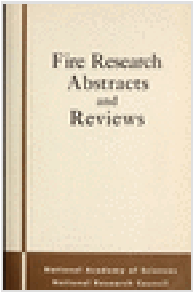

Fire Research
Abstracts
and
Reviews

Fire Research Abstracts and Reviews, Volume 8 (1966)

Committee on Fire Research and the Fire Research Conference of the National Academy of Sciences; National Research Council

Pages
306

Size
6 x 9

ISBN
0309309352

Volume 8 1966 Number 1

Fire Research Abstracts and Reviews

National Academy of Sciences
National Research Council

FIRE RESEARCH ABSTRACTS AND REVIEWS

Robert M. Fristrom, Editor

The Committee on Fire Research

FIRE RESEARCH ABSTRACTS AND REVIEWS will abstract papers published in scientific journals, progress reports of sponsored research, patents, and research reports from technical laboratories. At intervals, reviews on subjects of particular importance will be published. The coverage will be limited to articles of significance in fire research, centered on the quantitative understanding of fire and its spread.

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Volume 8 Number 1

Fire Research
Abstracts and Reviews

Committee on Fire Research
Division of Engineering
National Academy of Sciences—National Research Council

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
Washington, D. C.
1966

FIRE RESEARCH ABSTRACTS AND REVIEWS is published three times a year by the Committee on Fire Research of the National Academy of Sciences—National Research Council, 2101 Constitution Avenue, Washington D. C. It is supported by the Office of Civil Defense of the Department of the Army, the U. S. Department of Agriculture through the Forest Service, the National Science Foundation, and the National Bureau of Standards. The opinions expressed by contributors are their own and are not necessarily those of the Committee on Fire Research.

Library of Congress Catalog Card Number 58-60075 rev

Available without charge from the
Office of the Committee on Fire Research
National Academy of Sciences—National Research Council
Washington, D. C. 20418

FOREWORD

The Volume 1, Number 4 (November 1965) issue of *Fire Technology* contains an editorial entitled "Bridging the Gap" by George Tryon, which we have reprinted on page iii. This answer to informal inquiries by the Committee on Fire Research of the National Academy of Sciences—National Research Council is an encouraging sign that a permanent, two-way line of communication can be opened between the scientific community interested in fire research and the practical fire-prevention engineers and fire fighters. The field of fire research would profit by such a fostering of understanding and sympathy between these groups. Their viewpoints are divergent but they are both striving toward the same ultimate goal—that of reducing the incidence and severity of fires.

The lack of understanding between the practical and scientific communities is not new or unique to the fire field. It exists throughout our society. These frictions are due to many factors, but we feel that an important one is the time scales with which the two groups view the problem. Of necessity, the practical fire engineer must view the fire problem as an immediate one which brooks no delay and must be fought with today's weapons. By contrast, the scientist views the problem as one of laying the groundwork for tomorrow's technology and understanding. He judges a study not by its immediate usage, but by its ultimate utility. Both groups are right.

Scientists are no more gifted with prophecy than the average man. Therefore, in building for a tomorrow which is only dimly seen, they feel the only certain course must involve an understanding of the basic elements of the problem, linking it to the main body of science. If the immediate problem is too complex for his understanding, a scientist cuts off a section which is his own size, no matter how small. In this way, every scientific worker can make some contribution. The process can be likened to solving a jig-saw puzzle. In the early stages, it seems a hopeless jumble of tiny pieces, but as the pieces fall into place, patterns slowly appear, and suddenly a recognizable whole bursts forth and the last pieces almost place themselves. One of the best statements of this over-all philosophy of scientific work was given by two eminent physical chemists, G. N. Lewis and M. Randall, in their classic book, *Thermodynamics*:*

> "There are ancient cathedrals which, apart from their consecrated purpose, inspire solemnity and awe. Even the curious visitor speaks of serious things, with hushed voice, and as each whisper reverberates through the vaulted nave, the returning echo seems to bear a message of mystery. The labor of generations of architects and artisans has been forgotten, the scaffolding erected for their toil has long since been removed, their mistakes have been erased, or have become hidden by the dust of centuries. Seeing only the perfection of the completed whole, we are impressed as by some superhuman agency. But sometimes we enter such an edifice that is still partly under construction; then the sound of hammers, the reek of tobacco, the trivial jests bandied from workman to workman, enable us to realize that these great structures are but the result of giving

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* G. N. Lewis and M. Randall, "Thermodynamics," McGraw-Hill Book Co., New York, 1922.

> to ordinary human effort a *direction* and a *purpose*. [Italics are mine.—Editor]
>
> Science has its cathedrals, built by the efforts of a few architects and of many workers. In these loftier monuments of scientific throught a tradition has arisen whereby the friendly usages of colloquial speech give way to a certain severity and formality. While this may sometimes promote precise thinking, it more often results in the intimidation of the neophyte. Therefore we have attempted, while conducting the reader through the classic edifice of thermodynamics, into the workshops where construction is now in progress, to temper the customary severity of the science in so far as is compatible with clarity of thought. . . ."

We feel that fire research is in the stage of assembling bits and pieces. However, there is every hope that a useful understanding will develop and this is the goal toward which the fire scientist is working.

This issue carries a reprint (in part) from the *Tenth Symposium* (*International*) on *Combustion*, "Fundamental Problems of the Free Burning Fire," by Professor Howard Emmons. We feel that this represents a very cogent summary of the present status of the scientific understanding of the fire problem.

Several meetings of fire-research interest have been scheduled: the Western States Section of The Combustion Institute is sponsoring a meeting April 25–26 in Denver with Fire Research as one of the topics; and the Eleventh Symposium (International) on Combustion, scheduled for August 14–19 at the University of Calififornia at Berkeley, California, will have an evening session on Fire Research. The year seems off to an encouraging start.

Robert M. Fristrom, *Editor*

BRIDGING THE GAP*

GEORGE H. TRYON

National Fire Protection Association

The Fire Research Committee of the National Academy of Sciences—National Research Council, is doing a bit of soul-searching that can mean good news to fire protection. The committee has discussed a fundamental change in policy—a change which in essence recommends that, in addition to stimulating basic research of fire phenomena, the committee should proceed with a definite eye to the *practical gains to be achieved*. Here is recognition that the demands of technology must be met. Looking at the fire problem from Olympian heights with the academician's eye is appealing to the scientist, but the very pressures of the fight against uncontrolled fire (the realm of fire protection) demand more than a benevolent gaze from sympathetic friends. It's time we sat down together for frank discussions . . . and our academic friends are eager to join in a dialogue.

It is obvious, though, that before science and technology can become locked together in productive cooperation there are problems to overcome. First, we must learn more fully how to talk to each other. Between the combustion scientist and fire protection engineer there is a gulf, coursed by tidal currents of uncommon terminology and goals. These currents are carrying us out to sea. Dr. Howard Emmons, Gordon MacKay professor of mechanical engineering at Harvard University, in his paper, "Fire Development Theory—An Overview" (August 1965 *Fire Technology*) alluded to the need for building an effective bridge over the gulf, foreseeing the time when practical application of predicted data will lead to new ideas and methods of attack on old fire problems.

The initiative in bridging the gap does not rest with the NAS—NRC Committee alone. The committee is making its move . . . now it is up to fire protection to do its part. Already there is the embryo of an idea . . . a plan of action. Conceivably a "skull session" could be arranged between a group of fire-protection engineers and top flight combustion scientists interested in problems of uncontrolled fire—men such as Hoyt Hottel of the MIT Fuel Research Laboratory, Walter Berl of the Johns Hopkins Applied Physics Laboratory, Perry Blackshear of the University of Minnesota Mechanical Engineering Department, Walter Olson of NASA Lewis Research Center, Edward E. Zukoski of the Cal Tech Jet Propulsion Laboratory, and Howard Emmons.

The benefits would be many. Here would be the forum for combustion scientists to tell us what they know of fire phenomena in an atmosphere of mutual respect where ideas could be exchanged and aired. Of course, it's a two-way bridge. Some of us, who have not really understood combustion scientists, would become more aware of their goals; consequently we could offer them suggestions for programs with more immediate practical application.

The Combustion Institute is planning a meeting next year [August 14–19, 1966—Ed.] at which it may be possible for combustion scientists and fire-protection

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* Editorial from *Fire Technology*, Volume 1, Number 1 November 1965, George H. Tryon, Editor.

engineers to meet for a stimulating evening's discussion on problems of free-burning fire. Fire Protection does have a story to tell Institute members, and they in turn should have much to inquire of us.

That is one idea. Another is for an extended meeting next summer—say a week in some quiet atmosphere—at which we could break bread and converse with our academic friends. It would call for sacrifice and work, but the results would be a firm foundation on which progress could be built.

Fire Technology, with its avowed purpose of reporting on fire protection engineering and research, is only an instrument in others' hands to encourage and chronicle advances made in bridging the gap between the scientific-engineering and practical approaches to controlling fire. The "gutwork" has to be done by others—by men with the intense desire to see the gap firmly bridged. This, then, is where you come in!

Your help is needed to demonstrate that within fire protection there are men eager and willing to join in frank and open discussions with our academic counter parts. Without your support the suggestions put forth in this editorial cannot be nourished into productive life. Those responding to this call would be candidates for the proposed meetings. The right is reserved to select those who actually would participate in the interest of forming a well-rounded group to represent fire protection engineering. We pledge that the results of all discussions will be communicated to *Fire Technology's* full readership.

The call is out. Will you be a candidate designer for our bridge of progress?

CONTENTS

Volume 8 Number 1

VI. Radiation

VII. Suppression of Combustion

VIII. Model Studies and Scaling Laws

IX. Atomization of Liquids

X. Meteorological Interactions

XI. Operational Research Principles Applied to Fire Research

XII. Instrumentation

XIII. Fire-Fighting Techniques, Equipment

XIV. Miscellaneous

BOOK REVIEWS, REPORTS, AND TRANSLATIONS

REVIEWS

Fundamental Problems of the Free Burning Fire*

H. W. EMMONS

Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts

ABSTRACT

The growth of knowledge about the free burning fire is observed to be of the slow evolutionary type of cut and try, as man has had to attack the unwanted fire through the centuries. Since such fires are the result of intimate interaction of geometry, chemistry, thermodynamics, fluid mechanics, and heat transfer, each at an advanced level, it has not been possible prior to the present century—almost the present decade—to use accumulated scientific know-how; there simply was too small an accumulation. This condition is changing and changing rapidly. In this paper some of the problems of the free burning fire are described, an indication of the present state of understanding is given, and some suggestions are made for those avenues of approach that appear hopeful of successful attack in the near future.

Specifically, fire spread over building materials, through buildings, and through forests, is described in sufficient detail to indicate where we are today, where we should be going, and what it might get us if we went. The innumerable detail problems which must be individually solved and combined to produce solutions to the larger problems are little more than hinted at in the discussion. But it is clear that many man-years of research, worth many millions of dollars, will be required to solve these problems, but with the cost of fire to society of many billions of dollars every year the indicated research is more than urgent.

THE FIRE

Everyone has at one time or another watched a fire out of control consume a building or move across a dry grass field. A few readers will have been personally and emotionally involved in the building from which the flames issued. A few readers will have been on hand when the field of dry grass has been replaced by a much larger "model" in the form of a forest being consumed. We all, regardless of the scale of the fire out of control, have been awed by the power of the demon thus released by nature and humbled by the relatively puny efforts of man's extinguishment operations.

During the entire span of history man has had to cope with the uncontrolled fire which would destroy his home and his habitat. All through these centuries man has attacked these fires with every means at his disposal. During the last few centuries man's enormously increased knowledge of, and control over, materials and processes has likewise given man an enormously increased knowledge and control over the unwanted fire.

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* Reprinted (in part) from the *Tenth Symposium (International) on Combustion*, pp. 951–964 (1965) with permission of The Combustion Institute.

Until the present century almost the entire understanding and control over nature which had found use in the market place was empirical. By examining the process of interest, by following a hunch for a new approach, by selecting that which worked best from all the tries, remarkable progress has been made. The empirical approach is man's version of nature's evolution.

As soon as man got past the view of fire as a supernatural demon, he observed the three necessary ingredients: heat, fuel, and air. Furthermore, there are always a series of gross features which can be distinguished. There is always a beginning, the initial process by which some part of the fuel is heated to ignition. There is always a growth phase in which more fuel and air in the neighborhood of the ignition source becomes involved. There is always a fully involved "steady state" phase in which the combustion rate is at a very high value. There is always a decay stage in which the final bits and pieces of burning fuel are consumed. There is always a cool-off phase in which everything, unburned fuel and noncombustibles, return to ambient temperature.

These most important qualitative observations lead directly to the most important means of prevention and suppression.

Search for and remove ignition sources.
Clean up combustible rubbish.
Separate as far as possible necessary combustibles, i.e., with fire walls, wide streets, fire breaks, tank moats.
Cool the burning fuel, i.e., use a firehose, sprinklers, foam, cover with dirt.
Separate fuel and air, i.e., use a smother blanket, foam or dirt.
Shut off heat transfer to a pyrolyzing fuel, i.e., cover with foam or dirt, spray water with a fog nozzle.

The development and method of use of all of these fire suppression devices has been largely empirical.

During the past 50 years, and at an ever-increasing rate, man's latest contributions to the evolutionary process—science, mathematical analysis, and the computer—have made it possible to devise more and more subtle solutions to the toughest of long-standing problems. All the basic processes of fire are far better understood today than a half century ago. In one area after another the fundamental laws behind natural phenomena have become understood in a quantitative way; a way so precise that many hunches can be tried more quickly on paper rather than in the laboratory. More important, the nature of inspirations on which new solutions to new and old problems are based are drawing ever more heavily upon the quantitative understanding of the basic processes.

UNDERSTANDING FIRE

To "understand" has a large range of meanings. In a very real sense we already understand fire. A fire burns because of the geometric distribution of the fuel which mixes with air, is heated, and reacts, liberating a great deal more heat. The process can continue provided adequate feedback mechanisms are present. Some of the liberated heat must be returned to the fuel to preheat and ignite it. The products of combustion must so move that they leave the region of the fire and cause fresh air to move into the fire. This qualitative description has been the basis of our most important methods of extinguishment and control, as listed above.

To understand fire can mean much more than this qualitative statement. It may mean that experimental data has been obtained over a wide range of circumstances and correlated against the appropriate variables, thus permitting quantitative predictions of events in new cases. It may mean that the fire process has been decomposed into such elements that each can be calculated as a heat transfer, a fluid mechanics, a thermodynamic, or a chemical rate process, using basic macroscopic laws of nature. It may mean that the atoms and molecules and their interaction is understood so well that the entire phenomena can be described on the microscopic level.

At the present time the level of man's understanding of fire lies somewhere between the qualitative description and the correlation of data. There are, of course, never any absolutes in such statements. A few fire problems have been carried well through the fundamental macroscopic calculation. Many problems still await sufficient accurate measurement in order to attempt any correlation at all.

It is a purpose of the present symposium to bring up for discussion some of the attempts currently being made to advance our understanding of the fire out of control, from the qualitative to the quantitative level, and thus to supply the basis for more subtle and, hopefully, more powerful methods of prevention and control.

FIRE SPREAD

As soon as a more quantitative description is sought, the range of phenomena to be considered must be more restricted. As always, an approximate solution can be a model for many different cases, while an exact solution is necessarily restricted to a very narrow range of cases. We will here restrict our consideration to the simplest case of burning; namely, the rate at which a combustion zone moves through a fuel bed.

One's first reaction is that surely the steady state burning of a homogeneous fuel is simpler than the nonsteady fire propagation process. Actually it is not simpler, but is in fact identically the same. If the fuel and air are homogeneously distributed throughout their respective portions of space and the fire has burned long enough to be propagating steadily through the fuel, a change of coordinates to an origin fixed in the fire reduces the steady propagation to one of steady state.

We can see in a general way what determines the rate of travel of the fire. Various rate processes (chemical, convective, diffusive) permit the consumption of fuel to take place at rate w (mass/time) in a region of size C (length). Of the heat thus liberated, an amount $\mathcal{Q}$ (Btu/time) will be fed back to the unburned fuel. This feedback heat will take the fuel from its initial state to a state at which an ignition process can make it a part of the fire front. In the simplest thermal-ignition case the heat $\mathcal{Q}$ must raise the fuel up to an ignition temperature T_i. In more complex cases the diffusion or convection of material into the unignited fuel may be important, too. In a certain sense firebrands fall in this last category. In any case, the energy and convected mass must be spread over the fuel proportional to the rate of fire spread. Thus there results a relation of the form

$$I = I_F M U, \tag{1}$$

where I is the heat and/or mass transferred from the fire to the unburned fuel per unit of time, I_F the heat and/or mass required by a unit mass of fuel in order to ignite, M the mass of fuel per unit area (or volume) in the unburned state, and U the rate of propagation of the fire (ft/sec) normal to the fire front. The exact nature and magnitude of both I and I_F depend upon the particular fuel and its configuration. I and I_F can and often do depend upon the fire spread rate. But regardless of the immediate complications, the balance of fuel preparation requirements and fire production of the heat and materials needed for this preparation determines the spread rate in all cases.

Mallard and LeChatelier,[1] in 1883, wrote such an equation for a premixed gaseous mixture in which the thermal energy returned to the fuel depended inversely upon the rate of burning, since the higher burning rate means shorter time and thus a thinner flame and thus a steeper temperature gradient toward the fuel. They set this equal to the energy required to heat the fuel to ignition. Thus,

$$\frac{\lambda\alpha(T_\infty - T_{ig})}{U} = \rho C(T_{ig} - T_0)U, \tag{2}$$

or

$$U = \left[\alpha k\left(\frac{T_\infty - T_{ig}}{T_{ig} - T_0}\right)\right]^{\frac{1}{2}}. \tag{3}$$

This initial treatment has in the past decade been replaced by a more adequate treatment by writing the general equations for specie, energy, and momentum conservation. And in those cases where sufficient chemical detail is known, the solutions agree with experimental flame speeds.[2,3]

FIRE SPREAD IN BUILDINGS

Fire propagation of interest in the uncontrolled fire is almost never of this simple premixed-gas type. The more common fire creeps along a wall or a floor. The fire is blown up through the partitions. The fire moves along the under side of a ceiling or roof.

Under these conditions the fuel is generally of a cellulosic nature. Before cellulose will burn, it must be raised in temperature well past the temperature where the complex organic molecules decompose, producing an array of more or less combustible gases. Thus the feedback heat not only raises the temperature of the fuel, but supplies the heat for the endothermic pyrolysis reactions. In fact, as the burning zone moves along the solid fuel surface, only the surface of the unignited fuel is heated. These materials are generally poor conductors of heat (white fir thermal conductivity $\lambda \approx 0.06$ Btu/hr ft °F, thermal diffusivity $\kappa = 0.0068$ ft^2/hr). Thus the surface heats rapidly and begins to decompose while the lower layers heat up by conduction much more slowly. The decomposition gases from the lower layers tend to cool the upper layers by transpiration. Finally, the fire moves close enough to ignite the combustible gases.

The mechanisms by which the surface is heated are largely radiative and convective, since conduction is poor. Thus the propagation of flame over the surface will depend critically upon the total geometry. Propagation up a vertical surface would have convection dominant, while propagation downward is probably caused largely by radiative heat transfer. Thus the convective movements of the air, decomposition gases, and products of combustion must be studied and included in the propagation process. And while the burning zone moves along the surface of the material, the conduction of heat continues to propagate the decomposition zone into the fuel.

The quantitative prediction of the process of propagation of flame along a surface is necessary for the quantitative prediction of the rate of spread of fire through a building. It is, of course, by no means sufficient. Similarly, the rate of propagation of fire through the sheet fuel is necessary for the prediction of the rate of destruction of a building, but is by no means sufficient either. Such propagation prediction is only the first step. It is, however, an essential first step—and a relatively simple one.

Although this step has not yet been taken, some hints of its importance are indicated by Fig. 1, which shows a correlation of data on ignition of 2.5% carbon in

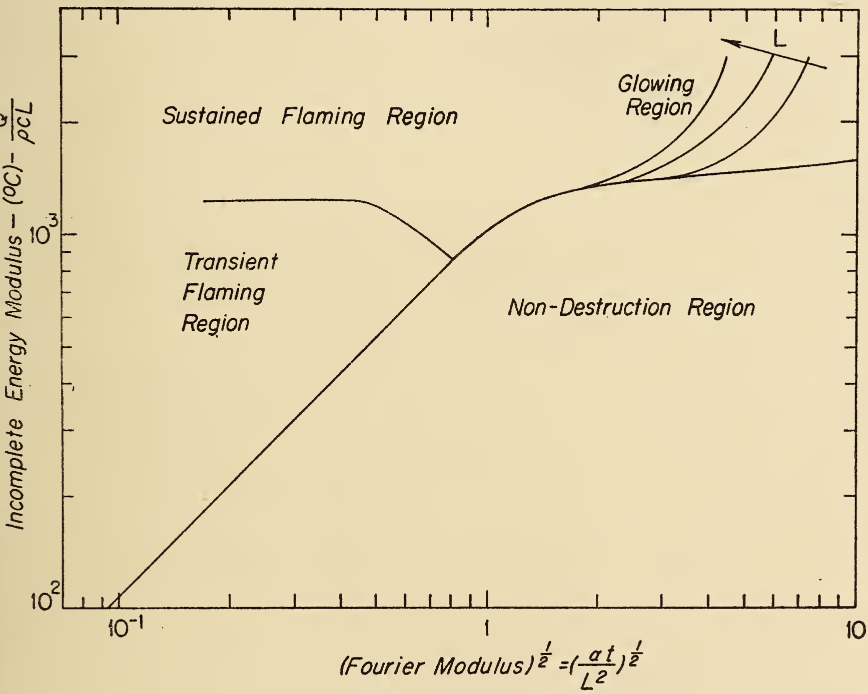

FIG. 1. Ignition of α-cellulose containing 2.5% carbon black by a radiation pulse (see Refs. 4, 5). $\mathcal{Q}$ is the total radiant energy per unit surface area, ρ the density of α-cellulose sheet (mass per volume), c the heat capacity of α-cellulose (energy per unit mass per degree celsius), L the thickness of irradiated sheet, α the thermal diffusivity of α-cellulose, and t the time of irradiation.

α-cellulose, nominal density 0.73 gm/cc, 8 thicknesses, by a radiation flash.[4,5,6] In the upper region the material burns up completely by flaming or by glowing combustion. In the lower right region the heat $\mathcal{Q}$ is added so slowly that it all conducts away without raising any material to a high enough temperature to ignite—or even pyrolyze. In the transient flaming region the heat is added so quickly that the surface layers become very hot, pyrolyze and ignite before the heat can be conducted away. However, subsequent heat conduction (radiation and convection) are so large that the fire goes out for want of adequate further pyrolysis. Some progress has been made on the burning of liquid fuels in pools, the burning of wood cribs, and fires in enclosures,[7–11] but even such attempts at analysis as exist[12–14] are controversial.

To complete the analysis of the rate of spread of fire through a building requires a knowledge of the connectivity of the building itself. Are there many open doors? How porous are the walls and floor? How can such questions be usefully answered? Are buildings classifiable into types on a connectivity basis as well as on a materials of construction basis? Can we thus get a useful classification of buildings into rate of value destruction classes so as to be useful in an operations analysis of firefighting operations?

Only the merest beginning has been made to supplement the hunches based upon experience with quantitative information on how to proceed with the development of less combustible construction materials, less combustible building designs, less easily destroyed values in case of a fire, and more easily extinguished fires.

In the above discussion of fire spread nothing was said about extinguishment. The reason is simple. If no attempt has yet been made to quantitatively understand the fire spread process, it is impossible to make any quantitative progress on the manner of action of suppressive activities except in an empirical manner. Actually, so little really-well-controlled experimental work has been done on fire-suppression processes, that a useful empirical correlation has yet to be made. The start that has been made on the suppressive effectiveness of water sprays, metal salts, or bicarbonate powders are described in Refs. 15, 16, and 17.

As an illustration of further work that should be done, one could measure the fire-spread rate and rates of destruction over a standardized surface of a standard material and then observe the effect of various extinguishment applications. Such tests must include the identification of and the measurement of all pertinent parameters. Many physical properties of the fuel and the geometry would have to be measured and used in the correlation of the results. The tests themselves should largely ignore the "practical" ranges of variables and concentrate on the appropriate "practical" phenomena. By this it is not meant that identifiable significant dimensionless variables should be ignored. The tests should indeed be kept in appropriate practical ranges of such variables. However, for many physical variables the dimensionless variables and ranges are not now known. For example, at what rate should water as an extinguishing agent be applied? One might say we consult the fire hose and sprinkler and cover this range. I disagree. This is entirely wrong. Many spreading fires are not reached directly by a hose stream. What is the effect of a much lower application rate as by a splash? What is the effect of airborne fog? What is the effect of hot airborne water vapor? For very dry winter woodwork, can any of these low application rates lead to more rapid spread rate or more rapid destruction?

If such data as this were available, one might conceivably discover that there is an optimum rate and method of water application to a building that would minimize the ultimate value destruction. Clearly, the fire in a burning building would be immediately quenched if the building could be picked up and dunked in the ocean. However, such an extinguishment procedure would produce a very high destruction of values. Do present extinguishment procedures apply water too fast or too slowly, in the best way or in a very poor way? The present best estimate is that too much water, by several orders of magnitude, are used in extinguishing real fires. Exactly how much water is needed, and the far more important question of how to operationally apply it in the confusion of a burning building, remain for the future to disclose.

FIRE SPREAD IN FORESTS

The same principles of feedback of heat and materials that move a fire front through a premixed gas mixture or along a wall board, also move a fire front through the natural fuels of field and forest. However, the fire problem presented by a building and a forest are very different. A building has combustible surface elements connected together in a wide variety of ways. Thus, while the fire spread over an element appears as not too difficult a problem, the fire spread through a building is a formidable problem.

The forest, on the other hand, is made up of elements distributed in somewhat random fashion and through which the fire front moves. There is little hope and little incentive to try to understand the rate of fire spread along a particular branch of a tree. Rather it appears more profitable to try to find a statistical method of defining the fuel distribution and then to find the fire-front-propagation rate as a statistical average.

At the present time the fuel description is limited to a few numbers. Pounds of combustibles per acre, fuel moisture, and kind and health of trees, are clearly of major importance. However, they fall far short of the information required. Somehow we need to know how thick and how combustible the foliage is; how thick, how high, and how dry the underbrush; how significant and how green is the grass; how thick and how combustible the duff on the forest floor. We obviously do not want a detailed blueprint of the forest, acre by acre. This would supply too much information. If this is too much, and no information is too little, what do we want? At the present time we don't know what we want with any exactness. The forest services of the world have developed (from experience supported by various measurements of important quantities like fuel moisture, air moisture, wind, and slope) a number of fire-danger rating scales. These not only codify operating procedures but give a first-approximation answer to questions like: How many fires likely today? How many men should we keep in readiness? Is it safe to lend some of our equipment to an adjacent area now in trouble?

Although it is not known exactly what to measure, nor know to measure it, there is an obvious need for new data by new methods. Generally, a forest fire moves primarily through the underbrush, killing many of the larger trees by burning the surface of the trunks. Sometimes the fire includes the brush and the crowns. On rare occasions the fire can rush through the crowns without burning the underbrush. Thus over-all forest data is not enough. Something about its vertical distribution is also important.

If we watch a forest fire, we see the heating of the unignited trees and brush largely by radiation from the flames and embers in the fire and the flames above the trees. Unless there is a very strong wind, there will be some cooling of the unignited trees by air moving into the fire. The net heating causes first drying and them pyrolysis of the fuel. The fuel thus prepared finally ignites in one of several ways. The temperature may rise high enough to start the self-supporting exothermic reactions. Combustible pyrolysis products may become sufficiently concentrated to ignite in the fire and flash over to the new fuel. A flame may rise from an advancing fire below and ignite the heated branches above. Burning twigs and leaves may fall from an advancing fire above and ignite the fuel below. Occasionally a considerable pocket of combustible gas accumulates and ignites explosively. This is especially spectacular when the crown of a tree seems to burst into flame all at once.

Essential parts of a forest fire are the convective air movements in and above the fire. The buoyant plume of flame, smoke, and brands is both the detectable sign of a fire and the essential mechanism for the movement of new air into the fire. The smoke not only hampers operations on the ground but also so obscures the fire front from the air that aerial photographs have not yet been able to get accurate fire-front-advance rates, although modern infrared photography shows much promise. The flames in the plume as blown toward or away from the advancing fire front exert a considerable influence on the heating, drying, and pyrolyzing of new fuel. Finally, the high-velocity-rise rate of the gases in the buoyant column picks up leaves, twigs, or even branches and carries some of them into new unignited forest. Thus new fires are started, ranging from a few feet to many miles away.

To take account in any fire spread theory of so many diverse phenomena—even if we were able to calculate every one of them with precision—would be clearly impossible. At the present time it is not known on what level of sophistication practical success is to be found. A few years ago the present author[18] made a try at a fire spread theory with potential application to the forest fire problem. . . .*

In many areas a start has been made. For example, the pyrolysis products obtained under various conditions have been studied together with the heat of decomposition. Chromatographic analysis has been made of the gaseous products obtained with various woods and with variously treated cellulosic materials in vacuum and in various inert gases with heating at various rates. The thermal effects have been studied by differential thermal analysis. At present there is considerable confusion, since the results are highly variable, dependent upon small—sometimes unknown—effects.

Poplin (cotton cloth), for example, decomposes in vacuum to 17.4% volatile at room temperature, 76.3% tar, 5.2% char.[19] At present, the exact detail of pyrolysis needed for an understanding of fire spread is not known, but in addition to the amounts of various products one would at the least need information about their heat of reaction after active burning begins.

The turbulent plume above a fire is reasonably well computed,[20–26] using the theory introduced by Morton, Taylor, and Turner.[20] The kind of agreement that can be attained is illustrated by Fig. 2.[21] There are many unanswered questions remaining. For example, the whole question of the interaction between two or more fires is nearly untouched. A start has been made on this problem by the correlation of some data on flame heights for small multiple jets.[27] The plume interaction needs examination over a wider range including convection plume temperature and velocity, properties, various fire sizes, and using fires of liquid pools, and wood cribs so that the interaction can include the rate of burning.

The fire whirl or fire tornado is a special feature which frequently accompanies a strong rising convection plume in a wind. If there is a horizontal wind shear, it is easy to understand the whirl formation, qualitatively. As air is carried aloft by the fire plume, new air moves in and by conservation of angular momentum reaches a

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* This section of the paper has been deleted. It was reviewed in *Fire Research Abstracts and Reviews* *5*, 163 (1963).

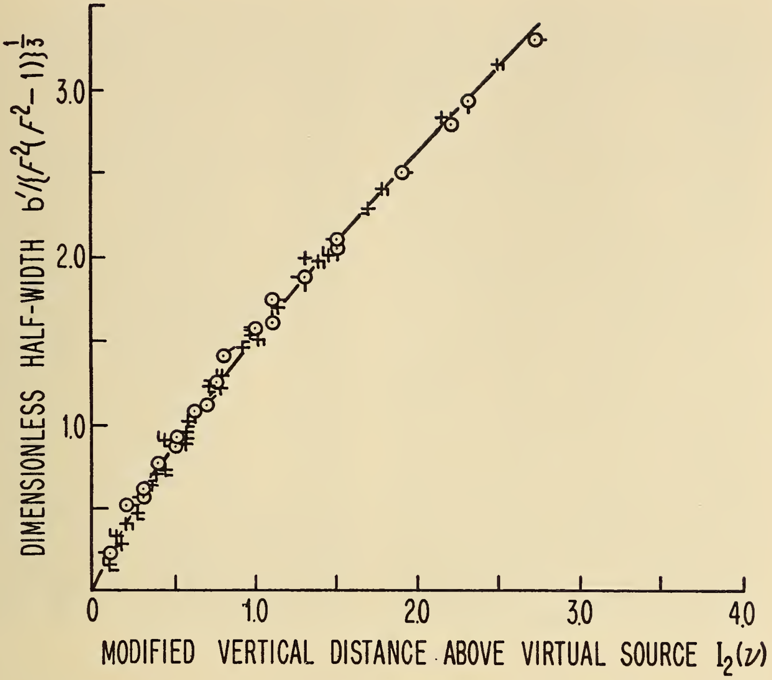

FIG. 2. Comparison of experimental and theoretical half-width of a line fire convection plume (see Ref. 21).

