can be attributed to the newly assigned aircraft. In practice, the aircraft from other airports will be used to satisfy the demand for second and subsequent aircraft. Therefore, the percentage of the first aircraft's savings which had been satisfied from other airports will be applied to the second aircraft's unsatisfied demand:

(20)
$$S_{i,2,1} = \frac{TS_{i,1,1} - UD_{i,1,1}}{TS_{i,1,1}} \times TS_{i,2,1}$$

Also, the difference between the new savings for aircraft 2 and the previously accounted for savings is calculated:

(21)
$$DS = S_{i,2,1} - (TS_{i,2,1} - UD_{i,2,1})$$

Similarily, the percentages of the second airtanker's savings are applied to the third (and the difference calculated), and so on until the percentages of all previously partially accounted for savings have been shifted to the subsequent aircraft and each difference calculated. Lastly, the savings for the airtanker type which result from the assignment of the aircraft under consideration is given by:

(22)
$$S_{i,J,1} = UD_{i,1,1} + \sum_{j=2}^{J} S_{i,j,1}$$

By substituting $S_{i,j,1}$ for $TS_{i,j,1}$ the equations in section (1) (a) can be used to calculate $TS_{j,1}$ for the first aircraft at each base airport.

(b) at all subsequent airports in the sequence:
The newly assigned aircraft can account for some of the unsatisfied demand for those aircraft which have had their savings previously partially accounted for. The procedure is as follows:

Any aircraft where UD = 0 is eliminated. For all other aircraft where UD < TS (in other words, where some of the savings have been previously accounted for) the procedures discussed above under (1) and (2,a) are used. These procedures also apply to the first (and only the first) aircraft where TS has not been reduced (TS = UD) -- i.e. none of the original savings have been accounted for. In other words, at each airport the effect of the additional travel distance is computed, the savings for the same airtanker type as the one assigned are calculated, the savings for the other types are calculated and a new UD is calculated in each case. Finally, the results for each airport are totalled. The total is added to $TS_{j,1}$ to yield TS_j for the currently assigned aircraft.

(3) For the second or subsequent aircraft assigned to an airport:

(a) at the base airport:
Use the same procedure as in (2) (a) except that the application is to the first aircraft in the sequence where UD ≠ 0. This will no longer be the first aircraft at the airport. The shifting of UD commences with the first aircraft where UD ≠ 0.

(b) at all subsequent airports in the sequence:
The second aircraft at a base airport can account for not only the second aircraft's savings at subsequent airports as in (2)b, but it can also account for some of the first aircraft's savings at neighboring airports which could not be satisfied by the first aircraft at the base airport. If there are two aircraft at the base airport and fire is burning, which requires only one aircraft, the second aircraft may be dispatched to neighboring airports. The percentage of one aircraft fires (PF_{jk}) at the base airport is equal to the percentage of the first aircraft's UD which can be satisfied at neighboring airports by the assignment of the second aircraft to the base airport. This procedure can be extended to three or more aircraft by using the percentage of fires which require j - 1 aircraft at the base airport, where j is the number of assigned aircraft.

In addition, there is the percentage of the savings which can be accounted for as described in (2)b. The aircraft under consideration can account for one percentage or the other, but not both at once. To solve this problem, the cross product of ($PF_{j,k}$) and the percentage in (2)b is added to the larger of the two (rather than simply adding the two). This value is then applied as described in (2)b.

E. Summary

In summary, the aircraft selection and allocation model consists of three main parts. (1) determination of input data, which is run only once, (2) selection of the optimum aircraft-airport combination and (3) tabulation of the total savings attributable to each assignment. The last two parts are repeated as many times as there are aircraft to be assigned, with each run depending on the results of previous runs.

The general procedures outlined above will yield preliminary estimates of the mixture and distribution of a hypothetically optimum fleet. These procedures will not yield the final answers however, as the inter-relationships between aircraft transfer costs, base maintenance costs, and system effectiveness will have to be examined in detail before final decisions can be made with regard to either of these topics.

5. Estimation of the Optimum Fleet Size

It is hypothesized that the slope of the function describing the savings which can be attributed to increasing airtanker fleet size is similar to the normal single input, single output production function (see Figure 6). Initially, as the number of airtankers is increased, each additional airtanker is complementary, i.e., the savings for two or more airtankers acting together is greater than the sum of each of these units acting independently, and the marginal savings increase (A through B, Figure 6). A point is reached when additional airtankers are no longer the critical factor and the marginal savings curve flattens out and eventually begins to decrease. This state continues until the marginal savings become negative and additional airtankers will decrease the total savings (B through C, Figure 6). Introducing airtankers into the system is economically justifiable only if the marginal savings are greater than the marginal cost. Between the point where marginal savings begin to decrease and the point where marginal savings are less than the marginal cost is the region where rational managers operate (B through C, Figure 6). Before point B is reached, adding an airtanker increases the average saving of each airtanker previously added. After point C has been passed, an additional airtanker will decrease the total savings. The optimum number of airtankers is at the point where the marginal savings are the greatest. The point of maximum savings is the point where the last airtanker produced a saving which was just greater than the cost of adding the airtanker. To maximize profit, the manager operates with close to the optimum number of airtankers. To maximize savings, the manager increases the number of airtankers until point C is reached.

In previous analyses, total costs and total savings for each airtanker in the system were calculated. By accumulating these values from zero through a large number of airtankers, total system costs and savings can be calculated for any number of airtankers. Further, the marginal costs and savings can also be calculated for any number of airtankers. By plotting these values, a series of functions such as are described in Figure 6 are obtained. Since the suppression of forest fires is in the public interest and financed primarily with public funds, it is assumed that maximum savings rather than maximum profit is the point at which the system should operate. Therefore, the optimum fleet size with respect to economic criteria will be that number of airtankers which is closest to (but not past) point C.

If the objective function is the maximization of the reduction of area burned, an analysis of the function beyond point C is necessary. In this region, the system is operating at a net loss, while saving a greater area than is the case at point C. For each airtanker added beyond point C the loss in savings can be divided by the number of acres saved, yielding a cost per acre saved. Since each additional airtanker saves some area, the manager must then decide on the value of his land, or failing that, he must decide on the amount of money he is willing to spend per acre saved. The size of the system then becomes the number of airtankers where the cost per acre saved of the last unit added is just less than or equal to the amount which the manager is willing to spend.

