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FOREST FIRE-FIGHTING MODELS

by

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November 1965

ORC 65-29

This research has been partially supported by the Pacific Southwest Forest and Range Experiment Station of the U. S. Forest Service under supplement 40 of Master Contract A5fs-16565, the Army Research Office under Contract DA-31-124-ARO-D-331, and the University of California. Reproduction in whole or in part is permitted for any purpose of the United States Government.

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INTRODUCTION

In 1961, the U. S. Department of Agriculture Forest Service entered into a cooperative agreement with the University of California to develop a long-range operations research program in the field of forest fire control systems. This program, which is being carried out at the Operations Research Center, College of Engineering, is charged specifically with conducting studies in the problem areas of:

1. Initial attack on forest fires.
2. Prefire disposition of suppression forces, and guidelines for changing the disposition.
3. Dispatchers' guidelines for committing of forces, and changing those commitments.
4. Nationwide movement of key fire specialists.
5. Logistics of large fire camps, including location and operation.
6. Fire control information storage, flow and use.
7. Other related topics as may be mutually agreed upon.

At the beginning, it was not at all clear which of these problems, if any, were important factors in fast fire control. It was decided to spend some time observing actual compaign fire operations.

In retrospect, it is amusing to recall our different experiences and the somewhat naive deductions about the nature of the problem. One early sug-

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[†] Based on a paper presented at the Joint TIMS-ORSA National Meeting, Minneapolis, Minnesota, October 7-9, 1964. All opinions expressed in the article are those of the author.

gestion was for a large technological effort to develop a gigantic tank which could literally crush out the fire; at the same time, the Forest Service was receiving several exotic proposals for the use of guided missiles to extinguish fires. The fire camp itself seemed to be a center of planned confusion - large queues of fire-fighters waiting for extremely good food (which included watermelon for dessert), then rolling up in paper sleeping bags for some sleep before their next hard 12-hour shift. To the industrial engineer, the entire situation seemed to require a vast program of work-improvement studies.

Since then, of course, we have learned that there are many good reasons for current practice, and many reasons why exotic proposals are not the answer. In fact, the real answer seems now not how to organize a large campaign fire camp, but rather how to prevent using it, and I would, therefore, like to describe in some detail the simplified models we have made of fire-fighting operations. First, let me discuss the nature of wildland fires, particularly as they are experienced in California.

NATURE OF WILDLAND FIRE

(An introduction to the nature of the wildland fire problem may be found in "Forest Fire Problems - A Progress Report", William S. Jewell, *Operations Research*, Volume 11, No. 5, September-October 1963, pp. 678-692). (Referred to hereafter as FFP.)

A BASIC TOTAL-COST MODEL

Most of the models of fighting forest and wildland fires have been based on a concept of the total cost of suppression plus damage. For example, if x denotes the number of forces of a given type or mix sent to fight a given fire, A denotes the ultimate area of burn, and T_c the total time of control from the instant of attack, so we might have a total cost:

$$C_{TOT} = C_o + C_B A + C_S x + C_H x T_c + C_E T_c \tag{1}$$

under the assumptions that damage costs are a linear function of area burned, suppression mobilization costs are directly proportional to the number of forces sent, etc. (See FFP for a fuller discussion of cost components). When optimizing the choice of x, the last two components are usually negligible; the hourly component, C_H, however, becomes important when comparing different mixes of forces.

The basic difficulty with a total cost model, such as (1), is that it assumes that the cost components are commensurate, when they are not. The costs of burn damage, for example, come from both the public and private sector, where they include not only the measurable loss of timber, grazing land, and watershed, but also intrinsic values such as recreation, wildlife habitat, etc. The costs of suppression, on the other hand, are most often taken from a "peacetime" budget of the appropriate fire-fighting agency, with a "blank check" emergency fund becoming available for fighting large fires.

Neverthless, even though these costs do not affect the same sectors, it is instructive to carry through the analysis as if they did. If the results seem untenable, then we could, for instance, impute back the "real worth" of damaged land, based on the "desirable" action suggested by experienced fire planners. Other criteria, such as "maximum acres burned" or "maximum time of control", must also eventually be put on an economic scale, in order to choose the appropriate level of service. Finally, many results which we obtain are useful for their form of solution, rather than for their exact numerical value.

INTERACTION BETWEEN FIRE AND SUPPRESSION FORCES

To predict total cost from (1) as a function of x, we need to know how the number of forces sent influences the growth of the fire. This requires a knowledge of two different "laws" of behavior:

a. A description of how fire spreads under given conditions of weather, fuel, topography, wind, etc.

b. A model of the way in which suppression forces affect these parameters, and thence stop the fire.