$b' = 0.59(b/b_0)$ ratio of width of plume to width of fire;
$F = (0.114/g^{3/2}b_0^{3/2})\,(\gamma_1/\Delta\gamma_0)^{3/2}\mathfrak{Q}$, Froude Number of fire;
$\mathfrak{Q} = 2gb_0u_0(\Delta\gamma_0/\gamma_1)$, fire buoyancy flux;
$x' = 1.07(x/b_0)$, ratio of height above fire to width of fire;
$x' = \{F^2(1 - F^2)^{1/3}\}\,\{I_2(\nu) - I_2(\nu_0)\}$, implicit definition of ν;

$$I(\nu) = \int_0^{\nu} \frac{\nu\, d\nu}{(\nu^3 + 1)^{1/3}}, \quad \nu_0 = (1 - F^2),^{1/3};$$

$\gamma_1 = g\,\rho_1$, ambient specific weight;
$\Delta\gamma_0 = g(\rho_0 - \rho_1)$, specific buoyancy;
b_0 = width of line fire.

The various symbols refer to acetone flames of various buoyancies.

high angular velocity. Such small scale whirls can occur without a wind shear provided there is a sufficient horizontal wind to produce a boundary layer along the ground of sufficient size. Again, air is carried aloft by the fire convection. This time the vorticity of the ground boundary layer is taken with it and since vortex lines are *never* broken there are produced vertical vortices between the fire plume cloud and the earth. Such fire whirls are frequently seen in forest fires and are often responsible for spreading firebrands into unignited fuel. Our knowledge of this phenomena is not yet sufficient to predict their occurrence or to take steps to suppress them. Some of the most recent work can be found in Refs. 28–32.

THE FIRE STORM

No general discussion of fire problems is complete without a reference to the very severe wartime fires of Hamburg and several other cities in which a number of square miles were burned out in some 6 hours of most violent fire. Winds grew to hurricane level, blowing everything loose into the heart of the fire. Needless to say, exact measurements are not available on winds, temperature, fire-plume characteristics, upper-level winds, stability of the atmosphere, and many other details which would need to be measured if reasonably complete understanding of the events were to be attained.

One thinks at first that the rising plume of a large-area fire might give rise to winds of the required magnitude. However, estimates do not seem to bear this out, since by mixing with cool air the density of the plume raises too fast to maintain the required buoyancy. If, however, the atmosphere were unstable at the time of the fire, the fire plume might be enhanced in altitude and buoyancy by contributions from the unstable air. This explanation is difficult to check since the velocities encountered in Hamburg were on the upper edge of any that nature ever produces.

An alternative explanation supposes a gigantic fire whirl.[29,32] If there were sufficient wind shear at the time of the fire, a fire whirl of enormous size might develop. Several qualitative effects of such air circulation are noteworthy. Since the air outside of the fire plume is rotating rapidly while that inside is not, the normal plume turbulent mixing process is prevented by centrifugal force, the plume stays hot to far higher altitudes and hence the high buoyancy required to produce high velocities is available.

Furthermore, the rotating air high above the ground produces a balancing radial pressure gradient. This radial gradient imposed upon the relatively noncirculating air near the ground drives the latter toward the center of the fire. Thus the air supplied to the fire comes from a layer near the ground and the resultant winds are far from tangential to circles around ground zero. Thus the fact that trees blown down in Hamburg did not show a distinct tangential air motion is not contradictory to the existence of a fire whirl a mile or more high.

In the laboratory it is easy to simulate the fire whirl as shown in Fig. 3. Thus acetone burning in a 4-in.-diameter can, which usually produces a flame about one foot high, could produce a fire whirl 18 feet high by adding a small angular momentum to the inducted air. In this laboratory the angular momentum was produced by a cylinder of 12-mesh window screen, 8 ft in diameter and 10 feet high, which rotates about 4 rpm. A careful study of this phenomena is under way on an NSF-sponsored High Temperature Gas Dynamics Project at Harvard. To date the results already reported by Byram[32]—e.g., outside of the fire plume, the motion is free vortex, the burning rate is increased by a factor of 4—have been confirmed and measurements and theory are directed toward the confirmation or refutation of the above qualitative description.

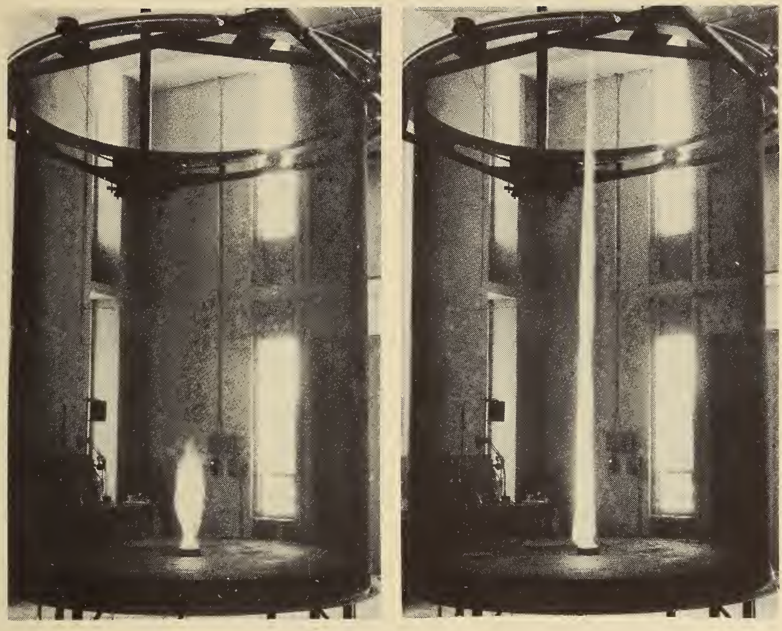

FIG. 3. Effect of ambient air vorticity on a fire free convection plume. Left: 1.5-ft-high flame of acetone burning in 4-in.-diameter can without screen rotation. Right: 15-ft-high flame in above apparatus with screen rotation of 4 rpm.

SUMMARY

In these brief pages one cannot do more than suggest a few important topics from the enormous dawing technology of the fire out of control. It has been the intention of this paper to point to some of the more promising immediate problems, problems which would be expected to be solvable with present knowledge of the basic subjects of thermodynamics, aerodynamics, heat transfer, and chemistry.

There are large numbers of problems which are in grave need of solution but whose solutions are in a wishful-thinking class. The magic suppressant which prevents cellulose from reacting with oxygen is highly desirable, but probably nonexistent. The fact that man with an atomic bomb can, in a fraction of a second, set a whole city afire is no indication that there exists an antifire bomb which in another second can put the fire out, or that there could exist an antishock wave which could restore the damage done by the blast.

In the new day of fire science, improvements in understanding and technics will come only after years of diligent careful work; there are no quick and easy routes to major breakthroughs that can be planned into any research program. Only patience will be rewarded—sometimes with a spectacular result but more often with further contributions to the evolutionary know-how of fire-control.

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COMMENTS

Dr. A. L. Thompson (*McGill University*): One part of Emmons' film showed firemen pouring water into a large brick building to no avail. It is possible that they should have directed the water into the upper stories if they really wanted to put out the fire? The water should, at least, reduce the upward progress of the fire by keeping the upper floors wet and the possibility of the water-gas reaction should be reduced if the water does not contact hot carbon. Water coming from above would also reduce the possibility of air being carried in by entrainment. Have any studies been directed along the lines of the above concept?

Prof. H. W. Emmons: The strategy of firefighting varies considerably from one place to another. There is no one clearly superior approach. A fire is more easily extinguished from below if it is accessible to water. On the other hand, water runs down and hence may reach less accessible places from above, at least if it can be applied in sufficient quantity. The importance of the water-gas reaction in connection with fire spread and extinguishment is an open question. No studies to my knowledge have been made to clarify its role, if any.

The importance of air entrainment during the process of water application has also received no careful study. The final answers to such questions as these will be possible only after a very long period of careful study of idealized fire situations, since the geometry of fuel distribution will have a great influence on the answers and fuel distributions in urban situations are very varied.

◆

Dr. P. H. Thomas (*Fire Research Station*, *Boreham Wood*): Although thermal plumes and the entrainment of air into them are aften discussed in the context of fires in the open, particularly of large ones, it is worth noting their relevance to fires in buildings of all sizes.

A fire, in its early growth, behaves as in the open, and fire alarms are able to detect the hot and smoky gases in the plume. When the fire is well developed, the air flow may no longer be describable in terms of entrainment, if the windows are small in relation to the scale of the enclosure. For small openings, the flow can be calculated from the "stack effect" of a column of hot gas the height of the window. For a large opening the inflow velocities are an order of magnitude less than this and are similar to those calculated from entrainment. That is, with a large opening, the fire behaves more like an unconfined fire. In many practical situations one may be in an intermediate regime.

One might expect that the greatest error in neglecting pressure changes in a large open fire would be in estimating the inflow velocity at the base of the fire. This may not matter much in the study of the upper plume but it could be very important in the study of fire spread in a continuous bed of fuel on the ground.

Prof. H. W. Emmons: Thomas is correct in observing that plume studies to date apply strictly to regions well above the fire and that the crucial problem, from a fire point of view, is near and at the fire itself, where present theories are inapplicable.

This is especially true when the fire geometry is made complex by nearby structures or confining walls. The adequate study of fires in enclosures has hardly begun and is of such complexity that it will take many, many years to complete.

◆

Mr. D. I. Lawson (*Fire Research Station, Boreham Wood*): Emmons said that data was limited on the amount of water necessary to extinguish fires in relation to the rate of heat release. Some years ago a survey made at the Fire Research Station showed that, for large fires fought by public brigades, the amount of water required was some 200 times that which would be required if all the water had been vaporized by the heat of combustion of the fuel. For small fires, the efficiency of firefighting is considerably greater. When water is applied to laboratory fires which are well developed, the amount required for extinction is not very different from that which would fill the fire compartment with steam. This suggests that, for fully developed fires, smothering by the displacement of oxygen is likely to be an important mechanism of extinction.

◆

Dr. E. R. Tinney (*Washington State University*): With regard to whirl, there is an analogous situation that occurs in hydraulic engineering. Air-entraining vortices (like inverted "dust devils" or whirls) can frequently be seen in the forebay of a dam whenever a spillway gate is partly opened or where the penstock opening is near the water surface. The vortices can be reproduced in a laboratory flame and the size, sign, and coalescence of one or more small vortices can be readily observed. In general, the characteristics of these vortices can be controlled by changing the fixed boundaries in the neighborhood of the gate or intake. Only by careful attention to symmetry can the vortices be eliminated. Not all of these vortices are apparent. In fact, only those that entrain air are at first observable. However, by adding a dye to the water surface, the core of additional vortices are delineated and it is surprising to see how many small vortices develop and quickly decay. This phenomenon seems to be quite analogous to the whirls around and in the case of a fire plume.

Prof. H. W. Emmons: Vorticity observations made in hydraulic systems are immediately useful in trying to understand the corresponding phenomena in air. In water, the open penstock serves to remove water below and to concentrate any vorticity already in the water. Similarly, a fire, by its buoyant gas production, serves to remove air above, thereby concentrating the available vorticity. The reason that many more fire whirls are not observed is presumably that they are lost in the strong fire turbulence.

◆

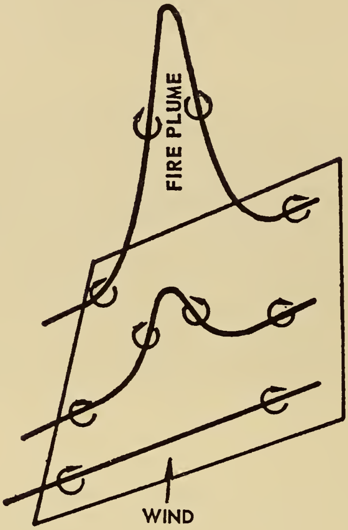
Dr. N. A. Chigier (*Israel Institute of Technology*): The experiment on fire, which was described by Emmons, is of particular interest in the general field of the effect of angular momentum on the behavior of a flame. Due to the centrifugal forces set up by the rotation of the screen, a radial pressure gradient is set up and, since the screen is at finite height, an axial pressure gradient will also be set up. The flow direction on the axis of the plume will, therefore, depend on the relative magnitude of the upward buoyancy forces and the opposing force due to the axial pressure gradient.

In experiments carried out at the International Flame Research Foundation at IJmuiden (Beer, J. M. and Chigier, N. A.: Swirling Jet Flames Issuing from an Annular Burner, 5me Joumee d'études sur les Flammes, Paris, Nov. 1963), the general effect of "swirl" on turbulent diffusion flames was found to lead to a shortening of the flame length and an increase in the angle of the flame. Emmons' experiments clearly show that the initial effect of rotating the screen leads to a marked increase in the length of the flame. From our experiments, I would expect that, as the angular momentum at the rotating screen is further increased, the axial pressure gradient would steadily increase until a point would be reached where air would be drawn downwards along the axis of the plume and consequently lead to a shortening of the flame length.

Prof. H. W. Emmons: The experimental fire whirl produced by a rotating screen does, of course, involve a balance between the "centrifugal pumping effect" of the rotating air and the buoyancy of the fire. For a given fuel source, say a small can of liquid fuel, the flame height increases very rapidly with small rotation rates. If the rotation is increased too much the flame shortens again in an interesting way. The fire whirl appears to "blow up" at the top, i.e., the whirl diameter somewhere near the top of the whirl increases by two or three times. This is a hydraulic jump, traveling down the surface of the upward-moving buoyant column. Some rough measurements have shown this explanation to be plausible, since the vertical velocity of the jump relative to the plume fluid was about equal to the rotational velocity at the plume surface, as it should be.

Dr. B. R. Morton (*Manchester University*): Fire whirls (like tornadoes, dust devils, and bath-plug vortices) obviously draw their vorticity from the surrounding air though there remains some doubt as to the precise orgins of vorticity of suitable strength and orientation in the atmosphere. Emmons has identified wind shear as a main source and has mentioned the boundary layer above the ground. This vorticity is swept into the fire, so that loops from the horizontal vortex tubes are carried up in the fire plume, as indicated in the sketch. Thus, the fire plume in a cross wind has the mean structure of a vortex pair, but cannot develop into a single whirl (with net vorticity, or angular momentum about the fire-plume axis); however, small transient whirls may be "calved off" from one side or the other of the inclined fire plume with appropriate sense of rotation.

The growth of fire whirls will normally depend on the presence in the atmosphere of vorticity with a vertical component. This may be found in the atmosphere near fronts, and in regions which have been subjected to sustained strong thermal convection.



A related effect has been described recently by Lakshminarayana and Horlock (I.U.T.A.M. Symposium on Concentrated Vortex Motion, Ann Arbor, 1964). They have sucked air over a horizontal plane into the downwards-facing end of a vacuum-cleaner tube, at inclination to the vertical. Under very quiet experimental conditions, a vortex pair was generated in the inflow to the tube, but a low level of vertically oriented disturbance vorticity (e.g., produced by movement of an onlooker) soon caused the replacement of the vortex pair by a single, more vigorous vortex.

Prof. H. W. Emmons: As a matter of geometry, the time-average vertical vorticity at any point is equal to the vertical component of the earth's rotation vector. This is too small for any fire consideration except, possibly, the very largest ones. Except for the earth's rotation, any vertical vorticity of one sign is necessarily compensated somewhere by vertical vorticity of the opposite sign. As Morton indicated, the lifting of a wind boundary layer by a fire generally leaves the positive and negative vorticity so close together that they cancel by turbulent mixing. If a fire is large, the positive and negative parts may be sufficiently separated so that one of these parts may concentrate and produce a dust devil or a fire whirl. The more probable and more potent cause will be wind shear, produced by causes other than the fire, which means, of course, that the positive and negative components have been separated prior to the occurrence of the fire.

Dr. J. H. Wiegand (*Aerojet-General Corp.*): A practical consequence of theoretical analysis would appear to be the lower bound, below which the fire is controllable. This involves aerodynamic considerations, as Thomas points out. In California, the substantial burning evident on the lower sections of redwood trees which continue to live indicate fire levels below which trees will survive. The analysis of allowable underbrush levels of fuel for each type of tree, which allows the tree to survive, is desirable. The use of controlled burnoff in forest management should provide excellent experimental situations for instrumentation and analysis of fire-spread rate, temperatures, etc.

A further practical aspect is the allowable level of fuel in the sense of furniture, curtains, etc., which a householder can tolerate without expecting complete destruction in the event of an ignition.

◆

Mr. J. Grumer (*U.S. Bureau of Mines*): One question about fire whirls is whether, in such air flows, the specific burning rate (per cent of mass burned/time) of a totally ignited fuel bed is greater than the maximum specific burning rate attained with the fuel burning is still air. Laboratory experiments with fire whirls have generally been done with small pools of liquid fuel; observed burning rates with whirling air are about threefold to fourfold those in still air. To my knowledge, it has not been proven that burning rates of pools in swirling air exceed those of "infinitely" large pools in still air. Burgess et al. [Burgess, D. S., Strasser, A., and Grumer, J.: Fire Research Abstracts and Reviews *3*, 177 (1961)] reported that burning rates of small pools in unidirected wind are equal to the rates for large pools in still air. Is such also the case for any size pool burning in swirling winds?

Prof. H. W. Emmons: The question raised by Grumer is a very difficult one to answer in the form asked, because of the uncertain significance of "an infinitely large pool". In still air, a large pool would burn in a series of fire plumes distributed over the surface in a manner related to the instability of the hot gases produced and as controlled by the Rayleigh Number (among others) for these gases. Furthermore, pool burning in a wind (and to a lesser degree without a wind) is sensitive to the exact nature of the rim of the confining walls. Even the fire whirl without a general wind has a horizontal stability and a burning rate, both of which are sensitive to the detailed pool geometry. There is no work known to the author, including our own, which can answer this interesting and important question, even for some specific, simple geometry, let alone attempting to answer it in the general form as asked.

ABSTRACTS

I. Ignition Phenomena

Cullis, C. F., Fish, A., and Gibson, J. F. (Imperial College, London, England) "The Oxidation of Hydrocarbons: Studies of Spontaneous Ignition. I. Ignition Limits in Small Vessels," *Proceedings of the Royal Society* (*London*) **A284,** 108–124 (1965)

This is a study of the spontaneous ignition of *n*-heptane + oxygen + inert gas mixtures at subatomospheric pressures and at temperatures from 440° to 650°C, a region where ignition takes place by a one-stage mechanism and no cool flames are observed. This investigation was carried out mainly under static conditions in a series of reaction vessels varying in shape, surface-to-volume ratio S/V, and material of construction.

The dependence of the pressure of fuel and oxygen in the limiting ignition mixture P_T on temperature T was found to be represented approximately by the expression

$$P_T = \text{const} \times \exp\{+E/RT\}, \tag{1}$$

where $E = 15.3$ kcal mole^{-1}. The reactant mixture composition X (expressing the mole fraction of fuel in *n*-heptane + oxygen mixtures) was held at five different values from 0.15 to 0.30 and the molar ratio of nitrogen to oxygen Y_{N_2} was fixed at 4.0. A spherical Pyrex vessel was used having a volume of 250 cm^3.

The dependence of P_T on the reactant mixture composition was represented by

$$P_T = AX^{-m} + B(1 - X)^{-n}, \tag{2}$$

where A, B, m, and n are positive constants. Observations were made at four different temperature levels between 436° and 539°C. Y_{N_2} was fixed at 4.0. A spherical Pyrex vessel of 250 cm^3 volume was employed. X was varied from 0.1 to 0.4. A shallow minimum in the plots occurs between $X = 0.2$ and 0.3.

The addition of nitrogen or helium promoted ignition. The influence of the addition of nitrogen is given by the following:

$$P_T^{-3} = c_1 Y_{N_2} + c_2, \tag{3}$$

where c_1 and c_2 are positive constants. Y_{N_2} was varied from 2.5 to 6.5. X and the temperature were fixed at 0.25° and 505°C, respectively. A cylindrical silica vessel was used; volume, 320 cm^3 and $S/V = 0.81$.

Pressure/composition ignition profiles were obtained with the use of a series of different vessel geometries and materials. The temperature was fixed at 505°C; $X = 0.25$ and $Y_{N_2} = 4.0$. For eight Pyrex and silica vessels, P_T varied linearly with S/V, over the range $S/V = 0.61$ to 1.17 cm^{-1}. However, this linear relationship does not correlate the data obtained with cylindrical vessels packed with Pyrex tubing ($S/V = 3.41$ and 4.35 cm^{-1}). However, it was shown that the data for both packed and unpacked vitreous vessels could be represented by

$$P_T = \text{const} \times (1/r^*)^{1.3}, \tag{4}$$

where r^* is the average distance of a molecule from the surface. Ignition was not attained in a densely packed vessel ($S/V = 11$ cm^3).

The pressure/composition profiles obtained with metal vessels were located at higher values of P_T in comparison with that for a similar Pyrex vessel. A rough copper vessel yielded a profile at the highest values of P_T. This was followed at progressively lower levels of P_T by polished copper, by brass, and finally by steel and aluminum.

An attempt was made to find what mechanism might control the phenomena observed. Three models were considered for ignition; the isothermal olefin, the isothermal aldehyde, and the thermal. The isothermal olefin model, in which hydrogen peroxide is the degenerate chain-branching agent, was shown to predict the following variations of P_T with T, X, r^*, and the molar ratio of inert gas to oxygen Y:

1. When X, Y, and r^* are constant,

$$P_T{}^3 = \text{const} \times \exp\{(E_5 + E_{10} - E_{11})/RT\}, \tag{5}$$

where E_5, E_{10}, and E_{11} apply, respectively, to the following reactions:

$$C_7H_{16} + HO_2\cdot = C_7H_5\cdot + H_2O_2 \qquad \text{(propagation)}$$

$$H_2O_2 + M = 2\,OH\cdot + M \qquad \text{(branching)}$$

and

$$H_2O_2 \overset{\text{walls}}{=} \text{inactive products} \qquad \text{(termination)}$$

2. When Y, T, and r^* are constant,

$$P_T = X^{-2/3}\,[a_1X + a_2\,(1 - X)]^{-1/3}, \tag{6}$$

where a_1 and a_2 are constants,

3. When X, T, and r^* are constant,

$$P_T{}^{-3} = b_1Y + b_2, \tag{7}$$

where b_1 and b_2 are constants,

4. When X, Y, and T are constant,

$$P_T = \text{const} \times (1/r^*)^{1.0}, \tag{8}$$

A comparison of theoretical [Eqs. (5)–(8)] with the experimental relations [Eqs. (1)–(4)] shows generally remarkable agreement. The theoretical relations produced from a similar analysis based on the aldehyde model and the simple thermal model do not give this support.

Important information may be obtained from the data, if it is assumed that the olefin model is valid. For example, with the use of accepted values for E_{10} and E_{11} (for vitreous walls), the reasonable value of 6 kcal mole^{-1} is determined for E_5. From an knowledge of b_1 and b_2, it was deduced that on a molar basis the efficiency of nitrogen as a second body in the branching reaction is greater than that of oxygen, and that of helium is less. Comparison of the relative values of E_{11} assessed for the different materials used shows that the efficiency of chain termination at the wall is highest for copper and less (in descending order) for brass, aluminum, mild steel, stainless steel, and Pyrex. Finally, the utility of r^* in the correlation of data for both packed and unpacked vessels is indicated.

Subject Headings: *Ignition, spontaneous, of heptane; Heptane, ignition of; Hydrocarbons, ignition of; Spontaneous ignition, of heptane.*

G. A. Agoston

Nagy, J., Dorsett, H. G., Jr., and Jacobson, M. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Preventing Ignition of Dust Dispersions by Inerting," *Bureau of Mines Report of Investigations* 6543 (1964)

This report summarizes the conditions under which dust dispersions may be rendered less combustible by inerting. Inerting is defined as reducing the atmospheric oxygen concentration, admixing an inert powder, or adding moisture to the combustible dusts.

The apparatus used by the Dust Explosions Research Section to study the explosibility of dusts is described elsewhere.[1] Briefly, fine dusts (through a No. 200 mesh sieve) are dispersed in a partially closed chamber in which the concentration of oxygen in the atmosphere, the concentration of admixed dry powder, or the concentration of moisture in the dust is controlled. The dusts are ignited with an induction spark, capacitor discharge, heated coil, or heated surface (Godbert–Greenwall furnace).

The inerting conditions under which the dusts could just be ignited, or under which propagating flames were arrested, were measured for 367 samples of dusts from cornstarch, coal, paper, other plant products, metals, plastics, and inorganic and organic chemicals. The factors affecting the inerting requirements were found to be: dust concentration, type of combustible, spark (ignition source) energy, ignition temperature, particle size of dusts and inert dry additives, and composition of the substances used for inerting.

The experiments were designed to study two variables at a time, with the others held constant. This method of testing did not develop possible interrelations between the variables. The results of experiments over a 25-year period are presented quantitatively in 17 charts and 6 tables. They may be summarized qualitatively as follows:

Effect of ignition source strength. The igniters were an induction spark, 25 W; a heated coil, 250 W; and a furnace at 1560°F, 2000 W. The inerting requirements increased with increasing source strength; that is to say, less oxygen and more admixed inert powder and/or water were required to prevent ignition, as the igniter power increased.

Oxygen reduction. As the oxygen concentration in the atmosphere was decreased by diluting with carbon dioxide or other inert gas, the dust concentration, spark energy, and/or ignition temperature had to be increased for ignition to take place. Dichlorodifluoromethane was the best atmospheric diluent for carbonaceous dusts; argon and helium for metallic dusts: and carbon dioxide for three metallic hydrides.

Admixed inert powder. Dilution of dusts with inert (noncombustible) additives such as calcined Fuller's earth raised the dust concentration, spark energy, and ignition temperature required to effect ignition. Sodium carbonate was the most effective of 13 dry additives tested. As the fineness of the inert additives was increased, less inerting was required to prevent ignition.

Admixed moisture. The dust concentration, spark energy, and ignition temperature required for ignition increased as the moisture added to the dust was increased.

Relative effectiveness of inerting methods. Linear relationships were found between the oxygen concentration and quantity of admixed inert powder; oxygen reduction versus quantity of admixed water; and admixed water versus dry powder, in the inhibition of dust (cornstarch) explosions.

Effect of dust concentration on spark energy and ignition temperature. As the dust concentration was increased slightly above the minimum value required for ignition with an induction spark, the spark energy and temperature for ignition dropped rapidly from their initial, high, no-ignition values to much lower values; the ignition energy remained constant at this low value, with increasing dust concentration, but the ignition temperature continued to drop slowly, approaching a limiting minimum value.

Fineness of combustible dust. As the dust particle size decreased, ignition could be effected at higher concentrations of dry inert powder and admixed moisture, and for lower oxygen concentrations in the atmosphere.

Industrial applications. After studying 367 carbonaceous and metal dusts, it was concluded that dust-explosion hazards could be minimized by using a controlled oxygen atmosphere containing no more than 5% oxygen. Water had the same relative effect on the ignition parameters as oxygen reduction and admixed dry powder, but it had to be mixed intimately with the dusts.

Reference

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Subject Headings: ***Dust, ignition prevention in; Ignition, prevention by inerting; Inerting, to prevent dust ignition.***

B. Greifer

Peloubet, J. A. (Dow Metal Products Company, Midland, Michigan) "Machining Magnesium—A Study of Ignition Factors," *Fire Technology* **1**, 5–14 (1965)

Although coolants are sometimes used to prevent fires in machining magnesium, dry machining is often desirable for reclamation purposes. Tests were carried out to evaluate the conditions under which chip ignition may occur, and in what circumstances the first hazard may be reduced.

Ignition is divided into two types—one appearing as short-duration sparks generated at the top of the tool bit, rarely causing fires; the other type may easily start a fire in a pile of chips, and is a "flare", or a burning chip. A standard lathe-testing procedure was set up, using a grooving tool with an oversize lathe, cutting standard-sized grooves in 6-in.-diam billets. Two alloys were used, containing small amounts of aluminum and zinc. The alloy containing the larger amount of aluminum was more likely to cause flares.

Flare production was a statistical phenomenon, and correlations were found between the probability of flares as a function of surface-speed and tool-feed rates. At feed rates from very low values up to 0.010 in./revolution, the probability of flash production was very high for surface speeds from 300 to 1400 ft/min. For surface speeds less than or greater than these values, the probability of flashes was small or zero. For feed rates in excess of 0.010 in./revolution, no flashes occurred at all feed rates, although such feed rates are considered by machinists to be too large for most machining. Under fine machining conditions, therefore, the surface-feed rate must be raised or lowered to get out of the critical region. The author could find no explanation for this critical region; it must be the result of the minimum thickness of a chip which can ignite as a result of heat generated by this friction of the tool on the material.

Increasing the relative humidity from 45% to 65% also increased the extent of the critical zone for flashing, but changing the value of the absolute humidity alone had no such effect. No explanation could be found for this effect either, except that it might result from unevaporated water droplets produced by the mechanical humidifier.

Other anomalous and unexplained effects were that a dull tool was less likely to produce flares than a sharp tool, and that carbide tools were less likely to produce flares than high-speed steel tools. With billets where the magneisum-aluminum compound is finely divided and in large quantity, flares are more likely to occur than when these pockets are coarse and sparsely distributed. Further work will be necessary to provide a better understanding of these phenomena.

Subject Headings: ***Ignition, by machining; Machining, ignition by; Magnesium, ignition of.***

J. K. Richmond

Rhein, R. A. (California Institute of Technology, Pasadena, California) "Preliminary Experiments on Ignition in Carbon Dioxide," *Combustion and Flame* **8**, 346–348 (1964) (Letter to the Editor.)

Carbon dioxide is ordinarily considered a fire-extinguishing agent. However, a number of metals, in powder form, have been found to ignite and burn in a carbon dioxide atmosphere. A crucible of powdered metal, with a thermocouple inserted in the metal, was placed in a tube with carbon dioxide passing over it. The tube was heated and ignition observed as a discontinuous temperature rise. Results are shown in the table and should be useful in planning safe procedures for handling powdered metals.

Metal	Particle size	Ignition temp. (°C)	Metal	Particle size	Ignition temp. (°C)
Lithium	$\leq 100\ \mu$	330[1]	Mischmetal	325 mesh	160
Beryllium	$\leq 0.1\ \mu$	25[2]	Titanium	1–5 μ	670
Calcium	325 mesh	293	Zirconium	3 μ	363[1]
Magnesium	325 mesh	749	Thorium	325 mesh	730
Boron	0.03 μ	—[3]	Uranium	200 mesh	235
Aluminum	0.03 μ	360, 420[4]	Maganese	325 mesh	696[5]
Cerium	325 mesh	172, 190[4]	Chromium	325 mesh	870[5]

[1] Vigorous. [2] Spontaneous. [3] No ignition at 960° C. [4] Two experiments. [5] Slow.

Subject Headings: ***Carbon dioxide, ignition in; Ignition, in carbon dioxide; Metal powders, ignition in carbon dioxide; Powders, ignition in carbon dioxide.***

W. E. Wilson, Jr.

Singer, J. M. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Ignition of Coal Dust–Methane–Air Mixtures by Hot-Turbulent-Gas Jets," *U. S. Bureau of Mines Report of Investigations 6369* (1963).

The paper under review both parallels and supplements a previous paper[1] by the same author on ignition of dust/methane combinations by laminar jets of hot nitrogen. In the present work, the jets were turbulent having been generated by sparkling mixtures of CH_2–O_2–N_2. Readers interested in the present paper are also referred to the previous one[1] as likely to be of value to them.

The purpose of the work was both practical and fundamental. The practical objectives included determination of the critical dimensions of a fine tube or channel that would prevent transmission of a gas-explosion flame into a dust/methane mixture: this information is required for the design of explosion-proof electrical equipment and flame traps. To investigate the flame-transmission characteristics of the channels being tested, these were screwed into the end of a 76 cm^3 capacity inner-explosion chamber containing the mixture to be sparked, and flame traversing the channel under test then jetted into an outer chamber of roughly 2 liters capacity containing a "hybrid" flammable mixture of methane and coal dust dispersed in air. The firing mixture in the inner chamber was a stoichiometric ratio of methane and oxygen, but diluted with varying quantities of nitrogen to temper its force. This force was measured by the ratio $[O_2/(O_2 + N_2)]$, which was called the "oxygen index" of the mixture.

In the tests, channels of dimensions ranging from 0.43 to 50 mm in length, and 0.6 to 5.0 mm diam were examined, the result of each test being reported as either ignition or nonignition of the hybrid mixture. Then, by appropriately increasing or decreasing the methane content of the hybrid mixture (at constant coal concentration) the ignition limit or point could be determined. Many such points were determined by appropriate variation of the following parameters: channel length, channel diameter, coal concentration, coal particle size, and oxygen index. All the data obtained are presented graphically in the paper on plots of oxygen index against methane percentage of the hybrid mixture, for constant channel length, channel diameter, coal concentration, and particle size. In all, eight such plots were constructed, and in general it can be said that they have something of a "U" shape with a tendency to a flat base (roughly constant oxygen index) between 4% and 10% methane. Outside those limits, the oxygen index was found to increase, implying that the flame required to ignite the mixture had to increase intemperature as the upper and lower limits were approached. With variation of channel length and diameter, the curves were displaced with some variation in absolute shape. In general, the oxygen index dropped with increase of diameter, which is to be expected. Channel length, however, showed an optimum: long channels quite reasonably required a higher oxygen index (flame temperature) than did medium length ones but short channels again required an increase in the oxygen index because the issuing jet spread out much faster and, dissipating its energy faster, was less effective Further changes due to channel geometry are too detailed to be described here; the reader is referred to the paper.