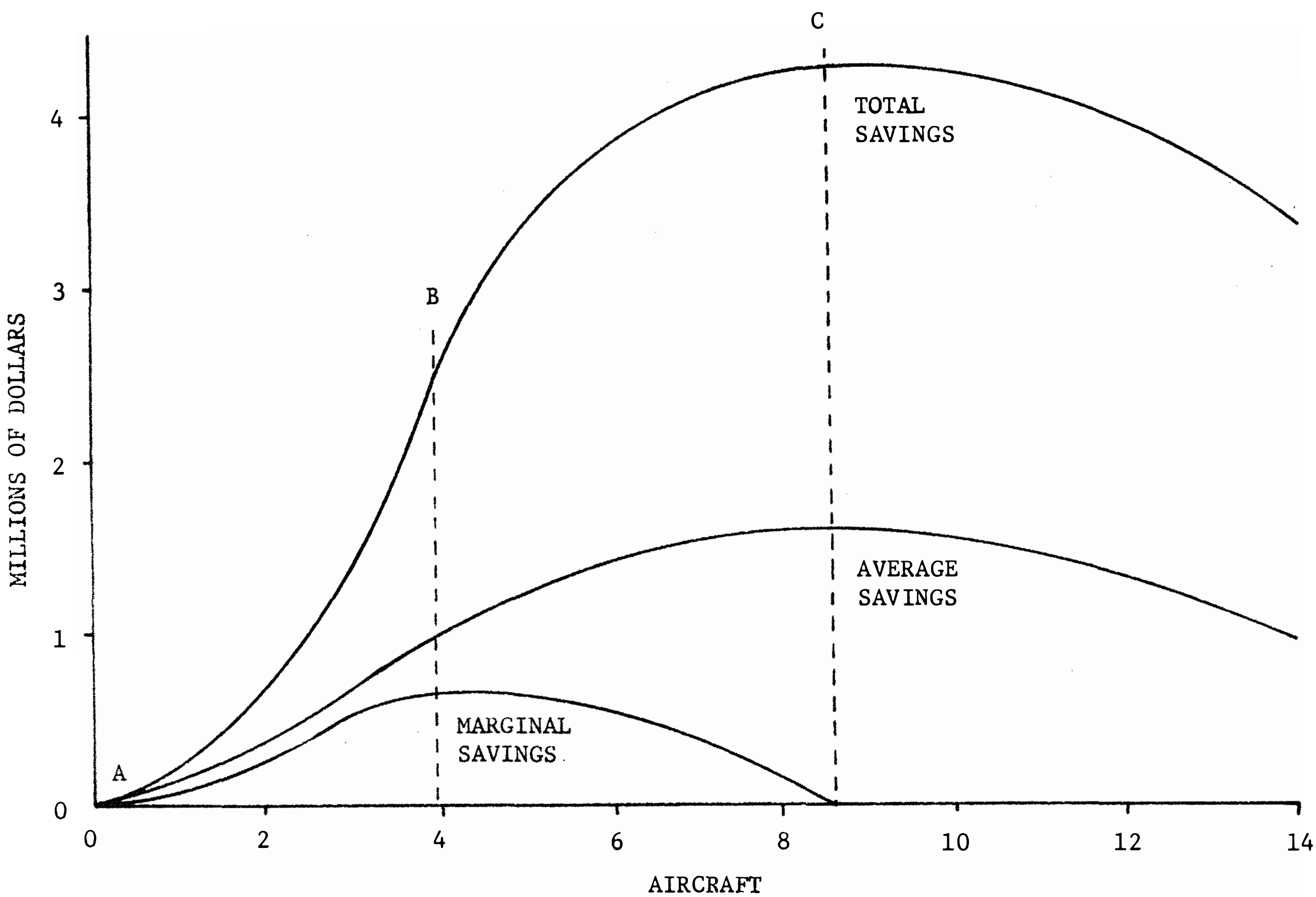
6. Determining the Effects of Aircraft Transfer

A. Daily and Short Term Transfer

Aircraft are transferred from one airport to another on a daily or short term basis for one or more of the following reasons:

(1) in anticipation of demand due to greater fire hazard,

FIGURE 6. Hypothetical total, average and marginal savings as a function of the number of aircraft in a fleet.



(2) to provide temporary protection at locations which cannot justify an aircraft on a full-time basis or
(3) to be closer to active fires.

If the question of transfer concerns only a single aircraft and two airports, the decision on whether or not to transfer can be based on the solution of a relatively simple equation:

(23) $$TB = [ES_2 - (PS \times ES_2)] - [ES_1 - (PS \times ES_1)] - TC$$

Where: TB = transfer benefits. If TB is positive, transfer should take place. If TB is zero or negative, transfer should not occur.
ES_2 = expected savings attributable to the aircraft at the airport that the aircraft would be transfered to.
ES_1 = expected savings attributable to the aircraft at the airport that the aircraft would be transfered from.
PS = percentage of savings at airport 2 which can be achieved by dispatching an aircraft from airport 1. If the two airports are sufficiently far apart that an aircraft from one cannot service fires at another they may be considered mutually exclusive, therefore PS = 0.
TC = transfer cost. If the receiving airport has no maintenance facilities the round trip cost is used. If there are maintenance facilities at the receiving airport the one way cost is used. In either case, the per diem. cost of the crew is added.

The expected savings are determined by the following relationship:

(24) $$ES = P_o \times P_a \times \bar{S}_{k,a}$$

Where: P_o = probability of fire occurrence (a function of the FFMC).
P_a = probability of an aircraft being required (a function of the FWI).
$S_{k,a}$ = average saving per fire at airport k for plane a, which is simply:

(25) $$\bar{S}_{k,a} = \frac{TS_a}{na}$$

Where: TS_a = total savings for plane a.
na = number of fires attacked by plane a. This procedure can be applied to the transfer of two or more aircraft by simply totalling the expected savings for each.

The decision as to when the aircraft should return to it's home base is partially governed by the facilities of the receiving airport. If the receiving airport has retardant mixing facilities only, the aircraft should return to the nearest base with maintenance facilities every night for daily preventative maintenance. In the case of a receiving airport with maintenance facilities, the aircraft does not have to return to it's home base until the transfer benefits (TB) minus the extra costs of maintaining the aircraft away from it's base becomes zero or negative.

When considering several aircraft at several airports the transfer problem becomes considerably more complex. Rather than simply considering individual aircraft, and airports, the objective becomes one of transposing the current deployment of the fleet or system state to a state which approaches the optimum by balancing total system transfer costs with total expected savings. All possible combinations of transfer have to be considered to insure the determination of an optimum solution.