It is in these areas that our real knowledge of fire control theory is wanting (see FFP).

A simple model of fire spread used in many early models (see FFP and Parks[†]) is that of a linear growth plus acceleration:

$$(2) \qquad dA/dt = G + Ht \qquad (t \text{ measured from time of detection})$$

which is certainly correct for simple geometries of the fire front, and linear velocity of flame spread. Presumably, the growth rate G (acres/hour), and the acceleration H (acre/hour^2), are predictable from the parameters for a given fire environment.

Then, under other assumptions, it is usually assumed that the effect of sending x forces of a certain type is to introduce a "deceleration force" of $-Ext$ into equation (2) with the "efficiency" E, possibly a function of G, H, and the size of fire at time of attack. This deceleration occurs either because the fire front is being rolled up at a linear rate, or because the future fuel area is being cut off in the same manner.

[†] G. M. Parks, "Development and Application of a Model for Suppression of Forest Fires", Management Science, Vol. 10, No. 4, pp. 760-766, July 1964.

Under these assumptions, we find the simple trade-off relations

(3) $$T_c = G/E(x-x_o) \ ; \ \ x_o = H/E$$

(4) $$A = G^2/2E(x-x_o) + \text{area burned at time of attack}$$

which satisfy our intuition about the effect of increasing x, even indicating a minimal size force, x_o, which must be sent. Figure (1) indicates how the total area burned might look as a function of time when 10 or 20 men are sent to fight a fire; note that fewer forces affect both the time of control, and the ultimate burned area.

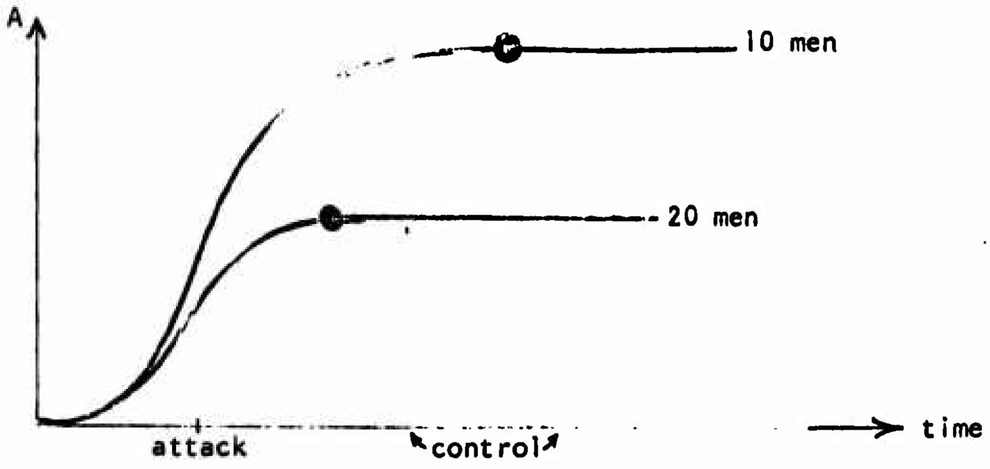

Figure 1

Figure 2 shows the cost components and the total cost of (1) as a function of $x-x_o$.

