TG-538
NOVEMBER 1963

WHAT BASIC FIRE RESEARCH CAN LEARN FROM FOREST FIRES

W. G. BERL

based on a lecture to
Division of Forest Fires
Society of American Foresters
Boston, Massachusetts
October 24, 1963

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
8621 GEORGIA AVENUE SILVER SPRING, MARYLAND

OPERATING UNDER CONTRACT NOw 62-0604-c, BUREAU OF NAVAL WEAPONS, DEPARTMENT OF THE NAVY

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

WHAT BASIC FIRE RESEARCH CAN LEARN FROM FOREST FIRES

INTRODUCTION

Fires whether in the forest, the city, or in industry are physical processes. This paper will restrict itself to these aspects and leave aside numerous consequences, each one of which deserves attention and without which an all inclusive discussion of fire is incomplete. No references will be made to fire effects in biology, ecology, sylviculture, medicine, psychology, design parameters for cities and forests, operational research, or economics. Alas, the absence of a single group in the United States that can pull all these threads together is a weakness in the approach toward the fire problem which has, as yet, not been resolved (Ref. 1).[1]

Before proceeding to the physics, chemistry, and aerodynamics of fires, a few numbers will be presented which delineate the magnitude of the task. They were collected from various sources (Ref. 2).

The first estimate has to do with the relative magnitude of heat generation from forest fires as compared to the heat generation from the combustion of fossil fuels. Using the currently relatively stable statistics relating to acreage burned per year in the U. S. (4×10^6 acres/year), multiplying by 10 (ratio of world forest area/U. S. forests), utilizing a tree count made by Professor Emmons (Ref. 3) as a "reasonable" fuel/acre figure (500 tons/acre), one arrives

---

[1] References may be found on pages 27 through 31.

at the rather startling heat release of 400,000 x 10^{12} Btu/year, which is roughly 10 times the world energy consumption/year from fossil fuels. However, a more realistic fuel consumption (per acre burned) is 5 tons/acre, which reduces the heat release figure to 1/10 of the energy release--a still respectable number (equivalent to the energy release of 10 megaton bombs).

A second calculation concerns the rate of energy release in a mass fire as compared to the "normal" heat release near the ground owing to human endeavors and by solar heating. As an example, in a city of 10^6 inhabitants, living in an area of 10 by 10 miles, the "normal" average heat output is 0.03 x 10^{12} Btu/hr. In case of a nuclear attack of sufficient magnitude to ignite this entire area and consume all combustibles within 3 hours (the combustible loading being set at 12 lb/ft^2--which is 250 tons/acre of 1/2 of the "Emmons" forest fuel loading), the heat release rate is 30 x 10^{12} Btu/hr or 1000 times "normal." By contrast, the solar input in an equal area on a bright day is 0.15 x 10^{12} Btu/hr (i.e., 5 times the "normal" human output, but 1/200th that of the fire). In the event of such a nuclear disaster, one should not be surprised to find unusual phenomenological effects from localized heat release on such a scale.

With regard to the physical phenomena of fires, it should be noted that the more highly-developed areas of fire technology, the important goals of which are the development of effective fire control measures, the accumulation of useful design data, the development of hazard indices and "stopping rules," and of training devices, are fields in which inventive genius and the sensible application of the tools of modern technology can make and have already made profound inroads. Widespread support of this technological branch is essential because modern society multiplies the fire hazards at such a rate so that, merely to hold the balance, improved techniques and practices must be instituted.

The scientific goals are set by a desire to understand the behavior of fires as a physical (and chemical) phenomenon. In view of the inherent complexity it is, perhaps, not surprising that the effort in the past has not been one of great vigor. Rare is the textbook which will discuss fires either as a subject fit for aerodynamicists or of combustion scientists. This is not an oversight. It is only within the past 15 years that men have gone through the difficult mental exercise of delineating several areas in which useful contributions could be made.

Fires belong to the class of "diffusion" flames, well known in combustion, wherein the oxidizer (generally air) is not intimately premixed with the fuel (wood). They resemble more conventional combustion systems in that they can exhibit a "steady-state propagation" of a reaction zone into the fuel bed, require "ignition" for this steady-state to be set up, and can be perturbed by "suppression" techniques to the point of complete extinction. From the standpoint of thermodynamics or thermochemistry they show no unusual behavior. However, the inherent factor which distinguishes fires from the more conventional all-gas premixed or diffusion flames is that the availability of fuel is determined by an intricate feedback of heat from the reaction zone to the fuel supply, and that, therefore, the energy release rate is based on an interplay of fluid flow, radiation, and reaction rate. In the simplest case, i.e., burning on the surface of "two-dimensional" liquid pools, a liquid has to be heated, evaporated, and mixed with the oxidizer. In the more complex case of solids, a gaseous fuel is commonly first generated by an involved chemical breakdown of the solid into gases (resembling, in principle, the process of ablation) which subsequently have to diffuse to the surface where they mix and react with the oxidizer. It should be clear that the subdivision of the fuel, its chemical composition, the aerodynamics of the mixing process are all involved and present an almost infinite number of permutations. Alas, most problems of practical import deal with the latter case.

In order to break through this complexity, a number of simple questions for very simplified systems have to be answered first. Intensive investigation of the fire problems under controlled and reproducible conditions is so recent, that, in fact, there is, at present, a dearth of applicable "physical constants," such as burning rates, ignition energy requirements, etc., without which one hardly dare to explain, from basic principles, why the magnitude of burning rates is what it is or what the limiting processes are that determine these values. Once such questions can be answered with reasonable assurance, but only then, will it be possible to construct realistic models of fire behavior, test them against known cases and apply them hopefully to situations which, for one reason or other, are not accessible to the conventional measurements of the fire technologist. The most urgent goal is, of course, the prediction of the behavior of fires on a very large scale--so large, that simulation by a "test" fire is out of question.

In the following sections the status of burning rates, ignition, suppression, fire plumes, and scaling will be discussed in detail.

BURNING RATES[2]

Even in the best understood combustion systems, the prediction (not the measurement) of burning rates from chemical kinetic and transport data has only recently been partially successful (Ref. 4) for one system (H_2-O_2). It is not surprising, therefore, that the burning rates of fires are still in the stage where experimental measurements are made in order to delineate the factors that have a significant influence on burning rate.

The simplest system considered is the "two-dimensional" burning off a liquid surface. Largely due to pioneer work by Blinov et al. (Ref. 5), sufficient phenomenological data are available to assess this system. It was shown (Fig. 1) that for a given fuel the burning rates at first rapidly decrease with increase in tank diameter, and after reaching a minimum, increase again toward a constant value which remains independent of tank diameter to the largest size studied (30 meters) (Ref. 6). Extension of similar work (Fig. 2) to liquids with widely differing heats of evaporation and combustion indicated (Ref. 7) that burning rate could be expressed by:

$$\frac{V_\infty(\Delta H_{vap} + \int_{T_f}^{T_s} C_f dt)}{\Delta H_{comb}} = 0.0076 \text{ cm/min},$$

---

[2] See "Two-Dimensional" and "Three-Dimensional" Fuel Bed Fires in the Bibliography.