The interdependency of aircraft and airports with each other prohibits the consideration of all possible combinations. As a result, a step-wise transfer model is used to derrive a solution. This model uses many of the procedures in the aircraft allocation model. $ES_{i,j,k}$ (expected daily savings) is substituted for $TS_{i,j,k}$ (total seasonal savings), and two constraints are added: 1) airports without aircraft do not have to be considered at this time, thus reducing the number of operations required, and 2) if it is known that an aircraft will fly a mission early in the morning (due to a fire out of control at the end of the previous day, or a fire detected early on the day under consideration), it will not be transferred. The transfer decision will be made at 9 am each morning. The model is in two parts: (1) initialization which establishes the system state at the time of analysis, and (2) transfer, which considers the possibility of aircraft transfer given the initial system state.

Initialization involves the calculation of ES_j for every aircraft in the system. Since ES_j for any aircraft depends on the location of all other aircraft, and the order of selection, the aircraft are sorted in order of decreasing ES_j. This is done with the same convergence routine used in the allocation model. As previously mentioned, the convergence routine repeatedly calculates the average ES_j for an ever decreasing number of alternatives in increasing detail, while dropping about half of the alternatives at each step. ES_j is then calculated for the aircraft with the highest value. As in the previous model, the process is repeated until ES_j has been calculated for each aircraft in the system. Then the total expected savings for the system (ES) are calculated:

(26) $$ES = \sum_{j=1}^{J} ES_j$$

With the calculation of ES, the initialization is complete. The transfer model then considers one aircraft at a time, starting with the aircraft with the lowest ES_j, since that aircraft has potentially the highest TB. ES_j $(j = J)$ is subtracted from ES, and from $ES_{j,k}$ wherever aircraft j has any influence. If $TB_{j,k}$ is zero or negative, for every combination, the program stops immediately, and no transfer occurs. If $TB_{j,k}$ is positive for one or more combinations, the aircraft is moved to the location where the highest $TB_{j,k}$ occurs.

At this point, the program returns to the start and recalculates $ES_{j,k}$ for every aircraft in the system, in a new order of decreasing $ES_{j,k}$ as well as a new ES, because a change in the status of any aircraft affects every other aircraft in the system due to their interdependency. As a final check, the new ES must be greater than the previous value in order for the transfer to be finalized. Since it is difficult to conceive of a situation where TB was positive and ES did not increase, the new ES will, in all probability be greater than the former value.

The program again considers the aircraft with the lowest $ES_{j,k}$ which results from the new calculations in the same manner as before, and transfers a second aircraft if TB is positive. In like manner, the program repeats the process of transferring an aircraft and recalculating ES until an aircraft is encountered which cannot be transferred, at which time the program stops. In many cases the resulting solution will be the optimum solution. Since all combinations were not considered, however, there remains a slight possibility that a sub-optimum solution is determined (i.e. a good solution but not the best). However, since this problem has to be solved once per day for several fire seasons, efficiency is essential. Furthermore, as long as the aircraft are reasonably well allocated, the precise allocation is not critical because of the speed with which aircraft can respond to changing situations. Therefore, the problem of sub-optimization is not considered to be an important factor.

B. Seasonal or Permanent Transfer

If each airtanker were a completely self sufficient entity it would be possible to assign them in proportion to local fire control requirements. Airtankers are not self sufficient however, in fact they are highly dependant on maintenance and support facilities. The establishment and operation of bases involves both fixed and variable expenditures over and above aircraft maintenance expenses. Since the costs of these bases are part of the total system costs the system should contain as few bases as possible, constrained, of course, by the reduction in overall fire suppression effectiveness and increase in daily transfer costs as the number of bases is reduced.

The two limits on the possible number of bases are intuitively apparent. The smallest number is a single centrally located base. This would obviously be the most efficient and least expensive with respect to maintenance operations. In contrast, the greatest number of bases would be one at every airport. This is obviously the most expensive type of maintenance operation. Since total savings for the system should be inversely related to the number of bases, a procedure for determining the optimum balance between the two must be developed. There are four possible alternatives at each airport:

(1) No facilities whatsoever - this means that the airport in question is not usable for fire suppression work.
(2) Retardant mixing facilities only - these bases can be used for daily fire suppression work but aircraft must return to a maintenance base each night.
(3) Replacement and minor repair facilities - it will be assumed that these bases also include retardant mixing facilities, if appropriate to the type of operation. The facilities would include a crew of mechanics, a stock of repair parts and sufficient equipment to perform repairs up to and including engine replacement. A minimum of permanent facilities is sufficient.
(4) Major facilities - each system normally requires only one such base. All repair work including air frame and engine overhall and modification are done at this base. Such a base requires extensive permanent shop and hangar facilities.

Since aircraft would travel to the major facility very infrequently (in fact perhaps not at all during the fire season) it's location has little or no effect on overall system effectiveness. Therefore, to simplify the analysis major facilities will not be considered.

Solution of the problem is relatively straightforward. The procedure involves the maximization of the function SS:

$$SS = SF - (CB + TC) \quad (27)$$

Where: SS = total savings for the system
CB = total cost of bases
SF = savings in fire suppression expenditures
TC = total transfer costs

A hypothetical example of this function in shown in Figure 7. Computationally, the maximization of this equation can be done using an iterative computer program to calculate SS for all possible combinations of bases using the following general procedure, which is diagrammed in a flow chart in Figure 8.

(1) A hypothetical state is established such that every airport has retardant mixing and minor repair facilities and aircraft are assigned as per the results of the distribution analysis. In this case, CB will be maximized and TC will be minimized. (Point K in Figure 7)

(2) Eliminate the maintenance base at the airport with the smallest total savings and re-compute SS.
CB and SF will be lower, TC will increase and SS should increase (point K-1 - Figure 7). If an aircraft was assigned to the airport, determine if the reduction in aircraft's effectiveness resulting from the transfer is sufficient to reduce it's total savings below it's total costs. If this has in fact occurred, and SS is greater than it was before the transfer, the aircraft is deleted from the system and SS is recalculated. If SS is less than it was before the transfer the aircraft is not deleted. The purpose of this operation is to adjust the fleet size with respect to base and transfer costs. Only marginal aircraft with very low net benefits will be eliminated by this step.

(3) For each maintenance base which is deleted, eliminate from one to as many retardant mixing bases as there are maintenance bases already eliminated. These should be eliminated in the same order as the elimination of maintenance bases. Calculate SS for each deletion.