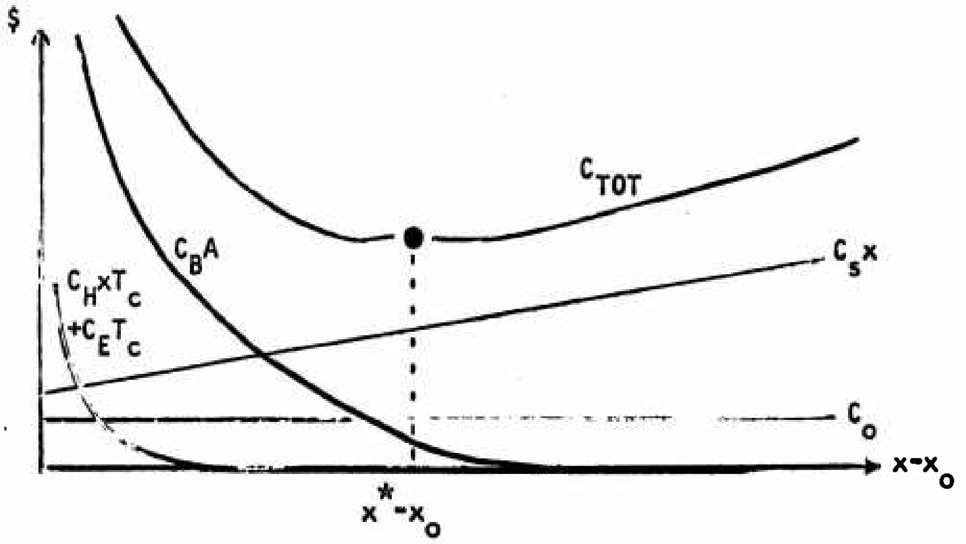

Figure 2

The point

$$x^* = x_o + G\sqrt{C_B/2C_sE} \tag{5}$$

represents the optimal choice of size of initial attack forces, neglecting the last two components of (1). As is usual in problems of this type, although the total cost is not too sensitive to non-optimal choices near x^*, the penalties for underestimating the forces needed are much worse than the penalties for overestimating.

APPLICATION OF THE SIMPLE INITIAL ATTACK MODEL

As an illustration of the use of the simple, let us consider the application made by Parks to fires in the Plumas National Forest in 1949. Parks took historical data on each fire, and found the optimal number of men that should have been sent to each fire, *given that the parameters of each fire and the* unit costs of damage and suppression were known in advance. He then adjusted these forces by adding costs of standby for various portions of the fire season, in order to limit the total number of men available in an overall-optimum sense. A brief comparison of his results with actual history is shown below in Table I. In order to eliminate some bias due to the costs of heavy equipment actually used to help fight the fires, these costs have been added to the theoretical suppression costs without taking into account their potential help in putting the fires out.

	Actual	Theoretical Optimum
Area burned	11,477 acres	281 acres
Damage costs	$4,211,000	$104,000
Suppression plus standby plus equipment costs	$ 754,000	$1,437,000

Table I. Results of Theoretical Study of Fires in Plumas National Forest, 1959.

Now, it is to be emphasized that this was strictly an idealized study in which the planners were assumed to have knowledge of the fires to occur. But, just as Figure 2 shows a broad optimum, so might we expect the problem above to have a broad optimum. If we replace "knowledge of the future" with "statistical prediction" of the future fires, enough data is available on number of ignitions, growth rates, etc. of fires as a function of fire danger rating, winds, time of year, location, etc., that fairly precise distributions of fire parameters would be available to the planners. Then, based on revised estimates of the situation as the fire season progresses, the size of standby crews could be adjusted so as to "hedge" the remaining decisions in an optimal manner.

To put it another way, it is difficult to believe that the 3/1 imbalance in total costs in Table I is merely due to a difference between a "perfect-information" model and the real situation, since doubling the number of "optimal" forces and multiplying the Theoretical area burned by a factor of 10 or 20 still indicates that a sizeable reduction in total cost could be obtained by better initial attack planning.

We may obtain some qualitative idea as to the reason for this imbalance by examining the scatter diagram in Figure (3) which shows Parks' estimate of the optimal theoretical number of forces, x^*, versus the number x actually sent for each fire which actually occurred in 1959.