So far as fundamental information is concerned, the most important would seem to be that relating to: (1) the behavior of the igniting jet on the process of ignition; (2) the influence of inhibitors; and (3) the variation of the coal and methane concentrations. Briefly, (1) the issuing jet was found to generate a vortex and recirculatory motion in the hybrid mixture, with coal-dust particles noted in the hot boundary region and thought to be an important part of the ignition mechanism. This would suggest that, in this system, the mechanism of heating the particles to ignition is by conduction–convection, not radiation. (2) The influence of inhibitors was found to be rather small. In the previous experiments on laminar jets, the inhibitor (bromotrifluoromethane) was found to be very effective, needing less than 1% to suppress the ignition of the hybrid mixtures; with the turbulent jets, the inhibitor had to be increased to nearly 9%. (3) As the coal-dust concentration was increased, and the methane concentration decreased, it was found that the joint effects of concentration and particle size were complex, involved, and difficult to determine; however, it appeared that the oxygen indexes required at any point (particularly at the flammability limits) were increased when coal was added. This was attributed to the heat-sink effect of the dust.

The reviewer regrets that the author did not also plot the limit data of coal dust concentration against methane percentage (at constant jet temperature) as he did in the previous paper.[1] This would have provided a further comparison with the author's previous data, together with those found by the reviewer[2] and by Ishihama.[3] This last paper is, in the reviewers opinion, the most complete and detailed regarding the influence of concentration, particle size, and coal rank, in mixtures with and without methane added. This paper can be strongly recommended to readers as a paper to read in parallel with one reviewed above. It should be particularly helpful in elucidating the particle-size effect.

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Subject Headings: ***Coal dust, ignition of; Gas jets, ignition by; Ignition, of coal dust-methane mixtures; Jets, hot, ignition by; Methane, ignition of; Turbulent gas jets, ignition by.***

R. H. Essenhigh

II. Thermal Decomposition

Browne, F. L. and Brenden, J. J. (Forest Products Laboratory, U. S. Forest Service, Madison, Wisconsin) "Heat of Combustion of the Volatile Pyrolysis Products of Fire-Retardant-Treated Ponderosa Pine," *U. S. Forest Service Research Paper FPL 19* (December 1964)

This is a report of an experimental investigation of the effect of fire-retardant treatments on the rate of heat release from wood during fire exposure.

It was found that, in the case of both treated and untreated wood, the heat of combustion of the volatile products is initially low, and then increases rapidly as devolatilization progresses. In the early stages of pyrolysis, where the heat of combustion of the volatile products is thought to be most significant with regard to ignition and spread of fire, the heat of combustion of the volatile products from treated wood was found to be lower than that of volatiles produced from untreated wood. In the case of both treated and untreated wood, the relationship between the heat of combustion of the volatile products and the degree of devolatilization appeared to be independent of the temperature at which the pyrolosis was conducted.

These results were obtained by pyrolyzing both treated and untreated ponderosa pine samples to different degrees of devolatilization under controlled time and temperature conditions, and then determining the weight and the heat of combustion of the char residue. The degree of devolatilization was calculated from the weight loss, and the average heat of combustion of the volatile products was taken as the difference between the heat of combustion of the original wood and that of the pyrolyzed residue.

The specimens employed were cylinders, 0.25 in. in diameter and approximately 1 in. long. The impregnation of the specimens with the chemicals was accomplished in a desiccator by a pressure-vacuum technique, the details of which are presented. Three different inorganic salts and a resinous polymeric material were used as retardants. Pyrolysis was accomplished in a thermogravimetric balance which permitted heating of the specimens in an atmosphere of nitrogen to any temperature between 240° and 822°C for almost any period of time to achieve a desired degree of devolatilization. A standard bomb calorimeter was used in the heat-of-combustion measurements.

Evidence found in preliminary and exploratory tests indicated that the geometry of the test specimen may have an effect on the results obtained. Furthermore, for a given geometry, the results were found to be dependent on the size of the test specimen: the heat of combustion of the volatile products decreased as the diameter of the cylindrical specimen increased. Assuming a temperature gradient to exist in the pyrolyzing specimens, these findings may be in agreement with one of the authors' main observations, namely, that the heat of combustion of the volatiles increases as the degree of devolatilization increases. The temperature gradient, the nature of which would depend on size and geometry, would establish a space variation in the degree of devolatilization within a specimen. Therefore, the average heat of combustion of the volatiles might be expected to vary with the size and geometry of the test specimen.

The data obtained are presented in six tables, and are illustrated differently in two figures. Also, an appendix is included, in which relevant data from the literature are tabulated and discussed.

Subject Headings: ***Fire retardants, pyrolysis products from; Heat of combustion, pyrolysis products; Pine, Ponderosa, fire retardants on.***

J. B. Howard

Roberts, A. F. (Safety in Mines Research Establishment, Buxton, England) "Calorific Values of Partially Decomposed Wood Samples," *Combustion and Flame* **8,** 245–246 (1964) (Letter to the Editor)

Sometimes when wood burns, in mine roadways with forced ventilation for example, combustion of the volatile matter occurs at some distance from the surface combustion of the carbonaceous residue. Therefore, it is important to know the calorific value of the volatile fraction and of the charcoal fraction separately.

A sample of wood dust from European beech was pyrolyzed under reduced pressure at each of seven temperatures from 255° to 380°C, until the samples retained from 89.5% to 25.8% of their weight before heating. They were cooled under nitrogen. Calorific values were then determined in a bomb calorimeter by the method of British Standard 1016.

If c_0, c_v, and c are, respectively, the calorific value of unheated wood, of evolved volatile matter, and of sample retaining $100y\%$ of the weight before heating, then

$$yc + (1 - y)c_v = c_0, \tag{1}$$

because the heat of reaction of pyrolysis is known to be small as compared with the calorific value. For $100y$ equal to 100.0, 89.5, 80.0, 72.4, 56.4, 48.6, and 25.8, c was 4.63, 4.73, 4.87, 4.96, 5.21, 5.47, and 6.56 kcal/g, respectively.

Rewriting Eq. (1) as

$$yc = yc_v + (c_0 - c_v), \tag{2}$$

indicates that yc is a linear function of y for which the data yield the regression line of yc on y as

$$yc = 3.96y + 0.70. \tag{3}$$

The probability that the correlation of data was due to chance was found to be less than 0.1%. Thus, the calorific value of the evolved matter was sensibly constant throughout the decomposition process.

From Eq. (3) and the assumption that the ultimate yield of charcoal lies between 16% and 20%, the calorific value of charcoal lies between 7.45 and 8.33 kcal/g. Thus, combustion of the charcoal accounts for 29% to 30% of the heat of combustion of undecomposed wood.

[Abstracter's comment: The result seems surprising since the earliest volatile products of pyrolyzing wood are largely incombustible, water and carbon dioxide, and the later products become richer in the more highly calorific components.]

Subject Headings: ***Calorimetry, of pyrolyzed wood; Pyrolysis, of wood; Thermal decomposition, of wood; Wood, thermal decompsition of.***

F. E. Browne

III. Heat and Material Transfer

Sparrow, E. M. and Lin, S. H. (University of Minnesota, Minneapolis, Minnesota) "Boundary Layers with Prescribed Heat Flux-Application to Simultaneous Convection and Radiation," *International Journal of Heat and Mass Transfer* **8,** 437–448 (1965)

This theoretical paper describes the determination of the distribution of surface temperature for both laminar and turbulent boundary-layer flows along a flat plate experiencing simultaneous convective and radiative heat transfer, aerodynamic heating, and internal heat sources and sinks.

The analysis begins with a consideration of the boundary-layer-energy equation for constant-property, nondissipative flow. Exact numerical solutions are tabulated for the laminar case having a prescribed power-law heat-flux distribution. Extension of these results to the case of a prescribed series heat-flux distribution is indicated.

To accommodate completely arbitrary heat-flux distributions an approximate solution had to be obtained. The solution was produced by superposing step-function solutions furnished by the integral energy equation. This solution is believed to be rather accurate because, when it was tested, excellent results were obtained upon introducing the power-law heat-flux distribution.

In the turbulent case, a surface-temperature distribution corresponding to a step-change in heat flux was obtained by the use of semi-empirical methods. Then, as in the laminar case, a generalized solution for arbitrary heat-flux distributions was constructed for constant-property, nondissipative flow.

The above procedure was repeated incorporating radiative heat transfer, aerodynamic heating, and heat sources and sinks. Aerodynamic heating was simply introduced by the use of the adiabatic wall-temperature concept. The radiation flux to the surface combined with an energy flux to or from the surface (arising from internal heat sources and sinks) is designated the total heat load e, which for simplicity is assumed to be constant. The emitted radiation flux is given by $\epsilon\sigma T_{aw}^4$, where T_{aw} is the adiabatic wall temperature, ϵ the surface emittance, and σ the Stefan–Boltzmann constant. The nonlinear integral equation obtained is treated by a special computation procedure to yield highly accurate numerical solutions.

Results for the surface temperature distribution have been computed both for laminar and turbulent flow. In both cases, graphs are presented showing the ordinate variable as the ratio of the local surface temperature T_w at position x to the adiabatic wall temperature due to convection alone T_{aw} and the abscissa as the ratio of the radiation coefficient to the convective coefficient for uniform heat flux. The abscissa for the laminar case is proportional to $x^{1/2}$, and that for the turbulent case is proportional to $x^{1/5}$. Curves are given each representing a different value of $e/\epsilon\sigma T_{aw}^4$. When the parameter $e/\epsilon\sigma T_{aw}^4$ exceeds unity, T_w/T_{aw} increases with x; the opposite variation occurs when the parameter is less than unity. When $e = \epsilon\sigma T_{aw}^4$, then $T_w = T_{aw}$ at all locations.

Auxiliary approximate calculations were made, based on the local application of heat-transfer coefficients for uniform wall temperature and for uniform heat flux. Curves of the two sets of results closely bracketted the exact solution in the laminar case. In the turbulent case, the approximate calculations yielded points which were in excellent agreement with the curves representing the solution of the integral equation.

In conclusion, it is pointed out that the use of the prescribed heat-flux formulation involves less complicated functions than those which arise with the use of prescribed wall-temperature formulation.

Subject Headings: ***Boundary layer, with radiation and convection; Convection-radiation interactions in flow; Flow, convection-radiation interactions; Radiation-convection interactions.***

G. A. Agoston

V. Combustion Principles

Anderson, H. E. (Intermountain Forest and Range Experiment Station, U. S. Forest Service, Ogden, Utah) "Mechanisms of Fire Spread Research," *Progress Report No. 1, U. S. Forest Service Research Paper INT–8* (1964)

Experimental fires burned in a combustion laboratory showed that rate of spread decreases linearly as moisture content increases. Irradiance forward of the fire decreases as moisture content increases. Flame depth and residence time appear not to vary linearly but reach a maximum when fuels have about 10% moisture content. Fuels having different physical characteristics, but similar loading factors, yield similar rates of spread but considerably different combustion rates. General temperature profiles through the flaming area and vertically above the fuel bed have been obtained. Steady-state burning conditions are obtainable as indicated by rate of spread, irradiance, and vertical temperatures.

Subject Headings: ***Fire spread, mechanisms; Mechanisms, of fire spread.***

Author's Abstract

Dixon-Lewis, G. and Williams, A. (Houldsworth School of Applied Science, The University, Leeds, England) "The Rate of Heat Release in Some Slow Burning Hydrogen–Oxygen Flames," *Combustion and Flame* 8, 249–255 (1964)

Extending earlier work,[1] the authors present new and old temperature profiles, inferred heat-release-rate profiles, and burning velocities for four slowly-burning very fuel-rich $H_2/O_2/N_2$ flames at atmospheric pressure. Theoretical burning velocities are calculated from the heat-release-rate profiles according to the treatments by Spalding,[2] Zel'dovich and Frank-Kamenetskii,[3] Semenov,[4] Lovachev,[5] and Dixon-Lewis and Williams.[6] Results are shown in Table I.

TABLE I

Data Summary

Flame	1	2	3	4
Per cent H_2	18.8	18.8	18.8	28.6
Per cent O_2	4.35	4.60	4.83	4.60
T_u, °K	351	336	335	350
T_b, °K	1042	1078	1125	1064
Maximum heat-release rate, cal cm^{-3} sec^{-1}	11.0	21.0	35.4	18.1
$\phi(T_m)$, cal cm^{-3} sec^{-1}	4.2	6.4	12.5	7.5
Experimental S_u (cm sec^{-1} at 18°C)*	7.4	9.2	12.1	11.3
Calculated S_u:				
Spalding	7.8	9.0	11.7	11.1
Zel'dovich *et al.*	5.0	6.3	7.7	7.0
Lovachev	7.5	9.2	12.2	10.9
Authors	6.8	8.2	11.5	9.7

* S_u = burning velocity.

The principal contribution of this paper appears to be gathering under one roof several approximate treatments for the theoretical prediction of burning velocities, together with an abbreviated discussion of the relative merits of each theoretical approach.

Spalding's centroid formula is said to normally make possible the prediction of burning velocities to within 1% or 2% from a knowledge only of the area and centroid position of the heat-release-rate curve. The complete heat-release-rate profile is, however, required to evaluate these latter parameters. The treatment by Zel'dovich and Frank-Kamenetskii, and by Semenov assumes that the reaction controlling the flame has a high activation energy, and occurs exclusively at or near the final flame temperature. It is not a very good approximation for the present experiments, in which it was found that the maximum rate occurs at about 75% of the total temperature rise. For flames having rate-controlling steps with lower activation energies, an alternative approach has been suggested by Lovachev, who approximates the true heat-release rate by

$$\phi(T)/\phi(T_m) = (T - T_u)/T_m,$$

where $\phi(T)$ is the heat-release rate at temperature T, T_m is the arithmetic mean flame temperature [i.e., $T_m = \frac{1}{2}(T_u + T_b)$], and T_u and T_b are the unburned- and burned-gas temperatures, respectively. The more successful final form of Lovachev's expressions for the mass burning velocity M is

$$M = \frac{2}{\bar{C}_p} \{\lambda_u \phi(T_m)/(T_m - T_u)\}^{1/2},$$

where $\bar{C}_p$ is the mean specific heat and λ_u the thermal conductivity of the unburned gases. To calculate M with this expression, only knowledge of the heat-release rate at T_m is required. Conversely, if M is known, the mean heat-release rate may be calculated. In the more successful final form of the Dixon-Lewis and Williams expressions, the 2 in the above relation is replaced by $\sqrt{2}$, and λ_u is replaced by λ_m.

As evident in Table I, substantial agreement exists between calculated and measured burning velocities, over the limited range of these experiments. Lovachev's theoretical expression is perhaps the best, as well as the simplest to apply, although the authors do well to draw no conclusions from these limited data.

Not as well advised, however, is the discussion of the kinetics of the H_2/O_2 flame, which concludes this paper. In contradistinction to their earlier work, in the present contribution the authors have included no local composition determinations. Their discussion of kinetics—while it may well be correct—is thus not substantiated by the results reported in this paper. Since, in addition the discussion of kinetics—which revolves around the HO_2 radical—adds no new material to the presently controversial questions relating to the importance or unimportance of HO_2 radicals in flame heat-release mechanisms, the prominence given to this discussion by the authors is questionable.

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Subject Headings: *Burning velocity; Flame, theory of; Heat release, rate of; HO_2 radical; Flame, hydrogen-oxygen; Flame, temperature profiles of.*

S. C. Kurzius

Hardacre, A., Skirrow, G., and Tipper, C. F. H. (Donnan Laboratories, Liverpool, England) "Hydrogen Bromide Promoted Oxidation in the Gas Phase," *Combustion and Flame* 9, 53–61 (1965)

Hydrogen bromide is a promotor of the slow oxidation of hydrocarbons, causing a considerable decrease in the temperature required for appreciable oxidation.

This is suspected to be due to the reaction of hydrogen bromide with intermediate peroxidic compounds to give enhanced chain branching. It is possible that the chemistry and kinetics of such reactions may have some bearing on the action of halogen compounds in preventing ignition.

In this study, the oxidation of propionaldehyde, methane, methyl formate, and *di-t*-butylperoxide catalyzed by hydrogen bromide were studied in a static system. With propionaldehyde at 123°C, the maximum rate of pressure change was proportional to $[C_2H_5CHO]$ $[HBr]$. The main identified products were perpropionic acid and its aldehyde addition compounds. The reaction had an over-all activation energy of $\approx$13 kcal/mole. A reaction scheme was proposed involving bromide atoms and propionyl and peroxypropionyl radicals as chain carriers, with branching occurring heterogeneously via peracid molecules. Various termination reactions were considered.

The other compounds, all sources of methyl radicals, required higher temperatures: methane, 385°C; *di-t*-butylperoxide, 180°C; methyl formate, 335°C. All consumed hydrogen bromide, and although reaction schemes were suggested, the results were too complex, for detailed analysis.

Subject Headings: ***Hydrogen bromide, promotion of oxidation; Hydrocarbons, oxidation, promoted by hydrogen bromide; Oxidation, promotion by hydrogen bromide.***

W. E. Wilson, Jr.

Homann, K. H. and Wagner, H. Gg. (University of Göttingen, Göttingen, West Germany) "Reactions in Rich Hydrocarbon–Oxygen Flames. II. Soot Formation in Acetylene Oxygen Flames at Low Pressure," *Berichte der Bunsen Gesellschaft für Physikalische Chemie* 69, 20–35 (1965) (In German).

Much of the work dealt with in this paper, which is one of two (the other appears on p. 35 of the same journal) concerned with measurements in rich, low-pressure hydrocarbon–oxygen flames, has been reported elsewhere (in English).[1] It describes measurements made on flat acetylene oxygen flames of mixture ratios (C_2H_2/O_2) between 0.75 and 1.6 at pressures from 10 to 60 mm Hg. Most of the results are at a pressure of 20 mm Hg.

The quartz-probe sampling system led directly to a time-of-flight mass spectrometer. The concentration of radicals and molecules could be measured up to Mass Number 800. Wall effects were minimized by using a large diameter probe and by sampling only the center of the molecular beam from the probe. The effect of the probe on the flame was measured and found to be small. By substituting a collecting grid for the spectrometer, samples of carbon particles were obtained for analysis of particle size and number, using an electron microscope. Temperature measurements in the flame were made using a quartz-coated Pt/Pt–Rh thermocouple (with radiation correction).

At the pressures used, the zones of reaction and carbon formation were found to extend about 5 cm above the porous disk burner and the authors could distinguish between the concentration profiles for 27 species up to $C_{12}H_8$. The majority of species studied were confined to the oxidation zone, the downstream limit of which was defined by the disappearance of molecular oxygen. Higher hydrocarbon radicals and molecules were formed toward the end of this region, species with even numbers of carbon atoms predominating. Beyond the oxidation zone, the concentrations of acetylene and polyacetylenes of the general formula $C_{2n}H_2$ up to $C_{12}H_2$ decreased to a constant value about 40 to 50 mm above the burner and, besides the oxidation products and soot particles, were the only carbon-bearing species found in the burned gases.

The concentration of these polyacetylenes increased with the fuel content of the flame and showed no discontinuity at the onset of carbon formation. In the region where the polyacetylene concentrations decreased, it was possible to relate their concentrations by equilibrium constants for reactions of the type $2C_2H_2 \rightleftharpoons C_4H_2 + H_2$.

The smallest carbon particles which could be detected by the electron microscope were about 40 Å diam and these were found in rich flames just downstream of the oxidation zone. In this region, where the polyacetylene concentrations decreased, it was found that the mean size of particles increased while the number decreased; the total carbon content of all the particles, however, became larger. The particles reach a diameter of about 150 to 170 Å at the end of this region and the only further change is that individual large particles tend to agglomerate.

To explain these observations, the authors propose that carbon formation in such flames takes place in three stages. First, in the radical rich oxidation zone polyacetylenes are formed by radical reaction reaching their maximum concentration near the end of this region. These polyacetylenes then tend to aggregate with the addition of smaller polyacetylene radicals and become detectable as small carbon particles. These particles grow further by agglomeration and by further addition of polyacetylenes until both the radicals and the smaller aggregates formed at the beginning of the carbon growth zone have disappeared.

Several pieces of information presented in this work favor this scheme. The whole soot formation process takes place in the region in which radicals are present. In the burned gases, where there are still appreciable concentrations of polyacetylenes and the temperature has fallen only a small amount, little growth of the carbon particles takes place, showing that the direct decomposition of acetylene and the lower polyacetylenes on the carbon particles takes place only slowly. Also, injection of small quantities of acetylene or hydrogen causes a shift in the polyacetylene equilibria and the extent of carbon formation only when the gas is injected from the side of the flame into the oxidation zone in which the radical reactions occur. Finally, injection of an inert gas along the direction of flow causes only a small increase in yellow emission in a flame which is just below the point of carbon formation. Injection of gas against the flow results in an intense yellow emission and formation of particles. In the latter case, flow stagnation or local recirculation of gases causes greatly increased residence times in the reaction zone.

This paper contains much experimental evidence in support of the hypothesis proposed previously that polyacetylenes and associated radicals are important intermediaries in the formation of carbon particles, and it represents a significant advance in the understanding of the reactions leading to carbon formation in rich hydrocarbon flames.

Reference

1. Bonne, U., Homann, K. H., Wagner, H. Gg.: Tenth Symposium (International) on Combustion, pp. 503–510, The Combustion Institute, 1965.

Subject Headings: ***Acetylene, flame of; Flame, reactions in rich hydrocarbons; Flame, structure of rich acetylene mixtures; Flame, hydrocarbon rich; Polyacetylenes, as soot precursors; Soot, formation in flames.***

F. J. Weinberg and R. Place*

* Department of Chemical Engineering, Imperial College, London, England.

Kydd, P. H. and Foss, W. I. (General Electric Research Laboratory, Schenectady, New York) "A Comparison of the Influence of Heat Losses and Three-Dimensional Effects on Flammability Limits," *Combustion and Flame* **8**, 267–273 (1964)

The theory of flammability limits due to heat losses, as published by Spalding in 1957, engendered a remarkable amount of experimental work with flat flame burners. The paper under review is yet another unit in the procession, and it probably will not be the last. There are two major contributions of this line of papers, (a) improvements in instrumentation, and (b) accurate experimental data on particular gaseous combustible mixtures in various flat flame geometries. However, the experiments have little bearing on the essence of the theory. For example, although the authors do not appear to realize it, the present study is focused on a side point that is not a key aspect of the theory. The emphasis on unimportant aspects of the theory was probably prompted by Spalding himself, when he and Yumlu published a note in which they claimed to have stabilized a flame with the lower of the two burning-rate eigenvalues by means of a flat flame burner. The subsequent experiments have shown beyond doubt that the accuracy of the Spalding–Yumlu experiment is insufficient to support their claim. However, this does not invalidate the basic theory in any way.

The essential point of the theory is the demonstration that, for steady-state, one-dimensional laminar flames with heat losses, there are conditions under which no solution for the burning velocity exists. For example, if the heat loss is given by $K(T - T_0)$ cal/cm^3 sec, where T is the local temperature and T_0 is the ambient temperature, then there is a maximum value of K above which a steady-state, one-dimensional flame cannot exist. The detailed shape of the temperature profile, and whether the heat loss occurs upstream or downstream, are immaterial to the basic argument; these aspects will depend on the heat-loss mechanisms determining the form of the heat-loss function. The heart of the result is that heat losses of any kind give rise to flammability limits. This is an extremely important conclusion, because no other phenomena have yet been shown, in a manner so incontrovertible to flame theorists, to produce flammability limits.

The fact that the heat-loss theories have always yielded two burning velocities for conditions under which any solution exists is more in the nature of a curiosity than an essential result. If flames generally burned at two different speeds, experimenters would have discovered that fact long ago. Obviously, one of the solutions is "unstable" in some sense, and extreme ingenuity in restricting the modes of instability will be needed to produce the lower burning velocity in the laboratory (if, indeed, it is at all possible). The basis for developing this ingenuity is not yet available because acceptable stability analyses have not been presented. (In the absence of such analyses, however, it would appear that an experimental search for a strange flame predicted by a one-dimensional theory had better be made in a geometry that is as nearly one-dimensional as possible—placing a solid plate or a diffusion flame normal to the flow direction in the burned gas prevents truly one-dimensional flow.) Moreover, there is no good reason to believe that numerical values of flammability limits predicted by the heat-loss theories should agree with experiment. The "unstable" phenomena, that prevent one from observing the lower burning-velocity branch, may exclude some of the upper burning-velocity branch as well. At their present stage of development, heat-loss theories are capable only of providing bounds within which the true flammability limits must lie.

After this tirade, it seems appropriate at least to mention what concrete results are contained in the paper under review. A 0.001-cm butt-welded Pt/Pt–10% Rh thermocouple wire, coated with silica to prevent catalytic effects, was used to measure temperature profiles of H_2–air, CO–air, and C_3H_8–air flames on a 10-in. diam, water-cooled, porous burner equipped with a downstream methane diffusion flame to reduce downstream heat losses and encircled by an annular premixed hydrogen–air flame to control edge heat losses. Measurements were made for various mixture ratios and flow velocities. In some cases, complete temperature profiles were recorded, but most experiments involved only the measurement of either the temperature 1 mm above the burner or the distance above the burner at which the temperature reached 450°C. The latter measurements were interpreted on the basis of a linear model that considered only conductive heat loss to the burner. Some visual and photographic observations of flames near extinction were also recorded, with special emphasis on the occurrence of "holes" of different types in the flame front.

Subject Headings: *Flammability, limits, heat losses and three dimensional effects; Heat losses, flammability limits.*

F. A. Williams

Salooja, K. C. ("Shell" Research Ltd., Chester, England) "Mechanism of Combustion of Diethyl Ether, Comparative Studies of Diethyl Ether, Pentane, and Acetaldehyde," *Combustion and Flame* 9, 33–41 (1965)

The preflame combustion characteristics of dimethyl ether, pentane, and acetaldehyde were studied in detail in order to throw some light upon the mechanism and extremely high reactivity of dimethyl ether in the presence of oxygen. All experiments were done in a flow system at equivalence ratios of 2. The temperature of the quartz furnace was raised gradually until ignition occurred at around 500°C. Composition analysis of final and stable intermediate products was done by gas–liquid chromatography and infrared analysis. Intermediates found included H_2, C_3H_4, CH_3OH, C_2H_5OH, CH_3COOH, and CH_4. In addition, CO, CO_2, O_2, and fuel concentrations were measured continuously. Great differences in reactivity of diethyl ether and pentane existed. The pentane oxidation began at 300°C while diethyl ether reacted initially at 200°C. Above 300°C the divergence of reactivities of these two compounds narrowed. Thus, it is not universally true that diethyl ether is 2500 times more reactive than pentane at any preignition temperature. This statement can only be applied to specific extrapolated temperature ranges.

Acetaldehyde began to react (consume significant amounts of O_2) about 50°C higher than diethyl ether. Its cool flame was highlighted by flashing at about 250° to 270°C.

C_2H_4 and C_2H_5OH were found in high concentration at $\sim$170°C and higher in the oxidation of $(C_2H_5)_2O$; CH_4 and CH_3OH were present in much lower amounts. CH_3COOH was present in the largest amount at the point of maximum cool-flame activity.

In the oxidation of CH_3COH, very little CH_4, C_2H_5OH, and CH_3COOH were found, while CH_3OH was very high in concentration.

Pentane combustion yielded large amounts and varieties of olefins, higher aldehydes, and ketones.

All of the reaction products identified during the combustion of diethyl ether (excepting acetaldehyde, the peroxides, and the hydroperoxides) did not undergo any oxidative degradation until the temperature reached 400°C. This temperature is well above the measured maximum cool-flame activity region of diethyl ether. Thus, it is concluded that the acetaldehyde and peroxides must be the reactive intermediates present to accelerate the $(C_2H_5)_2O$ degradation. One anomaly is the fact that $(C_2H_5)_2O$ undergoes rapid oxidative degradation. The hydroperoxide can form intramolecularly from diethyl ether while it forms only intermolecularly from CH_3COH.

The exceptionally high reactivity of $(C_2H_5)_2O$ is unusual, since the analogous reactivity of hydrocarbons increases with longer chain lengths, while increasing the chain length in the straight-chain ethers seems to decrease the reactivity greatly. The reason concluded here centers around the fact that acetaldehyde is produced during the early stages of oxidation as the most important reaction intermediate. Higher ethers would produce higher aldehydes, which are increasingly less reactive. Acetaldehyde is not an important intermediate in pentane oxidation, being replaced by large fractions of relatively inhibiting species, such as the olefins and formaldehyde.

Subject Headings: *Acetaldehyde, oxidation of; Ether, diethyl, oxidation of; Pentane, oxidation of; Flame, cool, of acetaldehyde, diethyl ether, and pentane; Oxidation, low temperature, of acetaldehyde, diethyl ether, and pentane.*

P. Breisacher

van Tiggelen, A. and Burger, J. (University of Louvain, Louvain, Belgium) "Considerations on the Theoretical Existance of Fundamental Flammability Limits in Gaseous Mixtures," *Combustion and Flame* **8,** 343–345 (1964) (Letter to the Editor)

The possibility of flammability limits in homogeneous gas mixtures, not subject to wall effects, is assumed to depend on the condition that "no heat is liberated by the over-all reaction", i.e., $qU \leq 0$, where q is the heat of reaction per unit mass, and U the rate of reaction. For the case of a steady-state chain reaction, this condition is written:

$$ZX(\alpha q_1 - \delta q_2 + FXq_3) \leq 0,$$

where Z is the collision frequency, X the mole fraction of chain carriers, α the probability of chain propagation, δ the probability of branching, F the efficiency of recombination, and q_1, q_2, q_3 the absolute values of the respective heat of reactions, the δ process of "formation of new radicals being evidently endothermic."

On this basis, it is concluded that flammability limits occur when

$$\delta \geq q_1\alpha(\alpha + FX_i)/(q_2\alpha + q_2FX_i - q_3FX_i)$$

for ordinary branching, where X_i is the mole fraction of reacting species. Furthermore, a generalized expression is discussed which is also valid for degenerate and quadratic branching.

The problem of temperature requirements is not considered. The authors seem to be unaware of Semenov's treatment[1] of flammability limits, in which endothermic steps are well taken care of by appropriate activation energies.

Reference

1. Semenov, N. N.: Some Problems in Chemical Kinetics and Reactivity, Vol. 2, Princeton University Press, 1959.

Subject Headings: ***Flammability, limits; Limits, of flammability.***

H. M. Cassel

VI. Radiation

Heselden, A. J. M. and Hinkley, P. L. (Joint Fire Research Organization, Boreham Wood, England) "Measurements of the Transmission of Radiation through Water Sprays," *Fire Technology* 1, 130–137 (1965)

This is an experimental study on the optimum use of water sprays in shielding structures from fire radiation. The fire is represented by a hot (~800°C) refractory panel of known emissive properties; two types of sprays are tested (a flat nozzle and a sprinkler) at different pressures and flow rates; finally, a radiometer measures the total radiation at different points of space behind the water curtain.

Transmission values were tabulated for several test conditions. A rough theoretical analysis showed the importance of the product $\mathcal{Q}d$ (volume flow rate per unit area x water-layer thickness) as a correlating variable. The transmission values collected in the tests were then plotted in terms of the product $\mathcal{Q}d$, with three values of the spray-outlet pressure showing as an additional parameter on the figure.

As expected, an increasing value of either flow rate $\mathcal{Q}$ or path length d decreased the beam transmission (Lambert–Beer's law). Increased pressures also decreased transmission: the suggested mechanism is that high pressure sprays contain finer droplets, thereby increasing the ratio of droplet cross section (radius square) to the droplet mass (radius cube).

By using a known value of the pure absorption coefficient of water, the authors establish that about a fourth of the total attenuation is due to scattering. It is therefore concluded that the existence of *large* radiating areas will lead to additional contributions to the emerging flux, because of multiple scattering.

Finally, a brief comparison was made with previous studies and some speculation made on the possible evaporation of droplets. Specifically, the paper predicts a transmission of 45% to 50% for a high-pressure water curtain flowing at 3 gal/ft/min and one of 30% to 40% at 4 to 5 gal/ft/min.