(4) Return to step (2) until only one base is left in the system. (Point 1 - Figure 7)

(5) Output the final results in the form of a table which lists SS for every possible combination of bases (which is limited by the order of selection as discussed in (2) above). That combination of mixing and maintenance bases for which SS is the maximimum is the optimum economic combination for the system.

From Figure 7 it can be seen that SS will be low if there are insufficient bases as the transfer costs will be high, and the total savings will be low. SS will also be low at the other end of the spectrum because base costs will be high. SS will be maximized at some point between the extremes, the exact point depending on SF, CB and TC.

7. Determine the Potential Effectiveness of the Hypothetically Optimum Fleet

The final step in the analysis of the hypothetically optimum airtanker system is measurement of the overall effectiveness of the aircraft system. This will be accomplished through the use of a simulation program. First, a fleet with configurations determined by the results of the previous analyses is established. Using the optimum operational practices (as previously determined) the fleet of aircraft fight fires by simulation as they occur. At the end of each year pertinent parameters such as cost and effectiveness are totalled. These final totals then become the goals which

FIGURE 7. SS, SF, CB, and TC as functions of the number of bases.

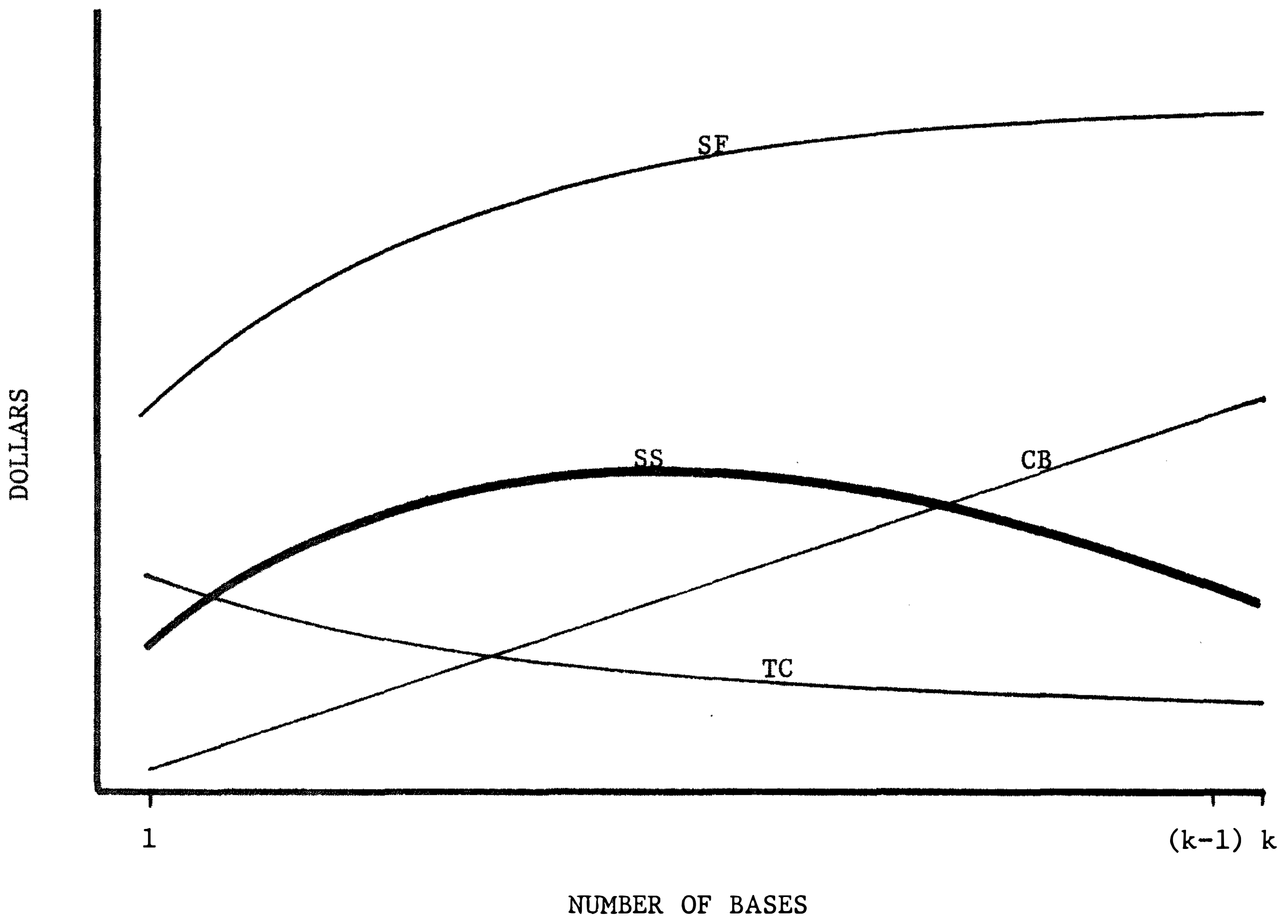
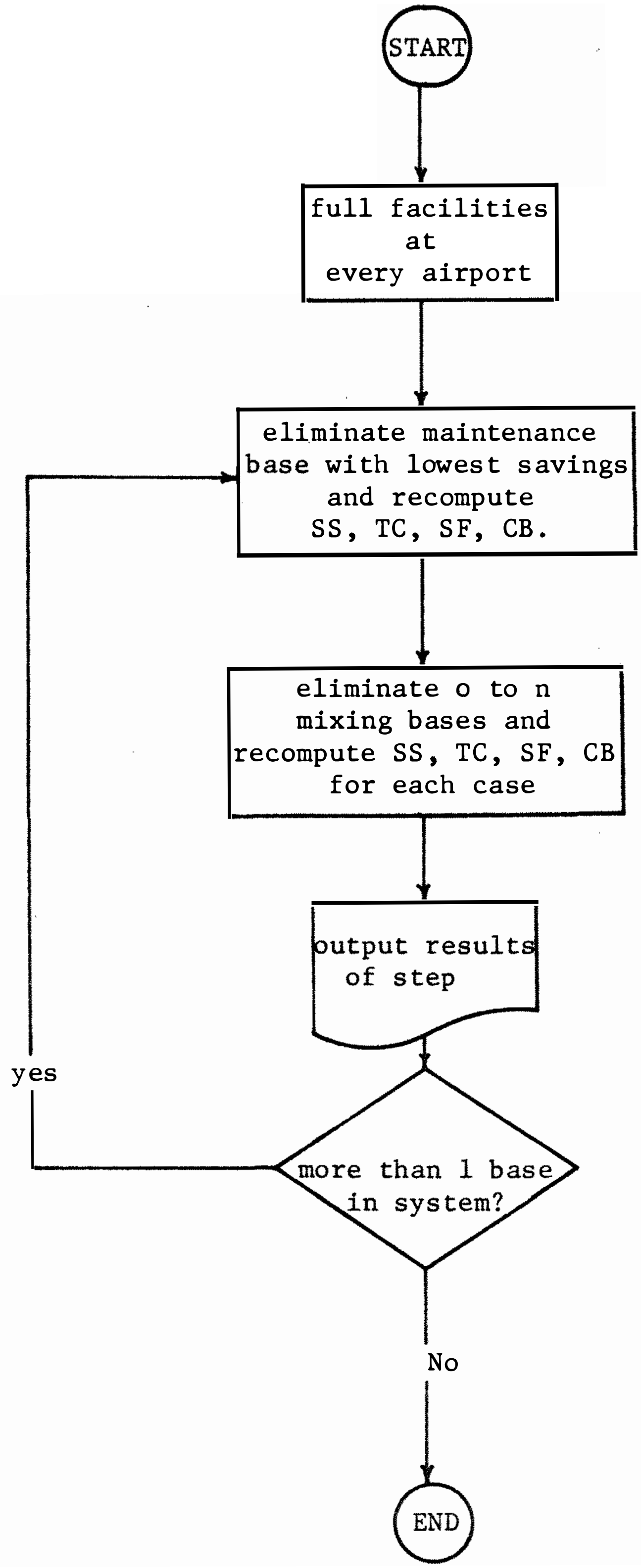