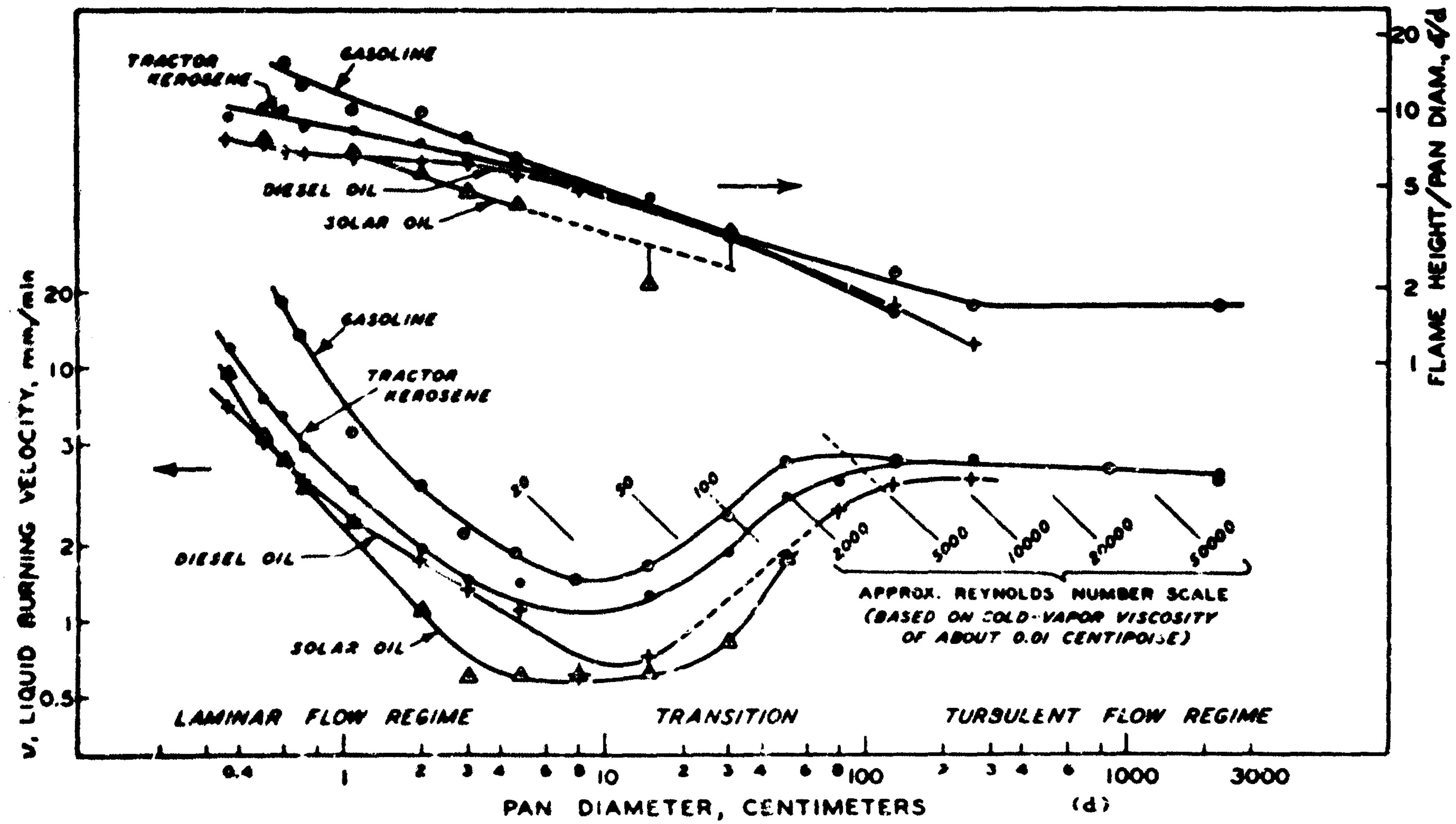

Fig. 1 CORRELATION OF "TWO-DIMENSIONAL" LIQUID POOL BURNING RATES VERSUS PAN DIAMETER (Ref. 6).

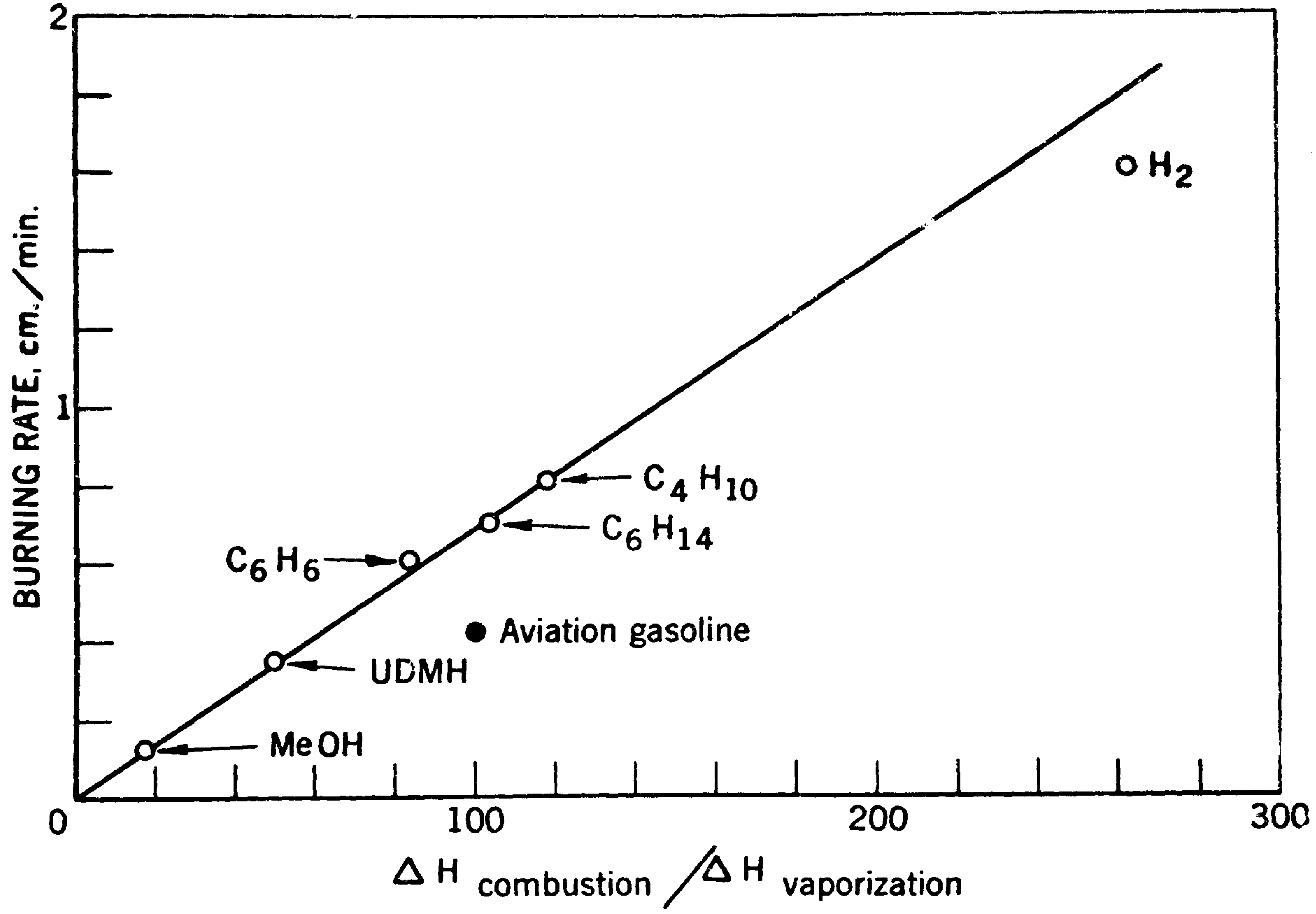

Fig. 2 "ULTIMATE" BURNING RATES OF VARIOUS LIQUIDS AS FUNCTION OF $\Delta H_{combustion}/\Delta H_{vaporization}$ (Ref. 7).

where V_∞ = burning rate of a "large" pan fire,

ΔH_{vap} = heat of vaporization,

ΔH_{comb} = heat of combustion, and

Integral = heat content of liquid.