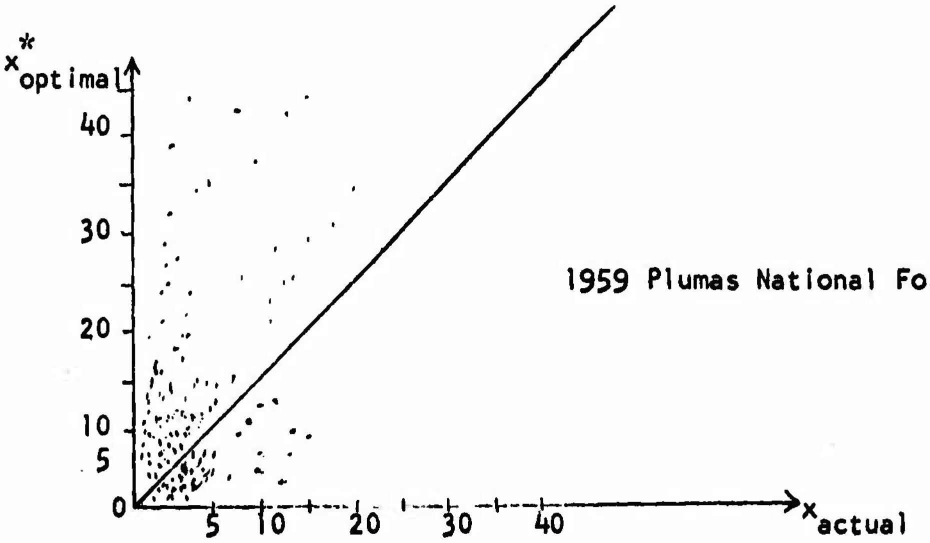

Figure 3

If the model were made more elegant, to reflect the uncertainty of the paramaters of the fire at the time of attack we would still expect to find a cluster of points about line $x = x^*$, or $x = 1.2x^* + C$, or some other small variation of this line. Instead, Figure 3 shows that there is reasonable agreement for small values of x^*, but that there are many fires with an extremely large x^* for which only a small increase, or none, was made in x. This suggests that either these were fires of an extremely explosive nature, or that a manning doctrine was used which limited the size of initial attack crew. In either case, one suspects that enough information was available on the potential (and disproportionate) costs of these fires so as to take greater risks, and send out larger crews. This is one example of the qualitative results obtainable from simple models.

In other words, even though there is plenty of room for disagreement on the exact values of the constants and the estimation of the parameters which go into a formula such as (5), there can be no arguing with its conclusion that more men should be sent to a fire with larger growth rate, or large estimated acceleration, or larger damage costs, or smaller costs of suppression mobilization, since, as we have pointed out, the penalties for under-estimating are quite severe.

RESEARCH DIRECTIONS

Now that we have outlined the elements of forest-fighting models and seen the application of a simple one, let us consider some of the further theoretical work which remains. We shall then briefly consider some of the research which is being carried out by the fire research group at the Operations Research Center, as well as describe some other work known to us.

We have already mentioned the problem of describing fire growth. Much work remains to be done in this area since very little macro-physical research on fire spread has been reported; even scaling laws are thus far only available on empirical fire-danger-rating scales. The problem of absolute prediction of fire growth is even more elusive. Some beginnings in applying statistical "epidemic" growth models have been made by the URS Corporation, Burlingame, California, to the problem of predicting fire growth following massive nuclear attack.

The second basic area of investigation is the effect of suppression forces on the fire. Parks has examined the appropriate models for three different fuel-removal doctrines for special fire geometrics, but we have no real descriptions of fire-fighting force interaction, the effects of fatigue, the influence of borate bombers, etc. Quantification of the effects of these tactics is essential to evaluating them and choosing the appropriate combinations of forces for a given fire.

We have given a simple example of initial attack optimization. As we may easily guess, a large campaign fire may require continued programming of reinforcements, shift of forces from fire to fire, optimal "hedging" of reserve forces against future fires, and so on.

Proceeding backwards in the fire history, it is clear that the size of attack forces is determined also by the mobilization time. One of the most interesting comparisons to be made is to determine if very expensive, rapid-deliver vehicles (such as helicopters) can be justified. Mobilization time also depends upon initial deployment of forces throughout the forest.

Earlier detection times would also reduce the costs of fires, since fires would be attacked in an earlier, more predictable, stage of growth; however, as pointed out in FFP, the use of expensive detection strategies may not be justified for small fires.

In any large fire or situation in which several fires occur simultaneously, the organization of suppression forces depends strongly upon the communication of fire data and the availability of forces. Thus, the structure of the communication network, as well as the communication doctrines in use during emergencies, may be of critical importance.

Finally, the problem of fighting a single fire must, for budgeting and staffing reasons, be considered within the longer range context of seasonal and longer term planning strategies. The introduction of new communication, transportation, or fire-fighting equipment; buy or lease arrangements; construction of new standby deployment camps -- all affect a long-term future history of fires which is knowable only in a statistical sense. Since this planning must come out of present budget dollars, any expansion must be carefully justified. Thus, economic models of planning must depend heavily upon results from the other areas disucssed above. Nevertheless, it is important to begin research into these models early, since they represent the area where real long-range economies are possible.

Having given these research directions a once-over look, let us now describe some current research in each of these areas.

LINE-BUILDING MODELS

Suppose that, as in figure 4, the exact form of a fire, $r(t,\theta)$ were predictable.

