CLEARINGHOUSE FOR FEDERAL SCIENTIFIC AND TECHNICAL INFORMATION CFSTI
DOCUMENT MANAGEMENT BRANCH 410.11

LIMITATIONS IN REPRODUCTION QUALITY

ACCESSION # AD 606456

☑ 1. WE REGRET THAT LEGIBILITY OF THIS DOCUMENT IS IN PART UNSATISFACTORY. REPRODUCTION HAS BEEN MADE FROM BEST AVAILABLE COPY.

☐ 2. A PORTION OF THE ORIGINAL DOCUMENT CONTAINS FINE DETAIL WHICH MAY MAKE READING OF PHOTOCOPY DIFFICULT.

☐ 3. THE ORIGINAL DOCUMENT CONTAINS COLOR, BUT DISTRIBUTION COPIES ARE AVAILABLE IN BLACK-AND-WHITE REPRODUCTION ONLY.

☐ 4. THE INITIAL DISTRIBUTION COPIES CONTAIN COLOR WHICH WILL BE SHOWN IN BLACK-AND-WHITE WHEN IT IS NECESSARY TO REPRINT.

☐ 5. LIMITED SUPPLY ON HAND: WHEN EXHAUSTED, DOCUMENT WILL BE AVAILABLE IN MICROFICHE ONLY.

☐ 6. LIMITED SUPPLY ON HAND: WHEN EXHAUSTED DOCUMENT WILL NOT BE AVAILABLE.

☐ 7. DOCUMENT IS AVAILABLE IN MICROFICHE ONLY.

☐ 8. DOCUMENT AVAILABLE ON LOAN FROM CFSTI (TT DOCUMENTS ONLY).

☐ 9.

PROCESSOR: *kah*

TSL-107-10/64

A COMMENTARY ON FIRE RESEARCH

Based on
The Mass Fire Study Group Conference,
The University of California at Los Angeles
(May 26-28, 1957)

James C. DeHaven

P-1140RC

July 24, 1957

The RAND Corporation
1700 MAIN ST. • SANTA MONICA • CALIFORNIA

PREFACE

The writer was invited to participate in the Mass Fire Study Group Conference jointly sponsored by the National Academy of Sciences and The University of California at Los Angeles on May 26-28, 1957. The Conference was attended both by practical fire fighters and by researchers. The Chairman, Dr. A. W. Boldyreff, asked some of us to prepare a commentary on the Conference suggesting research which might usefully be undertaken based on the description and discussion of hostile fires presented by the practical fire fighters. This paper is intended for use by Dr. Boldyreff, as he may see fit, in the preparation of the report on the Conference to the National Academy of Sciences.

A COMMENTARY ON FIRE RESEARCH

Based on
The Mass Fire Study Group Conference,
The University of California at Los Angeles
(May 26-28, 1957)

During the Conference there was a tendency to stress the differences which appear to occur during the course of various types of hostile fires. Thus, forest fires appear to be different from urban fires, factory fires differ in many respects from refinery fires, fires in buildings differ from lumberyard fires, and so forth. There was also at least the assumption that all hostile fires appear to be significantly different from friendly fires. The latter referring to combustion processes which man uses for his benefit whether they be in the open-hearth steel furnace, or in the jet aircraft engine. In contrast to emphasizing these differences which undoubtedly exist among these types of fires, it may prove useful to speculate on the similarities which may occur to determine what basic features of all may be common and if anything can be learned which will be helpful in the control of hostile fires by bringing to bear information which has been learned from the study of these other combustion processes.

SOME PHYSICAL AND CHEMICAL FEATURES OF FIRE

As a first general approximation one may state that solids do not burn directly, liquids do not burn directly, only gases burn in flames. This applies whether we are speaking of combustion in a jet engine or combustion in a brush fire on a mountainside. Thus, a first generalization is that all hostile fires are diffusion flames resulting from the rapid reaction of a combustible (reducing) gas with oxygen (the oxidizer).