Two interpretations have been given for this behavior. There is little doubt that in the first phase (decrease in burning rate with increase in diameter) the dominant heat input is from a liminar diffusion flame by heat transfer from the gas near the rim of the tank, where the reaction zone is in close proximity to the wall and the surface. As diameter increases, the system passes through a vibration stage into a "turbulent" stage. It is here that analysis of available data diverges (Ref. 8)--one assumption being that radiation from the products to the liquid is the dominant parameter, the other maintaining that turbulent convection would also give a diameter-independent result. The situation is not resolved at present.

This uncertainty regarding the important flow processes in this, the simplest, system is symptomatic of the entire fire problem. Implicit in it is that predictions of combustion volume (or flame height) and of radiation transfer, numbers that are of critical importance in the prediction of lateral propagation rates, cannot be made as yet. Equally unresolved are questions whether, as diameter increases, the burning rates will, in fact, remain constant and to what degree the burning rate of a large fire can be predicted from a knowledge of the behavior of individual, smaller segments when there are spacings between the burning units.

For "three-dimensional" structures (cribs), the analysis of burning rate and side-ways propagation is in an even more difficult situation. The experimental accumulation of rates as function of fuel spacing, fuel dimension, height, moisture content, wind, etc., has been admirably done by Fons (Ref. 9), providing useful data about the order of magnitude of the effects. It cannot be said, however, that a conceptual understanding exists as yet as to the relative contribution of convection and radiation on the propagation rate.

IGNITION[3]

A substantial amount of information has lately accumulated in the area of ignition, largely influenced by the intense interest in the consequences of ignition by radiation from nuclear explosions. Based on intensive studies of a variety of materials of different composition, thickness, and spectral characteristics, design data are on hand from which to draw conclusions about either the probable diameter of ignition in case of bomb explosions or the safe spacing of buildings when exposed to radiation from other burning structures. Since the two cases differ in the ignition mechanism they will be discussed separately.

Ignition by Pulses of Radiation - The steps involved in the ignition of an organic material, heated by radiation in air, are too complex to permit their description in detail. Suffice it to say that the process includes the establishment of a heat wave moving into the solid, resulting in chemical (and other) generation of gases which escape into the surrounding atmosphere. After mixing with air and remaining in contact with oxygen for a sufficient time, an

---

[3] See "Ignition" in the Bibliography.

explosion may set in in the gas phase (Ref. 10) or, in the presence of an already established high temperature ignition source, propagation of flame may commence and continue as long as gas evolution and mixing with oxygen continues. If the heat release from the chemical reaction is adequate, the initial radiation pulse may no longer be needed. The heat dissipation in the solid is crucial in determining the gas evolution rates; the boundary conditions (thick slab, thin slab, insulation, etc.) have a profound effect on the ignition energy requirements (Ref. 11); and the air-gas mixing and self-heating process itself (which is related to the scale of the irradiation) will influence the ignition energy limits.

A detailed study (Ref. 12) of ignition of thin α-cellulose sheets (of different absorptivity) as a function of irradiance has given useful information about the probable radius of ignition from a nuclear bomb, demonstrating the profound effect of atmospheric absorption and indicating how the position of the initiating fire ball in the atmosphere or beyond influences the ignition limit. Some uncertainty still exists concerning the interpretation of small-scale ignition studies (Ref. 13), taking into account the above-mentioned mixing steps exterior to the solid. Resolution of this will have a bearing on the most likely ignition radius, which, in any event, will be of such magnitude as to present an urgent fire hazard. Whether or not the numerous small ignition sources will coalesce into larger fires or go out depends on so many divergent causes that a generalized prediction of the course of such fires is not possible.

Ignition from Steady Radiation - A significant study (Ref. 14), based on laboratory studies of radiation from window openings in burning enclosures, has been presented recently from which estimates can be made concerning the "safe-spacing" of buildings so that the radiant flux from one full-involved structure does not set fire to a neighboring structure. Peak intensities of radiation from full-ventilated fires (the worst case) of 4 cal/cm^2/sec are postulated on the basis of a variety of model experiments, which permits estimating the intensity of radiation at points away from the source. Based on the criterion that long-time exposure of a relatively thick specimen to heat of a radiant input of 0.3 cal/cm^2/sec, in the presence of a pilot flame, is adequate to ignite most articles of practical interest, safe distances in the absence of artificial cooling or reduction in radiation transmission can be determined. The results, based in large measure on model experiments, give a valid basis for the establishment of building codes without recourse to intuitive "rules-of-thumb."

A model of a forest fire, in which propagation of flame is assumed to be by radiation only, has recently been proposed by Emmons (Ref. 15). It does not cover the more common flame propagation along a continuous line (in soil duff or tree crown, where convection and radiation effects are intimately intermixed), nor the setting of new ignition sources by brands. However, as an aerodynamic-ignition model it is unique and instructive, presenting a graphic picture of expected fire behavior as a function of fuel spacing (including "breaks" in fuel), energy flux, etc. Such modeling efforts uncover areas where experimental data are urgently needed for further progress.

SUPPRESSION[4]

Suppression, the inverse to ignition, is the main arena for the fire technologist. Much admirable work has been done, such as the evaluation of jet engines for rapid inerting of enclosures, aerial bombardments of developing fires, intense search for chemical inhibitors, etc.

Here, too, the scientist is confronted by more questions than he can answer with confidence. Thanks largely to the impressive work of Fristrom and colleagues (Ref. 16), a generally satisfying picture is emerging regarding the interplay between kinetics and transport properties in premixed flames. Once the coupled steps are known which are responsible for the formation of stable flames, it is relatively straightforward to explore the action of known inhibitors, to explain their actions, and to predict in which direction a search might be useful. It must be admitted that, as in the current search for effective drugs, the usual "screening process" of a large number of possible compounds is often faster and more dramatic in its results. It is clear, however, that the inhibiting action of halogen compounds, for example, is quite specific to particular flames and oxidizers. Unthinking extension of one set of "inhibitors" to other flame systems, without an understanding what steps one can or should interfere with, very frequently leads to unsatisfactory interpretations of results and erroneous conclusions.