Although there is not much doubt that these results are qualitatively correct, the reviewer would like to take issue with the unnecessary crudeness of both experimental and theoretical parts of the work. The tests described in the paper do not ascertain with any rigor the relevant parameters of the experiment (spray dimensions, the size, quantity, and motions of the droplets, wavelength range, etc.), and the theoretical expressions are crude—if not in error (absorption should be proportional to the volume of the droplet, not to its diameter). The role of scattering could have been simply and more exactly assessed by the use of available results in multiple-scattering theory. On a more practical standpoint, one wonders if the role of absorption-increasing additives should not be investigated in a study of this kind.

Subject Headings: ***Radiation, through water sprays; Shielding, by water sprays; Sprays, water; Water, sprays.***

R. Goulard

VII. Suppression of Combustion

McGuire, J. H. (National Research Council, Ottawa, Canada) "Large-Scale Use of Inert Gas to Extinguish Building Fires," *Research Paper No. 246 Division of Building Research, National Research Council, Canada* (June 1965)

In this paper, the author signals the requirement for extinguishing concealed or otherwise inaccessable fires in buildings, and he cites the critical parameters affecting the extinguishment of these fires by the application of inert gases.

The first parameter cited is the critical oxygen concentration, so aptly defined as that concentration of oxygen at which the upper and lower flammable limits for the fuel concentration supporting combustion in the oxygen-poor atmosphere coincide. For most fuels; this concentration was shown to lie between 9% and 12%, the notable exceptions being hydrogen, having a critical oxygen concentration of 5%, and carbon monoxide, with a critical oxygen concentration of 7%.

The second parameter concerned the oxygen concentration in a given chamber volume as a function of the rate of inert-gas injection. The author indicated that mixing should be rapid in practical situations (Table I), assuming complete gas mixing, the resulting chamber oxygen concentrations in enclosed chambers for two inerting gases (one containing no oxygen, and the other containing 5% oxygen) as a function of total number of "chamber volumes" of gas injected. The author assumed also that extinguishment of fires by inert-gas injection within 15 min following the commencing of injection was either desired or required, and used this criterion in the subsequent analysis. With this criterion for extinguishment, the critical oxygen-concentration parameter, and the concentration relationships of Table I for the injection-volume ratios given, the author concluded that approximately two unit volumes of inert gas must be injected into the confined fire configuration for each unit volume of the configuration.

TABLE I

Oxygen concentrations with complete gas mixing in a chamber as a function of chamber volumes of gas injected

	Final oxygen concentration in chamber of volume V_c	
$\dot{V}_1 t/V_c$	Using inert gas of zero oxygen concentration	Using inerting gas mixture containing 5% oxygen
0	20	20
1	7.4	10.5
2	2.7	7.0
3	1.0	5.7
4	0.4	5.3
∞	0	5.0

The third parameter discussed concerned the rate of inert-gas loss through chamber openings as a result of naturally occurring convective processes. For simplicity, a top or bottom loss was assumed, depending on the density of the inerting gas relative to that of outside air. The loss is expressed as

$$\dot{V}_1 = 288A[h(\rho_a - \rho')/\rho']^{1/2}, \tag{1}$$

where $\dot{V}_1$ is the volume rate of gas loss in cu ft/min, h the depth of inert gas blanket in ft, ρ_a the density of surrounding air, ρ' the density of the inerting gas blanket, and A the area of opening through which loss occurs, in sq ft.

The significance of this equation was discussed, considering first a stagnant stratification of inert gas and then assuming complete mixing of the inert and chamber gases. The author concludes that the volume of gas in a chamber will be replaced providing:

$$\dot{v}_i t > V_c, \tag{2}$$

where $\dot{v}_i$ is the volume rate of inert gas injection; t is time; V_c is the volume of the chamber.

Based on the above parameters, the author pointed out that, assuming fire extinguishment is to be accomplished in a given volume within 15 min of inert-gas injection by means of an apparatus of known injection rate, the maximum chamber or building volume the apparatus is capable of servicing may be determined, and further, within this volume limit, for a specified building volume, the maximum vent or window opening area (through which gas loss can occur) permitting extinguishment may also be estimated. Numerical examples were presented to illustrate these points.

Using the effect of gas density on convective gas losses through openings as given in Eq. (1), the author showed that the convective losses would be minimized if the inert gas at the temperature of extinguishment were of the same density as the air surrounding the chamber containing the fire configuration. Since carbon dioxide at 140°C has the same density as air at 0°C, it appears to be an ideal inerting agent, if it were not so expensive (in terms of the quantities required), inconvenient to use (requiring heavy cylinders, or refrigerated tanks), and hazardous. (It was reported that above 12% concentration in air, CO_2 causes loss of consciousness within 2 min of exposure.) The use of nitrogen was also cited; however, the use of combustion products gases was considered more practical, and various types of combustion gas generators were discussed.

Two systems of combustion-gas generation were cited, one using water-injection cooling and the other using a water-cooled gas-heat exchanger. With water-injection cooling, the resulting gas was comprised of a large fraction of water vapor, and with heat-exchanger cooling, the gas produced was composed of essentially nitrogen and carbon dioxide. The National Research Council (Canada) has constructed a generator burning propane, which may be operated as a water-injection cooled device, or a heat-exchanger cooled device. With water injection, the gas composition (3800 cfm at 100°C) was 68% by volume water vapor, 28% nitrogen, and 4% carbon dioxide, having a mean molecular weight of 21.9. Operated as a heat-exchanger cooled device, the gas mean molecular weight was 30.1.

The author pointed out that a gas turbine without afterburners cannot deliver a combustion product gas essentially oxygen free, in contrast to a device such as the NRC generator.

The anticipated performance of the NRC generator was demonstrated by tabulating three inerting schemes: the NRC generator with water injection, with heat-exchanger cooling, and with carbon gas. Their performance was characterized by estimating the permissible high-level opening in a fire-containing compartment 40 ft high, using the gas-delivery rates of the NRC generator, and three assumed compartment-temperature regimes (40° to 140°C, 200°C, and 500°C) with an external temperature of 20°C.

Actual fire tests with the NRC generator indicated that gas delivery from generator to a fire-containing volume could be achieved without substantial pressure loss in the gas ducting, and that gas mixing in the fire-containing volume was very rapid, there being less than 0.5% difference in oxygen concentration at three different sampling levels (3 ft, 18 ft, and 39 ft above floor level) in a chamber 40 by 40 by 40 ft.

Smaller-test volume fires were controlled, both with respect to flaming and smoldering, with inert-gas injection. However, the author did not consider that the results of these small-volume tests could be extrapolated to predict the performance of inert-gas injection in actual building fires. He recommends using prototype devices for combating building fires on a "trial basis" as the means of demonstrating the value of the inert-gas-injection techniques.

To avoid mixing of inert gas with the combustion-supporting atmosphere within a fire-containing compartment, the author cited the application of high-expansion foam (expansion ratios of 300 parts expanded foam to one part liquid, ranging up to 2000 parts foam to one part liquid), and also noted that foams *per se* have intrinsic fire-extinguishing value.

The summary concluded that high-level gas losses contribute the principal limitation on the effectiveness of inert-gas injection as a fire extinguishing technique and that further advancements in development of low-cost inert-gas generators may be anticipated.

Subject Headings: *Building fires, extinguishment, by inert gas; Fire extinguishment, by inert gas; Gases, inert, for fire extinguishment.*

J. E. Malcolm

Rodgers, S. J. and Everson, W. A. (MSA Research Corporation, Callery, Pennsylvania) "Extinguishment of Alkali Metal Fires," *Fire Technology* **1**, 103–111 (1965)*

The expanded use of alkali metals as heat-transfer and working fluids has made necessary further investigation of the safety and handling procedures for sodium, potassium, NaK lithium, rubidium, and cesium. The following methods and techniques of extinguishing were evaluated: (1) inert gas in the presence of reduced oxygen partial pressures; (2) inorganic salts; (3) organic liquids; and (4) foams.

TEC powder, a ternary eutectic compound developed in England, was found to be the most effective inorganic salt extinguishant for sodium, potassium, and NaK fires. Met-L-X was also found to be an effective extinguishant for these fires and may be preferred over TEC because of its lower cost.

For these extinguishants, the weight ratio of extinguishant to alkali metal ranged from 0.72/1 to 0.20/1 depending on the salt used and the size of the fire. For sodium fires up to 500 lb in size, the extinguishing time was of the order of 5 min when the salt was applied from a 350-lb extinguisher. Both TEC and Met-L-X were effective against rubidium and cesium spills, but were ineffective on quiescent pools of these metals. At temperatures of less than 700°F, polyurethane foam was found effective on burning pools of rubidium and cesium. Neither of the above salts was found effective on lithium fires. Graphite is recommended as the extinguishant for lithium fires.

* Based on Technical Documentary Report No. APL TDR 64–114 prepared by MSA Research Corporation for Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, 1964. Copies of the complete report are available from the Office of Technical Services, U. S. Department of Commerce, Washington 25, D.C.

Organic liquids did not prove effective extinguishants. Although they were somewhat effective on low-temperature alkali-metal fires, a secondary liquid fire ensued in all cases. These fires can be severe and troublesome.

Lithium, sodium, and potassium fires were also controlled by gas blanketing and reduction of oxygen partial pressure. At a partial pressure of 0.1 atm of oxygen, none of the above metals ignited, although sodium did emit an occasional spark, and potassium oxidized slowly.

In atmospheres containing 50% argon/50% air, sodium ignited. Lithium and potassium did not ignite although potassium was slowly oxidized. In atmospheres containing 90% argon/10% air, none of the metals ignited. Again, potassium was oxidized slowly.

Rubidium and cesium in quiescent pools exhibited different burning characteristics than sodium, potassium, and lithium. Although 100% of these metals were oxidized in a 90% argon/10% air atmosphere, there was essentially no smoke, emission of light, or formation of an oxide crust on the surface. Unlike the other alkali metals, the degree of oxidation could not be reduced by altering the atmosphere. Rubidium and cesium did ignite when ejected in a jet stream in a normal atmosphere, but did not ignite in an atmosphere of 50% argon/50% air, 90% argon/10% air, or air of 0.1 atm absolute pressure.

Subject Headings: *Alkali metal, fire of; Extinguishment, of alkali metal fire; Fire, cesium, extinguishment of; Fire, alkali metal; Foam, use of, in alkali metal fire; Graphite, on alkali metal fire; Gases, inert, on alkali metal fire; Inorganic salts lithium fire; Met-L-X, on alkali metal fire; Organic liquid, on alkali metal fire; Potassium fire; Rubidium fire; Sodium fire.*

A. L. Goldstein

VIII. Model Studies and Scaling Laws

Rodden, R. M., John, F. I., and Laurino, R. (Stanford Research Institute, Menlo Park, California) "Exploratory Analysis of Fire Storms," *Office of Civil Defense Contract N228-(62479)65419, OCD Subtask No. 2536D Report*, through Technical Management Office U.S.N.R.D.L., San Francisco, California (May 1965)

The present study is an evaluative review of existing knowledge and opinion relating to fire-storm phenomenology. It develops interim critical values of fire-storm parameters that may be used in target analysis to establish conditions for probable or possible occurrence of fire storms. Recommendations are included also for further investigation to improve the state of knowledge in those areas where valid information is lacking.

The definitions of a fire storm, commonly found in the literature, are accepted for purposes of this investigation, but the absence of a precise generally accepted description of fire-storm conditions makes it difficult to analyze the existing data on fires reported to be fire storms. For example, there is disagreement even among fire experts regarding which cities actually sustained fire storms in World War II.

It is clear from this lack of agreement among the experts, and from the various descriptions of fire-storm conditions in the published literature, that there are many concepts as to what critical values of the various fire parameters represent the necessary conditions for a mass fire to be classed as a fire storm.

The basic factors in the initiation and development of fire storms are identified and described. The report presents a pictorial concept of the important stages in fire-storm development, showing possible idealized conditions that might exist at four selected times during the evolution of a fire storm. Also given, as a function of time, are curves representing the rates at which thermal energy might be released into the atmosphere by the fires. The basic factors in the chronologic evolution of a fire storm are: (1) the time-space distribution of initial fires resulting from primary and secondary fires, (2) the rate at which thermal energy is being released into the atmosphere, (3) the influence of atmospheric conditions, and (4) the general pattern of air circulation.

The characteristics of fire storms and the basic factors in their development are organized into a format to serve as the framework for a fire-storm model. The development of a fire-storm model is divided into three stages: (1) the "definition" stage, in which a fire storm is defined and the boundary conditions for the existence of fire-storm conditions are established; (2) the "parametrization" stage, in which these boundary conditions are specified in terms of estimable parameters and methods for estimating these parameters are developed; and (3) the "implementation" stage, in which physical or analytical models are developed to simulate interactions of processes that produce and maintain fire sotrms.

The basic factors relating to initiation and development of fire storms are examined in detail. The incompleteness or, in many cases, the total absence of information and data adequate for a thorough analysis of these factors indicates the need for much further study. On the basis of currently available information, it is concluded that major parameters and constraints affecting the initiation and development of fire storms include fuel loading, initial fire density, size of the initial fire area, surface wind, and topography and configuration. It is considered that these factors are probably the ones that determine whether fire storms are possible in given circumstances. Factors that, in general, appear to determine the extent and nature of fire storms, as opposed to their possible existence, include combustibility, fire-intensity buildup rate, atmospheric stability, temperature, humidity, and precipitation.

Interim criteria for predicting the possible occurrence of fire storms are selected and discussed in detail in the report. These criteria are:

Fuel loading	≥ 8 lb of combustibles per square foot of fire area
Fire density	> 50% of structures in fire-storm area on fire simultaneously (for practical purposes, initial fire density)
Surface wind	< 8 mph at time of attack
Fire storm area	> $0.5\ \text{mi}^2$
Unstable atmosphere	+
Stable atmosphere	−

Except for the atmospheric stability factor, it is considered that all of the conditions shown must be approximately met. Fuel loadings in the severe fires, including fire storms of World War II, have in general been reported in terms of building density only and, to a first approximation, fuel loading may be estimated by building density; but fuel loading is dependent also on building heights, contents, and construction materials. Hence, it was decided to use fuel loading rather than building density in this investigation. The fuel-loading criterion given above is based largely on analyses of severe fires of World War II.

Two of three buildings in a 4.5 mi^2 area were burning 20 min after the incendiary attack began at Hamburg, and similar figures were reported for other German fire-storm cities. From this and other information presented in this investigation, it seems reasonable to accept, as an interim criterion for predicting the possible occurrence of fire storms, a figure of approximately 50% of the buildings simultaneously on fire and burning rapidly.

A strong surface wind in the very early stages of a severe mass fire will cause the fire to spread and thus to become a conflagration rather than a fire storm. On the basis of available evidence, the surface winds were light just prior to the fire storms of World War II. Accordingly, it is suggested that an 8 mph ground wind (on generally level terrain) be accepted as an interim limiting criterion for development of fire storms.

The smallest generally accepted World War II fire-storm area was the 1.5 mi^2 area of Darmstadt. Recent investigations in Germany, however, suggest that fire storms may be possible in areas as small as 1 km^2. Therefore, a minimum fire area of 0.5 mi^2 is proposed as an interim criterion.

It is concluded, on the basis of currently available evidence, that atmospheric stability is an important but not necessarily limiting factor in the initiation and development of fire storms. Therefore, as an interim criterion for fire-storm formation, it is recommended only that an unstable atmosphere be considered as favorable to fire-storm development.

The parameters and critical values selected must be looked upon only as "best possible" values at this time, and should be revised as new and better information becomes available.

The fire-storm parameters investigated in the study are considered with respect to their importance in the estimating of fire casualties. It is shown that final estimates for fire-storm fatalities are within a factor of 2 of each other, ranging from about 10% to somewhat over 20% of the unprotected population at risk. The concept of areas of "entrapment" from mass fires, or areas where mass fires are sufficiently widespread and intense to prevent movement of unprotected population to areas of refuge, is introduced. The study presents a possible method for predicting fire-entrapment areas, based on a determination of those areas in which the clothing of people attempting to escape through the streets would be ignited in a short time, assuming that most of the structures in the area are on fire.

For an understanding of fire-storm behavior adequate for predicting within a specified degree of accuracy the probable occurrence of fire storms in urban areas of the United States subjected to nuclear attack, much additional research, analysis, and experimentation will be required. Because of the high casualty rate of unprotected humans in urban areas and the extensive destruction of property accompanying fire storms, the subject deserves continued attention for the purpose of diminishing the effects of such fires on persons and property. Further investigation should be made also on other types of fires, such as conflagrations.

Many aspects of the enormous release of thermal energy associated with fire storms are inadequately understood. It is clear that a tremendous amount of energy must be released within a short time, but the mechanisms and constraints controlling the factors involved require further study. Because certain atmospheric conditions may be highly important to the initiation and development of fire storms, further research on these conditions appears to be warranted. Future studies may show that selected atmospheric conditions affect the development of fire storms in marginal situations, but become less important when an overwhelming thermal-energy-release rate is present.

Subject Headings: ***Fire storm, analysis of; Parameters, of fire storms.***

Authors' Abstract

Nielsen, H. J. (IIT Research Institute, Chicago, Illinois) "Fire Storm Environmental Model," *Office of Civil Defense Contract OCD–PS–64–50* (April 1965)

To further define the environment within a fire storm, an analytical model was developed which describes the conditions of flow and temperature of the fluid. In the model, the fire is considered to be an area on the ground with a higher temperature than that of the surroundings. The motion of the fluid produced by the temperature excess was obtained by solution of the equations of energy, motion, and continuity by a numerical integration technique.

Effects of viscosity and of thermal conduction are included in the analysis without the boundary-layer approximations that were used in a previous analysis of the convection column. For this reason, the results obtained in the region near the ground are not subject to the deficiencies of those of the previous analysis. Some of the effects of swirling flow are also included in the model by specification of rotation in the surrounding air.

A simplified analysis was also conducted to estimate the time required for the development of swirl flow. In the analysis, the entrainment by a convection column was represented by a line sink. A simple solution was presented for rate of growth of swirl flow for a fluid initially rotating at a speed that corresponded to the rotation of the earth.

Subject Headings: ***Fire storm, model for; Model, for fire storm.***

Authors' Abstract

IX. Atomization of Liquids

Long, V. D. (Imperial College, London, England) "A Simple Theoretical Model of Droplet Combustion," *Journal of the Institute of Fuel* 37, 522–525 (1964)

The paper under review is a simplified droplet-combustion analysis used by the author in teaching, and evidently published in consequence of referring to it during a Discussion[1] on droplet combustion following presentation of an experimental paper on the subject by Masdin and Thring.[2] In this reviewer's opinion, readers would probably find that this latter paper, and maybe also the Discussion, would repay study.

In the Discussion[1] referring to the paper by Masdin and Thring,[2] the author made the point that the use of Godsaves' analysis requires experimental measurement of the flame to drop diameter (d_f/d), in which case one might as well measure the burning time and avoid calculation altogether. He also dismisses Spalding's version as being based on an unclear physical picture. Other theories merely add further complexity to these two without gaining much (or anything) in precision of prediction because of the uncertainty of the physical constants involved. Long's analysis is, therefore, simplified to the point where burning rates and times (t_b) can be calculated directly from expressions where the flame-to-drop-diameter ratio has been eliminated, and evaluation is possible using only reasonable values of standard physical and chemical constants. By this approach, values of the burning constants K in the burning-time expression

$$t_b = Kd_0^2 \tag{1}$$

were evaluated giving agreement with experiment to within ±15%. The only concession made is the use of an experimental thermal conductivity k, found to be 30% to 50% higher than expected.

The analysis is otherwise quite standard, being based on the conventional spherical symmetry model of a drop surrounded by a spherical flame surface with steady-state heat and mass transfer. The model also invokes the assumption of thermal conduction from the flame surface to the drop as the combustion rate control to generate the usual reaction-rate equation (rate of mass loss per unit area, $\dot{m}''$)

$$\dot{m}'' = \frac{2k \ln [1 + c(T_f - T_s)/\mathcal{Q}]}{cd(1 - d/d_f)}, \tag{2}$$

where c is the specific heat of the vapor, $\mathcal{Q}$ the latent heat of vaporization, and T_f and T_s are the temperatures of the flame and the boiling point, respectively.

To eliminate the unwanted diameter ratio d/d_f, a mass balance is set up to provide an appropriate expression for this ratio. By substitution, the diameter ratio is eliminated, generating a much more complex expression for $\dot{m}''$; but evaluation shows that neglect of the mass-diffusion terms introduced by the substitution means only about 10% error, and is equivalent to taking d_f as infinity (i.e., free evaporation in an infinite atmosphere). With this assumption, Eq. (2) above can be integrated to give Eq. (1) with

$$K = c\rho_p/8k \ln [1 + c(T_f - T_s)/\mathcal{Q}], \tag{3}$$

where ρ_p is the drop density. With k chosen from experiment as 3×10^{-4} cal/cm sec °C, this expression predicts K to within 15%.

[*Comments by Abstracter.*—The mass balance to eliminate the diameter ratio is not quite so original as the author's presentation might seem to imply, having been used by Goldsmith and Penner[3] at least as early as 1953. A second point is that Long's calculations, showing that neglect of the diameter ratio involves less than 10% error, implies a flame diameter, d_f at least 10 times the drop radius and generally more. Unforunately, as discussed elsewhere,[4] these values would only seem to be physically true for very small drops (100 to 10 microns); and for the large drops, however, if one may assume that the ratio remains fairly constant (within the detectable limits of experimental error) at an intermediate value of, say, 5, then the predicted evaporation rates would be about 25% higher than the free evaporation rate (not 10% higher); also this would correspond to an effective thermal conductivity 25% higher than the true value, which starts to account for the discrepancy found by Long experimentally. This implies that, with some small interpretative reservations, Long's analysis is valid and useful for large drops; it may, however, be up to 50% in error for small drops. It would, therefore, be a useful contribution if this somewhat overlooked problem of the diameter ratio could be investigated.]

References

1. Long, V. D., J. Inst. Fuel *36*, 351 (1963).
2. Masdin, E. G. and Thring, M. W., J. Inst. Fuel *35*, 251 (1962).
3. Goldsmith, M. and Penner, S. S., California Institute of Technology, Tech. Report No. 2 November, 1953.
4. Essenhigh, R. H. and Fells, I., Discussions Faraday Soc. 30, 212 (1960).

Subject Headings: ***Combustion, of droplets; Droplets, combustion of; Theory, of droplet combustion.***

R. H. Essenhigh

X. Meteorological Interactions

Murgai, M. P. and Varma, R. K. (Defence Science Laboratory, Delhi, India) "Radiative Transfer Effects in Natural Convection above Fires—Transparent Approximation, Ambient Atmosphere Non-Isothermal," *International Journal of Heat and Mass Transfer* **8**, 833–839 (1965)

This paper considers the effect of radiative heat transfer on a buoyant axisymmetric turbulent plume in an atmosphere with various lapse rates. Previous analytical studies have dealt with the variations in plume width, velocity, and buoyancy as functions of vertical distance from the ground for two situations: (a) when the outside atmosphere has a stable or unstable lapse rate, and (b) when the atmosphere is neutral and radiation is included. The results of (a) showed that the plume velocity dies out or increases depending on the lapse rate. The effect of radiation revealed that the height for a certain decrease in buoyancy is much less than the corresponding case without radiation transfer. The present paper considers both effects simultaneously. It was found that when the lapse-rate variation and radiative transfer are considered, they act in unison when the lapse rate is stable in the ambient air. This makes the plume die out at a lesser height than it would when either one is present. With an unstable lapse rate, these two effects are in opposition.

If radiation transfer is not considered, the only means by which cooling occurs is by the mixing of the hot plume with the surroundings. When the temperature of the outside atmosphere steadly increases upward, the hot plume mixes with continuously increasing hot air. This results in the plume temperature and the ambient air temperature equalizing very soon with the rapid loss of buoyancy. Consideration of the radiation loss (leading to plume cooling) shows the buoyancy loss occurs sooner. The loss of buoyancy may continue for larger values of the lapse rates, until it becomes negative. The plume may continue to rise due to residual momentum with negative buoyancy opposing this motion, where negative buoyancy means outside temperature greater than plume temperature. When radiation is considered, the plume gains heat from the surroundings, thus making the buoyancy less-and-less negative until it becomes zero.

With negative temperature-lapse rates, the outside temperature decreases with height and the plume in its ascent mixes with continuously cooler air. For low values of the lapse rate, the temperature difference may become small, hence the buoyancy is lost and the plume terminates at some suitable heights. For large negative values of the lapse rate, the inside and outside temperature may never equalize and the plume continues indefinitely. Radiation of the plume causes its temperature to decrease, tending to equalize with the outside temperature. Either the radiation or lapse rate will dominate in this situation. It appears that for the opaque case considered herein, the radiative losses become increasingly dominant.

Subject Headings: ***Convection, above fire; Plumes; Lapse rate, effect on plumes; Heat transfer, radiant, effect on plumes.***

L. A. Povinelli

XI. Operational Research Principles Applied to Fire Research

Cohn, B. M., Almgren, L. E., and Curless, M. (Gage-Babcock & Associates, Inc., Chicago, Illinois) "A System for Local Assessment of the Conflagration Potential of Urban Areas," *Report for Office of Civil Defense Contract OCD–PS–64–74* (1965)

Modern warfare poses the threat of conflagrations to many urban areas. Good planning insures that large shelters, hospitals, communication facilities, and critical supplies be located so as to minimize the danger of loss to fire. Peacetime fire fighting, community planning, and urban renewal can also be improved through a better estimate of conflagration potential.

This study was sponsored for the purpose of devising methods of (1) estimating the relative propensity of city blocks to have conflagrations and (2) delineating the probable limits of such conflagrations.

The authors contend that weather, fuel, nonfuel combinations found in an entire city make accurate conflagration prediction difficult, but a practical method can be developed through an empirical approach based on fire-protection-engineering knowledge and experience.

To capitalize on the varied experiences of the available engineering staff, six persons were selected and assigned responsibility for independently developing a system for assessing the conflagration potential and for locating firebreaks in their community. Their system was to give uniform results in all parts of the country and to be consistent with the judgement of fire chiefs and experimental data when it was considered valid. Staff engineers studied these proposed systems. Concurrently, they developed a preliminary field-survey method for the determination of firebreaks and fire spread and studied the available literature. Selected references and results from preliminary field tests were used to develop subsequent revisions of a conflagration-assessment system.

The final system for assessing the conflagration potential within a city consists of establishing a relative rating for an entire city block based on the average conditions for the entire block as compared to the value derived from any other block in the community. The estimate of the limits of the conflagration is based on an examination of the line of buildings on each side of a potential firebreak in terms of the distance a fire could be expected to reach across. Conflagration hazard values are relative values which express fuel load and arrangement. It is argued that weather influences all blocks alike, so that can be eliminated from consideration. The effect of wind is recognized but not used in the determination of conflagration potential. An adjustment is made when establishing the conflagration limits. This adjustment is based on Hamada's formula and the average wind velocity of the community. Most consideration is given to building construction and arrangement, including roof construction. Fire spread from building to building is attributed in main to thermal radiation.

Several procedures were used to help determine the assignment of values to the various factors involved in fire growth and spread, but the engineer's experience and judgment were given high credence rating. "Proof" of the system is alleged to be the consistency with which the block ratings agreed with the experienced observer's evaluation. Graphs, tables, and forms were designed. Detailed procedures with and without aids (such as Sanborn Maps) were prepared. These instructions have been organized and designated as the "regular" and the "simplified" methods of "A System for Local Assessment of the Conflagration Potential of Urban Area." These are recommended to the Office of Civil Defense and fire departments for implementation, testing, and re-evaluation.

Subject Headings: ***Assessment, of fire hazards; Fire hazards, assessment of; Fire hazards, urban, assessment of.***

A. P. Brackebusch

Vodvarka, F. J. and Waterman, T. E. (IIT Research Institute, Chicago, Illinois) "Fire Behavior, Ignition to Flashover," *Final Report Task 2–C, Multi-task Contract No. OCD–PS–64–50* (June 1965)

This program extended the limit information available about the time interval between the ignition by nuclear detonation of a major furniture item and the subsequent flashover of the room. The information aids in determining the number and training of civilian personnel required for extinguishment of the fires, thereby preventing the developmenr of conflagrations or fire storms.

Experimental arrangements included:

a. Living rooms with conventional upholstery;
b. Living rooms with foam rubber upholstery;
c. Bedrooms with box springs; and
d. Bedrooms with open coil springs.

The burn room was a 12 × 12 × 8 ft structure of framing lumber, lined with a sheet metal and drywall sandwich. The ignition items were conditioned to approximately 6% moisture content before use, and ignition was aided by wiping selected sections with jet fuel before lighting.

The results show that 90% of the fires in Category (a) were beyond extinguishment by self-help efforts in 26 minutes, in Category (b) in 8 minutes, and in Category (c) in 12 minutes. Fires in Category (d) did not result in room flashover.

It was found that interior spaces of furniture apparently flashover in a fashion similar to a room. Smoke from burning foam rubber is so dense that visibility is zero except very near the floor. Unless the ignition item is a major one, flashover may not occur.

Further work is required to study the effects of smoldering ignitions on the flashover time. The mode of spread when the ignition item is not a major one should also be studied, as should the effects of room dimensions and ventilation. Also, a survey should be made to determine the type and number of potential kindling items in various types of neighborhoods.

The results to date indicate the need of means for reducing the number of ignitions and the rapidity of their development to flashover. Study of potential means should be initiated.

Subject Headings: ***Fire, development of; Flashover; Ignition.***

Authors' Summary

XII. Instrumentation

Milne, T. A. (Midwest Research Institute, Kansas City, Missouri) "High Pressure Sampling Conference"—May 1965. *Abstracts of Talks.*

This meeting brought together a small group with a variety of interests and experience to discuss the problems encountered in the direct sampling of systems at high pressures.

Titles of Abstracts

Continuum Flow Problems in Direct Sampling—F. S. Sherman
Nonequilibrium Effects in Freely Expanding Jets—J. E. Scott, Jr.
Mass Bias in Vacuum Sampling from High pressure—J. B. Fenn
The influence of Self Collisions in Supersonic Molecular Beams—J. M. Deckers

Collisions in Molecular Beam Colliminating Chambers—C. E. Nutt and M. S. Rifai
Comments on the Disturbances by Sonic Sampling Probes in Flames and Other Systems—R. M. Fristrom
Free Radical Sampling from Nonequilibrium Systems—A. A. Westenberg
Some Problems of Mass Spectrometric Direct Sampling—W. A. Chupka
Direct Sampling from a Shock Tube—R. W. Diesen
Beam Formation and Sampling of Neutrals from One Atmosphere Flames—F. T. Green
A Sampling System for Neutral Particles—K. H. Homann and H. Gg. Wagner
Ion Sampling from Gaseous Plasmas—G. N. Spokes
Ion Sampling from a Flowing Gas Stream—P. F. Knewstubb
Ion Sampling from Hydrocarbon Combustion Plasmas—W. J. Miller
Plasma Analysis with a Bendix TOF Mass Spectrometer—G. J. O'Halloran

Copies of the collected Abstracts can be obtained from Dr. Thomas A. Milne, Midwest Research Institute, 425 Volker Blvd., Kansas City, Missouri 64110.

Subject Headings: ***Sampling, of high pressure gases; Gases, sampling of.***

R. M. Fristrom

XIII. Fire-Fighting Techniques, Equipment

Firth, J. M. and Chandler, S. E. (Joint Fire Research Organization, Boreham Wood, England) "Preliminary Analysis of Fire Reports from Fire Brigades in the United Kingdom 1964," *Joint Fire Research Organization Fire Research Note No. 591* (March 1965)

The preliminary analysis of reports shows that during 1964 the Fire Brigades attended 182,434 fires in England and Wales, 14,125 in Scotland and 2319 in Northern Ireland. The number of incidents attended by each Fire Brigade is given.

No members of the Fire Service in the United Kingdom were killed while attending fires. In England and Wales 385 members of Fire Brigades were injured at fires; the corresponding figures for Scotland and Northern Ireland were 26 and 5, respectively.

The Fire Services assisted in the rescue of 495 persons from fires in England and Wales, 116 in Scotland and 13 in Northern Ireland. Further details of casualties, rescues, and escapes are given.

It was deemed advisable to evacuate a further 1815 persons (not directly affected by fire) in eight incidents in England and Wales, 739 of them in one incident.

The analysis is based on reports received up to 28 February 1965, and the figures given are subject to revision when outstanding reports have been received.

Subject Headings: ***Fire brigade reports, in the United Kingdom; Analysis, of fire brigade reports in the United Kingdom.***

Authors' Abstract

Gaunt, J. E. (Joint Fire Research Organization, Boreham Wood, England) "Preliminary Investigation of Fires Fought with 5 or More Jets," *Joint Fire Research Organization Fire Research Note No. 589* (March 1965)

A preliminary investigation has been made of the reports of fires involving 5 or more jets in the period July 1962 to December 1963. There were 201 such fires in the second half of 1962 and 509 in 1963.