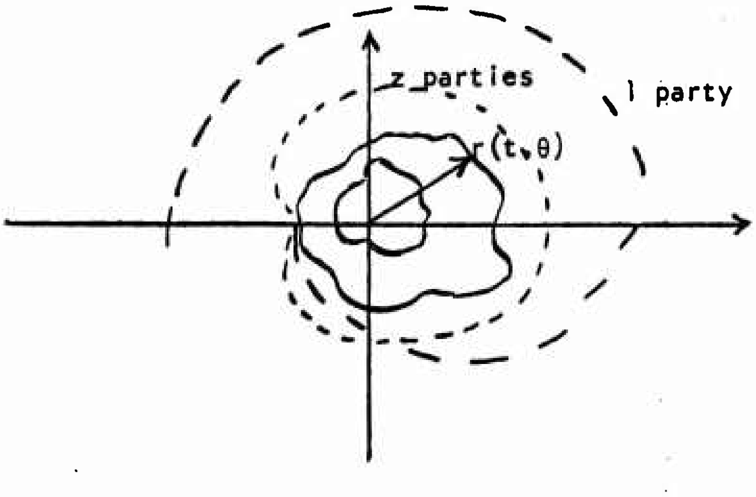

Figure 4

Under the assumption that fire suppression consists of removing fuel in a strip of known width at a constant rate depending linearly upon the number of forces available, it is possible to find "best" paths to completely circumscribe the fire. Obviously, this path depends upon how many parties are found from the original crew as shown in Figure 4. We then choose the number of parties so as to minimize the total area circumscribed. In some simple cases, the effects of walking time from some exterior point and a slowing rate due to fatigue, can also be included in the model.

When random growth effects are added to the fire spread, the model must include strategies for "hedging" against this growth, as well as provision for "falling back" or abandoning line which has been lost. If the minimum width of line which will stop a given fire is itself a random variable (say, if the intensity of the fire varies in a random manner with its growth rate), then this uncertainty is compounded.

Parks has already indicated some simple strategies for simple topologies, and research is being carried on in other directions - - particularly to models of fire spread which have independent or Markovian acceleration or velocity growth characteristics.

ATTACK STRATEGY-SIMULTANEOUS FIRES

When fires are detected simultaneously (Figure 5), as following a lightning storm, one may easily show that a formula, similar to (5), now applies for each fire independently; that is, it is not economical to send a large crew to one fire and then to the other. If the total number of forces is limited, however, and an optimal number of forces is not available for every fire, we can still show that the forces should be split up and sent to <u>every</u> fire immediately. For example, if the acceleration term, H , is zero, then the proportion of available forces sent

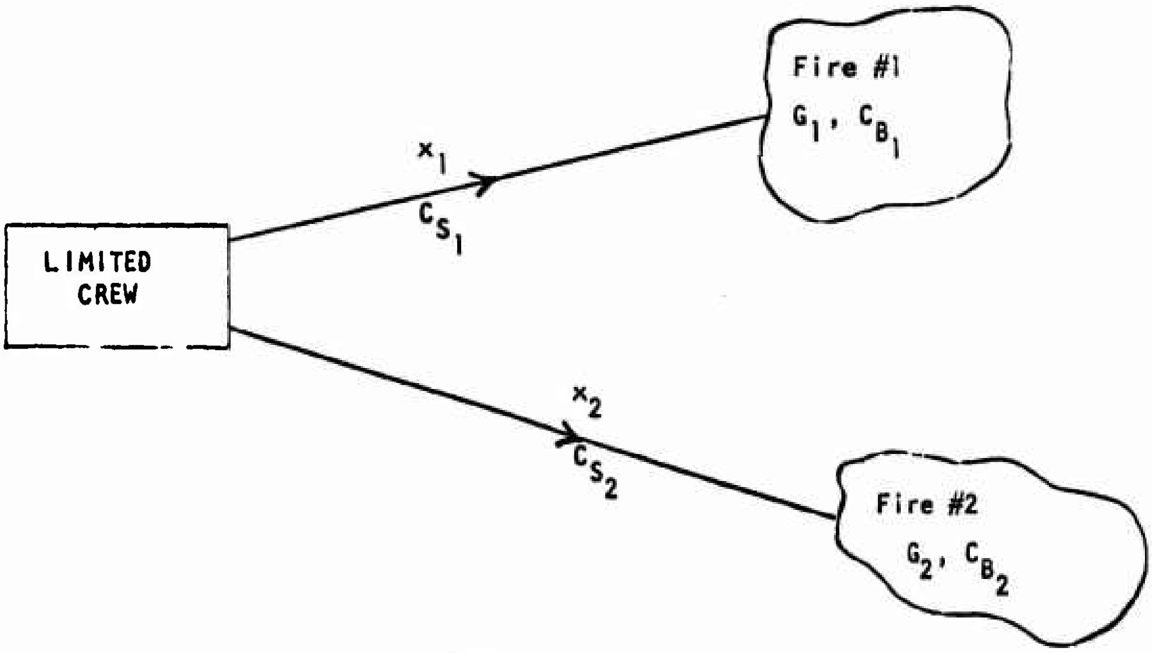

Figure 5

to fire i (i = 1,2,...,N) should be proportional to

$$(6) \qquad \sqrt{\frac{\overline{G_i^2} \cdot \overline{C_{B_i}}}{\overline{C_{S_i}}}}$$

where the bar indicates expected (or estimated) values of the parameters of each fire. Note that $\overline{G_i^2} > (\overline{G_i})^2$. In any case, extreme all-or-nothing strategies are <u>not</u> indicated for simultaneous fires.