How subtle the interacting threads by which inhibiting materials interfere with flame propagation are is shown by the ingenious experiments and explanations by Wise (Ref. 17)

---

[4] See "Suppression" in the Bibliography.

concerning the effectiveness of inorganic powders in extinguishing hydrocarbon diffusion flames. The superiority of $KHCO_3$ over other seemingly similar powders has been well established. The most consistent explanation of their action requires rapid evaporation and dissociation of the particles, formation of relatively stable compounds between metal atoms and flame radicals and subsequent reaction with another free radical to form a stable product. The metal atom acts as a catalyst to permit free-radical recombinations which, in its absence, would not be possible. To be effective, though, a particulate material must optimize several important requirements.

The action of water, the cheapest and generally most available extinguishing agent, has been under scrutiny under various situations (Ref. 18). Its effectiveness is clearly related to transporting it to the scene where it can be most useful, either as coolant of the gases (by reducing the emissivity of the flame), in reducing surface temperatures (by decreasing the rate of emission of combustible gases), as a radiation blanket to interfere with the radiation balance between fire and fuel, or as a means of raising the ignition energy requirements of the fuel. It has been established that water requirements are significantly less if the fuel surface is cooled in preference to the gas phase and that in the convection columns above fires the momentum of the water spray must be able to overcome the buoyancy of the convection plume. Quantitative deductions concerning minimum water requirements have shown that in large-scale operational fire extinguishments more than 100 times as much water is used than is necessary to successfully combat the fire! Such guidance, setting forth the achievable goals to the technologist, is one of the principal objectives of the research effort.

PLUMES[5]

Perhaps the best understood part of fires is the convection column by which the burned hot gases leave the combustion zone. Such wakes have been extensively analyzed for a variety of possible fluid dynamic conditions. The properties of the buoyant columns in a cross-wind, in atmospheres of different lapse rates, the rate of rise and structure of the initial thermal, the effect of moisture condensation and of radiation have been reported, either as an exercise in fluid mechanics or in connection with air pollution problems where knowledge of the behavior of the buoyant column under a variety of atmospheric conditions is important (Ref. 19).

The simplifying assumptions in all these analyses are:

1. that rate of entrainment of gas at the edge of the plume is proportional to some characteristic velocity;
2. that the profiles of mean velocity and mean buoyancy force in horizontal sections are similar at all heights, and
3. that the density variations are "small."

Applying the analysis to steady sources (fires or emissions from stacks), the strength of the source can be related to the height (under windless conditions) at which the buoyancy becomes zero and the plume ceases to rise (Ref. 20). The height of the plume (in meters) is

$$H = 31(1 + n)^{-3/8} Q^{1/4} ,$$

---

[5] See "Plumes" in the Bibliography.

where Q = rate of heat discharge at source in KW and

n = fraction of adiabatic lapse rate.

The general correctness of the model has been verified in experiments where a liquid of one density was injected into another of different density. The behavior of the expanding wake (flowing upwards, if a low-density liquid was injected into a high-density liquid; downward, in the opposite case) corresponded satisfactorily with the predictions.

Table I gives representative values of the computed height to which the fire convection column would be expected to rise in a wind-free atmosphere with a lapse rate of 6.5°C/Km (i.e. + 0.66).

These models, in general, do not concern themselves with the initial flow conditions at the point where the lowering of gas density occurs. Thus, the flows near the starting point do not conform to the simple "chimney" analysis.

One further example in which the fluid dynamic properties of the wake are predominant will be mentioned. Under conditions of cross wind, the transport and deposition of fire brands ahead of the reaction zone can be of crucial importance in setting the propagation rate of fires. This problem has been investigated more closely by Tarifa (Ref. 21) who has calculated the trajectories of burning particles of known drag and burning rate, from data obtained in a low speed wind tunnel. Flight paths, set by the vertical wake flow and horizontal winds, give the slant ranges which can be traversed by a still-burning brand. Despite somewhat artificial assumptions regarding the upward velocity in the

Table I

Computed Heights of Fire Convection Columns (H) as Function of Rate of Heat Discharge (Q)

SOURCE	RATE OF CONSUMPTION OF FUEL	Q (KW)	H (m)
Household Chimney	4 lb/hr of coal (1/2 of heat in flue)	8	80
Bonfire	400 lb wood/hr	450	200
Power Station	Heat equivalent to 1/2 MKW	5×10^5	1200
Forest	1000 tons/hr (at 4000 cal/g)	5×10^6	2200
Burning Town	250-500 houses/hr containing 10-20 tons combustibles (5000 tons/hr)	2.5×10^7	3200

wake and the interaction of the cross-wind on wake and particle trajectory, the calculations are an instructive first step of predicting distances in which brands can be troublesome.

SCALING[6]

None of the cases described previously have given any evidence that scaling-up of the area of a fire should bring with it an unusual behavior. The only semi-quantitative and frequently quoted "large-scale" measurement (from the Trensacq Fire as reported by Faure (Ref. 22)), has given flame heights and burning rates below what would be expected from correction of smaller crib burns, Fig. 3. Similarly in "two-dimensional" burns up to a diameter of 30 meters, no unusual behavior at the largest dimensions was noted.

This tranquil picture, however, is not in accord with two sets of field observations: (a) the reporting of winds of hurricane force at ground level during some incendiary fires in World War II and (b) the so-called "blow-up" of forest fires when a "normal" fire front appears to change its burning characteristic qualitatively and quantitatively. In the latter case a pronounced rotary swirl is frequently associated with the phenomenon.

Based on conservative estimates of burning rates and air requirements, it is difficult to account for the high surface winds unless the mechanism of air induction is

---

[6] See "Fire Whirls" in the Bibliography.