The analysis indicates that there were delays in discovery of more than half the fires. The delays were due almost entirely to buildings in which the fires occurred being unoccupied at the time of the fires. There was also a tendency for the fires to occur between the hours of 9 p.m. and 12 midnight, i.e., late at night when there are few people around. If automatic detection systems had been installed and linked directly to the fire stations or combined with security patrols within the buildings, it is very likely that there would have been a considerable reduction in the size and, consequently, the cost of a large proportion of these fires.

Where fire-protection systems are installed, it is always important to maintain them in working order. On several occasions where fires broke out, sprinkler systems, for example, had been shut down and drained.

A high percentage (more than 50%) of the fires were of an unknown source of ignition, which might be expected because the fact that the source of ignition cannot easily be traced for fires that are already large on discovery. Smoking materials were the most frequently reported known source of ignition.

The value of compartmentation as an effective means of reducing spread was very apparent although the saving could have been much greater had all doors been left in closed positions when buildings were vacated. In many instances where doors had been left open there was evidence of bad housekeeping—the doors being propped open with piles of boxes, etc.

Persons were trapped in 5% of the fires in 1963 and 20 people lost their lives.

Subject Headings: ***Fire, large, in the United Kingdom; United Kingdom, large fires in.***

Authors' Abstract

Harmathy, T. Z. (Division of Building Research, National Research Council, Ottawa, Canada) "Ten Rules of Fire Endurance Rating," *Fire Technology* **1,** 93–102 (1965)

For many years, it has been recognized by fire-protection engineers that the destructive nature of fire endurance tests made it practically impossible to classify all types of assemblies and combinations of materials through actual fire tests. Even in those cases where test results are available for similar constructions, the classification might not be immediately available. It is recognized that variations in dimension, loading conditions, materials, or workmanship may effect the performance of individual constructions.

For these reasons, there has been a real need for a reliable method for using available test data, that could be used in making appraisals of the fire endurance of new or proposed building elements. In this report, a number of rules have been developed which will provide guidance to those charged with administrating building regulations and to those engaged in the design or production of building components. The author has set out a number of excellent examples to illustrate the wide applicability of these rules.

TEN RULES

Rule 1—The "thermal" fire endurance of a construction consisting of a number of parallel layers is greater than the sum of the "thermal" fire endurances, characteristic of the individual layers when exposed separately to fire.

Rule 2—The fire endurance of a construction does not decrease with the addition of further layers.

Rule 3—The fire endurance of constructions containing continuous air gaps or cavities is greater than the fire endurance of similar constructions of the same weight, but containing no air gaps or cavities.

Rule 4—The farther an air gap or cavity is located from the exposed surface, the more beneficial is its effect on the fire endurance.

Rule 5—The fire endurance of a construction cannot be increased by increasing the thickness of a completely enclosed air layer.

Rule 6—Layers of materials of low thermal conductivity are better utilized on that side of the construction on which fire is more likely to happen.

Rule 7—The fire endurance of asymmetrical constructions depends on the direction of heat flow.

Rule 8—The presence of moisture, if it does not result in explosive spalling, increases the fire endurance.

Rule 9—Load-supporting elements, such as beams, girders, and joists, yield higher fire endurances when subjected to fire-endurance tests as parts of floor, roof, or ceiling assemblies than they would when tested separately.

Rule 10—The load-supporting elements (beams, girders, joists, etc.) of a floor, roof, or ceiling assembly can be replaced by such other load-supporting elements which, when tested separately, yield fire endurance not less than that of the assembly.

These rules will prove helpful in developing further methods by which materials and combinations of construction features may be developed and analyzed from the standpoint of fire resistance without the necessity for excessive destructive fire tests

Subject Headings: ***Endurance, fire, rating of; Fire endurance rating; Rules for fire endurance rating.***

J. J. Ahern

XIV. Miscellaneous

MacEwen, J. D., McNerney, J. M., Vernot, E. H. (Aerojet-General Corporation, Sacramento, California) and **Harper, D. T.** (United States Air Force, 6570th AMRL) "The Chronic Inhalation Toxicity of Chlorobromomethane," *Toxicity Report under Contract No. AF 33(657)–11305*

Albino rats and beagle dogs were exposed to the inhalation of chlorobromomethane vapors during 124 exposures (6 hr/day) over a 6-month period. The exposure levels of 500 and 1000 ppm chlorobromomethane produced only one demonstrable effect, which was the slight depression of growth in the albino rat. This finding, while statistically significant, was not indicative of gross changes in health status. The chlorobromomethane-exposed animals were normal in appearance, and they were not visibly different from the control animals. The blood bromide levels in both species were above 95 mg% in the exposed animals. According to Goodman and Gilman[1] and Brooks and Jacobs,[2] similar bromide levels in man would produce mild sedation. Therefore, it is entirely possible that the exposed animals were under continuous mild sedation which could conceivably modify their eating habits as well as their metabolic activity. During the first few weeks of the experiment, the chlorobromomethane-exposed animals appeared to be more lethargic than the controls, becoming alert only when the control animals disturbed them at the end of each daily exposure; however this was apparent only during the first few weeks.

From the data presented, the most significant factor in chlorobromomethane intoxication is the serum bromide ion concentration resulting from the metabolism of the chlorobormomethane. In the work reported by Torkelson *et al.*[3] animals exposed to 370 ppm of chloroboromomethane showed serum bromide levels below 50 mg %, which appears to be within the safe range. Therefore, it may be concluded from these experiments and the other experiments cited that the current ACGIH Threshold Limit Value for chlorobromomethane of 200 ppm is a satisfactory working level for chronic daily exposure.

References

1. The Pharmacological Basis of Therapeutics (Goodman and Gilman, Eds.), 2nd ed., The Macmillan Co., 1960.
2. Brooks, V. J. and Jacobs, M. B.: Poisons, 2nd ed., 1958.
3. Torkelson, T. R., Oyen, F., and Rowe, V. K.: Am. Ind. Hyg. J. *21*, 275 (1960).

Subject Headings: *Poisons; Inhalation, of chloromethyl bromide; Chloromethyl bromide, inhalation of; Toxicity, of chlorobromomethane.*

Authors' Summary

BOOK REVIEWS, REPORTS, AND TRANSLATIONS

Book Reviews

Moisture in Materials in Relation to Fire Tests, ASTM Special Technical Publication No. 385, 123 pp. American Society for Testing and Materials (ASTM), 1916 Race St., Philidelphia 3, Pennsylvania. 1965. $7.00

This book is a collection of eight papers presented at the 67th meeting of the ASTM in Chicago, Illinois in June 1964. As can be seen from the authors' synopses collected below, a wide variety of problems were discussed and as Dr. A. F. Robertson of the National Bureau of Standards points out in his introduction, a major conclusion brought out by the session is the desirability of further work on this multifaceted problem.

Moisture Equilibrium and Migration in Building Materials, by P. J. Sereda and N. B. Hutcheon (Division of Building Research, National Research Council, Ottawa, Canada).

"Factors influencing the moisture content of a variety of building materials in equilibrium with their thermal and moisture environments are discussed. Reference is made to forces, potentials, energies, pore structure, surface area, and hysteresis. The usefulness of the suction concept in dealing with moisture at conditions close to saturation and of the relationship of the suction scale to relative humidity is discussed.

The second part of the paper introduces a discussion of moisture migration under isothermal steady-state conditions, and indicates the complications inherent in the nonisothermal case. We refer to some significant work by others in fields where combined heat and moisture flow is of concern."

The Drying Process, by David Hansen (Department of Chemical Engineering, Rensselear Polytechnic Institute, Troy, New York).

"Recent research has yielded a qualitatively comprehensive picture of the drying process which differs from the classical theory in many details but confirms the general features of the constant-rate period and falling-rate period. Drying experiments including continuous precise measurements of drying rates, moisture distribution, and temperature distribution have been reported. The influence of the nature of the solid on the falling-rate period has been clarified. The existence of a characteristic temperature for the falling-rate period has been observed. Because of its correspondence to the wet-bulb temperature of the constant-rate period, this characteristic temperature has been named the pseudo-wet-bulb temperature. The falling-rate period is not yet amenable to general quantitative analysis although some progress has been made.

Further development of drying theory will depend on gaining a better understanding of the mechanisms of simultaneous heat and mass transfer in porous materials. Work on this subject is proceeding, but these mechanisms, and the material properties controlling them, are not sufficiently well defined at present to permit their incorporation into quantitative drying theory."

Moisture Content of Wood in Buildings, by A. F. Verrall (Southern Forest Experiment Station, New Orleans, La.).

"The moisture content of wood in buildings must be considered in terms of ranges likely to occur in different parts of buildings in different climatic areas. Accurate data are still insufficient to establish even ranges of moisture contents with certainty. The material presented here was pieced together from many fragmentary reports and is subject to revision as more complete data are secured.

The actual moisture contents in a given building will depend on: (1) the moisture conditions inside as influenced by the amount of vapor released, ventilation, type of heating plant, and refrigeration, (2) the degree of moisture control in crawl spaces, attics, and walls by ventilation, vapor barriers, and thermal insulation, and (3) the amount of protection afforded the exterior from rain seepage by roof overhang, gutters, and the applications of water-repellent preservatives.

Moisture contents can be greatly in excess of those in Table 1 when building design permits even, moderate rain seepage or condensation."

The Kiln Drying of Wood, by Raymond C. Rietz (Forest Products Laboratory, Madison, Wisconsin).

"The rate at which wood in the form of rough-sawn sawmill products can be safely dried is determined by its structure and physical properties. Water moves out predominately by diffusion. Drying conditions must be controlled to prevent defects occurring because of shrinkage stresses.

Two war periods stimulated drying research and equipment design. Prior to World War I, dry kilns were of the natural circulation type and often described as "hot boxes". Modern dry kiln equipment features forced-air circulation with automatic reversal of air flow direction, automatic dry-and wet-bulb temperature control, and controlled venting. The application of impingement drying processes is gaining favor. Kiln drying schedules to accelerate the drying rate and to minimize defect formation have been greatly improved. Time-based program controllers are being given industrial trial. Moisture content quality control is being attained to assure users of fabricated wood items better performance, enhancing satisfaction."

Drying Methods for Concrete and Their Effect on Fire Resistance, by M. S. Abrams and D. L. Orals (Research and Development Division, Portland Cement Association, Skokie, Illinois).

"This paper compares laboratory methods for the conditioning of concrete prior to exposure to the standard fire test (ASTM Method E 119) using slab specimens 3 by 3 ft by 6 in. thick. In the artificial conditioning methods the specimens were exposed to heated air in a kiln controlled at temperatures to 200 F. Such kiln drying was conducted both without controlled humidity and at several selected relative humidity (RH) levels. The drying of some slabs was accelerated by infrared heat radiation. Information is given on the effect of ambient RH level in the natural drying procedure described in Method E 119.

The effect of the several drying procedures on the time requirements to reach the desired concrete test humidities, the humidity gradient through the concrete sections, and the subsequent fire endurance of the concrete slabs was evaluated in terms of the results obtained on companion slabs naturally dried in air at 73 F and 35 per cent RH. It was found that all of the aritficial conditioning methods considerably reduced the time required to reach test humidity. However, the saving in conditioning time was accompanied by depressed fire endurance periods, that is, endurance periods substantially lower than those resulting from slabs naturally dried to the same test RH.

Effect of Moisture on the Fire Endurance of Building Elements, by T. Z. Harmathy (Division of Building Research, National Research Council, Ottawa, Canada).

"The effect of moisture on the performance of building elements in fire is closely related to the amount of moisture, and in turn, to the sorption characteristics of materials.

High moisture content may result in spalling. The probable mechanism of moisture clog spalling is discussed, and a criterion is developed for the fractional pore saturation at which spalling can be expected (Eq. 8).

If spalling does not occur, the presence of moisture is beneficial for the fire endurance. An empirical equation has been found which correlates the percentage gain in fire endurance due to 1% moisture with the fire endurance in the dry condition (Eq. 20). A nomogram is presented to facilitate estimation of the effect of moisture on thermal fire endurance (Fig. 9).

Possible utilization of the results in the field of fire endurance testing is discussed."

Fire Endurance of Small Gypsum Slabs, by J. V. Ryan (Building Research Division, National Bureau of Standards, Washington, D.C.).

"A study was undertaken to obtain increased knowledge of the relationship between moisture content of gypsum plaster and its fire endurance. Specimens 2-ft square were prepared in nominal thicknesses of 3, 1½, ¾, and ⅜ in. They were conditioned in air at 23°C and 50% relative humidity for periods ranging from 1 to 259 days. Each specimen was exposed to fire, controlled to produce the furnace time-temperature curve defined in ASTM Methods E 119. The fire endurance was taken as the elapsed time to a limiting temperature rise of 139°C on the unexposed surface.

The relationships between fire endurance and each of several factors—age, thickness, weight loss, and moisture content—are presented. It is shown that endurance did not change significantly during the initial aging period, despite appreciable change in moisture content. The initial period was followed by an intermediate period of aging marked by more significant changes in endurance. Finally there was an extended period of small changes in endurance. It was shown that endurance was affected by fairly small changes in the moisture content of gypsum plaster as equilibrium was approached."

Effect of Moisture on Surface Flammability of Coated and Uncoated Cellulosic Materials, by T. G. Lee, J. J. Loftus, and D. Gross (Building Research Division, National Bureau of Standards, Washington, D.C.).

"A method is described for the rapid *in situ* determination of the thermal inertia for surface heating (*kρc* product) of materials using a sensitive infrared detector. Experimental measurements are given of the effect of moisture content on the thermal inertia and on the surface flammability of selected cellulosic materials conditioned to equilibrium at relative humidities ranging from 0 to 99%. It is shown that (1) the thermal inertia of uncoated hardboard and fiberboard material can be represented as a linear function of its moisture content, (2) if the appropriate thermal properties are used, the flame-spread factor is inversely proportional to thermal inertia, and (3) the unbroken surface film of coated materials results in a lower ignition sensitivity than that predicted on the basis of thermal inertia."

Subject Headings: ***Drying; Fire tests; Fire endurance moisture.***

R. M. Fristrom

W. H. Burrows (Engineering Experiment Station, Georgia Institute of Technology) *Graphical Techniques for Engineering Computations.* Chemical Publications Co., Inc., New York, 1965, 435 pp. $15.00.

This interesting book discusses in detail the problems and practice of graphical computation. The author's thesis that graphical, nomographical, and slide-rule techniques are competitive, even where modern computational facilities are available, and provide useful substitutes where no such facilities exist. There is much truth in this view although, as with all theses, it should be taken in moderation. Limitations—such as precision, difficulties in construction, and other problems—require judgment in the application.

The book provides an extensive discussion of the theory and application of sliding scales, graphs, and nomographs to the solution of engineering equations, both simple and complex. Nomographs for handling as many as six variables are illustrated. The practical problems of constructing and using the devices are discussed in detail, and methods of reproduction of the devices for a large number of users are discussed.

Computation with scales is familiar in the form of the slide rule; with graphs, the most familiar computations involve integrations by determining areas under curves and derivatives by slope determinations and multivariable functions illustrated by the Mollier diagram; with nomograms, which is one often used for estimating pipe flows and other complex computations.

The fire engineer and scientist may find useful information in this book to aid in visualizing complex fire problems and perhaps nomograms could be constructed which would aid in making decisions in practical fire problems. Such devices would be particularly useful in teaching novice firemen the basis for the decisions which the experienced man makes intuitively. The structure of this information, when visualized in graphical form, could make an important contribution to the understanding of the complex problems of fire and fire fighting.

Subject Headings: ***Graphs; Scales; Nomographs; Computation, graphical.***

R. M. Fristrom

Joint Fire Research Organization (Boreham Wood, England) "Fire Research 1964," London: *Her Majesty's Stationery Office*

The Directors' annual review of work at the Fire Research Establishment, Boreham Woods, in 1964 is a worthy successor to the splendid summaries of previous years. [Fire Research Abstracts and Reviews *7*, 142 (1965).] This reviewer is again impressed by the clarity with which individual research and developmental topics are presented, by the high quality of the work, by the extension of investigations into new areas of signifiance and by the up-dating of "well-established" information. There is little doubt that the scale of operation of the Fire Research Establishment is sufficiently large to attract a competent group of research men, ably directed and supplied with adequate facilities. As a consequence, the output, as measured by useful inventions, correlations, and general advancement of the state-of-the-art, meets very high standards, indeed.

Of particular interest to our readers are the results of Modeling Tests in a long series of experiments dealing with venting of fires in single-story buildings, entrainment of air by flames, and with merging of flames. This work is best commented on by quoting the evaluations of the Committee on The Modeling of Fires (Professor M. W. Thring, *Chairman*): ". . . we have repeatedly emphasized the necessity of directing research towards understanding what is happening in a fire. This requires that the various rate-controlling processes and the ranges over which they are important must be identified, for example, the effects of ventilation and fuel load on the rate of burning in compartments of various sizes and shapes. Only by this approach can it be reasonably certain that the results on small-scale experiments are valid on full scale or can be applied with any confidence to actual problems."

"These principles are supported by the increasing number of occasions on which the predictions based on research using models are being verified on full scale or in practice. Instances of this are the agreement between the predicted and actual safe separation distances between burning timber stacks and nearby property, and predicted and actual conditions under which flames merge. Perhaps the most striking example yet is the work on the venting of fires in their early stages by automatic ventilators. We commented last year on the satisfactory agreement between the prediction of the laboratory work and the conditions found in an actual fire at the factory of Vauxhall Motors Ltd. at Luton, where ventilators had operated. During the current year, additional work has been carried out on the use of plastics rooflights of low melting points to vent and hence control much larger fires. This required experiments on full scale and the agreement between experiment and calculations has given additional confirmation that the data obtained from the small-scale models can be generally applied to the design of roof-venting systems for single-storey factories . . ."

Other subjects worthy of attention and effectively presented are (a) a concise summary of fire statistics in the United Kingdom, (b) preliminary observations on flames rising vertically along walls or advancing horizontally below combustible ceilings, (c) studies on generation of smoke in diffusion flames, (d) preliminary conclusions on spalling of concrete exposed to high temperatures, (e) possible toxic hazards from the burning of plastic piping, (f) fire resistance of timber columns and structural steels under realistic fire-load conditions, (g) possibility of interfering with the movement of smoke in buildings, etc. These and other subjects related to fires are approached with a desire to understand the relationships among variables and to present information in such a way that legitimate, quantitative design information can be extracted.

The staff, during the course of the year, presented 45 lectures, published 26 papers in professional journals, and issued 46 Fire Research Notes—a notable contribution to the slim storehouse of reliable information on fire behavior.

Subject Headings: ***Fire research, in United Kingdom.***

W. G. Berl

Directory of Forest Fire Research Projects (Forest Fire Research Institute, Ottawa, Canada) approx. 200 pp., Dept. of Forestry Publication No. 1129. 1965.

This very useful directory provides a listing and single-page summary of Canadian Forest Fire research projects. The two hundred odd projects are divided into active and completed work and then subdivided according to the subject listing given below. Seven pieces of information are given for each project: (1) The Oxford Decimal Classification, (2) Titles, (3) Purpose and Status, (4) Year Started, (5) Expected Completion Date, (6) Expected Availability of Results and Reports, (7) Project Leaders. In addition, an address for inquiries is given. Cross references are provided by subject and sponsoring organization.

It is similar in intent and content to the *Directory of Fire Research in the United States*, published by the Committee on Fire Research of the National Academy of Sciences—National Research Council (see FRAR 7–1, p. 27).

As can be seen from the list of projects given below, the breadth of the research is impressive, although, as with the United States, fire studies in basic research forms only a very minor section.

NUMERICAL LISTING OF PROJECTS

Prevention—Prev.; Detection—Det.; Presuppression—Pres.;

Suppression—Sup.; Miscellaneous—Misc.

Active—A; Completed—C

Project Number	Description
1	Wetting agents—Sup.–A
2	Dew—Pres.–A
3	Drought index table—Pres.–A
4	Microclimate—Pres.–C
5	Forest fire danger tables—Pres.–C
6	Forest fire danger tables—Pres.–C
7	Mildew-proofers—Sup.–A
8	Unlined linen hose—Sup.–A

Project Number	Description
9	Back-pack pumps—Sup.–C
10	Nocturnal relative humidity—Pres.–A
11	Microclimate—Pres.–C
12	Forest fire danger manual—Pres.–C
13	Smoke generators—Det.–A
14	Forest fire danger tables—Pres.–C
15	Forest fire danger tables—Pres.–C
16	Hose lays—Sup.–A
17	Hose folding device—Sup.–C
18	Portable mast—Det.–C
19	Low relative humidity—fire behaviour—Pres.–A
20	Herbicides and soil sterilants—Pres.–A
21	Forest fuel types—Pres.–C
22	Lightning—Pres.–A
23	Prescribed burning—Misc.–A
24	Burning rate of conifer needles—Pres.–C
25	Efficiency of prevention activities—Pres.–A
26	Moisture content of conifer needles—Pres.–A
27	Fire prevention requirements—Prev.–A
28	Blueberry production—Misc.–C
29	Aircraft loading device—Sup.–C
30	Slip-on tank pumper unit—Sup.–C
31	Hose washing unit—Sup.–C
32	Wetting agent injector—Sup.–C
33	Para-dropping container—Sup.–C
34	Quick-type hose patch—Sup.–C
35	Water dropping—Sup.–C
36	Wetting agents in water dropping—Sup.–C
37	Forest protection handbook—Pres.–A
38	Forest fire control plan—Pres.–C
39	Radio direction finder—Det.–C
40	Telescopic fire finder—Det.–C
41	Neoprene coated nylon tank—Sup.–C
42	Free dropping water equipment—Sup.C
43	Experimental prescribed burning—Misc.–C
44	Lined hose—Sup.–C
45	Explosives for fire line—Sup.–C
46	Prescribed burning—Misc.–C
47	Hose roller and stenciller—Sup.–C
48	Bentonite—Sup.–C
49	Fire marker—Det.–C
50	Air photo mosaics—Det.–C
51	Fuel-type overlays—Pres.–C
52	Weather modification—Misc.–A

Project Number	Description
53	Fuel-type map—Pres.–C
54	Back-pack tanks—Sup.–A
55	Fire damage appraisal—Misc.–A
56	Aerosol cans—fire cause—Misc.–C
57	Forest fire economics—Misc.–A
58	Forest fire damage—Misc.–A
59	Visual range determination—Det.–C
60	Logging slash—Pres.–C
61	I.B.M. data processing—Misc.–C
62	Forest fire report forms—Misc.–C
63	Forest fire danger instrument—Pres.–A
64	Fire control equipment census—Pres.–C
65	Lookout glasses—Det.–C
66	Pump and hose testing facilities—Sup.–A
67	Solo sprayer-duster—Sup.–A
68	Forest fire protection abstracts—Misc.–A
69	Fire weather forecasts—Pres.–A
70	Inflammability of forest fuels—Misc.–C
71	Mechanical equipment fires—Prev.–C
72	Lopping slash—Pres.–C
73	Training fire fighters—Pres.–C
74	Lightning paths—Misc.–C
75	Slash hazard—Pres.–C
76	One-man helicopters—Sup.–C
77	Fire retardants—Sup.–C
78	Horse pack-frame—Pres.–C
79	Radio carrying case—Det.–C
80	Fire control terms—Misc.–C
81	Cargo dropping—Sup.–C
82	Portable power winch—Misc.–C
83	Airdrive boat—Misc.–C
84	Scope fire finder sight—Det.–C
85	Smoke generator—Det.–C
86	Fire Danger Tables—NWT—Pres.–C
87	Cladonia Hazard Table—Pres.–C
88	Plastic Bags—Misc.–A
89	Water jet drive boat—Misc.–C
90	Streamlining water-drop tanks—Sup.–C
91	Electric trip for water drop—Sup.–C
92	Stearman aerial water drop—Sup.–C
93	Fungi in slash—Pres.–A
94	Forest Fire Res. Conf.—Pres.–C
95	Forestry Hose Specification—Sup.–C
96	Fire Control weather forecast—Pres.–C

Project Number	Description
97	Moisture budget as danger index—Pres.–C
98	Lee slope wind—Pres.–A
99	Forecast for end of drying periods—Pres.–C
100	Conservation knowledge Survey—Prev.–C
101	Hose carton—carrying case—Sup.–A
102	Inflammability of D. fir logging slash—Pres.–C
103	Effect of Slope—Pres.–C
104	Fuel evaluation in B.C.—Pres.–A
105	Martin Mars water drop assessment—Sup.–C
106	Prescribed burn in jack pine—Pres.–C
107	Effect of solar radiation and wind—Pres.–A
108	Fuel weight in different cover types—Pres.–C
109	Laboratory test fires—Pres.–C
110	Seasonal trend in M.C. of green foliage —Pres.–A
111	Inflammability of Christmas trees—Misc.–C
112	Organic soil consumed by fire—Misc.–A
113	Fiberglass cupola—Det.–C
114	"Super Cub" for water drop—Supp.–C
115	Modification—N.B. Danger Table—Pres.–A
116	Pocket danger meter—Pres.–C
117	Description of fire danger research—Pres.–A
118	Oven-drying and Xylene method—Misc.–A
119	Petawawa Fire Control Plan—Pres.–C
120	Hose couplings—Sup.–C
121	Pump testing equipment—Supp.–C
122	Fireline builder—Supp.–C
123	Visible area mapping system—Det.–C
124	Helicopter water drops—Supp.–C
125	Inward turning water drop tanks—Supp.–C
126	Grill for fires camps—Misc.–C
127	Fireguard construction and maintenance—Pres.–C
128	Camping equipment—Misc.–A
129	Foods and cooking equipment—Misc.–A
130	Manual hose winder—Supp.–C
131	Hose laying tool—Supp.–C
132	Lightning strike pattern—Pres.–A
133	Tower map materials—Det.–C
134	Radio publicity—Prev.–C
135	Tower-aircraft visibility comparisons—Det.–C
136	Aircraft vs. towers—Det.–C
137	Revision slash hazard tables—Pres.–A
138	Revision quick-drying hazard tables—Pres.–A
139	Recording rate of fire spread—Pres.–A
140	Air tanker-bentonite—Supp.–A

Project Number	Description
141	I.B.M. fire report forms—Misc.–A
142	Variations in R.H. with inversions—Pres.–A
143	Fuel type classifications, T.F.L. #1—Pres.–A
144	More efficient "water thief"—Supp.–C
145	Forest fire danger forecasts—Pres.–C
146	Project conservation—Prev.–C
147	Fire tolerance of trees—Misc.–A
148	Suction hose strainer—Supp.–C
149	Prescribed burns in hardwoods—Misc.–A
150	Airborne infra-red sensory equipment—Det.–C
151	Portable steam cooker—Misc.–C
152	Testing 2 cycle engine oils—Supp.–C
153	Forest Fire Control Standards for B.C.—Misc.–A
154	Use of crawler tractors—Supp.–C
155	Fire homing devices—Det.–C
156	Fire behaviour relationships—Misc.–A
157	Fire control research index—Misc.–A
158	Railroad fires in B.C.—Prev.–C
159	Non-metal containers for flammable fluids—Prev.–A
160	Training aids—Pres.–A
161	Power saw fire extinguishers—Supp.–A
162	Power saw originated fires—Prev.–A
163	Public Information Services—Prev.–C
164	Controlled burns in Newfoundland—Misc.–A
165	'Sferics investigation—Det.–A
166	Testing 'sferics equipment—Det.—A
167	Effects of various factors on water drops—Supp.–C
168	Guides for burning logging slash—Pres.–A
169	Models for economic standards—Misc.–A
170	Cost analysis, lookout vs. aircraft—Det.–C
171	Hose dryer—Supp.–A
172	Observation of going fires—Pres.–A
173	Use of aircraft in fire control—Misc–A
174	Gunsights for lookout alidades—Det.–A
175	Refresher courses in suppression—Pres.–A
176	New type rain gauge—Pres.–A
177	Williamson fire detector—Det.–A
178	Hose coupling gauge—Supp.–C
179	Friction losses in Gelgard—Supp.–A
180	Suction hose strainer—Supp.–C
181	Repairing covers for back-pack tanks—Supp.–C
182	Fire tower maps—Det.–C
183	Fire dynamics—Pres.–A
184	Controlled burns in jack pine slash—Pres.–A

Project Number	Description
185	Drying and wetting rates of duff layers—Pres.–A
186	Evaluating fire danger rating in Man.—Sask.—Pres.–A
187	Fuel types in Saskatchewan—Pres.–A
188	Organic moisture studies in Manitoba—Pres.–A
189	Prescribed burns for seedbed preparation—Misc.–A
190	Fire Research problems in Alberta—Misc.–C
191	Slash quantities—Alberta—Pres.–A
192	Physical qualities of slash—Alberta—Pres.–A
193	Slash flammability—Alberta—Pres.–A
194	Evaluating fire danger rating—Alberta—Pres.–A
195	Lodgepole fuel studies—Alberta—Pres.–A
196	Guy line marker—Misc.–A
197	Portable power winch—Misc.–A
198	Portable windsocks—Misc.–A
199	Weather forecasts—Maritimes—Pres.–A
200	Evaluating weather stations—Maritimes—Pres.–A
201	Infra-red scanner—Supp.–A

CROSS REFERENCE BY SUBJECTS

(Note: One project may appear under several headings)

A. *Prevention*

(1) *Socialogical*

a. Studies of human fire causes.
Active projects Nos. 27, 162
Completed projects Nos. 56, 71, 158

b. Education and propaganda.
Active projects Nos. 25, 27, 162, 199
Completed projects Nos. 94, 100, 134, 146

c. Fire laws.
Nil

(2) *Physical*

a. Equipment safeguards.
Active projects Nos. 159, 161, 162
Completed projects Nos. 56, 71, 158

b. Hazard reduction.
Active projects No. 23, 93
Completed projects No. 28, 111

c. Firebreaks.
Active project No. 20
Completed project No. 127

d. Weather modification and lightning studies.
Active projects Nos. 52, 165
Completed project No. 74

B. *Detection*

(1) *Discovery* (equipment and techniques)

a. Fixed lookouts.
Active projects Nos. 13, 165, 166, 174
Completed projects Nos. 18, 40, 59, 65, 84, 85, 113, 123, 133, 135, 136, 170, 182

b. Aerial patrol.
Active projects Nos. 173, 201
Completed projects Nos. 50, 85, 135, 136, 150, 170

c. Surface patrol and public reports.
Active project No. 177
Completed project No. nil

d. Location marking.
Active projects Nos. nil
Completed projects Nos. 39, 49, 50, 155

(2) *Cold trailing*

Active projects Nos. 177, 201
Completed project nil

(3) *Communications* (equipment and techniques)

Active projects nil
Completed project No. 79

C. *Presuppression*

(1) *Meteorological* (equipment and techniques)

a. Fire danger studies.
Active projects Nos. 2, 3, 10, 19, 25, 26, 63, 88, 107, 110, 112, 115, 117, 137, 138, 142, 186, 188, 200
Completed projects Nos. 4, 5, 6, 11, 12, 14, 15, 24, 70, 86, 87, 97, 99, 109, 116

b. Lightning and precipitation studies.
Active projects Nos. 22, 52, 132, 165, 166
Completed project No. 74

c. Weather forecasting.
Active projects Nos. 69, 199
Completed projects Nos. 96, 99, 145

(2) *Fire dynamics and behavior*

Active projects Nos. 19, 26, 98, 107, 112, 139, 143, 147, 149, 156, 172, 186, 201
Completed projects Nos. 43, 70, 102, 103, 106, 109, 111

(3) *Fuel studies*

Active projects Nos. 26, 93, 104, 107, 110, 112, 143, 149, 172, 187, 188, 191, 192
Completed projects Nos. 21, 51, 53, 60, 70, 75, 102, 108

(4) *Personnel training and labour supply*

Active projects Nos. 37, 160, 175
Completed projects Nos. 73, 94

(5) *Hazard reduction*

Active projects Nos. 20, 23, 93, 149, 164, 168, 192
Completed projects Nos. 28, 60, 72, 75, 106, 127

(6) *Fire control planning*

Active project No. 37
Completed projects Nos. 38, 73, 119

D. *Suppression*

(1) *Equipment and tools* (and techniques for their use)

a. For application of water, chemicals, retardants.
Active projects Nos. 1, 7, 8, 16, 54, 66, 67, 101, 140, 161, 171, 173
Completed projects Nos. 9, 17, 30, 31, 32, 33, 34, 35, 36, 41, 42, 44, 47, 48, 64, 73, 77, 90, 91, 92, 95, 105, 114, 120, 121, 124, 125, 130, 131, 144, 148, 152, 167, 178, 180, 181
b. For fire-line building.
Active projects Nos. nil
Completed projects Nos. 45, 64, 73, 122, 154
c. For camping, feeding, transport, communication.
Active projects Nos. 128, 129, 140, 173
Completed projects Nos. 29, 33, 64, 73, 76, 78, 79, 81, 82, 83, 89, 126, 151

(2) *Suppression operations* (strategy, tactics, safety)

Active projects Nos. 140, 173
Completed projects Nos. 73, 119, 154

E. *Miscellaneous*

(1) *Fire reports and other data*

Active projects Nos. 55, 61, 141
Completed projects Nos. 62

(2) *Standards, economics, damage appraisal*

Active projects Nos. 55, 57, 58, 147, 153, 169
Completed projects Nos. 170, 190

(3) *Uses of fire* (for silviculture, sanitation, hazard reduction etc.)