We may further generalize by stating that with few exceptions all those gases and the materials which produce or supply the gases are organic in nature; further, that the gases are largely hydrocarbons, and that the materials supplying the gases are either wood or petroleum products. Thus, from the standpoint of the chemistry of fires, we are not confronted with as wide variety of situations as faces the practical fire fighter. On a muggy, hot day and without humidity control on his blast air, the blast furnace operator or cupola furnace operator has a difficult time maintaining high enough temperatures in his furnaces to produce economic quantities of iron at the desired temperature above the melting point. Under similar atmospheric conditions of high relative humidity or high total moisture content in the air, the Fire Warden can relax his vigilance somewhat knowing that he is not as likely to be confronted with a forest fire. As the jet pilot climbs to higher and higher altitudes and as the concentration of oxygen is reduced in his engine's combustors, he is more likely to encounter a flame-out. Similarly may the practical fireman obtain a flame-out with an oil fire as he reduces the oxygen concentration by applying impermeable coverings or carbon dioxide gas to his fire.

Inasmuch as the combustion of wood or wood products is involved in the great majority of hostile fires, it may be useful to speculate about the mechanism of this combustion process. Wood like coal (a wood product) is made up largely of organic compounds having a wide range of boiling points. Some of the heavier, larger molecules contained in wood decompose with increasing temperature rather than volatilize directly. There is also a small percentage of inorganic compounds which ultimately end up in the ash, as wood is burned. Water is also an important compound appearing in wood. It is essential not only for the growing process of the plant but has important effects on the ignition and the combustion of the wood. It may be present in the wood material both in the liquid form and as chemisorbed water vapor. If wood is exposed to a source of high temperature, it will heat up at a rate which depends among other factors on the heat capacity of the wood and the conductivity of the wood representing its ability to transmit heat away from the area of impinging higher temperature. It is quite likely that because of the high heat capacity and thermal conductivity of water in comparison with the other materials present in wood that to a large degree the rate of heating of wood is quite dependent upon the total water content. In addition, the large heat of vaporization of liquid water provides a signigicant buffer against the temperature rising above 212°F until this water has been completely boiled away. It is a perhaps less well-known fact that adsorbed water vapor has a somewhat higher heat of vaporization than liquid water thereby providing an additional heat sink of no mean practical importance.

It is likely that as our wood increases in temperature to 212°F and as water vapor is given off in increasing amounts, that a process of steam distillation takes place whereby certain organic chemicals of a particular constitution and boiling range are carried along with the steam. These materials may be aldehydes or acids which are irritating to humans, or they may originally be alcohols or other hydrocarbons which are oxidized to these irritating materials at the elevated temperatures. It is not likely at this stage that the gases present will actually burn as flames because of the high relative concentration and temperature reducing influence of water vapor which is present. If our specimen of wood is exposed longer to the source of heat, both the liquid water and the chemisorbed water with their temperature leveling influence will have all disappeared and the temperature of the wood will increase causing the volatilization of additional organic compounds from the wood. As these compounds reach their ignition temperature, they will react with the oxygen of the air causing flames and a self-sustaining combustion process. As the heat is transferred from the flame back to the wood more and more of the volatile constituents will be driven off and burn. With further increase in temperature thermal cracking of some of the less volatile or even solid organic materials in the wood is likely to occur to provide additional sources of volatile gases. In this cracking process free carbon is also produced which when not completely burned gives the typical dark appearance to the smoke.