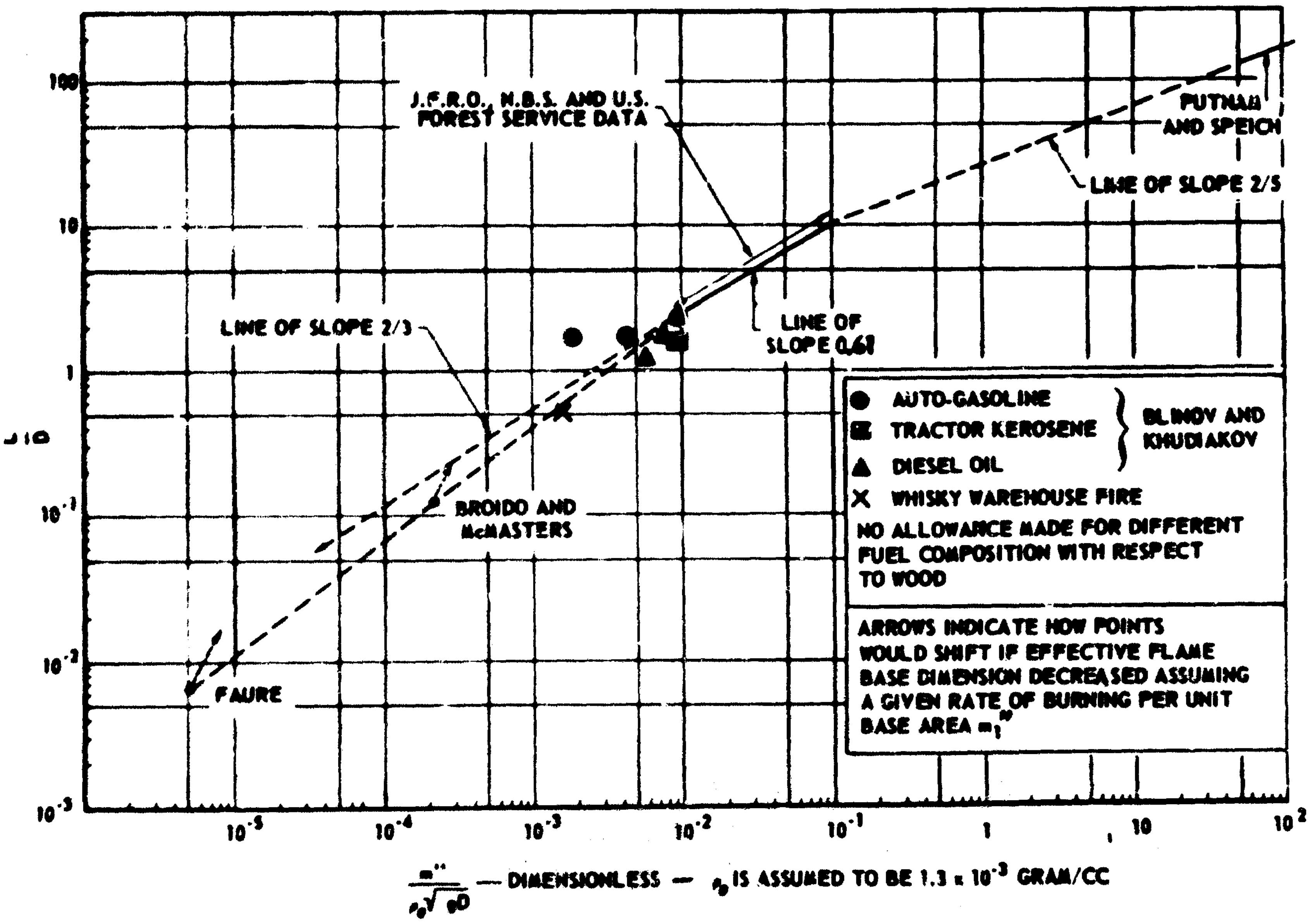

Fig. 3 CORRELATION OF FLAME HEIGHT, BURNING RATES AND DIMENSIONS FOR "THREE-DIMENSIONAL CRIB FIRES (Ref. 23).

basically different from that of the conventional line or area fires, namely that a large-scale vortex flow is established. This introduces flow problems previously recognized in dust whirls, dust devils, tornadoes, and hurricanes possessing rotating columns in which the angular momentum is several orders greater than in the surroundings. It is by no means clear under what conditions such large-scale fire whirls form and by what mode air is introduced into this rotating vortex near the ground. Similarly, little evidence is available from which to judge whether, if such a cyclonic flow is established, a substantial effect on the burning rate of the fuel bed should be expected. (Byram has observed a burning rate increase of 3 in model experiments (Ref. 24).) Only qualitative bits of evidence for circulation have been obtained, more or less by accident, in photographing air flow patterns near large fires, frequently not within the main heat release zone but in regions behind the convection column in the direction of the prevailing wind, Fig. 4. These secondary "tornadoes" appear related to the flow of wind around the fire column or the wood crib (Fig. 5).

Since the field observations of whirls occur at a scale which is difficult to reproduce on an experimental basis, their study has become, perhaps, the most challenging problem in the fire research field. The recent model experiments of Morton (Ref. 27) on the behavior of low density liquids injected into a rotating tank, Fig. 6, are probably the first clear-cut indications that buoyant columns in a vortex field, while showing behavior which is not at variance with general expectations of vorticity, will produce effects which cannot as yet be predicted with any degree of assurance.

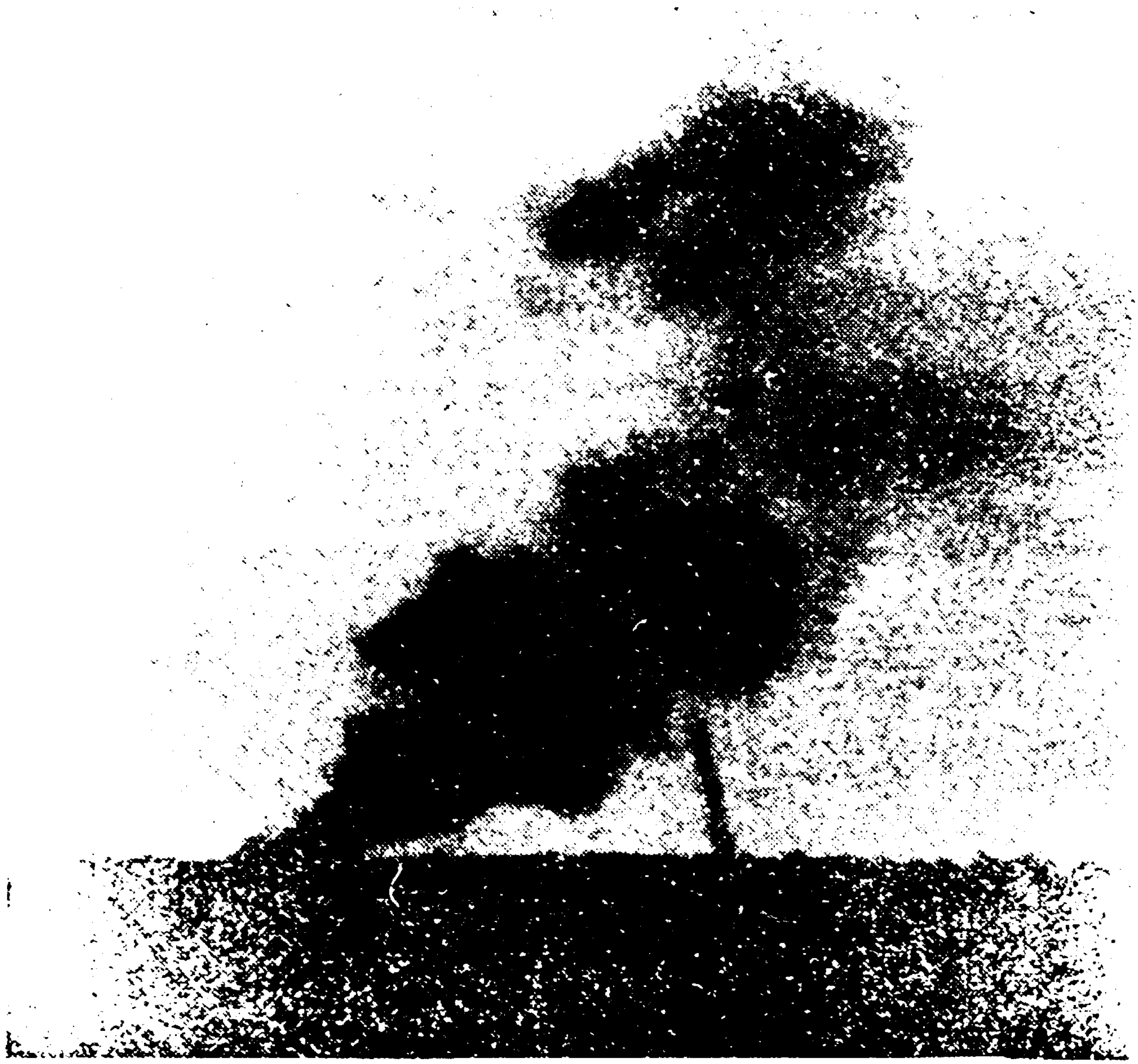

Fig. 4 VORTEX COLUMN IN THE LEE OF A FIRE PLUME GENERATED BY 100 BURNERS REGULARLY SPACED OVER AN AREA 125 BY 125 METERS BURNING ONE TON OF FUEL PER MINUTE. THE SMOKE TUBE IS ABOUT 10 MILES IN DIAMETER, 200 INCHES LONG AND ABOUT 525 MILES FROM THE FIRE. HORIZONTAL WIND SPEED 100 MILES PER MINUTE (Ref. 25).