FIGURE 8. General flow chart for determining the optimal number of bases.



all other configurations of systems will attempt to reach.

The simulation model will contain the following basic segments which are flow charted in Figure 9.

A. Aircraft transfer - once per day at 9 a.m. if warranted.
B. Fire generation - each fire will be considered in order of occurrence.
C. Aircraft dispatch - a combination of aircraft as close as possible to the optimum for the specific fire will be dispatched from the nearest airport where aircraft are available.
D. Fire suppression - both ground crews and aircraft are used to suppress the fire.
E. Tabulation - costs and measures of effectiveness are tabulated for each fire, season and overall.

Each of the above segments of the model with the exception of aircraft dispatch have been discussed in detail elsewhere in this paper. Aircraft dispatch with alternative aircraft and base possibilities (none of which may be optimum) has not heretofore been considered.

With a computer, it would be possible to dispatch the optimum combination of aircraft, given any specific state of the system at the time of an outbreak. When dispatching aircraft to fires there is only one, or at most very few fires which have to be considered at one time. This fact drastically limits the number of possible dispatch combination which have to be considered. As a result, network analysis would be a readily adaptable and practical method of optimizing aircraft dispatch. This technique requires a computer, however, and it will be many years before operational dispatchers in forest fire organizations have this capability. As a result, current practices normally involve dispatching the closest aircraft or group of aircraft regardless of type.

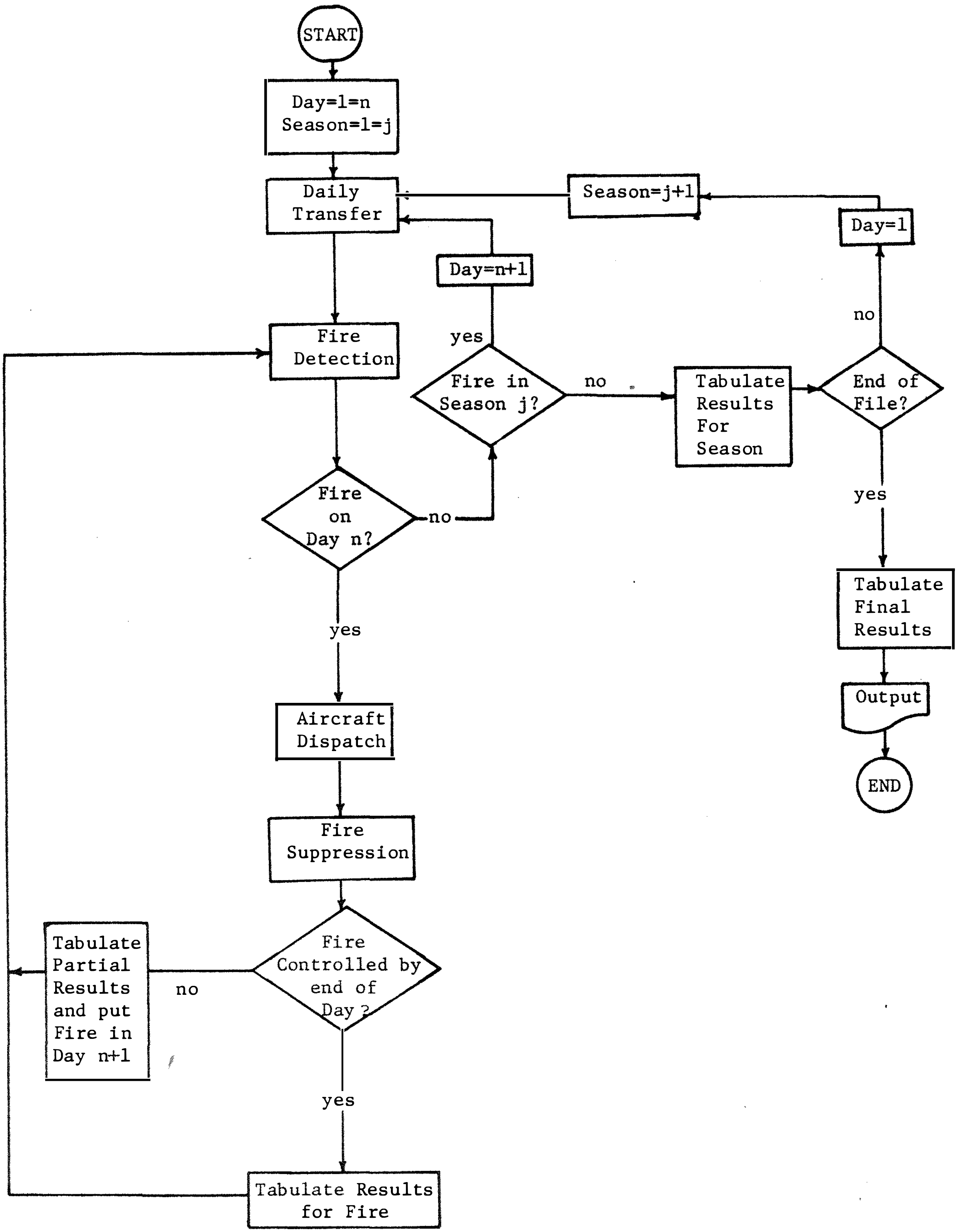
A procedure will be followed in the simulation model which approximates that which would be used in real life. An attempt will be made to dispatch from the airport closest to the fire. If there are no aircraft or an insufficient number of aircraft at that location, the airport closest to the first airport will be considered. If necessary the second closest and so on will also be considered until sufficient aircraft are found (if available).