Once the wood in say a stand of brush is ignited and reaches the stage of continuous combustion, the flame front travels by having the heat generated from the initial combustion process transferred to adjacent wood by convective and radiation heat transfer processes. It is interesting to note that vegetation has evolved over the millennia into particularly efficient heat transfer forms. The very life of a tree depends upon its effective capture of energy transferred to it from both the sun and the surrounding atmosphere by radiation and convective transfer. Thus, the leaves and generally dispersed branching forms of a tree make it particularly effective in capturing heat transferred from an advancing flame front. But trees and other vegetation also have a built in control device to prevent temperatures from rising too high within them during their normal lifetime exposures to incident solar radiation and high ambient atmospheric temperatures. Under these conditions vegetation transpires large amounts of water vapor through their leaf surfaces to prevent their temperatures from rising to a level which will kill the tree. This transpiration of water vapor keeps the temperature low both by providing a heat sink through the heat of vaporization of water and probably also by reducing the incident infra-red radiation which can pass through the water vapor film on the leaf surfaces. Thus the normal built-in protective device of vegetation helps to prevent and reduce the ignition and burning of trees except under those situations of atmospheric conditions of very low water content in air and soil such that the tree has insufficient supply of water available to it to utilize fully its natural temperature reducing mechanism.[1]

When all the volatile material has been boiled out of the wood and the remaining material becomes carbonized, a different combustion mechanism probably takes over. It is generally believed that the reaction in which solid carbon burns involves first a gas-solid surface reaction between oxygen and/or possibly carbon dioxide and the solid carbon to produce carbon monoxide which is evolved and burned subsequently with oxygen in the air producing the typically bluish carbon monoxide flame. Apparently this reaction under hostile fire circumstances is neither so readily self-sustaining nor so difficult to bring under control as for the situations where the volatile constituents are burning. One may often observe trees or brush still standing in burned-over areas (or timbers remaining in buildings) where the wood material has largely been reduced to carbon. It is likely that this latter type of reaction will prove self-sustaining only under situations more favorable for the hostile fire such as fairly high density of fuel (carbon) and an adequate supply of oxygen continuously brought in the proximity of the burning carbon by relatively higher air velocities.

---

[1] This principle has been applied to the cooling of the inside of rocket motor combustion chambers; even the name <u>transpiration cooling</u> has been carried over in this application.

POSSIBILITIES FOR RESEARCH

However gross the foregoing description of the mechanism of hostile fire may be, it may at least serve as a basis for speculating as to useful physical and chemical research which may develop improved fire fighting techniques and devices. Water is used almost universally for fighting all types of fires. There are undoubtedly good economic and technical reasons why nothing much better than water has been found nor may likely be developed. It is cheap, almost universally available, and has a unique combination of chemical and physical properties which make it so effective in combating fires. It is non-toxic and has the well-known cooling effect through its very high heat of vaporization. Not so well known is the very high heat of desorption of water vapor, which was mentioned earlier. Probably not quite so well known either is the very high absorptivity in the infra-red region which the gaseous water molecule exhibits. Thus, water vapor is a very effective medium for reducing heat transfer by radiation. The infra-red absorbing properties of water vapor may be more or less important depending upon the type of fire. The typical patterns of forest fires with their rapidly forward moving fronts and relatively slower moving flanks might suggest that convective heat transfer is much more important in the spread of forest fires than is radiation heat transfer. In contrast, perhaps radiation transfer is a more important mechanism in fires in closed areas. We know too that radiation energy is dispersed or scattered by fine particles suspended in the air. The effectiveness of this Rayleigh-type scattering depends on the wave length of the energy scattered and the particle size in relation to this wave length. Probably there are sufficient particles of the optimum size resulting from fog-nozzle use to play an important part in reducing radiant heat transfer in fires. Whether there are sufficient water droplets of the most desirable size created by the present nozzles to most effectively reduce radiant energy transfer might well be examined, if it has not already been done so.

Are there other ways in which water might be improved as an anti-fire agent? One of its deficiencies for example is that it does not always stay around long enough during the atmospheric conditions when a fire is likely to occur. Our practical fire fighters tell us that there is not much point in wetting down bands of forest or brush areas in front of an advancing fire because the water will evaporate before the fire reaches the area of wet-down. Combining this feature of water with the fact that fire fighters often can not get close enough to an advancing front to apply water directly on it, because of the high temperatures and dangers involved, means that the fire fighters have inadequate tools to attack an advancing front but rather must attempt to pinch in the fire from the flanks.