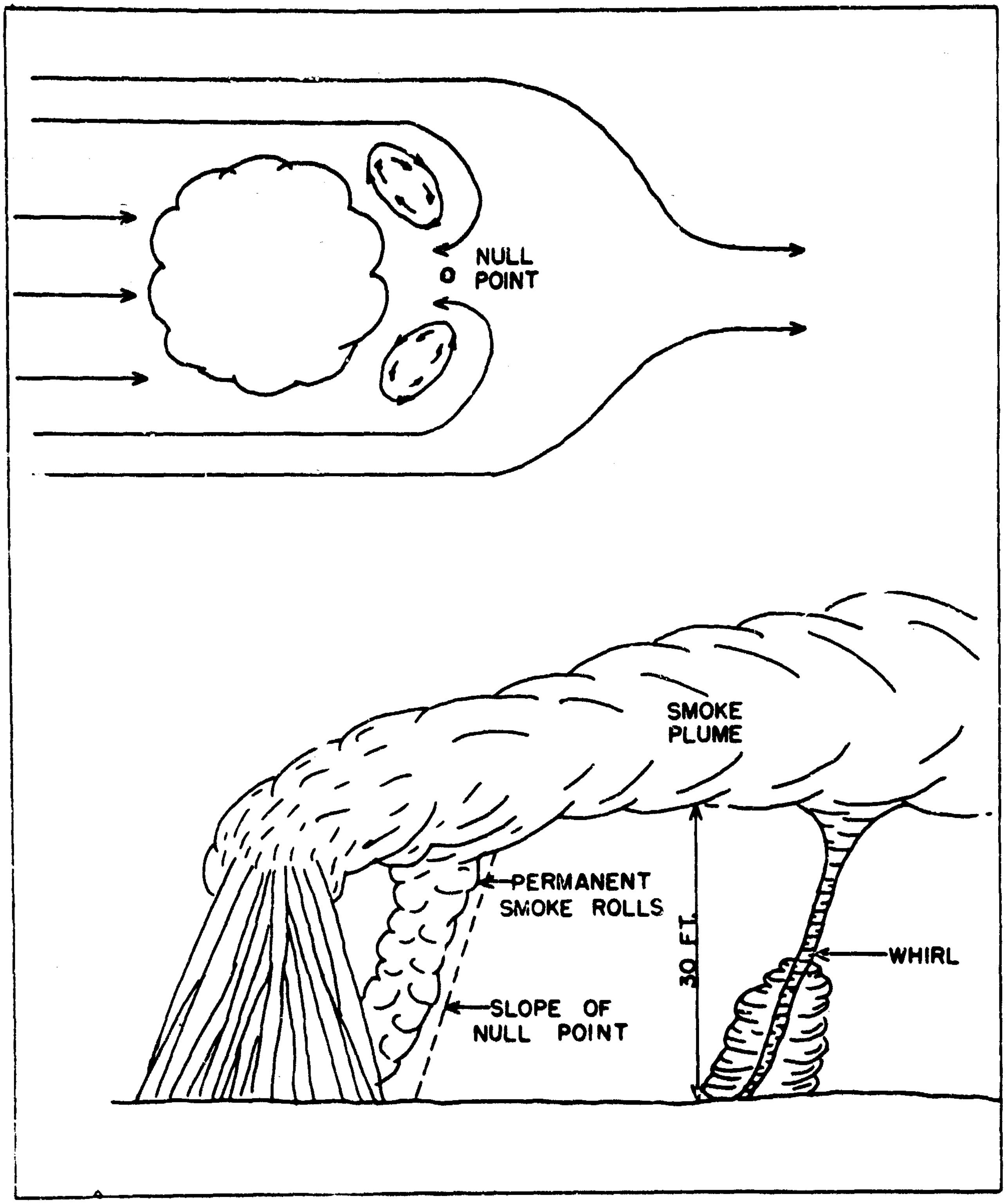

Fig. 5 SCHEMATIC DIAGRAM OF FIRE WHIRL DEVELOPMENT BEHIND A BONFIRE. THE WHIRLS ARE REPORTED TO BE FORMED WHEN ONE OF THE "SMOKE ROLLS" BREAKS OFF FROM NEAR A NULL-POINT IN BACK OF THE WOOD STRUCTURE. (Ref. 26).

Fig. 6 DEVELOPMENT OF A POSITIVELY BUOYANT DOWNWARD JET OF SALT SOLUTION IN A ROTATING TANK (1.23 RADIANS SEC). THE JET RAN FOR 15.2 SECONDS. THE PICTURES WERE TAKEN AT 5.2 SECONDS, 20.8 SECONDS, AND 40.2 SECONDS, RESPECTIVELY, AFTER THE START OF THE JET. IN THE FINAL PICTURE THE JET HAS SEPARATED INTO TWO ROTATING COLUMNS WITH ALMOST VERTICAL EDGES. (Ref. 27).

CONCLUSION

Fires pose questions to the physical scientist that will be answered only after the expenditure of much thought and ingenuity. Despite a few bold and successful thrusts the results to date are only moderately encouraging. This should be a warning signal to those whose concern is the conservation and proper utilization of natural resources. Excessive empiricism and exclusive dependence on technical brilliance alone can choke the applied effort which, while making encouraging progress, is presented with increasingly more difficult problems. A parallel effort must be made toward describing correctly the complex phenomena and understanding the physical processes that are responsible for fire behavior. Much help has already been extended from the fields of fluid flow and meteorology, from combustion and high-temperature chemistry. Yet, the fire problems are too urgent and too specific to be solved merely by waiting for results from related fields.

Is the current effort as good as it might be? Despite much laudable effort, there are serious deficiencies such as the absence of a really professional and broadly-based organization, unencumbered by parochial interests, with recognized channels of communication between its members and with the scientific community, joining together all those who invest their professional efforts in this field. Consider the handicap of a newcomer to the field of fire research, in his search to discover and to acquire the background sources from which his own contributions must start. In this field even the expert has a harder task to communicate with his peers than is generally the case. While efforts have been made and are being made to remedy this weakness, a fully adequate solution is not at hand at this time.

REFERENCES

1. A thoughtful discussion of various aspects of Fires is given in "A Study of Fire Problems." NAS Publication 949 (1961), National Academy of Sciences - National Research Council, Washington, D. C.

2. Energy input and energy consumption data are effectively presented in the book "Energy in the Future," by P. C. Putnam (D. Van Nostrand Company, Inc., New York, 1953). Data concerning Forest Fire Losses in the United States during the past 10 years were supplied by Mr. A. A. Brown (Forest Service).