ATTACK STRATEGY-NEAR SIMULTANEOUS FIRES

Another research problem currently being studied is that of near-simultaneous fires. Suppose, as shown in Figure (6) that a fire of known characteristics occurs at time zero at Location 1. Depending on the size of the crew sent to #1, there is a chance that another fire will occur at Location 2 before the crew returns (and is rested). When there is only a limited crew available at home base, it is clear that one may wish to "hedge" against a second fire occurring by sending a smaller than optimum crew to fire #1. This "gamble" must clearly take into account all possible locations of #2, as well as the growth rates of 1 and 2, and time of occurrence of 2 -- thus, it would be different at different times in the fire season.

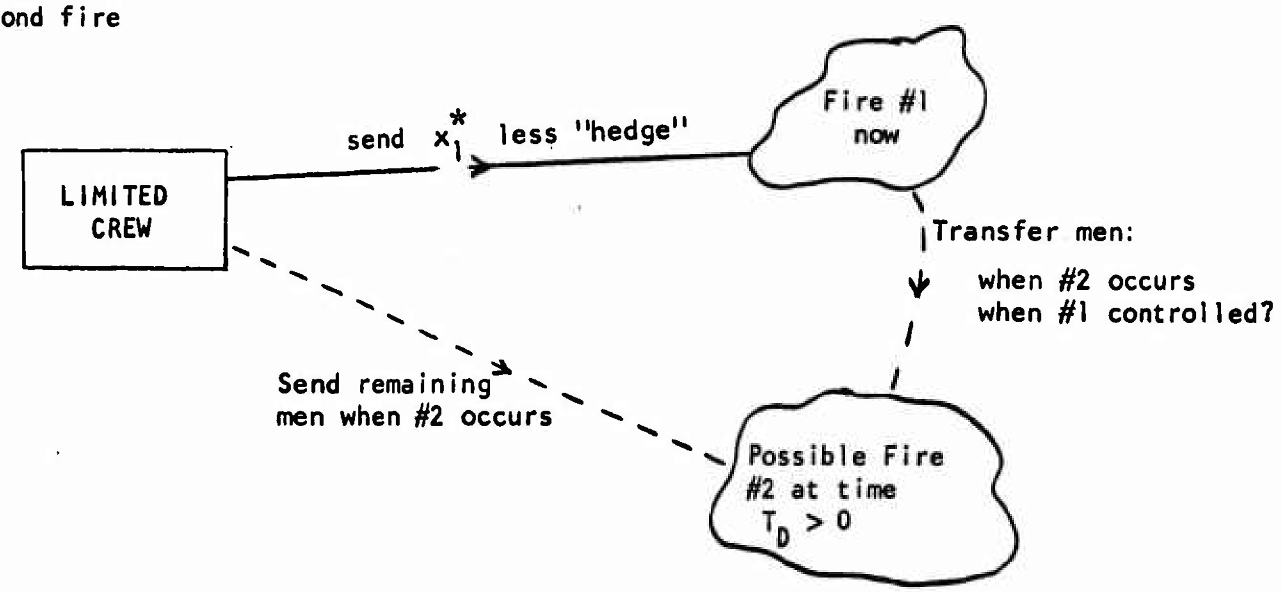

Figure 6

Preliminary analysis of this model by A. W. MacMasters indicates some unexpected strategies. For example, if the probability of a second fire is high and inter-fire transportation costs low, then there is an "anti-hedging" effect when enough men are available; that is, <u>more</u> than the optimal number of men are sent to the first fire so that it will be controlled earlier, and the men can be sent on to the next fire. Of course, introducing a fatigue factor or increasing inter-fire transportation costs changes the situation back to "hedging", with some men held back at the fire camp.

Besides answering specific manning problems, the results of this research are also expected to be useful in delineating initial attack crew sizes as a function of the fire danger, and specifying the total size of standby crews needed in a given forest region.