The need to use the airport closest to the first airport rather than second closest to the fire results from the necessity of simplifying the amount of computation involved. If airports were selected in strict order of proximity to each fire, it would be necessary to compute the distance between every fire and every airport and then sort the airports in order of ascending travel distances. Such a procedure would be lengthy, and it is felt that the error introduced by using the airport distances to determine the order of selection will not be significant. Since distances between airports have already been calculated, the only distances which have to be computed are those between the fire and the nearest airport.

A few general rules to be used for aircraft dispatch are outlined below. It is anticipated that a more detailed decision making process will be developed during the course of the analysis.

(1) If the potential rate of production available at the closest airport (using expected rates for each aircraft operation combination at each airport) equals or exceeds the rate of production of the optimum solution, dispatch the most economical combination of aircraft which is closest to the optimum rate of production.
(2) If there are no aircraft available at the closest airport go to the second airport and repeat the first step. If necessary continue until an airport with available aircraft is encountered.

FIGURE 9: Generalized Flow Chart of the simulation model which determines aircraft effectiveness.



(3) If the available expected production rate is less than that of the optimum solution, dispatch the available aircraft, test the second airport (as in (1) above) against the remaining production rate required and dispatch if applicable under (4) and (5).
(4) If in either 2 or 3 above, aircraft are stationed at an airport, but are on other missions at the time of the new outbreak, the time when they would be free is compared with the time when aircraft could arrive from more distant airports. The aircraft combination which would arrive at the fire first is dispatched.
(5) If the available production rate is less than the optimum, but sufficient to contain the fire within a specified time limit, no further dispatch is made. The time limit for this rule is the lesser of either twice the time taken by the optimum solution, or the maximum endurance of the aircraft, or four hours.
(6) An initial attack mission will not be aborted once the attack has begun. Aircraft may be diverted to alternate targets while still enroute to their original destination. However, part of an attacking fleet may be diverted to a second target after the attack has commenced if sufficient aircraft remain to keep the original fire within initial attack status.
(7) All fires which cannot be contained by aircraft within four hours of detection (or dawn of the next day if the time of detection is too late for dispatch on the day of detection) are considered as extended attack fires. Extended attack fires have a lower priority than initial attack. An aircraft will not fly an extended attack mission if an initial attack mission is required. Furthermore, an aircraft will be withdrawn from extended attack in favour of an initial attack mission.
(8) If an aircraft has to fly for more than two hours to get to a fire it will not be dispatched unless the additional production rate changes the fire's status from extended to initial attack. Planes may be transferred as backup to an airport which is close to the fire however, under the terms discussed in the aircraft transfer section.
(9) On all fires which cannot be contained by aircraft within one day, the use of aircraft is considered to be in a supporting role only. This type of mission has the lowest priority.

These rules will be applied to all fires in the sample. For the purpose of simulation we are assuming that the decision as to whether or not a fire justified the use of aircraft has been correctly made by the dispatcher (subject to the conditions specified in the sample selection section). This simulation model simply attempts to make the best use of available aircraft, using decision criteria of a type which a well trained dispatcher could apply in real life, with some modification of the portion which depends on prior knowledge of the optimum solution for each fire. At some future date, should dispatchers acquire access to computers, a computer oriented procedure could be developed which always optimizes aircraft dispatch. Some of the above rules could then be applied as constraints to such a system.

III. APPLICATION OF THE MODELS

In the previous two sections of this report the input parameter analysis and aircraft simulation model development were described. The main purpose of this project is the development of these analytical tools which can be used to study aircraft systems as related to forest fire control operations. In this section, potential applications of the models are discussed. When analysing practical applications, there is one important consideration which cannot be accounted for by mathematical models. That is the variable policy, administrative or political constraints within which individual agencies must operate. For this reason, application of the models to a specific administrative region would necessitate consultation with the agency which administers the region. At this time, only a generalized analysis by geographical configuration will be undertaken to insure that the models are operational and to provide general answers which will have the widest possible applicability. Subsequently, detailed analyses of specific areas could be undertaken in response to requests from individual fire control agencies.

1. Analysis of Currently Operating Aircraft Systems

Previous analyses have yielded measurements of benefits which might be derived through the employment of a hypothetically optimum fleet. This benefit can be considered as a goal which other systems will attempt to achieve. Practically speaking, however, regardless of the finding of the previous analyses, fire protection agencies will not be able to initiate wholesale changes in their current systems. This would be particularly difficult if the hypothetically optimum fleet were significantly different from that which is currently operating. Use of the results of the preceding analyses is therefore limited to long range planning and policy decisions.

For the above reason it was decided to modify the models so that they could be used to analyzed current systems and the effects of minor modifications to these systems as an aid to fire control managers for making short term decisions. The modified models would also yield an estimate of how close to the hypothetical maximum benefit any current system was and, in fact, whether or not any significant changes were necessary or desirable.

For any currently operating system, there are four alternatives which could be analyzed:

A. fleets in their current configuration
B. addition of aircraft and/or bases
C. elimination of aircraft and/or bases
D. substitution of aircraft and/or bases.

A. Fleets in Their Current Configuration

The effectiveness of a fleet in it's current configuration must be known in order to make comparisons with modified versions. It is not necessary however that the fleet be deployed in exactly the same manner as is currently employed. Certain alterations could be made to present systems which do not require capital expenditures. For example, the priority of aircraft assignment and some methods of operation can be changed with relatively little difficulty. The purchase of aircraft or construction of new bases is another matter however. It stands to reason therefore that the analysis of the fleet in it's current configuration should be on the basis of the best possible deployment and operational policies for the existing systems. Unless all systems are compared on this basis, the comparisons cannot be considered valid. To analyze a fleet in its current configuration the following steps would be undertaken:

(1) Determine the effectiveness of each type of aircraft in the current fleet. From the analyses described in II, 2., the effectiveness of all aircraft types are available. By using slightly modified versions of the computer programs used to determine the inputs in sections II, 4, C., tables can be prepared for aircraft in the current fleet in the same manner as for the best aircraft.