3. H. Emmons: "Fire in the Forest" in Draper Anniversary Volume "Air, Space and Instruments," (S. Lees, Ed.) p. 396, McGraw Hill Book Company, 1963.

4. G. Dixon-Lewis and A. Williams: "Some Observations on the Structure of a Slow Burning Flame Supported by the Reaction Between Hydrogen and Oxygen at Atmospheric Pressure," Ninth Symposium (International) on Combustion, p. 576, Academic Press (1963).

5. A summary of the extensive Russian study can be found in "Diffusion Burning of Liquids," V. I. Blinov and G. N. Khudiakov, Moscow, 1961: Translation available from Office of Technical Services, U. S. Department of Commerce, Washington, D. C.

6. See the Review by H. C. Hottel of "Certain Laws Governing Diffusive Burning of Liquids," by V. I. Blinov and G. N. Khudiakov in Fire Research Abstracts and Reviews, 1,41 (1959). Under different experimental conditions, the initial decrease in burning rate can be eliminated (H. W. Emmons: "Some Observations on Pool Burning," International Symposium on the Use of Models in Fire Research, p. 50, Publication 786, National Academy of Sciences - National Research Council, Washington, D. C., 1961.)

7. D. S. Burgess, J. Grumer, and H. G. Wolfhard: "Burning Rates of Liquid Fuels in Large and Small Open Trays," in International Symposium on the Use of Models in Fire Research, p. 68, Publication 786, National Academy of Sciences - National Research Council, Washington, D. C., 1961.

8. See Comments and Discussions on "The Burning Rate of Liquid Fuels from Open Trays by Natural Convection," between D. B. Spalding and D. Burgess, J. Grumer in Fire Research Abstracts and Reviews, 4, p. 234 (1962).

9. W. L. Fons, H. B. Clements, and P. M. George: "Scale Effects on Propagation Rate of Laboratory Scale Crib Fires," in Ninth Symposium (International) on Combustion, p. 860, Academic Press, 1963.

10. D. L. Simms: "Ignition of Celulosic Materials by Radiation," Combustion and Flame, 4, 293 (1960).

11. See, for example, the analysis of heat flow by C. H. Bamford, J. Crank, and D. H. Malan: "The Combustion of Wood: Part I," Proc. Cambridge Phil. Soc., 42, 166 (1945).

12. The papers by S. Martin et al., as listed in the Bibliography should be consulted.

13. Comments by H. C. Hottel, "The Ignition of Thin Sheets by Radiation from Nuclear Weapons," submitted for publication in Fire Research Abstracts and Reviews.

14. Margaret Law: "Heat Radiation from Fires and Building Separation," Joint Fire Research Organization, Fire Research Technical Paper No. 5, 1963.

15. See Ref. 3.

16. An excellent summary on "The Mechanism of Combustion in Flames," by R. M. Fristrom, has been published in Chemical & Engineering News, p. 150, October 14, 1963.

17. W. A. Rosser, Jr., S. H. Inami, and H. Wise: "The Effect of Metal Salts on Premixed Hydrocarbon - Air Flames," Combustion and Flame, 7, 107 (1963).

18. D. J. Rasbash: "The Extinction of Fires by Water Sprays," Fire Research Abstracts and Reviews, 4, 28 (1962).

19. A most useful discussion of Buoyant Convection, Plumes and other Meteorological Effects is given by R. S. Scorer in "Natural Aerodynamics," Pergamon Press, 1958.

20. B. R. Morton, G. I. Taylor, and J. S. Turner: "Turbulent Gravitational Convection from Maintained and Instantaneous Sources," Proc. Roy. Soc. (London), 234, 1 (1956).

21. C. Sanchez Tarifa et al.: "Open Fires and Transport of Fire Brands," Second Annual Report, Instituto Nacional de Tecnica Aeronautica "Estaban Terradas" Madrid, Spain, 1963.

22. The Trensacq fire was discussed by J. Faure in a paper on "Study of Convection Currents Created by Fires of Large Area," in International Symposium on the Use of Models in Fire Research, p. 130, Publication 786, National Academy of Sciences - National Research Council, Washington, D. C., 1961.

23. P. H. Thomas: "The Size of Flames from Natural Fires," Ninth Symposium (International) on Combustion, p. 844, Academic Press, 1963.

24. G. M. Byram and R. E. Martin: "Fire Whirlwinds in the Laboratory," Fire Control Notes, 23, 13 (1963).

25. J. Dessens: "Man-Made Tornadoes," Nature, 193, 13 (1962).

26. A. H. Glaser: "Tornado Studies," The A. & M. College of Texas, Final Report A. & M. Project 129 - Reference 57-3F, U. S. Weather Bureau Contract Cwb 8696, January 1957.

27. B. R. Morton: "Model Experiments for Vortex Columns in the Atmosphere," Nature, 197, 840 (1963).

BIBLIOGRAPHY

"Two-Dimensional" and "Three-Dimensional" Fuel Bed Fires

V. I. Blinov and G. N. Khudiakov: "Certain Laws Governing Diffusive Burning of Liquids," Dokl. Akad. Nauk. SSR 113, 1094 (1957).

D. S. Burgess, J. Grumer, H. F. Wolfhard: "Burning Rates in Liquid Fuels in Large and Small Open Trays," International Symposium on the Use of Models in Fire Research, Publication 786, National Academy of Sci., 1961.

H. W. Emmons: "Some Observations on Pool Burning," International Symposium on the Use of Models in Fire Research, Publication 786, National Academy of Sci., 1961.

W. L. Fons, H. B. Clements, and P. M. George: "Scale Effects on Propagation Rate of Laboratory Crib Fires," Ninth Symposium (International) on Combustion, p. 860, Academic Press, 1963.

D. Gross: "Experiments on the Burning of Cross Piles of Wood," J. Res. Natl. Bur. Standards, 66C, 99 (1962).

H. C. Hottel: "Review of 'Certain Laws Governing Diffusive Burning of Liquids,'" Fire Research Abstracts Revs., 1, 41 (1959).

A. A. Putnam and C. F. Speich: "A Model Study of the Interaction of Multiple Turbulent Diffusion Flames," Ninth Symposium (International) on Combustion, p. 867, Academic Press, 1963.

D. B. Spalding: "The Burning Rate of Liquid Fuels from Open Trays by Natural Convection," Fire Research Abstracts Revs., 4, 234 (1962).

P. H. Thomas: "Buoyant Diffusion Flames," Combustion and Flame, 4, 381 (1960).

P. H. Thomas: "The Size of Flames from Natural Fires," Ninth Symposium (International) on Combustion, p. 844, Academic Press, 1963.

Ignition

S. Akita: "Studies on the Mechanism of Ignition of Wood," Report of the Fire Research Institute of Japan, 9, 1, 51, 77 (1959).

C. H. Bamford, J. Crank, and D. H. Malan: "The Combustion of Wood: Part I," Proc. Cambridge Phil. Soc., 42, 166 (1945).

A. Broido and S. Martin: "Effect of Potassium Bicarbonate on the Ignition of Cellulose by Radiation," Fire Research Abstracts and Reviews, 3, 193 (1961).