PERIODIC REVIEW MODEL

One special case in which the effect of random growth of a fire can be handled explicitly is for a single fire whose status is reviewed periodically; this is often the case in large campaign fires where the situation is reviewed twice a day, decisions made on reinforcements, and relief of forces for the next twelve hours. By making simple assumptions about the costs of changing the level of suppression forces, a simple "critical-number" policy of staffing can be developed which gives "reorder" (reinforcement), or "disorder" (remove) levels at which to make decisions. Since the underlying model is statistical, one cannot guarantee that the fire will ever be out with probability one, but must specify some "risk guarantee" (Pr(fire out) $\leq \beta$); this is merely due to the idealization of the model.

Some beginnings have been made by G. Shah and R. Chandrasekaran toward investigating the problem of periodic review and multiple fire situations, but here the problem of determining optimal policies seems much more difficult.

DEPLOYMENT OF MEN AND EQUIPMENT

We have mentioned previously that deployment of men throughout a forest may save mobilization time and hence, reduce total costs of fires throughout the season. Figure 7 indicates one idealized model which has been investigated in great detail by D. Heyman.

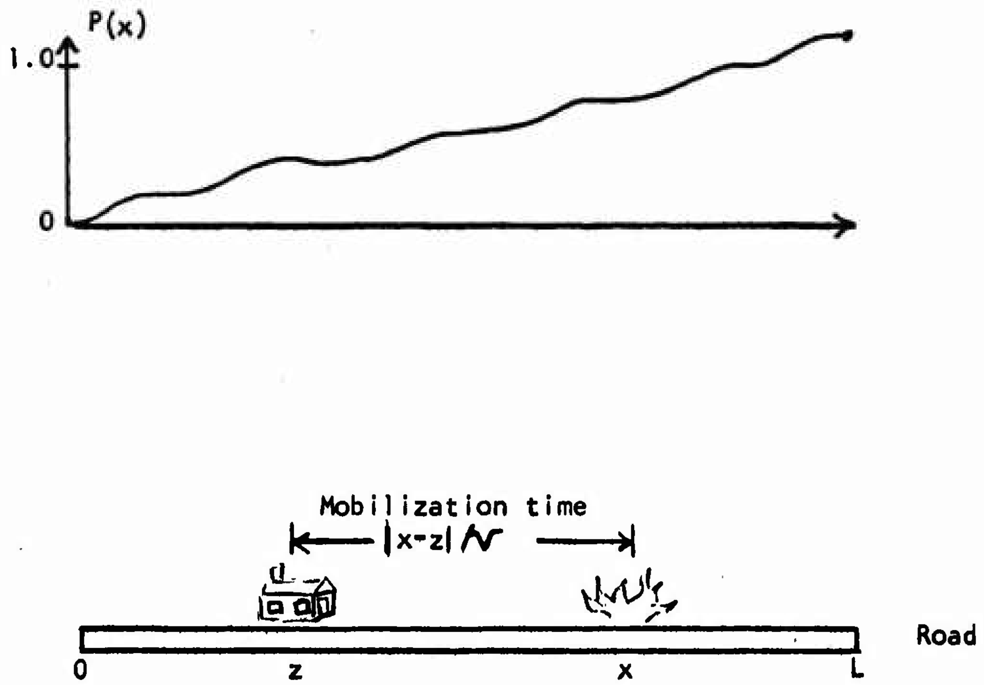

Figure 7

Suppose a given length of road, L, has associated with it a probability distribution, $P(x) = Pr$ (a given fire occurs at location $\leq x$) $(0 \leq x \leq L)$, and suppose that all other fire parameters are statistically independent of their location on or near this road. If a single standby camp were to be located on this road at point z, we know that the time to reach the fire at point x will be some constant mobilization time plus $|x - z /V|$, where V is the velocity along the road.

We can show that the total cost (assuming we can always send the optimal number of men) has then the quadratic form:

$$C_{tot} = C_1 + \alpha \frac{|x-z|}{V} + \frac{\beta}{2} \left(\frac{x-z}{V}\right)^2 \tag{7}$$

α is related to the cost parameters plus G and H, while $\beta = C_B H$. From these assumptions, one can show that the optimal location z^* is given by the solution of

$$(8) \qquad 1 - 2P(z^*) = \frac{\beta}{\alpha V}(z^* - \bar{L})$$

where $\bar{L}$ is the "average" location of fires. One can then show from (8) that if $\beta/\alpha V$ is small, the camp should be located at the median road location (50% of the fires to the right and 50% to the left); as $\beta/\alpha V$ increases (more acceleration, costlier fires, or slower transportation), the location shifts toward the point $\bar{L}$.