Active projects Nos. 23, 112, 143, 147, 149, 164, 168, 189
Completed projects Nos. 28, 43, 46, 106

(4) *Research equipment and techniques*

Active projects Nos. 13, 63, 66, 88, 117, 118, 139, 157, 166, 176, 201
Completed projects Nos. 12, 18, 43, 85, 109, 120, 121, 123

(5) *Meterology and weather modification*

Active projects Nos. 52, 69, 98, 142, 156, 165, 166, 176
Completed projects Nos. 4, 11, 74, 96, 99, 145

(6) *Bibliography, abstracts, glossaries, information retrieval*

Active projects Nos. 68, 157
Completed project No. 80

(7) *Multi-purpose equipment*

Active projects Nos. 88, 128, 129, 159, 173, 196, 197, 198
Completed projects Nos. 29, 64, 76, 78, 82, 83, 89, 151, 152, 154

ORGANIZATIONS SUBMITTING PROJECT REPORTS

	Project Numbers									
Name	Active						Completed			
Department of Forestry	1	2	3	7	8	10	4	5	6	9
	13	16	19	20	22	23	11	12	14	15
	25	26	54	55	57	58	17	18	21	24
	63	66	67	68	88	101	43	56	61	62
	104	107	110	112	115	117	64	65	86	87
	118	137	138	139	147	168	102	103	105	106
	169	172	173	177	183	184	108	109	111	116
	185	186	187	188	189	191	119	120	170	190
	192	193	194	195	199	200				
	201									
National Parks Branch, Dept. NA & NR							78	79		
Meteorological Branch, Dept. of Transport	52	165								
National Research Council							44	77	95	130
							131			
Newfoundland, Dept. of Mines & Resources							46			
Nova Scotia, Dept. of Lands & Forests	179						47	144	148	178
							180	181	182	
New Brunswick, Dept. of Land & Mines	132	174	175	176			133	134	145	146
Ontario, Dept. of Lands & Forests	27	37	128	129	149	171	28	29	30	31
							32	33	34	35
							36	38	39	40
							41	42	80	81
							90	91	121	122
							123	124	125	126
							127	150	151	152
Manitoba, Dept, of Mines & Resources							48	49	53	167
Saskatchewan, Dept. of Natural Resources	69									
Alberta, Dept. of Lands & Forests	196	197	198				82	83	84	89
British Columbia, Forest Service	98	140	141	142	153	156	50	51	60	97
	157	166					99	154	155	158
Batineau Forest Protection Assn.							59			
Brice Brothers Forest Protective Assn.							45	135		
St. Maurice Forest Protective Assn.							113	114		
Newfoundland Forest Protection Assn.	164									
Manusapscal Forest Research Station							72			
Pulp & Paper Research Inst. of Canada							71	74	75	
Laval University Forest Res. Foundation							70			
University of Toronto	93									
Canadian Pulp & Paper Assn., Woodlands Sec.	159	160	161	162			94			
Canadian Forestry Association							100			
Canadian Institute of Forestry							163			
World Meteorological Association							96			
Canadian International Paper Co.							76	85	92	136
Consolidated Paper Co.							73			
Celgar Limited	143									

Subject Headings: ***Canada, fire research in; Forest fire research, in Canada; Directory of Canadian forest fire research.***

R. M. Fristrom

Proceedings of the First/Second Symposia on Combustion. The Combustion Institute, 1965, Union Trust Building, Pittsburg Pennsylvania 15219. $14.00

The Combustion Institute is to be congratulated on reprinting these papers from the two symposia held in 1928 and 1937. A number of the papers are of current interest and several of them are classic works in combustion science. A list of the titles is given below:

CONTENTS

First Symposium

Introduction—George Granger Brown
Diffusion Flames—S. P. Burke, T. E. Schumann
Measurement of the Temperatures of Stationary Flames—A. G. Loomis, G. St. J. Perrott
Radiant Energy from Flames—W. E. Garner
Bunsen Flames of Unusual Structure—Francis A. Smith, Samual F. Pickering
The Flicker of Luminous Flames—D. S. Chamberlin, A. Rose
Flame Speed of Hydrogen Sulfide—D. S. Chamberlin, D. R. Clarker
The Gaseous Explosive Reaction at Constant Pressure—F. W. Stevens
The "Normal" Propagation of Flame in Gaseous Mixtures—William Payman
Gaseous Explosions. VI. Flame and Pressure Propagation—J. V. Hunn, George Granger Brown
Some Flame Characteristics of Motor Fuels—G. B. Maxwell, R. V. Wheeler
Importance of Mixture Ratio in Rating Fuels for Knock—John M. Campbell, Wheeler G. Lovell, T. A. Boyd
Action of Accelerators and Inhibitors upon the Oxidation of Liquid Hydrocarbons—T. E. Laying, M. A. Youker
Partial Oxidation of Methane and Ethane in the Presence of Catalysts—T. E. Laying, Roy Soukup
Relative Rates of Reaction of Olefins in Combustion with Oxygen and in Oxidation with Aqueous Potassium Permanganate—Harold S. Davis

Second Symposium

Introduction to the Symposium. The Development of Combustion Research and the Present Outlook—Bernard Lewis
Chemical Action in the Glow Discharge. XV. Reactions Preceding Ignition—A. Keith Brewer
The Mechanism of Ignition by Electric Discharges—B. W. Bradford, G. I. Finch
The Ignition of Gases by Local Sources—H. G. Landau
Ignition Regions of Hydrocarbons—D. T. A. Townend
The Slow Combustion of Gaseous Paraffins, Especially Propane—Robert N. Pease
Observations on the Oxidation of Propane—E. J. Harris, A. Egerton
The Oxidation of Hydrocarbons at High Pressure—D. M. Newitt
The Mechanism of the Combustion of Hydrocarbons—Guenther von Elbe, Bernard Lewis
The Mechanism of the Combustion of Hydrogen—Louis S. Kassel
Theory of Flame Propagation—Bernard Lewis, Guenther von Elbe
Problems in Flame Propagation—H. F. Coward, W. Payman
The Measurement of Flame Speeds—E. F. Fiock, C. F. Marvin, Jr.
Problems of Stationary Flames—Francis A. Smith
Comparison of Ideal and Actual Combustion Temperatures and Pressures: Anomalous Effects; Gas Vibrations—Guenther von Elbe, Bernard Lewis
Flame Temperatures and Vertical Gradients in Natural-Gas Flames—H. H. Kaveler, Bernard Lewis
Flame Temperatures in Engines—A. E. Hershey
A Mollier Diagram for the Internal-Combustion Engine—H. C. Hottel, J. E. Eberhardt
Inflammation Limits and their Practical Application in Hazardous Industrial Operations—G. W. Jones
A Thermodynamic Analysis of the Rate of Rise of Pressure in the Otto Cycle—George Granger Brown
Chemistry of Otto-cycle Engine Combustion—Harold A. Beatty
The Combustion Process in the Diesel Engine—G. D. Boerlage, J. J. Broeze

Factors Controlling Diesel Engine Performance—A. M. Rothrock, R. F. Selden
Methods of Rating Diesel Fuels—P. H. Schweitzer
The Knock Rating of Motor Fuels—H. W. Best
Molecular Structure of Hydrocarbons and Engine Knock—Wheeler G. Lovell, John M. Campbell

Subject Headings: ***Combustion symposia; Symposium, on combustion.***

R. M. Fristrom

"*Manual of Firemanship—A Survey of the Science of Firefighting. Part 1: Theory of Firefighting and Equipment.*" Home Office (Fire Service Department), London, England (1963)*

This manual is part one of a nine-part series of a comprehensive textbook on firemanship used for training in the United Kingdom. The volume (388 pages) deals with the theory of fire fighting and current fire-fighting equipment and covers the following subjects: (1) physics and chemistry of combustion, (2) extinguishing fires, (3) methods used by the fire service, (4) hose, (5) hose fittings, (6) ladders, (7) ropes and lines, (8) hand and stirrup pumps, (9) portable chemical fire extinguishers, (10) foam and foam-making equipment, (11) breathing apparatus, (12) resuscitation, (13) small gear.

The manual begins with a elementary treatment of the physics and chemistry of combustion. Starting with the properties of matter—divided into two sections, physical and chemical—the discussion emphasizes the nature of chemical and heat energy using various chemical oxidative reactions as examples. It then treats the necessary conditions for combustion, which is defined as a chemical reaction accompanied by light and heat, the three requirements being: (1) combustible, (2) oxygen, and (3) heat. Definitions of some of the common combustion terms are given, e.g., spontaneous ignition temperature, fire point, flash point, limits of inflammability, etc. Spontaneous combustion is described and the combustion of carbon, oxidizable metals, explosives, solid fuels including dusts, hydrocarbons, liquids, and gases are considered. The discussion is extensive and the following tables are included: (1) the atomic weights of the common chemical elements, (2) valencies of common radicals, (3) common and chemical names and formulae of typical household chemicals, (4) the composition of various combustible solids such as coal, coke, wood, (5) the composition, flash point, calorific values and spontaneous ignition temperatures of various liquid fuels, (6) the composition, calorific value, limits of flammability, and spontaneous ignition temperature of common gaseous fuels. A brief description of the structure of hydrocarbon flames burning as a gas mixture in air is included in the technical discussion.

Fire extinguishment is described as the process of eliminating one or more of the three necessary conditions for combustion. These are described as (1) starvation, or limitation of the combustible, (2) smothering, or limitation of the oxidizer, and (3) cooling, or the limitation of temperature by removal of heat. The cooling principle of fire extinction is described as the most commonly employed method and, therefore, the use of water as a fire-extinguishing agent is recommended as the most useful for general purpose fire fighting.

With completion of the theoretical aspects of combustion and the principles of

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* British Information Services, 845 3rd Ave., New York 22. Paper bound $1.60; cloth bound $3.00.

fire extinguishment, various fire-fighting methods are considered. Here the main aim of fire fighting is given—namely, to save life, secondly, to extinguish fire. A discussion of the appropriate fire fighting methods applicable to the various classes of fires is given. The role and importance of special materials for lifesaving and fire fighting is emphasized. The specialized equipment in use in the United Kingdom for these purposes is then discussed.

The chapter on hose is quite detailed, providing British specifications for both pressure and suction hose, the history of hose development from leather to rubber and modern synthetics. Details of hose construction care and maintenance, methods of storing, methods of repairing, results of tests on drying, and periodic tests to assure operationability are given.

The chapter on hose fittings is even more detailed, covering the wide variety of standard British and American quick-coupling devices, screw-type couplings, branches and nozzles, hydrants, valves, breechings, adaptors, and other plumbing equipment employed with hoses.

The chapter on ladders is comprehensive and covers fixed length, extension, hook, and scaling ladders. Proper and approved methods of using ladders, maintenance and testing of ladders from a practical viewpoint are stressed.

The chapter on ropes and lines covers British specifications, materials of construction, methods of manufacture, and correct methods of using ropes and lines for rescue, lowering, escape, guying, and other applications. Care and maintenance of ropes, methods of inspecting for defects, tests to assure operationability are emphasized.

The chapter on hand and stirrup pumps covers theory of operation, description of various types of pumps, and a discussion of advantages and disadvantages of each type of pump. Cross-section drawings aid in showing the pumping mechanism and mode of operation.

The chapter on portable chemical fire extinguishers covers the entire field from soda acid, foam, carbon dioxide, dry powder, to halogenated hydrocarbon types. A detailed description accompanied by schematic illustrations is provided for each type of extinguisher. Stress is laid on the proper use and maintenance, periodic inspection, and knowledge of the advantages and disadvantages of each type.

Foam and foam-making equipment is divided into two sections (1) chemical and (2) mechanical. Both types of foams are described and tables provided to show the foam delivered for various water-flow rates and hose and nozzle sizes. Illustrative schematic drawings are used profusely to clarify the modes of equipment functioning.

The breathing-apparatus chapter covers the elementary physiology of respiration and describes the historical development of artificial-breathing apparatus to the modern oxygen-breathing apparatus. It includes details of assembly of compressed-air, self-contained, and regenerative types of breathing devices. It gives examples to enable one to calculate the working duration of each type of unit under various oxygen consumption conditions. Tables are provided to show the oxygen consumption rates under varying degrees of effort. Design details are shown in disassembly views and the proper method of affixing and working each unit is shown in photographs.

The chapter on resuscitation covers principles of inducing resumption of normal respiration in a casualty. It covers both manual and mechanical techniques, and describes hand-controlled, lung-controlled, and fully automatic units. For rapid emergency use, the mouth-to-mouth method is recommended.

The last chapter covers small gear and miscellaneous equipment, dealing with hand tools such as axes, hooks, crowbars, bending bars, and concluding with lamps and lighting equipment.

This manual constitutes an excellent survey of the currently available equipment and approved methods for fire fighting. It is highly recommended for the fire-fighting trainee and can serve as an ideal reference work for the practical daily operations of urban fire-department personnel.

Subject Headings: ***Fire-fighting manual; Manual, of fire fighting.***

D. Dembrow

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II. High-Energy Propellant Combustion

III. Effect of Aerodynamics on Heterogeneous Combustion

IV. Condensation

Subject Headings: ***Combustion, heterogeneous; Heterogeneous combustion.***

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INDEX OF AUTHORS

INDEX OF SUBJECTS

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Volume 8 Number 2

Fire Research Abstracts and Reviews

Committee on Fire Research
Division of Engineering
National Academy of Sciences—National Research Council

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
Washington, D. C.
1966

FIRE RESEARCH ABSTRACTS AND REVIEWS is published three times a year by the Committee on Fire Research of the National Academy of Sciences—National Research Council, 2101 Constitution Avenue, Washington D. C. It is supported by the Office of Civil Defense of the Department of the Army, the U. S. Department of Agriculture through the Forest Service, the National Science Foundation, and the National Bureau of Standards. The opinions expressed by contributors are their own and are not necessarily those of the Committee on Fire Research.

Library of Congress Catalog Card Number 58-60075 rev

Available without charge from the
Office of the Committee on Fire Research
National Academy of Sciences—National Research Council
Washington, D. C. 20418

FOREWORD

This issue begins with an interesting essay by Professor B. R. Morton, which gives a lucid discussion of the relation between meteorology and fire problems. It is directed toward the nonspecialist research worker and provides a good review for those outside this area.

Recently, two interesting meetings have been held. "Pyrolysis" was the topic of a technical meeting held in Washington, D. C. on January 7. The morning was spent in reviewing the status of pyrolysis research related to char penetration in wood, hybrid rocket combustion, and heat shield ablation and the afternoon in discussing various aspects of cellulose pyrolysis. This meeting was sponsored by the Committee on Fire Research of the National Academy of Sciences—National Research Council and was organized by Professor P. L. Blackshear, Jr. Civil Defense fire problems were discussed at a meeting of the contractors of the Office of Civil Defense held March 7–11 at Asilomar, California. This meeting was organized by Dr. M. L. Gibbons.

Two forthcoming meetings are of particular interest to fire research workers. On June 23 and 24 the Committee on Fire Research is sponsoring a seminar on "Inhibition of Combustion by Chemical Means." This meeting is being organized by Dr. W. G. Berl* and will be held at the Applied Physics Laboratory, The Johns Hopkins University. The second meeting, which has been mentioned in a previous issue of *Fire Research Abstracts and Reviews*, is the Eleventh Symposium (International) on Combustion to be held at the University of California, Berkeley, California, August 14–20. Dr. A. Berlad** has organized this meeting and sessions on fire research are planned.

A report seems appropriate concerning our proposal† for mitigating discrimination against fire research studies. Many of these manuscripts fitted only poorly onto the Proscrustean bed provided by the existing hierarchy of journals. Therefore, it was proposed to use *Fire Research Abstracts and Reviews* as a clearinghouse and medium for recording or publishing such manuscripts. There has been only a trickle of inquiries regarding this offer. We think this is a good sign which indicates that the present publication situation is reasonably satisfactory. The policy will remain in effect with the expectation that it will be used occasionally and the hope that it will be only rarely necessary. One minor modification seems desirable. The American Documentation Institute Auxillary Publication Project of the Library of Congress†† will be used as the ultimate repository for manuscripts. This will provide a more general, long-lived, and accessible source of material than is possible using the slim resources of *Fire Research Abstracts and Reviews*.

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† *Fire Research Abstracts and Reviews*, 7, No. 3, Foreword, (1965).

†† American Documentation Institute, Auxillary Publication Project, Library of Congress, Washington, D. C. 20036.

CONTENTS

Volume 8 Number 2

V. Combustion Principles

VI. Radiation

VII. Suppression of Combustion

VIII. Model Studies and Scaling Laws

IX. Atomization of Liquids

X. Meteorological Interactions

XI. Operational Research Principles Applied to Fire Research

XII. Instrumentation

XIII. Fire-Fighting Techniques, Equipment

XIV. Miscellaneous

BOOKS, MEETINGS, NEW JOURNALS

Books

Meetings

New Journals

REVIEWS

Fire and Wind*

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Fire is not a normal part of meteorology, but local conditions of wind, temperature, and humidity may play a critical role in determining the progress of large fires, and these fires may in their turn produce fire tornadoes with wind velocities exceeding 100 miles per hour. Although only limited theoretical and experimental progress has been made with fire problems, they are now attracting more research attention. The following account describes some important features of fires burning in the open, and some of the problems at present being studied.

FIRE

The heated wax of a burning candle melts and is drawn as vapour into the flame; it burns there on mixture with ambient air, and part of the heat liberated is radiated back to the wax stock. These are the typical elements of fire: a flame or combustion region where fuel vapour mixes with oxygen and burns; a solid or liquid fuel-complex from which vapour is generated by heat; and radiative or other heat transfer from flame to fuel. The essential feature of fire is this thermal coupling between flame and fuel, and the rate of burning is governed primarily by the return flux of heat. Thus a bunsen flame is *not* a fire, as the rate of burning is controlled arbitrarily from the gas tap; but a (rather artificial) "bunsen fire" might be produced by using the output of a radiometer placed near the flame to control the opening of the gas tap.

The rate at which fuel vapour burns is very nearly the rate of intimate mixture with air, as most chemical reactions involved in combustion proceed rapidly to equilibrium. Thus the air flow in and around the flame and the dynamics of mixture determine the local rate of heat generation, and in a still atmosphere these are produced wholly by buoyant convection. Small flames have laminar flow, and burning is confined to the flame envelope where fuel vapour mixes with air by molecular diffusion. Flames of medium size are unsteady. And large flames are generally turbulent, with correspondingly more vigorous mixture of air throughout the flame by eddies of flame scale and smaller, and with fluctuating combustion throughout the flame interior. Fire plumes, consisting of the flame and its plume of hot combustion products, are normally turbulent when a square metre or more of fuel is committed.

In the absence of wind, fire plumes rise vertically above their burning fuel. Typical upward velocities in the plume from a bonfire, for example, are a few metres per second, decreasing rather slowly with height. Turbulent plumes generate a slow inflow of ambient air at all heights, with velocities at the plume edge an order of magnitude smaller than mean upward velocities; but near the ground a

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* Reprinted from Science Progress *52*, 249–269 (1964), by permission of the publisher.

stronger inflow may be driven by the radial pressure field. Velocities associated with stronger fire plumes increase approximately as the one-third power of the total rate of heat output. These thermally induced velocities tend to be small relative to natural winds, except for large fires. Thus a bonfire is greatly influenced by external wind; the fire plume is swept downwind, and the burning rate is increased by gusty intrusions of fresh air. (This increase may be specially marked in a bonfire, as the fuel is often so lightly packed that much of the flame is within the fuel complex.) There are two effects of wind on a *stationary* fire in a fixed region of fuel: the combustion rate in the flame is increased by more rapid mixture of air and fuel vapour; and the thermal flux between flame and fuel may be altered by a change in flame shape.

Weak winds always deflect the upper parts of a fire plume, but have little effect on a stationary fire until they exceed a velocity that is critical for the particular fire, and characteristic of convective velocities produced by the fire under calm conditions. Except for very large fires, critical velocities will correspond with light winds in the atmosphere.

Winds play a much more important role in *propagating* fires, where a narrow burning front propagates across an extensive area of fuel, as in grass or forest fires. Such fires spread slowly in the absence of wind, but as the wind rises the local rate of burning increases and in addition burning brands are carried aloft and deposited downwind where they may start fresh fire centers if fuel conditions are suitable. Fire branding of this kind can be effective over a number of miles, and it greatly increases the danger of rapid fire spread.

The foregoing comments apply to fires of small or moderate scale burning finely divided fuel in the open, and notable variations in fire behaviour may be caused by more complicated geometric structure of the fuel. Thus, when fire propagates through grass the fuel will burn rapidly and completely in the short time taken by the fire front to pass. But the fuel structure of a forest is more complex: at the ground there is the litter of dry leaves, twigs, etc.; the layer above this contains the brush or undergrowth of shrubs and young trees; in the next layer most of the fuel is in heavy trunks, inaccessible to rapid burning; and the uppermost layer consists of the crowns of the trees with smaller branches and many twigs and leaves. Some forest fires consume the readily available fuel at all levels as they advance, leaving a skeleton forest of blackened trunks and limbs. Others burn less completely, because of weaker thermal coupling between the layers; thus in a forest with dry upper foliage and low undergrowth, a fire may 'crown' and race ahead in the uppermost layer with remarkably little damage to lower levels. In the evening as the humidity increases and temperatures fall, the fire may drop from the crowns because it no longer generates enough heat to propagate there, and it may then burn quietly in the lower levels with only occasional local crowning and damage to the foliage of larger trees. At the other extreme, periodic controlled burning is being used in the United States to keep down undergrowth and prevent the establishment of undesired species in well-established open woods. Low undergrowth can be destroyed without damage to the main stand of trees by rapid runs of fire through the undergrowth under carefully selected conditions. Completely different types of behaviour are produced by the constraints imposed on enclosure or building fires; thus the rate of burning in a room after the fire has taken hold depends very little on the contents ('fuel loading') of the room, and is determined by the air flow through open windows or doors (and this is analogous to weir flow in hydraulics).

Fires in which the length scale of the fuel elements (e.g. room diagonals in a house) are comparable with the length scale of the fire or flame are much more difficult to handle theoretically than those in which the fuel may be treated approximately as homogeneous. Hence the most rewarding cases to treat are likely to be those with homogeneous fuels, such as *pool fires* on shallow pools of inflammable liquid, and very large fires in fuels such as grass, scrub and forest, where fuel scale is dwarfed by fire size. Disastrous city fires involving large areas of dense building must be included also.

CONFLAGRATIONS, FIRE STORMS AND BLOW-UP FIRES

Large fires involve major economic loss and often loss of life, and they represent a hazard by no means within present methods of control. A survey of particular cases will help to establish certain typical features of these fires.

There have been many disastrous city fires. Some have started by accident and resisted early attempts at control, like the Great Fire of London (1666) which in three days destroyed most of the old city within the wall. Others have followed earthquakes, like the San Francisco fire (1906) which burned for three days, or the Tokyo fire (1923) which destroyed about five square miles of close wooden building in as many hours and finally burned twenty-five square miles. And city fires have always followed war, as when Moscow burned for five days in 1812, or more recently when a central area of about five square miles of Hamburg was utterly consumed by fire after fire-bombing raids in 1943.

Observation under conditions of massive fire is extremely difficult, but a certain amount of information is available. Thus Pepys noted in his diary* that the wind was blowing strongly from the East on the first day of the Great Fire of London, and that there had been long drought. Seasoned wood is a hydroscopic fuel that ignites and burns best when dry, that is after conditions of low humidity and above average temperatures; and such conditions are common for large fires in both forest and city. Pepys noted also that there was much movement, with people carrying out household goods from threatened houses throughout the main period of the fire. Especially in the later stages, the fire was fought strongly by the demolition of houses to produce firebreaks.

A valuable eye-witness account† has been given of the fire which followed the 1923 Tokyo earthquake. This fire spread much more rapidly than the Great Fire of London, and some five square miles (roughly a third of the total area involved) was burned in four hours. The rapid burning was undoubtedly due in part to the fact that the fire started after the earthquake with a dozen or more fire-centres about half a mile to a mile apart; but it may have been due also to the relatively lighter fuel loading of the area. Although the city was closely built, the wooden houses were lightly constructed and only one to two stories high, whereas houses in seventeenth-century London would probably have averaged three stories and been much more heavily constructed and furnished. The wind was from the north to north-east at the start of the Tokyo fire, but swung to south to south-east after an hour and increased in velocity to about 45 m.p.h. This change in wind pro-

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* See e.g. *The Diary of Samuel Pepys*, edited by H. B. Wheatley, Vol. 5 (1895), also quoted by Bryant (1949) in Chapter 14.

† Presented by Boris Laiming to the NAS–NRC Study Group on Fire Problems held at Woods Hole, Massachusetts, in 1961.

duced a clear change in the direction of propagation of the individual fires, by this time burning in a series of fronts between which it was possible to walk for some time. Even when the fire was burning strongly it would sometimes run down the buildings on one side of a street without igniting those on the other side.

A description of the Hamburg fire and other wartime fires has been given by Bond (1946, 1955). Buildings in Hamburg were typically six-storied with brick or masonry walls, but with heavy interior woodwork and much furniture. The city was raided heavily after about a month of unusually dry weather. In spite of the lack of fire communication through the dividing walls, the bombing was so intensive that it has been estimated that within twenty minutes of the start of the raid two-thirds of the buildings in a central area of 4·5 square miles were on fire. At this stage the individual fires merged into a single mass fire which covered about five square miles and burned furiously for three hours. Temperatures in the mass fire were above ignition level so that it acted as a great furnace, and no trace of combustible material was left in the area after the fire. A huge fire plume was generated, described by flyers as stormy at 13,000 feet; and at ground level near the edge of the fire men were swept off their feet, cars rolled over, and trees up to three feet in diameter uprooted by winds of hurricane force, while induced winds exceeding 30 m.p.h. were recorded a mile and a half outside the edge of the fire.

These fires differ in type rather than in scale: they may be classified as conflagrations (London, Tokyo) or fire storms (Hamburg). A *conflagration* is characterised by moving fire fronts driven by a strong external wind. A number of fronts may be burning at once, but each will be advancing with the wind into fresh "fuel" leaving burnt-out fuel behind it. A change in wind direction will produce a corresponding change in the direction of propagation of the fronts (Tokyo); it will often be possible to walk between the fronts (Tokyo, and probably London); only a small proportion of the fuel is burning at a time; and islands of unburned fuel may survive the fire. A *fire storm* is produced when many separate fires scattered over a region of fuel interact so that the entire area ignites and burns at the same time. The scale of a fire storm is sufficient to generate very strong induced winds (probably about 100 m.p.h. at the edge of the Hamburg fire) and these dominate any external wind. In fact, fire storms probably develop only in conditions of light wind, though this is not certain as few fire storms have been identified positively. The strong induced inflow into a fire storm prevents any significant outward spread of fire into regions initially unaffected; and the entire inner region is heated to temperatures such as to produce very rapid and very complete burning of all the available fuel. Conflagrations and fire storms are massive fires which are dominated by external and induced winds, respectively. It is not clear whether a fire must exceed a particular critical size and fuel loading to develop into a fire storm.

Forests usually burn in a series of fire fronts. The simplest case is that of a ragged line of fire advancing with the wind and consuming the available fuel as it goes, and the local burning time determines the thickness of the front. With stronger winds the inclined fire plumes carry up burning brands which are deposited ahead to start spot fires in fresh fuel, and these may develop into a broken series of fire fronts extending into the fresh fuel as the fire runs downwind. When the fuel is dry and the wind strong these fires may easily assume the magnitude of conflagrations, and even on flat terrain they can be fought only by backburning or cutting fire breaks so as to deprive the fire of fuel, or by using changes in humidity or weather which may reduce the intensity of the fire to an extent where some control is possible. In mountainous terrain the difficulties of control are even greater because of difficulties of access, and because fire will sweep up wooded inclines carried by its own upflow of heated air.

Blow-up fires, which are the forest equivalent of the fire storm, form a serious hazard of forest fire fighting. When fires develop in depth they may pass their critical state and grow rapidly in intensity with violent burning of an area of fuel; very strong winds are induced, and the fire plume is sufficiently vigorous to carry large firebrands high into the atmosphere, after which they may fall out over a wide area. A special feature of these blow-up fires is their tendency to develop strong rotational flow with a concentrated vortex core. The resulting *fire whirls* or *fire tornadoes* have many of the properties of normal tornadoes except that they are attached to the fire, and in particular they produce thin layers of spiralling inflow near the ground with wind speeds which may reach 100 m.p.h. or more in a large fire whirl. A fire tornado developed during the Poleline Fire in Southern California in 1958. The fire was burning in chaparral, an aromatic scrub which is highly combustible when dry, and the vortex formed in a double line burning operation with an upwind fireline intended for convective control and a downwind fireline to make a firebreak. A United States Forest Service film* shows a ring of flames at the base of the vortex swept into the pattern of rotation, and a flickering core of flame weakly visible through the smoke; it was estimated that this line of flame rose up the core of the vortex to a maximum height of some 2000 feet. This extreme penetration is due to the greatly decreased lateral mixing across the vortex plume, with a consequent decrease in the rate of combustion of ascending fuel vapour.

Any distribution of vorticity present in the atmosphere will be subject to convective amplification in the vigorous fire plumes produced by blow-up fires. This process may be thought of in terms of the stretching of vertical vortex tubes entrained into the fire plume from its environment by the mean motion within the buoyant plume, and it has been shown (Morton, 1963) that the degree of amplification depends on the state of buoyancy of the plume; and it is reasonable to suppose that fire plumes will be more effective than buoyant plumes from simple heat sources because of their extended region of heat release. However, the degree of amplification is probably several orders of magnitude too small for the generation of a fire whirl directly from the background vorticity due to the rotation of the earth, and fire whirls will develop only when the level of the vertical component of vorticity is already high in the environment. An increasing level of ambient voriticity can be produced by precisely the same mechanism when there is persistent strong thermal convection from a strongly heated underlying land surface, and if this vorticity level is sufficiently high when a blow-up occurs then a fire vortex will be generated. It may be noted that strong heating is the prerequisite also for dry fuels and high fire hazard. Thus it might be anticipated that some blow-up fires will develop into fire whirls, and that in particularly hot conditions after long drought there would be a doubly increased likelihood of whirl formation. This raises the question as to whether some or perhaps most fire storms are also fire tornadoes. There seems to be surprisingly little direct evidence on this point. Although the wind velocities for the Hamburg fire storm suggest a fire tornado, there appear to be no supporting statements by pilots who flew through the fire plume, and the question must be regarded as open.

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* This film was shown to the Study Group on Fire Problems at Woods Hole in 1961.

Blow-up fires need not be on a vast scale, and they are actually used in forestry for the controlled burning of brush or scrub when land is being cleared. The fires are set only on still days, and in the spring when the flush of green vegetation is difficult to burn. A firebreak is cut around an area of perhaps twenty acres, and a tractor driven across the area to form a lattice of lines of crushed scrub. The fire is then set with oil at many points in the crushed scrub. The individual spot fires grow independently until their flames reach about head height, and then a strong interaction develops with rapid growth of flame height to perhaps 50 or 60 feet. These fires show little tendency to spread because the induced wind is inwards, and their control is easy when the surrounding scrub is green. Small blow-up fires show little tendency to develop fire whirls, presumably because of their size and because of the unfavorable nature of the conditions generally regarded as suitable for brush burning.

MODELLING FIRE BEHAVIOR

An understanding of fire behaviour requires knowledge of the chemical kinetics of the flame, of the dynamics of fluid transport and mixture, of the radiative and convective heat transport, and of the chemistry of pyrolysis or thermal degradation of the original fuel. Moreover, these physical and chemical aspects of fire are closely interrelated so that, for example, a small change in the character of the fuel may modify the fuel vapour produced by pyrolysis and so in turn change the concentration of unburned carbon particles in the flame with a substantial effect on flame radiation and hence, perhaps, on the rate of burning. This strong coupling of processes of comparable importance makes the development of model theories for fire behaviour difficult, and suggests the use of laboratory scale experiments as the best means of studying fire. However, the difficulties involved in model experiments are almost as great, largely because radiation depends on flame temperature and optical path-length in ways that cannot easily be modelled at the same time as the dynamical features of the problem. A discussion of experimental modelling of radiating hot plumes has been given by Hottel (1961), and some remarks by Spalding (1963) are also relevant.