Margaret Law: "Heat Radiation from Fires and Building Separation," Joint Fire Research Organization, Fire Research Technical Paper No. 5, 1963.

D. I. Lawson and D. L. Simms: "The Ignition of Wood by Radiation," British J. Appl. Phys., 3, 288 (1952).

S. Martin and W. Lai: "Ignition of Alpha-Cellulose by Pulses Simulating Nuclear Weapons Air Bursts," USNRDL-TR-252, 1958.

S. Martin, C. A. Lincoln, and R. W. Ramstad: "Influence of Moisture Content and Radiant Absorptivity of Cellulosic Materials on Their Ignition Behavior," USNRDL-TR-295, 1958.

S. Martin: "On Predicting the Susceptibility of Typical Kindling Fuels to Ignition by the Thermal Radiation from Nuclear Detonations," USNRDL-TR-367, 1959.

S. Martin and A. Broido: "Thermal Radiation and Fire Effects of Nuclear Detonations," USNRDL-TR-652, 1963.

D. L. Simms and D. Hird: "On the Pilot Ignition of Materials by Radiation," Joint Fire Research Organization, F. R. Note, No. 365, 1958.

D. L. Simms: "Ignition of Cellulosic Materials by Radiation," Combustion and Flame, 4, 293 (1960).

Suppression

U. Bonne, W. Jost, and H. Gg. Wagner: "Iron Pentacarbonyl in CH_4-O_2 and Air Flames," Fire Research Abstracts Revs., 4, 164 (1962).

J. E. Dolan and P. B. Dempster: "The Suppression of Methane-Air Ignitions by Fine Powders," J. Appl. Chem., 5, 510 (1955).

R. M. Fristrom: "Radical Concentrations and Reactions in a Methane-Oxygen Flame," Ninth Symposium (International) on Combustion, p. 650, Academic Press, 1963.

R. R. Neill: "The Hydrocarbon Flame Extinguishing Efficiencies of Sodium and Potassium Bicarbonate Powders," Naval Research Laboratory Report 5183 (1958).

D. J. Rasbash: "The Extinction of Fires by Water Sprays," Fire Research Abstracts Revs., 4, 28 (1962).

W. A. Rosser, Jr., S. H. Inami, and R. Wise: "The Effect of Metal Salts on Premixed Hydrocarbon-Air Flames," Combustion and Flame, 7, 107 (1963).

B. J. Wood, H. Wise, and W. A. Rosser, Jr., "Burning of Liquid Droplets IV. Combustion Inhibition in a Fuel-Oxidizer System," J. Chem. Phys., 27, 807 (1957).

Plumes

C. H. Bosanquet: "The Rise of a Hot Waste Gas Plume," J. Inst. Fuel, 30, 322 (1957).

J. F. Keffer and W. D. Baines: "The Round Turbulent Jet in a Cross-Wind," J. Fluid Mech., 15, 481 (1963).

S. Lee, H. W. Emmons: "A Study of Natural Convection Above a Line Fire," J. Fluid Mech., 11, 353 (1961).

B. R. Morton, G. I. Taylor, and J. J. Turner: "Turbulent Gravitational Convection from Maintained and Instantaneous Sources," Proc. Roy. Soc. (London), 234, 1 (1956).

B. R. Morton: "Buoyant Plumes in a Moist Atmosphere," J. Fluid Mech., 2, 127 (1957).

B. R. Morton: "The Ascent of Turbulent Forced Plumes in a Calm Atmosphere," Int. J. Air. Poll., 1, 184 (1959).

M. P. Murgai and H. W. Emmons: "Natural Convection Above Fires," J. Fluid Mech., 8, 611 (1960).

M. P. Murgai: "Radiative Transfer Effects in Natural Convection Above Fires," J. Fluid Mech., 12, 441 (1962).

C. H. B. Priestley and F. K. Ball: "Continuous Convection from an Isolated Source of Heat," Quart. J. Roy. Met. Soc., 81, 144 (1955).

A. O. Rankine: "Experimental Studies in Thermal Convection," Proc. Phys. Soc. (London), 63, 417 (1950).

H. Rouse, C. S. Yih, and H. W. Humphreys: "Gravitational Convection from a Boundary Source," Tellus, 4, 201 (1952).

W. Schmidt: "Turbulent Expansion of a Stream of Heated Air," A.A.M.M., 21, 265, 357 (1941).

R. S. Scorer: "The Behavior of Chimney Plumes," Int. J. Air Poll., 1, 184 (1959).

G. I. Taylor: "Flow Induced by Jets," J. Aero/Space Sciences, 25, 464 (1958).

G. I. Taylor: "Fire Under Influence of Natural Convection," Int. Symp. on the Use of Models in Fire Research Publication 786, U. S. Nat. Academy of Sci., 1961.

J. S. Turner: "The 'Starting Plume' in Neutral Surroundings," J. Fluid Mech., 13, 356 (1962).

J. S. Turner: "The Motion of Buoyant Elements in Turbulent Surroundings," J. Fluid Mech., 16, 1 (1963).

B. Woodward: "The Motion in and Around Isolated Thermals," Quart. J. Roy. Met. Soc., 85, 144 (1959).

S. Yokoi: "Upward Convection Current from a Wooden Burning House," Int. Symp. on the Use of Models in Fire Research, Publication 786, U. S. Nat. Academy of Sci., 1961.

Vortices and Fire Whirls

G. M. Bryam and R. M. Nelson: "The Possible Relation of Air Turbulence to Erratic Fire Behavior in the Southeast," Fire Control Notes 12, 1 (1951).

G. M. Bryam: "Atmospheric Conditions Related to Blow-up Fires," Southeast Forest Experiment Station, Station Paper 35 (1954).

G. M. Bryam and R. E. Martin: "Fire Whirlwinds in the Laboratory," Fire Control Notes 23, 13 (1962).

J. Dessens: "Man-Made Tornadoes," Nature 193, 13 (1962).

A. H. Glaser: "Tornado Studies," The A and M College of Texas, Final Report A and M Project 129 - Reference 57-3F, U. S. Weather Bureau Contract Cwb 8696, January 1957.

H. E. Graham: "A Fire-Whirlwind of Tornadic Violence," Weatherwise 5, 59 (1952).

H. E. Graham: "Fire Whirlwinds," Bull. Am. Met. Soc. 36, 99 (1955).

J. E. Hissong: "Whirlwinds at Oil-Tank Fire," San Luis Obispo, California, Monthly Weather Review 54, 161 (1926).

R. L. Ives: "Behavior of Dust Devils," Bull. Am. Met. Soc., 28 (1947).

R. R. Long: "Vortex Motion in a Viscous Fluid," J. Meteor. 15, 108 (1958).

R. R. Long: "A Vortex in an Infinite Viscous Fluid," J. Fluid Mech., 11, 611 (1961).

J. E. Miller: "A Tornado Model and the Fire Whirlwind," Weatherwise 8, 88 (1955).

B. R. Morton: "Model Experiments for Vortex Columns in the Atmosphere," Nature, 197, 840 (1963).

J. S. Turner and D. K. Lilly: "The Carbonated-Water Tornado Vortex," J. Atmospheric Sci., 20, 468 (1963).

N. R. Williams: "Development of Dust Whirls and Similar Small Scale Vortices," Bull. Am. Met. Soc., 29 (1948).