There is one technique for keeping water around longer under adverse conditions that might be investigated. This is to mix a humectant with the water which might be spread in bands before an advancing front. A humectant is a material which has great affinity for water and which will retain it in liquid form under conditions of relative humidity and temperature under which it would normally have evaporated. The usual organic-type humectants employed in materials like tobacco, paper and textiles would probably not be satisfactory for this purpose because they would provide additional fuel for the fire. There are, however, many inorganic, non-combustible humectants which might be considered.

Materials such as activated silica can retain up to 50 per cent of their weight as water when the relative humidity is as low as 10 per cent. It is possible that one of the features of sodium calcium borate which has demonstrated a rather startling effectiveness in retarding flames is its humectant characteristic or ability to hold the water in place until the fire reaches the borate-treated band. There may very well be materials which are superior to sodium calcium borate in this water holding ability. This possible technique for improving the effectiveness of water in combating fires might be investigated.

Perhaps materials like sodium calcium borate have other characteristics than their humectant qualities which assist in retarding fires. For example, solutions of this material appear to form a film over the wood material, which when exposed to the elevated temperatures and when the water they contain is ultimately evaporated, form very light colored, adherent, refractory coatings on the combustible material.[1] The white color may actually reflect a significantly greater amount of the radiant energy than the dark green of the leaves or dull wood color to reduce radiant heat transfer; or, the refractory insulating film produced may, at least for a period of time reduce convective heat transfer from the flame front to the yet unburned wood. It is just possible that films of this type may operate also to decrease the vapor pressure of the volatile constituents of wood in a manner similar to that whereby cetyl alcohol has been shown to reduce the vapor pressure of water when deposited as monomolecular films over water-storage reservoirs. Some more or less fundamental study of these sorts of characteristics of sodium calcium borate may provide leads to materials which are much more effective than this compound for combating fires. It may not be completely hopeless to anticipate that such materials might be found. The example of

---

[1] The addition of wetting agents may improve the film and increase the area covered.

the control of magnesium burning illustrates what can happen along this line in a somewhat analogous fire situation.

Everyone is familiar with the incendiary characteristics of molten magnesium metal. In fact it was not until magnesium producers learned how to control the burning of magnesium that it became possible to produce it as an engineering material. The high vapor pressure of liquid magnesium and its relatively low boiling point cause it (again in the gas phase) to burst into flames unless preventive measures are taken. In the earliest days of its use the protective materials were such as sulphur and certain borates. In more recent years it has been found that certain complex silicofluorides, mixtures of rare earth metals, and beryllium are particularly potent in preventing the burning of magnesium. It is especially interesting to note that very small amounts of beryllium, less than 0.003 of 1 per cent, will completely prevent the ignition and burning of molten magnesium even when it is exposed to the air without any protective flux covering. The reason why beryllium is so potent in this respect is not understood. It may be that beryllium forms compounds with magnesium and/or nitrogen and oxygen which form monomolecular films on the surface of the magnesium which reduce significantly the vapor pressure of magnesium and the transfer of magnesium molecules into the gas phase so that it can not react with oxygen in the air. It is not suggested, of course, that beryllium compounds will prove effective in the same manner with fires from carbonaceous materials. There is the possibility, however, that the bottom of the barrel has not been reached yet in finding materials which may, either by themselves or in combinations with water, prove tremendously more effective in controlling fires of the more usual types than water alone.

OPERATIONS RESEARCH AND FIRE FIGHTING

One of the objectives of the Conference was to explore the potentialities for applying techniques of Operations Research to the problems of fighting or controlling fires.