Although much of the work on fire has been concerned with enclosure fires or empirical studies of special situations, there have been two lines of progress on unenclosed fires. The first has been to treat especially the chemical aspects of the problem in isolation: thus the pyrolysis of cellulose has been studied (see e.g. Broido and Kilzer, 1963), and use can be made of the extensive knowledge of combustion. The aim of this approach is to replace the chemical aspects by simple approximate laws so that the dynamics of the problem can be handled. Thus as a first approximation it can be assumed that a cellulose fuel ignites when the thermal impulse reaches a known critical value (good for intermediate rates of heating), and that the rate of pyrolysis and generation of carbon monoxide and hydrocarbon gases thereafter is constant and proportional to the rate of heating until pyrolysis is complete. Again, that the rate of combustion in the flame is equal to the rate at which fuel gases and oxygen are mixed; and so on. Even with these simplifications the problem remains difficult; some comments may be found in *A Study of Fire Problems* (1961). The second line of progress has been the systematic study of some very simple fire configurations, including pool fires on pans of liquid fuel and propagating fires in long lattices of wood lath. Attention has been concentrated almost entirely on fires in a still environment, and as yet little work has been done on the interesting problem of interactions between induced and external air streams.

When a pool fire burns, back radiation from the flame boils a continuing supply of fuel vapour from the liquid surface, and this fuel in turn burns on mixture with ambient air. Blinov and Khudiakov (1957) have reported an extensive set of experiments on the burning of petrol and various oils in pans of diameter from 0·37 to 22,900 cm. They found that when the pan diameter exceeds about a meter the flame is turbulent, the rate of burning is independent of diameter, and the flame height is approximately two pan diameters. These experiments have been extended with broadly similar results by a number of workers, including Emmons (1961). In spite of the fact that this is the simplest case of fire, a full approximate theory has yet to be given. However, a number of the elements of such a theory are available, and they show how a theory may be synthesized for the case of a turbulent fire plume. The fire plume over a large pool burning in the absence of wind may be considered in three levels: (i) the flame, a region of turbulent combustion at temperatures of order 1000°K; (ii) an intermediate region of falling temperature in which radiation is still important; and (iii) the upper region of buoyant plume where radiation may be neglected. Treatments applicable to region (iii) have been given by Murgai and Emmons (1960) and Morton (1959); they are based on the assumption that the entrainment velocity is proportional to the mean upward velocity in the plume at each level. Murgai (1962) has also given a treatment for region (ii) taking account of radiation, but otherwise assuming small temperature variations in his dynamical treatment. This is not wholly satisfactory, as radiation is important when temperature variations are *large*, and the original entrainment assumption is then invalid; it can, however, be extended by taking the ratio of the entrainment to upward velocity as proportional to (ambient temperature mean plume temperature)$^{1/2}$; and a sound treatment given for the middle region. The method may then be extended to the flame region if simplifying assumptions are made about the combustion reactions; this treatment is being developed at present. Two of the difficulties associated with modeling may be noted here: the effect of radiation depends on the opacity, and on the optical path lengths and hence on the local length scale, so that for radiation modeling the opacity must be varied with the scale length; again, although the entrainment into small fire plumes is due solely to turbulent diffusion, the flow into the lower parts of very large fire plumes is enhanced by radial pressure gradients caused by the high column of hot gas in the lower parts of the plume.

The work on propagating fires is in a more primitive state. Fons and his coworkers (see, e.g., 1963) have developed reproducible propagating fires in "cribs" consisting of standard stacks of wood lath, and some results have been obtained with crib fires. And a greatly simplified model theory for a propagating fire in a homogeneous fuel structure has been described in *A Study of Fire Problems* (1961).

Some of the most interesting work at present is related to fire whirls. Although little information has been published yet, Byram and Martin (1962) are carrying out experiments on swirling pan fire in cylindrical enclosures with tangential air entry, Dessens (1962) has been observing fire whirls over a large set of oil burners in the open, and Morton (1963) has been experimenting with vortex plumes in a rotating tank of water.

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Subject Headings: ***Fire, and meteorology; Meteorology, and fire; Wind, effect on fire.***

ABSTRACTS

I. Ignition Phenomena

Beach, R. (Robin Beach Engineers Associated, Brooklyn, New York) "Preventing Static-Electricity Fires," *Chemical Engineering* **71,** 73–78 (1964); **72,** 63–66 (1965), **72,** 85–88 (1965)

This paper is a series of three articles dealing with various aspects of electrostatically initiated fires or explosions. The first article deals with the necessary conditions for initiating explosions in dusts or vapors of flammable fluids. The properties and explosive limits of selected flammables are presented along with their autoignition temperatures. The author shows by selected industrial examples how the combination of flammable vapors or dusts in air and a mechanism for generating electrostatic charges results in potentially hazardous situations. He cites the equations and shows the procedures for determining the charge that can build up when two insulators having different dielectric constants are pressed into contact and then separated rapidly.

In the second article he gives the equations for calculating the voltage of transferred electric charge and the capacitor for holding the accumulated charge as well as the energy dissipated in a spark discharge. The principal mechanism for developing high electrostatic voltages is rapid separation of two insulators or one insulator and one conductor. Although theoretical values of 100 kV can be attained with separations of only 1 cm, in air a spark-over occurs long before such high voltages are established. The author cites the minimum ignition energy for several flammable mixtures but does not list the threshold values for the materials previously selected. He also lists the dielectric constant series (similar to the electromotive series) for insulators which, with the use of the Coehn equations, enables one to calculate the resultant electrostatic charge and its polarity. Examples are given to show how persons storing electrical energy on their bodies can inadvertently ignite a mixture of flammable gases in air.

The author points out that denser than air vapors are a particularly hazardous material which can sometimes act as fuses to propagate a flame to considerable distances from the source of fuel leakage. The less volatile liquid fuels cannot be considered safe, especially under highly turbulent conditions. For example, kerosene ignited at less than 80°F under rapid agitation. Process plants which use gas are particularly susceptible to electrostatic initiation and those using hydrogen enrichment are even more hazardous due to potential detonation when the hydrogen enrichment level exceeds 40%.

The final article gives detailed case histories of electrostatically initiated fires—one dealing with pumping kerosene into a barge tank, another with mechanical mixers used for blending silicones. The author concludes with a recommendation for the use of electrostatic neutralizers, surveying the types commercially available, namely high voltage air ionizers, radioactive materials, and induction devices. He gives a brief account of the merits and disadvantages of each.

Subject Headings: ***Dielectric contact series; Ignition, by static sparks; Ignition, static electric; Ignition, spark.***

D. Dembrow

Burgoyne, J. H. (Imperial College, London, England) "Explosion and Fire Hazards Associated with the Use of Low-Temperature Industrial Fluids," *The Chemical Engineer* No. 185, CE7–CE10 (1965)

Explosion and fire hazards of low-temperature fluids are discussed in this paper under four headings: (1) physical explosion, (2) gas explosion, (3) fire, and (4) chemical explosion. These hazards, according to the author, "are similar in kind to those of other fluids but differ in magnitude and emphasis."

Physical Explosion

Because pressure valves and vents of a container may become blocked with ice and solid carbon dioxide, low-temperature liquids are particularly prone to physical explosion. The pressure which may develop with total vaporization of a low-temperature liquid is dependent on the level to which a closed vessel is filled. The author notes that a completely filled vessel of liquid methane can attain a pressure of 935 atm. Under such conditions the pressure rises rapidly above the critical and the change from liquid to gas occurs without perceptible phase change.

For a partially filled vessel the rise in pressure is at first comparatively slow. After vaporization is complete, however, the pressure rises sharply since latent heat requirements no longer exists. With a defectively insulated vessel the rise can be greatly accelerated.

The mechanical properties of the vessel material may be adversely affected by the low temperature of the liquid it contains. Impact strength decreases in the case of low-carbon steel and the resulting increased brittleness makes a failure by vibration or shock more dangerous due to increase fragmentation. Other metals which are more ductile at low temperature are recommended by the author.

Gas Explosion

This section of the paper discusses the explosion phenomenon resulting from the ignition of a mixture of vapor of a low-temperature liquid and air in a confined space.

The principles of the explosion are discussed by the author. Ignition may be spontaneous as a result of exposure to a sufficiently high temperature or local by introducing a source of energy release of sufficient power. The fuel/oxidant ratio of the mixture must be within a specific range in order to have flame spread. The lower and upper values of this range are the limits of flammability. As the flame spreads throughout the mixture pressure increases in the confining vessel causing it to burst violently.

To effect ignition a minimum ignition energy, or the least amount of energy discharged from a condenser to initiate flame spread, is required. This is related to the minimum flame volume which is self-propagating, and in turn is related to the volume to which the flame front must be reduced by confining walls for extinguishment. The distance between the walls is the quenching distance.

Numerical values for these parameters at low temperatures are not plentiful. Work that has been done showed that for methane in air the lower flammability limit rises from 6.1 vol % at room temperature to 7.3 vol % at liquid air temperature. More recent research indicates an approximate linear relation of the same limit with the temperature of the mixture. The author states, however, that if one assumes a constant adiabatic flame temperature for a methane–air mixture at low temperatures the rate of rise of the lower limit with decreasing temperature is less than indicated by the linear relation. Thus he concludes, "The indication is, therefore, that the assumption of constant adiabatic flame temperature gives a pessimistic view of the rise in the lower limit with decreasing temperature."

A substantial rise in the relative pressure increase as the initial temperature of explosive mixture is lowered is predictable. An approximate eightfold increase in pressure results from exploding a stoichiometric methane–air mixture at 300°K. This increase corresponds roughly to a temperature rise of 2100°K. Since this rise is independent of initial temperature (as a first approximation) an explosion at an initial temperature of 112°K (the boiling point of methane) results in a temperature of 2112°K, and a relative pressure increase of nearly 20. If one considers dissociation the difference is still greater.

The minimum ignition energy is known to increase with decreasing temperature. The author concludes, therefore, that to adopt atmospheric temperature values, which for hydrocarbon–air mixtures is 0.25 mJ, at low temperature would "err on the safe side." He asserts however, that low temperature measurements of minimum ignition energy should be made since such information is useful in assessing the hazard of ignition due to static discharge.

As with minimum ignition energy, quenching distance increases with decreasing temperature, varying approximately in an inverse relation with the square root of the absolute temperature. Because of this, flame arresters and flameproof electrical equipment which are safe at normal temperatures should give, at low temperatures, a greater margin of safety. The author cautions, however, that this should be confirmed with a reasonable number of measurements.

The formation of explosive mixtures in the vicinity of low-temperature liquids is next covered by the author. Several references on this subject are cited. In one it was shown that, if efficiently insulated, a container of liquid methane would evolve gas at such a temperature that it would rise and no flammable mixture would accumulate at low levels around the container.

In another study the mixing with air of a gas layer of different density was found to be a function of a dimensionless parameter composed of air velocity, air density, density difference between the gas and air, volume of gas flow, and width of the gas layer. The influence of this parameter is important in the case of a defective container evolving cold gas which could form flammable mixtures in and around the vessel. A similar situation would arise in cases of spills where, after an initial high rate of evaporation, the rate of gas evolution per unit area becomes convection-controlled and remains rather constant for a given wind speed.

Fire

To minimize evaporation the vent on a low-temperature flammable-liquid container is generally made small. It usually is sufficiently small so that a flame will not stabilize in the issuing gas in case of ignition. This suggests that an "nonignitable" container could be produced by sizing the vent. Even where a stabilized flame is established on a container vent the author feels that it can easily be extinguished by capping or by using an appropriate extinguisher.

The danger of having two vents in a container is brought out by the author. The ignition and burning of gas issuing from one vent may cause air to be drawn into the container through the other. The formation of an explosive mixture in the container ensues and a flame flashback could cause a vessel-shattering explosion.

Fire associated with spills of a low-temperature flammable liquid is a more serious hazard. As studies have shown the burning rate for pools of flammable liquids, under wind-free conditions, increases linearly with increasing pool diameter, tending towards a constant rate above a certain size. Since low-temperature liquids are at their boiling point when spilled they tend to burn at the normal burning rate when ignited. However, if ignited during the rapid vaporization period immediately after spilling the burning rate is initially higher. Liquid methane has been found to burn with much the same linear rate as other hydrocarbons, producing approximately the same heat radiation hazards. Liquid hydrogen, on the other hand, burns at a much greater rate.

The extinguishment of low-temperature liquid fires can be a problem. The effectiveness of liquid fire-extinguishing agents is reduced because of the low temperature of the burning liquid surface. The author suggests the use of inert gas, foam, and dry powder extinguishers.

Chemical Explosion

Low-temperature flammable liquids can form explosive mixtures with liquid or solid oxygen, and to some extent with air. The author cites several studies in which explosive mixtures were formed when low-temperature hydrocarbons were mixed with liquid oxygen. The explosive range for these mixtures were quite wide. The fact that the fuel and the oxidant is not completely miscible does not preclude the danger and hazard of chemical explosions. Even where the solubility is exceedingly low, explosions have occurred.

Because of the very low temperature of liquid hydrogen, contamination with condensed oxygen-rich air can result in chemically explosive mixtures. Even solid air–liquid hydrogen mixtures have been shown to be explosive.

Subject Headings: ***Explosion hazards, of industrial fluids; Fire hazards, of industrial fluids; Fluids, explosion and fire hazard of; Industrial fluids, fire and explosion hazards of.***

W. Y. Pong

Guest, P. G. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Oily Fibers May Increase Oxygen Tent Fire Hazard," *The Modern Hospital* **145**, 180–182 (1965)

Tests were run on the ignition of oily materials used in the construction of oxygen tents using standard spark ignition methods.[1–4] The results indicate that the over-all probability of ignition is very low, but not completely negligible.

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Subject Headings: ***Ignition, of oily materials; Oily materials, ignition of; Oxygen tent materials, ignition of.***

Editor

Ishihama, W. (Resources Research Institute of Japan, Kawaguchi, Japan) "Studies on the Critical Explosion Density of Coal Dust Cloud," *Eleventh International Conference of Directors of Safety in Mines Research, Warsaw, Poland* (October 16–24, 1961)

* *In the century and a quarter since Faraday's pioneering experiments,[1] research on the ignition and combustion mechanism of coal dust clouds has been in progress. However, in terms of acceptable results, the knowledge gained is appallingly small in view of the immense expenditure of time and money, particularly over the last 50 years. It is possible to say in general terms, with many qualifications, that the flammability (or flame-producing ability) of coal dusts decreases with both coal rank and particle size; it is also known that a methane flame can be augumented by coal dust and that the flames can be suppressed by rock dust. However, that is really about as far as it goes. Experiments over many years under many experimental conditions have shown that the quantitative values of flammability, extinction limits, ignition temperatures (so-called) etc. are so variable as to be valueless for more than general test purposes of explosibility (and even these results are sometimes suspect—for example, ignition temperatures which have been quoted in the range 400° to 1400°C). The reason for this state of affairs is partly the atrocious nature of the experimental problem and partly poorly designed equipment, which has compounded the difficulties. For almost a century the majority of experimental devices required the projection of a dust sample generally on a blast of air, either into or out of a container, and directed at, or into, or through, or around, or over, or across an igniting source such as a tube furnace, a hot coil, an electric spark, a powder flash,*

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* This section represents the Reviewers considered opinion of the field as a whole.—*Editor.*

or something similar. It is naive to believe that such methods will not markedly affect either the cloud conditions, or the igniting source, or both. For preliminary investigations this is understandable; to continue to use them is absurd. Yet the present reviewer recently made a list of some 40 or 50 such devices used over many years, that have produced masses of figures which are meaningful only when applied to the specific dust in that specific test apparatus and under the specific conditions of test. Useful and valid generalizations are practically impossible. A considered opinion of one leading authority is that over 90% of research results on dust explosions are fit only for the wastebasket, and that most continuing research programs are going round in circles. This belief naturally is not shared by those in the criticized research who honestly believe they are producing quantitative results because certain parameters are being measured. The fallacy of this reasoning is a failure to realize that assigning numbers to measureable parameters is hardly a starting point; what is also required is the development of valid generalizations preferably in terms of equations to show relations between the quantities, together with meaningful reasons to explain the nature of the equation obtained, preferably by its development from first principles. That such an approach is in fact possible is demonstrated by the few successful attempts that have been made in the past, notably in the Mason–Wheeler[2] series of experiments with Cybulski's[3] extensions. Earlier than that, equations of less value were also reported (see particularly Review by Godbert[4]); these failed because of the high complexity of the fitted empirical equations, the large scatter that rendered almost valueless an implied precision, and because of the sensitivity of the assigned coefficients to the experimental method. It was, however, at least a step in the right direction. Recently, however, the steps seem to have been, if anything, retrograde. Current fashion is often to determine the measurable parameters, and show that they can be correlated with a high level of confidence. In the so-called "statistical" sciences, this is an entirely suitable course of action, if properly planned; but, in the "mathematical" sciences, such an action is generally an act of despair and an implicit confession that the problem is beyond a mathematical analysis by the investigator. The end point of this, to show that the measurable parameters of the system do correlate, is no more than the starting point of the mathematically minded. Experimentally, matters are no better. Of the systems that have been used, most tests have been run on devices that project a sample of dust vertically upwards, to disperse momentarily, and then settle, all within a second or two. To believe, as some do, that such an experiment is meaningful is incredible. It is certainly reproducible (so long as other parameters such as particle size, sample weight, etc., are also accurately reproduced), but such reproducibility, within dubious limits of error, is primarily a demonstration of the continuing operation of statistical laws. So far as interpretation is concerned, that is quite another matter. In upward projection the dust concentration is a parameter with a wide range of values that are also changing rapidly in both space and time. The material starts out flying upwards, comes momentarily to rest (even as some parts of the cloud are already starting to settle), and then settles out of suspension. There may also be a degree of elutriation, with fines being left in suspension after the coarse has settled. The moment of ignition could be anything at all: an optimum concentration (round the source), or the moment of minimum velocity past the source, or the right proportion of fines round the source. It is also typical of such systems that the variables to be investigated can seldom be changed independently. Thus, when experiments are reported purporting to show increased flammability with increased fineness (which is quite possibly true in some cases though it was not found in some of the reviewer's experiments[5]) the direct reason for the lowering of ignition energy could easily be a more favorable concentration round the *igniting source, or a more favorable velocity, or maintenance of the suspension for a slightly longer period. In fact the number of* causal *explanations (as opposed to statistical correlations) is so great that the experiments are quantitatively meaningless, and their continuance a waste of time. In short, the experiments are imprecisely defined and planned. Many investigators are aware of the shortcomings of the methods, are aware that the cloud is nonuniform, yet they continue to report results in terms of a dust concentration measured by dividing the volume of the test chamber into the quantity of dust used (when the chamber is not always filled and most of the dust anyway often lies close to the chamber axis). Such "concentration" values must be regarded with reserve; many quoted values are hopelessly inaccurate or meaningless. Yet, there is no reason why such poorly defined experiments should ever have been carried out because better systems can be, and have been devised. It is true that dusts will not remain in suspension, but settle out. Yet this fact can be taken advantage of by generating a dust cloud using some steady feeding unit to feed dust into the top of a tube, or even freely into the air, and this produces a cloud of surprising uniformity, as recent experiments have shown. But this method is not new: it was first used in 1878, by Professor von Weber,[6] who used a tapped sieve to generate his cloud, and a small cylinder with end flaps to measure the concentration. Weber said at the time that the method was too crude to be accurate and that he expected improvements on the system in the near future. The improvements however took 70 years when in 1948 Jones and White used a tapped sieve to feed dust into the top of a vertical tube to measure low limit concentrations. In the reviewer's opinion, Webers values obtained with his "too crude" method are certainly as accurate as many being reported today and probably more so in some cases.*

This reviewer would, therefore, concur with the authority quoted above that most research results on dust explosions are worthless. We have only a few reliable values of low limit concentrations of any *dusts; and practically none of upper limit concentrations. We have practically no accurate values of flame speed in quiescent dust clouds, and, so far as the reviewer is aware, only one set of measurements of moving flame speed in a dust as a function of dust concentration. In stationary flames the position is a little better though most of the work has been done on coal, and there is still a factor of 10 spread in the reported values (which can be explained as a function of ignition distance though this is still not generally accepted). We can present acceptable and entirely reasonable arguments to show that most organic dusts are likely to ignite by a prior devolatilization and ignition of the volatiles; yet, we cannot say that this has been proved and, in fact, recent experiments by Howard,[7,8] shortly to be published, have shown that ignition of his coal dust flames started with ignition on the solid particle at about 1000°C, and* before *any significant evolution of volatiles. Again, mechanisms of flame propagation are mostly guessed at or ignored. The mechanism is almost certainly a thermal one, but which mode of heat transfer predominates (if any) is unknown. In the area of combustion mechanism the situation is both better and worse. Work in the last five years on coal has now established the principal mechanism of carbon burn-out (after devolatilization) to be a chemical control, incidentally upsetting the 40-year-old diffusion theory; the mechanisms of certain metals, notably magnesium and aluminum, have recently been examined because of their role as rocket-propellant components or additives, but in the rest of the dust field of a 1000 or more explosive dusts, there would seem to be a practically complete blank.*

It is against the preceding comments that the paper under review must be considered. Against this background the paper is outstanding; experimentally, it is something of a break-through. The work concerns the measurement of lower explosion limits of coal dust clouds, ignited by an induction-coil spark, as a function of particle size, coal rank, methane concentration, and rock-dust percentage. The author has been concerned with designing an experimental method in which the variables to be investigated could be controlled, measured, and varied independently. The variables were then varied independently, and the results drawn up in a rational, meaningful manner most likely to show causal interrelations. For some of the experiments the results were collated by means of empirical, but simple and reasonable, mathematical expressions.

The experimental method utilizes a tapped sieve generating a cloud falling (as advocated by Weber[5]) into a $4\frac{1}{2}$ liter chamber of 15.6 cm diameter and 24 cm high. The particle size was partly controlled by changing the sieve mesh. The rate of feed, and concentration, were controlled by changing the tapping rate. The concentration was measured by starting the sieve-tapping mechanism and running it until dust just started to settle on a white sheet at the bottom of the explosion chamber. The sieve was then stopped, and after the rest of the dust had settled out this was collected and weighed. Divided by the chamber volume, this gave the dust concentration. Ignition was by a continuous induction-coil spark situated about the center of the chamber; in a combustion test, this was only switched on after the coal feed had been started and the chamber was uniformly filled with a dust cloud. (Dust starting to settle out would not contribute to the explosion flame.) When the effect of rock dust was investigated, this was premixed with the dust. (In the short distance of fall, any significant preferential elutriation of the rock dust is unlikely.) When the effect of methane was investigated, this was added to the chamber beforehand, care being taken to seal the sieve top with polyethylene film to prevent escape of gas. The combustion chamber was of glass, with a small cellophane blow-out panel, so the flame could be photographed. The author discussed the problem of deciding when a true ignition had occurred (as opposed to an "inflammation" in the region of the ignition source) but essentially he took it as being the stage when the combustion chamber was completely filled with flame.

In the first set of results, the low dust-concentration limit was first determined by itself, and then again with progressively increasing percentages of methane until the point of zero coal was reached at the low limit of methane. The results were tabulated, but also presented graphically as the curve of methane per cent against coal concentration. The experiment was then repeated with, successively: 10% (one point), 20%, 30% (one point), 40%, 60%, 70%, 80%, and 100% admixtures of rock dust in the coal. In all cases but the last, the methane concentration falls as the dust concentration increases, but the rate of fall diminishes as the rock-dust percentage increases, with an estimated 85.7% of rock dust being required to give a horizontal line, i.e., the ratio at which the increasing coal dust and rock dust exactly annul each other's effects so that the methane percentage remains constant. The curves were found to obey the following relation

$$p_g \pm C = p_L \exp(-AD), \qquad (1)$$

where p_g is the methane percentage in the air; D the dust concentration; p_L the methane low limit; and A and C are two constants found to vary with ignition energy, type, and composition of both coal and rock dust.

In the next sequence of experiments, the effect of fineness was investigated. For the first coal examined (Shinhoronai 46% V.M.) the low-limit concentration decreased with increasing fineness. The results are presented as a curve of concentration (D) plotted against specific surface of the dust (S). The curve was found to be a rectangular hyperbola of the form

$$(D-a)\ (S-b)=\text{const}, \tag{2}$$

where a and b are the assymtotic limits of, respectively, concentration at high specific surface, and specific surface at high concentration. This shows that, above a certain fineness, the limit becomes independent of fineness; when the coal is coarse, a higher concentration is required but, above a certain coarseness, the cloud will not ignite (The reviewer would expect this limit to depend on the ignition-source intensity.)

Repeat of this experiment with seven other coals of different rank (27% to 50% V.M.) gave the same result (a rectangular hyperbola), with the constant a (the concentration assymtote) falling with decrease of rank; but with the specific surface assymtote b apparently independent of coal rank.

To show more clearly the influence of rank, the same results were also plotted as limit concentration against volatile per cent for four of the different sieve fractions used. (The volatile per cent changed slightly with sieve cut, and this was taken into account.) The results show that the concentration decayed with increasing volatile per cent, again in a manner similar to a rectangular hyperbola, the equation this time being of the form

$$(D-a)\ (V-b)^n=\text{const}, \tag{3}$$

where a and b are again (different) assymtotic values of D and V; and n is a constant of value of about 2 and independent of fineness. The other two constants (a and b) were both dependent on fineness, both decreasing as the fineness increased. The value of "a" is particularly interesting as it dropped from 14% to 10% V.M. as the limit below which the coal would *not* ignite. This just straddles the value of 12.5% V.M. deduced by Mason and Wheeler[2] in the explosion gallery tests 30 years ago; equations similar to (2) and (3) were first established by these two investigators (see also References 9 and 10 for a combined equation based on their data).

In a final sequence of experiments the effect of the nature of the rock dust as a suppressant was compared in effectiveness with the inherent ash of the coal. To do this the ground coal was first sieved in water into four size ranges and then separated into five specific gravity ranges in a mixture of CCl_4 and benzol. To the lowest gravity fraction, brick powder was then added to bring the total incombustibles up to the level of the other four gravity fractions, the size consistency of the powder being the same as that of the coal fraction to which it was added. The results of the variation of low limit with particle size, presented graphically, showed only a small displacement between the samples with added brick dust and those containing only natural ash of the same total quantity. Such differences indicated that the samples with added brick dust were slightly less flammable but they might not be significant. An alternative plot of low limit against brick-dust per cent at constant particle size was slightly more significant. It suggested that, at ash contents of more than 35%, the mixtures with added brick dust were slightly more explosive; but below 35% the reverse was apparently the case. The differences, however, were small and not necessarily conclusive.

To the above summary, the reviewer would add the following comments. About the most significant result, in the reviewer's opinion, is the conclusion that the low limit is generally particle-size dependent, but becoming substantially independent for particle sizes less than 50 microns. The significance depends partly upon the view taken of the ignition mechanism; but if the view expressed elsewhere[9] is accepted, that in gallery explosions the whole coal particle is involved and the low limit is unaffected by rank, but that in small test apparatus the ignition is by prior devolatilization (involving rank), then it follows that these experiments show the importance of particle size in devolatilization. If this is controlled by the rate of diffusional escape after its initial formation, then the time taken to form an explosive concentration of volatiles becomes particle-size dependent. If the escape rate depends on the rate of formation by pyrolysis, this is particle-size independent. The conclusion to be drawn then is that above 50 microns the particle is large enough for the escape rate to be controlled by internal diffusion; but below this size the escape rate is controlled by the pyrolysis rate.

Also of interest is the curve of the variation of the low limit in mixtures of methane and coal dust. The author showed [Eq. (1)] that the data fitted an empirical equation of exponential form (but having very small curvature). This may be compared with a linear equation obtained by the reviewer[9] on the basis of replacement of coal by methane or a thermal basis (see also Refs. 11 and 12 for comparable curves).

In conclusion it can be said that more could have been made of an interpretation of the results in terms of possible mechanism of combustion; but this criticism in itself is a commendatory comment on what has been achieved experimentally, i.e., that the experimental results are clearly good enough, sound enough, and sufficiently unambiguous to justify spending the time on an interpretation. To cavil at what was not done is scarcely fair to what has been achieved. The experimental side of the paper is its forte; and it is profoundly to be hoped that this technique will at last be the cause of consigning all other experimental "test" devices to the oblivion they should have reached 50 years ago.

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Subject Headings: ***Clouds, coal dust, explosion of; Coal dust, ignition of; Explosion, critical density of coal dust; Dust, coal, ignition of; Explosion, of coal dust; Ignition, of coal dust.***

R. H. Essenhigh

Martin, S. B. and Holton, S. (U. S. Naval Radiological Defense Laboratory, San Francisco, California) "Preliminary Computer Program for Estimating Primary Ignition Ranges for Nuclear Weapons," *U. S. Naval Radiological Defense Laboratory Report USNRDL-TR-866* (1965)

A machine computer program is described for estimating the free-field, primary incendiary effects of nuclear weapons detonated under a variety of environmental conditions. The computational procedures are designed to treat (1) the dependence of thermal pulse duration on air density, up to 20 or 30 miles altitude, (2) the dependence of radiant exposures required to ignite kindling fuels on pulse duration, local humidity and the physical properties of the fuel, (3) the attenuation of thermal radiation by the atmosphere for a variety of atmospheres including clouded and hazy and (4) the enhancement of radiant exposure levels by high albedo surfaces such as snow and cloud cover. Output of the program takes the form of radiant exposure contours and primary ignition ranges expressed as horizontal distances from the burst point (or surface zero) in miles.

Subject Headings: ***Computer program, for ignition, by nuclear explosions; Ignition, by nuclear explosions; Nuclear weapons, ignition by; Ignition, range of, by nuclear weapons.***

Authors' Abstract

Weatherford, W. D., Jr., Sheppard, D. M., and Valtierra, M. L. (Southwest Research Institute, San Antonio, Texas) "An Experimental and Mathematical Study of the Mechanism of Wood Ignition," *Final Report for Office of Civil Defense Contract OCD-05-62-89 through National Bureau of Standards Contract CST-1102* (November 15, 1965)

The results of experimental piloted ignition studies, when considered in the light of theoretical calculations, indicate that the primary criterion which must be satisfied in order to achieve sustained ignition of cellulose slabs in the continued presence of the ignition and heat sources is the attainment of a fixed fuel generation rate per unit surface area. Correlations of the experimental results (based upon four nominal slab thicknesses, three nominal slab densities, and three source temperature levels) reveal that the ignition criteria are substantially influenced by the physical and thermal properties of the slabs.

Subject Headings: ***Cellulose, ignition of; Ignition, of cellulose; Ignition, of wood; Wood, ignition of.***

Authors' Abstract

II. Thermal Decomposition

Blackshear, P. L., Jr., Murty, K. A., and Murayama, N. (University of Minnesota, Minneapolis, Minnesota) "Some Research Pertaining to the Problem of Predicting the Burning Rate of Cellulosic Fuels," *Office of Civil Defense Contract OCD-OS-62-89—National Bureau of Standards Contract CST-1127 Technical Report No. 3* (August 30, 1965)

The present work is composed of an experimental study of the burning rates of different thicknesses of cellulose cylinders and a comparison of an experiment with theory.

Cellulose cylinders 3, 4, and 5 cm in thickness were burned starting at the bottom surface in free convection. The burning rates of these cellulose cylinders and the temperatures at the surface and at the base were measured as functions of time. The base temperature remained substantially constant.

The experiments show that the burning rates with thicker cellulose are higher than that with thinner cellulose.

To explain the experimental results, the one dimentional thermal diffusion equation was solved under the following conditions:

1. Exothermic reaction is neglected.
2. Heat from the flame is conducted to the cellulose surface; there is a net heat loss by radiation from the burning surface.
3. Base temperature at the rear surface of cellulose is assumed constant.

The temperature distribution was obtained by solving the thermal diffusion equation; it is shown that the theoretical decomposition isotherm propagates faster into the thicker than into the thinner cellulose slab.

Finally, a first order pyrolysis rate was assumed and was integrated over a certain time interval and over the whole length of the cylinder employing the temperature distribution above. The calculation showed that the mass loss by degradation of the burning cellulose increased with the thickness, in agreement with the experimental data.