More complicated models take into account the variation in C_B and G and H with location, but give, essentially, the same results with a "cost-average" location used instead of $\bar{L}$.

By considering the fixed and variable cost of maintaining a standby camp, one can decide how to locate a variable number of camps along a given road, and thence decide on the optimal number of these camps. Other modifications particularly pertinent to California include the use of "constructive" miles (different speeds up-and-down hill), and comparison of trips to extreme locations by means of faster, but more expensive equipment such as helicopters.

DETECTION STRATEGY

The most interesting "break-through" in problems of detecting and observing fires has been through the use of infra-red equipment; the U.S. Forest Service is currently pursuing a detailed research program in this area, and initial trials are very promising.

Still unresolved are the problems of detection strategy - particularly the routing and timing of aircraft and flight paths. This problem has much in common with the well-known "search" problem, except for an unusual feature of"growth" -- if the sough-for object (a fire) is missed during the first pass, the chances are greater that it will be detected during a later pass over the same location. Any model of this type must consider the costs of the infrared equipment, processing and interpretation, as well as its physical scan and "overlook" characteristics.

COMMUNICATION AND COMPUTER SYSTEMS

Several preliminary studies have been made of the communication requirements for the U. S. Forest Service by P. Rech. The basic problem seems to be one of budget limitations on investing in new systems; current expansion must be justified primarily on the basis of "peacetime" (non-fire) usage, and compatibility with current communication equipments. This is an area where it is easy to point to technical weak links in the system (such as an observed case where four communication links, using three different frequencies, were needed for a fire crew to talk to the pilot of a borate bomber), yet it is difficult to justify expenditure of a large sum of money to correct the situation.

Some theoretical traffic flow studies indicate that only a modest increase in number and flexibility of the equipment will greatly reduce waiting lines of messages in a given network.

Many of the decisions which are currently made in regional control of forest fire-fighting operations require only adequate communications and good pre-fire organization of data on available resources. However, if even some of the advanced decision-making techniques under consideration are ever implemented, then computational assistance will have to be furnished to the "tactical commander", as well as to the long-range planner. It appears that such "command and control" requirements are fairly modest, at least for, say, the western states, but this does not necessarily mean they are unsophisticated requirements. One might envisage that each fire boss would have a console or other means of communication with a central computer into which various information on the status of a fire and the forces fighting it would be entered. This computer would then take historical data, information from infra-red reconnaissance, file data on available resources, and the status of other parts of the region into consideration and suggest a course of action for the regional commander.

Only detailed investigation and the development of supporting research in organizational methods will indicate whether such an automatized approach is desirable.

RELATED PROBLEMS

There are many related problems of the forest agencies which have a direct bearing on their fire-fighting ability. In FFP, for example, we have mentioned the problems of forest treatment to reduce ignition hazard, including the planned construction of systems of fire breaks.

Another area of economies has to do with problems of leasing and buying equipment. One problem currently under study by W. Whisler is the stockpiling of rental equipment, which is related to the problem of leasing borate bombers. This problem is somewhat different than classical inventory problems because after the customer has "demanded" an "item" from "inventory", it is returned by him, after some random time has elapsed. Hence, a typical stockpile review will include decisions to return items to the lessor, as well as requests for more items.

GENERAL COMMENTS

It is hoped that this review of simple forest-fire models does not leave the reader with the impression that all problems of interest have been investigated. Indeed, there remain many problems of testing, application, and implementation yet to be carried out. Collection of data remains a major problem. The U. S. Forest Service has recently set up an operations research group to continue investigation of some of the ideas reported here, as well as to develop other areas of interest to them, such as equipment maintenance, multiple-land-use development, tree-harvesting, and so on.

Also, there are many areas in which forest agencies can use technical support from outside firms and research agencies. However, the author feels that a cautionary note is needed here. The technical problems of fire-fighting do <u>not</u>, it seems to me, require radical new technologies of: detection (except for the program of infra-red detection currently underway); delivery of suppression forces; or methods of fighting fires.

The problem is, rather, to develop more efficient methods of organizing and directing the current forces at our disposal, <u>and</u> of providing sound ways to justify the large prefire expenditures needed to accomplish this reorganization.

For, we easily see that if we could detect every wildland fire within half an hour, and put sufficient manpower, bulldozers, and tankers on that fire within another half an hour, the days of the campaign fire would be over. The problem is then to honestly justify the organization which can provide this strong initial attack.