Words of caution are in order regarding the application of Operations Research to this field in order that the practical fire people may not become over-enthusiastic at the start and later become disappointed with the results which may be obtained. Even those who practice Operations Research do not have a commonly agreed upon definition of what this science or art really is. It is generally conceded to be the application of the scientific method to problems involving men and machines in mutual operation towards the accomplishment of an objective. Some people do not even acknowledge that there is a truly new and different area of professional activity which can be designated Operations Research, but rather that the field so designated is but the practical application of economic and engineering principle more intensively than they have been used previously in certain areas of human activity.

Other individuals while acknowledging the useful contribution of Operations Research to the military area will question its similar value in ordinary civilian operations. They point out that in military operations the commanders may be confronted with a combination of situations which were completely different from what they had anticipated or planned for in pre-war exercises. Under these circumstances the techniques of operations analysis can provide a substitute for experience which may enable the commander to arrive at better decisions as to his operations or deployment in less time than would otherwise be possible.

In contrast most civilian activities whether they be manufacturing operations or fighting fires result in a continuous build up of experience from day to day and year to year. The military commander is suddenly confronted with the new situation whereas the fireman fights fires everyday and gains experience in this process which enables him continuously to alter and to improve his decisions and operations. Operations Research may thus have less chance to make such spectacular contributions to fire fighting than it has to certain military operations.

On the positive side one might expect that the very study of fire fighting operations by groups of trained and disciplined researchers can hardly help but yield some improvements. Then, too, Operations Research has a better opportunity to perform effectively where lots of good data are available or are readily collectible. In these respects fire fighting may have an advantage over military operations. In studies of certain other civilian activities such as oil refining or the scheduling of air line operations, the tools of Operations Research rather than the application of the methods themselves have resulted in some considerable savings. These studies showed that oil refiners and air line operators were doing a pretty good job in making their decisions about their operations under changing conditions. Some of the tools provided in the form of electronic computors and linear programming, however, enabled these people to make their decisions under changing conditions much faster and with much less cost than when they used their previous methods. This may apply to the problems of fire fighting.

A fertile field for investigation (and I am uncertain whether this should be called Economic Analysis or Operations Research) are studies of optimum allocations of resources among the different activities and services provided by the Federal, State, Municipal and other local entities. As an example, with a budget of a certain size, should the city of Los Angeles allocate more or less to the Fire Department, to the Police Department, to Public Health Services or the combating of juvenile delinquency. The city fathers and the taxpayers should have some idea as to the average return to the city for each dollar expended for these different services. But, more particularly they should be concerned with the incremental or marginal value of the return for each of the services or activities resulting from an increase or decrease in the expenditures to each. Ideally the city should spend its money, distributed among these different services, such that the marginal return from each expenditure is equal.

At the next lower level of decision-making in the city, each department head should desire to distribute the funds at his disposal among the different activities under his cognizance such that the returns on the margin from each activity are equal. If, for example, in the Fire Department, each dollar spent on the inspection of potential fire hazards yields a return of four dollars, whereas the last incremental dollar spent on fire fighting equipment returns less than one dollar, the Chief should wish to redistribute the funds at his disposal to spend more on inspection and less on the purchase of new equipment. There appear to be no studies published which address themselves either to the average or marginal cost and returns for the different functions carried out either by municipal or industrial fire departments.

One study at hand has addressed itself to this question in connection with the Forest Service.[1] This study indicates that at least as late as 1953 the marginal return from Forest Service fire control was much less than that

---

[1] Operations Research and Government Budgets, Roland N. McKean, a RAND Corporation study, P-999 RC, March 7, 1957.

from certain other activities of The Forest Service such as, for example, management of forests.

If further study indicates that this situation is truly existent, The Forest Service might well consider redistributing the funds among their different activities so that the marginal returns are more nearly equal. A possible alternative decision on their part would be to spend more of their funds on research and development directed towards improving the state of the art of fire control methods, and through technological improvements, to increase the return per dollar expended on this specific operation.