(2) Using this data the aircraft allocation algorithm described in the same section can be used to determine the best allocation of the available aircraft. Although the fleet mixture is predetermined, the allocation of specific aircraft types in the optimum manner is not. The deployment procedure would use only current bases for this analysis.

(3) Measure the effectiveness of the current fleet. Using the best tactics and methods of operations for the region and aircraft types the maximum potential effectiveness of the current fleet can be measured. The simulation program described in II, 7, can be used without modification for this purpose.

B. Addition of Aircraft and/or Bases

In this analysis, those aircraft which were found to be optimum for the use conditions under consideration under II, 2, would be added to the current fleet. The analysis described in A. above would then be repeated. From a minimum of one up to any number of aircraft could be added. The effects of adding each aircraft on the overall system benefits would be determined. A sufficient number of different quantities of aircraft can be tested to permit the development of a function relating the addition of aircraft to system effectiveness.

In addition, potential benefits of the establishment of new bases can also be determined. For this analysis, the models described in II, 4 and II, 6, would be used. As with aircraft, the number of additional bases could vary from a minimum of one up to the number of useable airports in the province. A function relating system benefits to base additions would also be developed.

C. Elimination of Aircraft and/or Bases

The procedures used in this analysis would be similar to those outlined above except that aircraft and bases would be deleted rather than added. Functions would also be determined which relate system benefits (which may be negative) to deletions.

D. Substitution of Aircraft and/or Bases

This analysis would use procedures similar to those described in B and C above, except that the least effective aircraft will be deleted from the system and the most effective aircraft added. With respect to bases, the analysis could involve the replacement of a base by another one at a better location, or conversion from one type of operation (such as water based) to another (such as land based). Because of the numerous possible combinations of modifications this phase would require the greatest number of trial runs unless a limited number of predetermined and specific alternatives were being considered.

Upon completion of the above analyses, it would be possible to state quantitatively the benefits derived from the current use of aircraft. It would also be possible to determine whether or not minor modifications to current systems would be significantly beneficial and if so, the nature of the modifications to consider. Having developed this background information, it would be possible to consider the additional benefits which would accrue through the provision of supplemental aircraft assistance, over and above what individual protection agencies can justify by themselves. This topic will be discussed in the next section.

2. Analysis of the Need for Supplemental Aircraft Assistance

It has been suggested that individual protection agencies cannot individually justify the maintenance of a fleet of aircraft which would be sufficiently large to cope with the worst possible fire occurrence situations. A preliminary analysis of the requirements for and benefits of a supplemental centrally dispatched fleet has been completed (Simard and Forster, 1971 a, b).

Due to the abbreviated nature of the analysis, the results can only be considered preliminary. Despite this fact, the study clearly demonstrated that a centrally dispatched supplemental fleet would be the most economical method of satisfying the demand for aircraft assistance across Canada. However, a strong opinion has been expressed that the policy, operational and practical problems of such an operation are so great as to render the solution unworkable. Lacking quantitative data, to either confirm or refute such an opinion, the controversy will have to remain unsettled. The sole objective of this section is to discuss procedures which could be used to provide precise quantitative data with respect to the need for and benefits of a supplemental centrally dispatched aircraft fleet should the desire for such a system manifest itself at some future date.

This application of the models would require three analyses:

A. determination of the demand for supplemental assistance
B. determination of the optimum types of aircraft
C. determine the effectiveness of various supplemental systems

A. Determination of the Demand For Supplemental Assistance

In general, this analysis would be carried out in a manner similar to that used for the analysis of provincial aircraft systems. The same simulation models and procedures would be used, but the input data would be modified somewhat. More specifically, in determining the benefits of an aircraft system managed by an individual protection agency, the effectiveness of the unaided ground suppression system was used as the basis for comparison. Carrying the process one step further, in determining the benefits which could accrue through supplemental aircraft assistance, the unaided provincial ground and aircraft systems would be used as a basis for comparison.

The sample selection procedure discussed under II, 3 would be modified as follows. Instead of starting with a list of all fires which have occurred, the selection process would start with the list of fires requiring aircraft assistance. From the latter list all fires for which the aircraft demand is not adequately satisfied will be placed on a third list, along with complete data on the state of the fire and the attacking force which has been dispatched. Fires which will not be included in the third list are:

(1) Fires with adequate dispatch. If a fire is successfully attacked it will not be considered even though the attack may not be as effective as the hypothetical optimum.
(2) Fires with negative benefits. It is assumed that during a heavy fire load period there will be sufficient work required on positive benefit fires that dispatch to the former will not be considered simply due to the lack of aircraft.

One point to consider is which of the current fleets to use as the basis of comparison, current configurations or modified versions. Since the results of this analysis would be used as the basis for both short and long term planning, an attempt would be made to estimate future needs as well as current. Therefore, three versions of the current fleets would be considered: current configurations, modified versions which yields the greatest net return, and versions about halfway in between.

B. Determination of the Optimum Types of Aircraft

This analysis would consider a number of questions:

(1) the effectiveness of each aircraft type with respect to fire suppression
(2) the compatibility of each aircraft type with current systems
(3) the maintainability of each aircraft type at remote locations
(4) the relationship between effectiveness and transfer costs
(5) uniformity of aircraft types - the greater the number of different types of aircraft - the greater will be the maintenance costs and operational difficulties.

Other questions could develop during the course of this analysis. It is anticipated that answers to most of the above questions could be obtained by nothing more sophisticated than an examination of the data which has been acquired in the previous analyses - particularly II, 2. Further analysis specifically related to an operation of a Canada-wide nature may be necessary but if such is the case it should prove to be fairly straightforward.

C. Determine the effectiveness of various supplemental systems

In the analysis of current fleets it was possible to use a deterministic approach to determine the optimum number of aircraft for the fleet. Such an approach was used because most of the demand for each aircraft was sufficiently close to the base airport that transfer would generally not be necessary to satisfy initial attack requirements. Since aircraft transfer in anticipation of demand was not expected to be a major component of current systems, it was possible to determine the approximate fleet size in the absence of transfer, and then adjust the size on the basis of information derived from the analysis of the effects of transfer.

In the case of a supplemental centrally dispatched Canada-wide fleet there would be no permanent bases with respect to operations. Furthermore, transfer in anticipation of demand would be a major component of such a system. Since the amount of transfer required to satisfy the demand would be inversely related to the number of aircraft available, the two factors must be considered simultaneously. Lastly, both of these factors would affect the overall system benefits which implies that all three have to be considered simultaneously.

An interval halving approach could be used to determine an optimum solution. That is, the benefits of a fleet which contains more than the optimum number of aircraft would be determined. Then the benefits of a fleet which contain half that number of aircraft are determined. Following this, the interval which is most likely to contain the maximum benefit is halved and the benefits at the mid point are calculated. This procedure is repeated until that number of aircraft which produces the greatest net benefit is determined. The model used to measure system effectiveness described in Section II, 7 would be used for this analysis.

The method of computing the number of aircraft to be used for the first step in the above procedure would be as follows: potential savings are analyzed on a daily basis. An array of n aircraft is established where n is greater than or equal to the maximum number of aircraft which were required on any single day. For the first day of the season, the highest savings are attributed to the first aircraft, the second highest to the second aircraft, and so on until all the demand for that day is accounted for. Nothing is attributed to those aircraft which are not used. The same procedure is followed for each day, by adding savings to the previous values. The initial number of aircraft would be that number where the total savings just exceeds the fixed costs of maintaining the aircraft. Since aircraft will not always be in the optimum location, and since aircraft transfer costs were not considered, this number of aircraft will clearly be greater than the optimum number.

One last point to consider is the method of calculating fixed costs. If a supplemental fleet were completely separated from current systems the total aircraft fixed costs would have to be used. On the other hand, if aircraft from current fleets were used to form part or all of a supplemental fleet, that portion of the fixed costs which have already been accounted for within the current systems would have to be excluded. The result of this exclusion would be to allow a greater number of aircraft to be used in a supplemental fleet. To examine the effect of such an operating policy, three alternative fleet compositions could be examined:

(1) a fleet composed entirely of newly acquired aircraft
(2) a fleet composed of newly acquired and currently operational aircraft
(3) a fleet composed entirely of currently operational aircraft.

More than one alternative could be examined under (2) above.

SUMMARY

The Forest Fire Research Institute, in cooperation with the Forest Economics Research Institute, is conducting a study to determine the optimum use of aircraft for forest fire suppression. In the analysis two objective functions are used: (1) minimize suppression expenditures and (2) minimize area burned. The fact that these goals are not complementary necessitates a dual approach which will minimize each independently of the other. Following this, differences between the two solutions will be resolved to achieve a balanced result.

1. Input Parameter Analysis

A. Fire Behaviour and Occurrence

A basic requirement for the analysis of any fire suppression system is an understanding of and the ability to predict the behaviour and occurrence of forest fires. Since the recently developed Canadian Forest Fire Weather Index is expected to be considerably more accurate in predicting fire growth and fire occurrence, a thorough analysis of the index is necessary. The major topics to be investigated under this section are:

(1) Free burning rate of growth
(2) Rate of growth during suppression
(3) Probability of fire occurrence
(4) Fire weather index analysis.

B. Effectiveness of the Ground Suppression System

The standard against which aircraft suppression systems will be evaluated is the basic ground suppression system. The various elements of the ground suppression model are combined with the fire behaviour model to determine by simulation the size at which a fire can be controlled with ground forces only. The components of the ground suppression system are:

(1) Travel time
(2) Rate of line construction
(3) Rate of mop-up
(4) Effect of multiple simultaneous fires.

C. Economic Analysis

The purpose of the economic analysis is (1) to provide the necessary data for the minimization of suppression costs, and (2) to provide data for the establishment of realistic constraints for that portion of the study which will minimize area burned. Topics to be analyzed under the economic analysis section are:

(1) Ground suppression costs
(2) Relative land values
(3) Acceptable average annual area burned.

D. Analysis of parameters related to aircraft operations

In this section data are accumulated with which it will be possible to compare the efficiency of aircraft operations with ground operations. It will also be possible to compare the various aircraft with each other. Input parameters to be analyzed are:

(1) Fire to lake distance distributions
(2) The amount of water or retardant required to control wildfires
(3) Water or retardant distribution patterns on the ground
(4) Aircraft characteristics.

2. Aircraft Systems Analysis

Simulation models are being developed which will facilitate analysis of any or all of the following:

A. Determine the optimum aircraft and methods of operation
B. Establish the demand for aircraft assistance
C. Determine the preliminary fleet mixture and distribution
D. Estimate the optimum fleet size
E. Analyze aircraft transfer and final fleet optimization
F. Determine the potential effectiveness of the hypothetically optimum fleet.

3. Application of the Models

In order to assess the benefits which could be derived through the provision of supplementary assistance, the benefits of the presently operating airtanker systems must be determined. With the models developed in section 2, analysis of any or all of the following alternatives could be undertaken:

A. Analysis of currently operating aircraft systems
   (1) The current configuration
   (2) Addition of aircraft and/or bases
   (3) Elimination of aircraft and/or bases
   (4) Substitution of aircraft and/or bases
B. Analysis of the need for supplemental aircraft assistance

The models which were developed for analysis of individual systems can be modified to analyze the need for supplemental assistance. Determination of whether or not this step would be warranted will be based both on the results of the previous analyses and the amount of interest which is generated.

PROJECT PROGRESS REPORT

I. ACQUISITION OF DATA

A. Fire Data (individual provinces)

	provinces completed
1. Fire Data Received	7
2. Supplemental Data Received	7
3. Maps and Overlays Complete	7
4. Coding Complete	4
5. Data Edited	2
6. Data Processing Complete	2

B. Weather Data (C.M.S.)

1. C.M.S. Data Processing Complete	10
2. Stations Selected	10
3. Weather Data Received	9
4. FFRI Data Processing Complete	9
5. Fire Weather Index Completed	9

C. Fire and Weather Tape Merged 2

II. INPUT PARAMETER ANALYSIS

Data Distributions	2
Free burning fire growth	1
Probability of Fire Occurrence	2
Fire Weather Index Analysis	9
Travel Time	1
Rate of Line Construction	1
Rate of Mop-up	1
Effect of Multiple Fires	1
Ground Suppression Costs	2
Relative Land Values	1
Acceptable Annual Area Burned	0
Fire to Lake Distance Distributions	4

III. AIRCRAFT SYSTEMS ANALYSIS

This analysis is currently in the programming phase.

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