Subject Headings: ***Burning rate, of cellulose; Cellulose, burning rate of; Pyrolysis, of cellulose.***

Authors' Abstract

Lipska, A. E. and Parker, W. J. (U. S. Naval Radiological Defense Laboratory, San Francisco, California) "Kinetics of the Pyrolysis of Cellulose Over the Temperature Range 250°–300°C," *USNRDL-TR-928* (4 November 1965)

Pure alpha cellulose samples were subjected to isothermal pyrolysis in a fluidized bath in a nitrogen environment at temperatures ranging from 250° to 298°C. Results were reported in terms of volatilization (based on weight loss measurements) and decomposition (in term of glucosan loss). The findings indicate that there are essentially three distinct chronological phases of pyrolysis at each temperature studied. After an initial rapid decomposition and weight loss period, both the volatilization and the decomposition obey an apparent zero-order expression, followed by a kinetically first-order phase for the weight loss, resulting in a residual char deposit which does not undergo further pyrolysis. The degree of decomposition and volatilization occurring during the zero-order phase increases with increasing temperature.

A single activation energy of 42 kcal/mole describes both the decomposition and volatilization rates over the entire 250° to 298°C range.

Subject Headings: *Cellulose, kinetics of pyrolysis of; Degradation, of cellulose, Kinetics, of cellulose pyrolysis; Pyrolysis, of cellulose.*

Authors' Abstract

III. Heat and Material Transfer

Finlay, I. C. (National Engineering Laboratory, East Kilbride, Scotland) "Progress in Heat Transfer—Review of Current Literature," *Chemical and Process Engineering* 45, 437–445 (1964)

This survey lists typical heat transfer articles published in 1963. The author mentions the following broad headings which may be useful in the fire problem.

Conduction

Two papers deal with thermal transients in buildings during heating or cooling.[1,2] Simplified models are discussed and the effects of ventilation, heat storage, and walls are evaluated.

Convection

The density variations in natural convective flows can be visualized and measured by the Mach–Zehnder interferometer.[3] The natural convection from a thin vertical cylinder with uniform temperature rise is analyzed by Viskanta.[4] Combined free and forced convection is analyzed, with a new approximation method by Brindley.[5] The important problem of heat transfer across turbulent boundary layers is reviewed by Kestin and Richardson.[6] It should be noted that the recent work on hypersonic boundary layer combustion has immediate application to fire problems.[7,8] Knuth has studied the use of "reference" states in facilitating calculations of mass transfer with chemical reactions.[9–11]

Change of Phase

The problem of cooling a hot gas by an evaporating spray is analyzed.[12] Old and new methods for the measurement of latent heats are discussed.[13]

Radiation

Sparrow details an approximate technique for calculating configuration factors for the radiant heat exchange between surfaces.[14] Adrianov advocates, on grounds of accuracy and simplicity, novel differential methods for studying radiant heat transfer, employing tensor representation of heat flux.[15]

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Subject Headings: ***Heat transfer, survey of; Literature, of heat transfer; Survey, of heat transfer literature.***

D. Dembrow

Gill, W. N.,* Del Casal, E., and Zeh, D. W.** (Syracuse University, Syracuse, (New York) "Binary Diffusion and Heat Transfer in Laminar Free Convection Boundary Layers on a Vertical Plate," *International Journal of Heat and Mass Transfer* **8,** 1135–1151 (1965)

Free convection in laminar boundary layers with coupled momentum, heat, and binary mass transfer was theoretically investigated. The particular model examined was a boundary layer produced on a vertical flat solid surface by injection of the separate species H_2, He, H_2O vapor, and CO_2 through the surface into pure ambient air. The boundary layer contained buoyancy forces existing because of temperature and concentration gradients, the latter being sustained by interfacial mass transfer.

In the analytical treatment, boundary-layer equations (for nonreacting systems) of continuity, momentum, energy, and diffusion were transformed to total differential form. Final coupled and nonlinear equations to be solved included appropriate transformation variables and dimensionless transport quantities such as Nusselt, Sherwood, Prandtl, Grashof, and Schmidt numbers. In addition to providing a solution of the general problem, the authors developed a method of integrating the coupled transport equations which appears to be faster than previously used techniques. In previous methods, the momentum equations were solved by iterating

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on both a boundary condition and a function; in the present solution, there is iteration only on a boundary condition. In the new scheme of computation, there is much less computer time for solution of the momentum equation.

Data results are reported in the form of figures that show for the various binary systems the relationship between heat transfer and: (1) mol fraction of component, (2) mass flux, and (3) interfacial velocity. Also given are data showing the effect on heat transfer of physical property variation such as specie enthalpy, thermal conductivity, viscosity, and density. These were studied individually and in various combinations. Interactions of Prandtl number and interfacial effects for sample component mass transfer systems were also investigated.

The authors noted the difficulty of deriving a complete solution to a problem that contains so many variables which are nonlinearly coupled. They believe their most critical assumption to be neglect of Soret-Dufour diffusion effects which have been shown by others to be quite pronounced, especially in free convection systems where the injected foreign fluid is of low molecular weight relative to the ambient fluid.

The study revealed that the most striking effects were produced by specie enthalpy and thermal conductivity differences. The predicted heat transfer rates for injection of H_2, He, and H_2O systems were found to increase at low mass transfer rates, then to decrease at higher rates. The initial increase in heat transfer for He and H_2 was attributed to the concentration-induced buoyancy effects augmenting the convection, and to the much larger thermal conductivity of He and H_2. The decrease of heat transfer at higher mass injection rate was attributed to the larger heat capacity of He and H_2, and to increased boundary layer thickness induced by increased transverse velocity. Physical property variations of the H_2O–air system were less than for the He and H_2 air systems. Theoretical data of effects of H_2O reflected the low thermal conductivity of H_2O with respect to air, and substantiate the attraction of H_2O as a coolant material.

For CO_2–air, the effects of physical property variation with concentration were relatively slight. Of primary importance in this system was the opposition of effects of concentration-induced and thermally induced buoyancy, tending to reduce convection rates and to inhibit heat transfer.

Finally, data were given for a typical liquid system of Prandtl number = 10 and Schmidt number = 500 that indicated that free convection in this system was caused almost completely by thermal effects since the diffusion boundary layer is much thinner than the thermal boundary layer.

Subject Headings: ***Boundary layer convection; Convection, in boundary layer; Diffusion, heat transfer; Convection, laminar.***

J. M. Singer

Mason, E. A. (University of Maryland, College Park, Maryland) **and Monchick, L.** (Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland) "Survey of the Equation of State and Transport Properties of Moist Gases," *Humidity and Moisture*, Volume Three, New York, Reinhold Publishing Corporation, 257–272 (1965)

The properties of water vapor and its mixtures are difficult to predict or calculate, mainly because of the unsymmetric force field of the water molecule. The best way to determine a particular property of a moist gas would be to measure it directly.

Since the data on moist gases are rather meager, one must have recourse to whatever theory is available to predict these properties. Although the approximate theories presently available are not accurate enough to give really good predictions of various properties, they are excellent guides for the interpolation and extrapolation of the available scanty data. The purpose of this paper is to survey the present status of experimental and theoretical knowledge on the equation of state (virial coefficients) and transport properties (viscosity, thermal conductivity, diffusion, thermal diffusion) of moist gases, especially moist air, and to outline the methods of making the necessary theoretical calculations. There are embarrasingly few accurate experimental measurements available, and it is necessary to rely on theory rather more than one would like, in view of the complex nature of the water molecule. A number of calculations are tabulated for use in engineering applications.

We have relied on the Stockmayer potential to describe the water molecule and a Lennard-Jones potential to describe air and its constituents. Our calculations show that air can be regarded as a single substance to a very high degree of accuracy. The forces between a molecule of water and a molecule of air should preferably be found by experiment, but this is often not possible and an educated guess must be made with the help of semiempirical rules. No improvement in the second virial coefficient of moist air over the values of Goff and Gratch is possible without further experimental data, but some improvements in the prediction of the third virial coefficient are possible. Diffusion coefficients are the critical quantities in the calculation of both viscosity and thermal conductivity, but neither the combination rules nor the available diffusion data are very satisfactory for this purpose. The diffusion data have been fitted by a Lennard-Jones potential and the theory then used to calculate diffusion coefficients outside the range of the available experimental data. These results have been used in conjunction with experimental data on pure water vapor and pure air to predict the viscosity and thermal conductivity of moist air. The thermal diffusion factor has been calculated theoretically, and is probably the least dependable of the predicted transport coefficients.

Subject Headings: ***Equations, of state for moist gases; Moist gases, equations of state and transport properties of; Transport properties, of moist gases.***

Authors' Abstract

Patankar, S. V. and Taylor, R. G. (Imperial College, London, England) "Diffusion from a Line Source in a Turbulent Boundary Layer: Comparison of Theory and Experiment," *International Journal of Heat and Mass Transfer* **8**, 1171–1175 (1965)

In a paper presented at the International Heat Transfer Meeting in 1961, Spalding presented a method of calculating heat transfer from a surface in turbulent flow for a stepwise discontinuity in the surface temperature. The work was amplified and generalized in a subsequent paper.[1] The results derived in these two papers are directly applicable also to the problem of mass transfer. The present authors have taken Spalding's results to obtain specialized solutions corresponding to the mass transfer from a line source to a turbulent boundary layer. The theoretical predictions could then be compared with the experimental ones obtained by Poreh and Cemak.[2] In these experiments the diffusion of ammonia into air was investigated, and measurements were made of concentration profiles at various distances along the surface. The comparison was based in particular on the variation of the concentration normal to the wall, on the change of concentration at the wall as a function of distance, and on the position of the point at which the concentration had dropped to one half of its original value. The experimental data agreed well with the values computed from the theory, but only as long as the concentration boundary layer was significantly smaller than the velocity boundary layer.

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Subject Headings: ***Boundary layer, turbulent diffusion in; Diffusion, in turbulent boundary layers; Diffusion, line source; Turbulent boundary layer and diffusion.***

R. H. Sabersky

IV. Diffusion Flames

Brzustowski, T. A. and Glassman, I. (Princeton University, Princeton, New Jersey) "Vapor-Phase Diffusion Flames in the Combustion of Magnesium and Aluminum: I. Analytical Developments," *Progress in Astronautics and Aeronautics* 15, 75–115 (1964)

The familiar thin-flame, spherically symmetrical model of droplet burning is applied to the combustion of magnesium and aluminum particles. These metals can burn in the vapor phase because their boiling points are beneath those of the direct combustion products MgO and Al_2O_3. The peculiar features of the flames are:

1. The highly endothermic effects of metal oxide vaporization followed by partial dissociation of the vapor according to

$$2\,MgO \rightarrow MgO + Mg + O$$

or

$$Al_2O_3 \rightarrow AlO + Al + 2\,O$$

normally limit flame temperatures to the boiling points of MgO and Al_2O_3.
2. The presence of condensed oxides in the flame zone makes thermal radiation a major factor in heat transfer between the flame, the droplet surface, and the surroundings.
3. The condensed oxide product does not diffuse at an appreciable rate and hence leaves the flame zone only if convected. The criterion for the existence of an outward bulk motion in the flame gases is that each mole of oxidant must yield more than one mole of gaseous products.
4. The rate of transport of metal from the droplet to the flame may not be fixed by the diffusion of the metal vapor, for the evaporation process at the droplet surface may also be slow.

5. The latent heats of vaporization of the metals are very high, $\lambda=30$ kcal/g-mole for Mg and 70 for Al, while the specific heat of the vapor C_p is about 5 cal/g-mole°K, giving λ/C_p values of 6000° and 14,000°K. By contrast, for hydrocarbons λ/C_p usually falls between 50° and 500°K.

The equations describing metal droplet combustion on the quasi-steady-state theory developed in this paper are:

1. Two energy balances, one between the droplet and the flame, and the other between the flame and the surroundings, both taking thermal radiation into account.
2. Two material transport equations, derived from modified forms of Stefan's law, describing the transport of fuel and oxidant up to and of gaseous products away from the flame.
3. A modified Knudsen-Langmuir equation for the evaporation of metal away from the droplet surface.

The input parameters in the solution of the equations are the droplet radius, the ambient temperature and pressure, the ambient gas composition, and the chemical nature of the fuel. The unknowns or output parameters are the burning rate; the droplet temperature; the metal vapor pressure at the droplet surface; the radius of the flame zone; and (a) the flame temperature, or (b) in the event of partial vaporization of the metal oxide product, the degree of vaporization (the flame temperature then being fixed at the boiling point of the oxide).

The equations have been solved twice, first in a highly simplified form to establish the basic trends, and then more rigorously. The results are presented graphically using dimensionless parameters. Some of the main trends to be observed are: The higher the heat of vaporization of the fuel, the thinner is the film between the droplet surface and the flame. The thinner film reflects the adjustment of the temperature gradient to produce a higher conductive heat flux. On the other hand, the film thickens with increasing radiative transfer, since less heat needs then to be transferred by conduction. Droplet surface temperatures may be hundreds of degrees below the boiling points of the metals. The fraction of the oxide dissociated in the flame zone increases with oxidant concentration in the ambient and decreases with increasing total pressure and droplet size. When the fraction dissociated falls below a critical value, the removal of condensed oxide by convection stops and agglomeration of condensed oxide in the flame may then begin.

The theoretical calculations have been backed up by experimental investigations.[1–3] Apart from the peculiarities of their fuels, the major consideration introduced into droplet burning theory by the authors appears to be the idea of the evaporation process as a possible slow step limiting the combustion rate. The calculations evidently indicate that evaporation becomes limiting at about the same point at which the notion of a collapsed reaction zone becomes untenable.

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Subject Headings: ***Aluminum, diffusion flame; Diffusion flame, of aluminum; Diffusion flame, of magnesium; Magnesium, diffusion flame.***

H. A. Becker

Markstein, G. H. (Cornell Aeronautical Laboratory, Inc., Buffalo, New York) "Analysis of a Dilute Diffusion Flame Maintained by Heterogeneous Reaction," *Progress in Astronautics and Aeronautics* **15,** 177–202 (1964).

In this paper a mathematical model of a spherical dilute diffusion flame maintained exclusively by a heterogeneous reaction is presented and discussed in view of data on a Mg–O_2–Ar system, previously published.[1] In the present context, a spherical dilute diffusion flame consists of a mixture of one gaseous reactant and a large excess of an inert carrier gas flowing radially outward from a point source at a constant rate. The mixture issues into an atmosphere consisting of another gaseous reactant and an excess of inert gas.

In a homogeneous reaction situation the reactions are all gas phase. For the heterogeneous case, the one of interest here, the reaction is assumed to take place on a solid condensed phase reactant product.

In the previous experiments[1] for which the present model was constructed, magnesium vapor was carried in an argon stream which issued into an oxygen-argon atmosphere. The solid condensed phase was MgO and a proposed mechanism was that of the reaction of magnesium vapor and oxygen on the MgO surface. The assumptions for the model of the present paper were:

1. Convective transport of nozzle reactant is negligibly small compared to diffusion transport.
2. Inert diluent gas is present in sufficient excess to maintain the gas temperature constant throughout the reaction zone.
3. Atmosphere reactant is present in sufficient concentration so that its depletion in the reaction zone may be neglected.
4. Reaction product is present only in the form of condensed-phase particles, which move radially outward with the flow velocity of the inert carrier gas.
5. The rates of consumption of nozzle reactant and of growth of particle size are due exclusively to heterogeneous reaction, and are proportional to the collision frequency of nozzle-reactant molecules with the particle surface, and independent of the concentration of atmosphere reactant.
6. The condensed-phase particles are spherical.
7. Nucleation of condensed-phase particles takes place only within a small central region of the flame, and is not considered in the analysis, which deals only with the flame zone outside the region of nucleation.

The solutions of the resulting nonlinear system of two first-order differential equations contain two adjustable parameters that are related to the nucleation process, one a function of the width of the initial radii distribution and the other a function of the initial radii of the nuclei. From a comparison of the data given in

Ref. 1 with the mathematical model one concludes that the nucleation process could have taken place in a region very near the flame center if the initial nuclei were characterized by a broad distribution.

From further comparison of the mathematical model and the data of Ref. 1 Markstein calculated an average collision efficiency of 7.5×10^{-2} and an average particle number density of 4×10^{12} cm^{-3}.

The basic deficiency in the present model was the exclusion from direct consideration of the nucleation process. That seemed to be done out of the current lack of understanding of nucleation processes rather than from a drive toward mathematical simplicity.

Reference

1. Markstein, G. H.: Ninth Symposium (International) on Combustion, p. 137, Academic Press, New York, 1963.

Subject Headings: ***Diffusion flame, of magnesium, into oxygen–argon; Diffusion flame, heterogeneous; Magnesium, diffusion flame, with oxygen–argon; Oxygen–argon, diffusion flame, with magnesium.***

R. N. Gurnitz

V. Combustion Principles

Baldwin, R., Thomas, P. H., and Wraight, H. G. H. (Joint Fire Research Organization, Boreham Wood, England) "The Merging of Flames from Separate Fuel Beds," *Joint Fire Research Organization Fire Research Note No. 551* (May 1964)

In this report, the conditions for the merging of flames from separate fuel beds are determined from a simplified equation of motion and expressed in terms of dimensionless groups. The height L^* of a flame from a burning fuel bed of side D is given by

$$L^*/D=A[\dot{m}/\rho(gD)^{1/2}]^{2/3},$$

where A is constant, $\dot{m}$ is the mass burning rate per unit area, ρ the density of air (assumed constant), and g the acceleration due to gravity. The flame height L_n of a flame composed of n burning beds of side D placed together is given by the approximate relation

$$L_n/L^*\approx n^{1/3}.$$

That is, one would expect, the flame height of the massed burning beds is greater than that of the single bed. The resulting increase in radiation may increase the heat transfer back to the fuel, accelerating the spread of the fire.

In the situation where the fuel beds do not touch, the flames will lean toward each other, as illustrated in photographs included in this report. At some critical separation, the two flames will just merge. The largest forces acting on the flames are the buoyancy and the pressure thrust normal to the axis of the flame, taken in this approximation as straight. If the angle between the flame axis and the normal to the fuel bed is defined as ϕ, then the buoyancy B and the pressure thrust are related by

$$B \sin \phi = P.$$

The pressure thrust was evaluated by the use of Bernoulli's equation. When the expressions for B and P are inserted into the above equation, a relation is found between the flame height L at the critical separation S and the width D and the length W of two rectangular fuel beds. This relation is

$$\frac{L}{D} \propto \left(\frac{S^3}{W^2 D[1-(S^2/4W^2)]} \right)^{1/2}.$$

The constant of proportionality includes a factor which estimates the pressure drop in the channel between the two flames. A very similar expression was found for a symmetrical array of 4 square fuel beds.

Two lines on a plot of the dimensionless groups were computed, corresponding to two different estimates of the pressure drop. Data from several different arrays of gas burners and a timber yard fire were plotted on the same graph. Although, as the authors themselves note, there may be a systematic deviation from the computed lines, the agreement is reasonably good over a fiftyfold change in L/D. A rational specification of the important factors, flame height, fuel bed separation, and fuel bed dimensions is thus possible.

Subject Headings: ***Flame, merging of; Merging, of flame.***

P. R. Ryason

Berl, W. G. (Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland) "A Brief Review on the Combustion of Boron Hydrides," *Progress in Astronautics and Aeronautics* 15, 311–326 (1964)

This article is an interesting summary of the 15-year effort to develop boron hydride fuels for aircraft use (turbojet and ramjet engines). A bibliography of 56 references gives a good coverage of the unclassified literature; unfortunately, much of the work on boron hydride fuels remains classified.

The history of boron hydride fuels illustrates vividly the importance of basic chemical knowledge. Based on the concept that air-breathing propulsion could be improved if boron hydrides were substituted for conventional hydrocarbon fuels, a large-scale program of fuel and power-plant development was initiated. This attempt was unsuccessful for three reasons: the development of rockets provided a superior delivery system, deposition of liquid combustion products on turbine blades limited the fuel to afterburning and ramjet use, a lack of knowledge of thermochemistry of the combustion products led to an over-estimation of the possible improvements. The article describes how the discovery of new combustion products and improvement of thermodynamic functions led to decreases in the calculated performance.

A number of unusual properties of boron hydride fuels are described: high flame speeds, formation of condensed products in the flame zone, influence of these condensed boron products on further burning of the hydrogen or hydrocarbon part of the molecule, reaction of fuel with water—a combustion product, reaction of boron hydrides with nitrogen and nitrogen compounds to form solid boron nitride. Although a number of studies have been made no convincing combustion mechanism has been developed. Nevertheless a considerable amount of information exists that will be useful to anyone faced with the problem of fighting boron hydride fires.

Subject Headings: ***Boron hydrides, combustion of; Combustion, of boron hydrides; Hydrides of boron, combustion of.***

W. E. Wilson, Jr.

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von Engel, A. and Cozens, J. R. (University of Oxford, Oxford, England) "Flame Plasmas," *Advances in Electronics and Electron Physics* 20, 99–146 (1964)

An understanding of ionization in combustion gases, in addition to shedding light on a large class of elementary reactions between free radicals, ions, and electrons, has become necessary in the design and optimization of (magnetohydrodynamic) power generators[1] and rocket-propelled vehicles whose system performance can be seriously degraded by the effect of highly ionized exhaust plume gases[2] on transmitted electromagnetic signals. von Engel and Cozens have reviewed the extensive history of flame ionization studies, with emphasis on implications as to the physics and chemistry of electron production and decay. While not rejecting plausible mechanisms in which the primary ionization step is a *chemi-ionization* reaction[3–5] of the type $A+B \rightarrow C^{+}+D+e^{-}$ (for which compelling experimental evidence, not cited by von Engel and Cozens, has been accumulating) these authors propose that electron impact itself may be an important ionization step, hitherto unconsidered. Unfortunately, the depth of the treatment of either of these schemes has been seriously compromised by devoting a significant fraction of the paper to historical details, flame properties (e.g., diffusion flame length, stability, temperature distribution) and experimental techniques (e.g., thermocouples, sodium line reversal) more carefully documented elsewhere and largely incidental to the subject under review.

Upon restating the arguments which rule out *thermal* (equilibrium) ionization of flame gas constituents (e.g., observed ionization levels in unseeded hydrocarbon–air flame zones are orders of magnitude greater than those predicted by the Lindemann–Saha equation and do not correlate with measured flame temperatures), several eligible nonequilibrium schemes are considered. At this point, however, the discussion is more qualitative than it need be and, perhaps inadvertantly, misleading. Thus, immediately following the statement that the approximately thermoneutral chemi-ionization reaction $CH+O \rightarrow CHO^{+}+e^{-}$ "may well" contribute to the ionization level, we find the reservation that "no information is at present available" as to whether the rate is sufficient (i.e., the rate constant "may well" be too small). Interestingly enough, using quantitative estimates and available experimental data, it has recently been argued[5] that this reaction "may well" readily account for observed ionization levels! That additional measurements have to be made is agreed upon by all. However, von Engel and Cozens do not boldly confront these postulated mechanisms with *available* experimental observations, which by now are quite extensive.

von Engel and Cozens proceed to introduce what might be considered to be a "dark horse" mechanism in which ionization by electron impact plays a dominant role. In this scheme the electron precursors are either hot by virtue of collisions of the second kind with excited combustion intermediates, or "cold," in which case the reacting partner must be excited. In support of the former postulate, it is pointed out that high electron temperatures have indeed been measured in flames (using Langmuir probes), and an order-of-magnitude calculation is provided which suggests that the competition between hot electron production due to chemical heat release (followed by collisions of the second kind with existing electrons) and drainage due to inelastic electron-molecule collisions is sufficient to *maintain* an appropriate number density of hot electrons. Notably absent, however, is a discussion of how the electron level can build up to the appropriate level in the absence of imposed electrical fields, and why it does in some flames (e.g., propane–air) and not in others of comparable exothermicity (e.g., hydrogen–air or carbon monoxide-air). Thus, methodologically we appear to be confronted with a "bootstrap" situation, viz., electron concentrations in hydrocarbon–air flames are larger because in such flames electron impact processes play a more dominant role!

In summary, while this review paper re-collects a great deal of historical material and raises some interesting questions, in the opinion of this reviewer the arguments are incomplete and qualitative at crucial points, and make inadequate use of the mechanistic implications of available experimental facts. As a result, the subject appears to be in a greater state of disarray than that revealed in the Proceedings of, say, the Tenth Symposium (International) on Combustion[6] and the recent AGARD Panel Meeting.[7]

References

1. Way, S. and Hundstad, R. L.: *Eighth Symposium (International) on Combustion*, p. 241, Williams and Wilkins, 1962.
2. Rosner, D. E.: "Ionization in Rocket Exhaust Plumes," AeroChem TP-85, March 1964; DDC AD 447 304; to appear in Plasma Technology, Aerospace Applications (J. Grey, Ed.), Prentice-Hall, 1966.
3. Calcote, H. F.: Combust. Flame *1*, 385 (1957).
4. Calcote, H. F.: *Ninth Symposium (International) on Combustion*, p. 622, Academic Press, 1963.
5. Calcote, H. F.: "Ionization in Hydrocarbon Flames," AeroChem TP-119, August 1965; Proc. 26th Meeting of Propulsion and Energetics Panel, AGARD (Pisa, Italy) September 6–9, 1965 (in press).
6. See, for example, the excellent review by Sugden, T. M.: "Elementary Combustion Reactions—Charged Species," pp. 539–544, and the papers on Ionization Phenomena in the Discussions on Elementary Combustion Reactions, and on the Electrical Properties of Flames, *Tenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1965.
7. *Loc. cit.* (cf. Ref. 5).

Subject Headings: ***Chemi-ionization; Flame, plasmas in; Ions, in flame; Plasmas, in flame.***

D. E. Rosner

*Comments by A. von Engel and J. R. Cozens**

At the editor's invitation we offer some observations on the foregoing. Until recently the production of ions and electrons in flames has been attributed to molecule–molecule (radical) collisions. In contrast, the authors have suggested that ionization by various electron–heavy particle collisions must be considered; the elevated mean electron energies observed support this contention. Whether these latter processes are predominant only in torch flames, as used by the authors, or in other flames too, is not yet clear. But there is the other suggestion concerning the role of species carrying a substantial amount of potential energy which may be vibrational or electronic or both. The exchange of this energy in collisions (of the second kind) has not been considered in the past.

The favored chemi-ionization reaction quoted was thought to be associated with a low ionization cross section (reaction rate constant) and thus it produced too few electrons of practically zero energy. To overcome this difficulty the second idea proposed has been recently incorporated in this process by assuming that the radicals involved are in excited states. Moreover, according to Sugden's latest work (AGARD, Pisa, 1965), the mechanism of alkali-seeded flames seems to require electron collision reactions. Only more patient work, and an unemotional approach to this interesting problem, will lead to a solution.

* It was the opinion of the editor that a short statement by the authors would help provide a more balanced account. Dr. Rosner very graciously assented to this request.

Wehner, J. F. (University of Notre Dame, Notre Dame, Indiana) "Flame Processes—Theoretical and Experimental," *Advances in Chemical Engineering* **5**, 1–36 (1964)

Although the author states that his major interest is in the use of flames for new methods of chemical syntheses, this article is essentially a survey of the present state of combustion theory and the extent to which it can illuminate experimentally observed behavior. Since most writers in this field tend to be either exclusively theoreticians or exclusively experimentalists it is refreshing to find both viewpoints combined in an interesting and readable article. In 31 pages the author gives an excellent review of the present knowledge of flame processes for both premixed laminar flames and solid propellant combustion. Included are 114 references. The section on stabilization of flames will be of particular interest to those concerned with suppressing fires.

The author traces the history of flame studies from the early measurements of burning velocity to the present day determinations of heat release and composition profiles. Since burning velocity determines heat release rates and burner design depends on this parameter, much early effort was devoted to the measurement of burning velocity. Many approximate theories were developed to correlate the variation of burning velocity with changes in temperature and pressure and to predict the burning velocity of new mixtures. However, the involved interaction between thermal, diffusional, and chemical kinetic processes which occur in a flame makes it impossible to develop a simple method for the estimation of burning velocity. Nor can the ability to predict trends in burning velocity be considered an adequate verification of a theory. At the present time flame theory is sufficiently developed that, provided the kinetic and diffusion constant are known, composition and temperature profiles, as well as burning velocity, can be determined for a fairly complicated system. If the kinetic constants are not known, flame theory may be used as a tool for deriving kinetics from experimental profiles.

Wehner gives a very good summary of the present state of theory for laminar premixed flames. The derivation of the equations, the various techniques for handling boundary conditions in the cold gas, the problems involved when intermediates exist in non-steady-state concentrations, and the mathematical techniques for solving the differential equations are examined. This section is an excellent introduction to flame theory because the reader can understand in a qualitative way how flame theory is formulated, how it can be used, and what problems remain, without being lost in complicated mathematics.

Experimental determinations of temperature and composition profiles in low pressure flames are then described. Using the methane flame as an example the author shows how the combination of experimental and theoretical studies has led to a very good understanding of the chemistry and kinetics of this complex flame system. The author points out that the major unsolved problem in understanding flames is the lack of experimental knowledge of the free radical concentrations.

The stabilization of flames are discussed under flammability limits, ignition, and transition to detonation. One of the most characteristic features of flame propagation is the flammability limits. Although experimentally the composition limits within which flames will burn are well known, there is as yet no satisfactory theory of fundamental flame limits. The design of suitable techniques for ignition remains an art. Since a steady-state flame profile is independent of the previous history of the gases, a number of routes may lead to ignition. Most studies, aimed at determining ignition energy, have been based on a thermal theory of ignition; however, a theory based on the introduction of active intermediaries (free radicals) may prove to be more useful. The differences between deflagration (normal burning) and detonation (shock wave maintained by chemical energy) and the process by which detonations develop are examined.

There is an elementary discussion of solid propellants. Burning rates of solid propellants increase with pressure in contrast to gaseous flame velocities which are little influenced by pressure. A burning rate theory for double base propellants may be developed in terms of a normal gaseous flame coupled to the solid surface by the heat transfer necessary to gasify the solid. Calculation of burning rates for composite propellants are more difficult but several theories are described.

A final section discusses the use of a flame as a chemical reactor. There are three principles by which such a flame process may be designed. A flame may form a desirable product by reacting to a favorable equilibrium, e.g., preparation of chlorinated hydrocarbons or boron nitride. The stabilization of an intermediate species may be achieved by quenching, e.g., formation of carbon black or acetylene. The condensation of solids from flame products may be controlled to give desirable physical properties to the solids, e.g., preparation of titanium dioxide for paint pigment.

Subject Headings: *Flame, processes; Flame, theory of; Processes, in flame; Theory, of flame.*

W. E. Wilson

Zeegers, P. J. Th. and Alkemade, C. Th. J. (Physics Laboratory of the State University, Utrecht, Netherlands) "Radical Recombinations in Acetylene–Air Flames," *Combustion and Flame* **9**, 247–257 (1965)

In this paper an analysis is given of the behavior of excess radical concentrations, H, OH, and O as a function of height above the reaction zone in premixed acetylene–air flames at 2200°–2400°K and 1 atm pressure. The intensity was measured of the Li resonance line which is related to the H concentration through the lithium–water equilibrium. The OH concentration was measured by absorption of the (0, 0) band of OH at 3064 Å. The H, OH, and O concentrations are related to one another by rapid, binary exchange reactions with stable flame molecules. A rather elaborate but complete mathematical expression is derived, which takes into account (i) the four recombination reactions, H+H, H+OH, O+O, and CO+O, and the reverse reactions; (ii) the variation of stable molecule concentrations due to radical recombination; (iii) the effect of varying temperature on the flame equilibria. The experimental results were found to be consistent with theory. By making use of some additional literature data, it appeared that the decay of excess radicals in our flames is mainly governed by H+OH and (to a less extent) CO+O recombination. The binary rate constant for the first reaction, which was found in this investigation to equal $(1.3\pm0.4)\times10^{-13}$ cm^3 sec^{-1}, agrees with literature data obtained in hydrogen flames. As a side result of this investigation the dissociation energy of LiOH was found to be 110±5 kcal/mole which narrows the uncertainty in this quantity when combined with two other values reported in the literature.

Subject Headings: *Acetylene flame; Flame, radical recombination; Recombination, in flame; Radical, recombination in flame.*

Authors' Abstract

VI. Radiation

Gille, J. and Goody, R. (Harvard University, Cambridge, Massachusetts) "Convection in a Radiating Gas," *Journal of Fluid Mechanics* **20**, 47–79 (1964)

Of considerable interest in astrophysics and geophysics is the onset of convection in a radiating fluid. Although the critical conditions for such onset can be measured only with great difficulty in the large-scale phenomena, the authors have demonstrated that the effects can be quite accurately measured on a laboratory scale. Convection develops in a fluid when the work done by buoyancy forces exceeds that required to overcome friction. An important dimensionless number, called the Rayleigh number (Ra), was found to have a critical value (for onset of convection) of 1786 for a nonradiating gas, such as air, and a much higher value (4870) for a a radiating gas, ammonia.

$$\mathrm{Ra}=(C_p g\alpha/K\eta)\rho^2,$$

where C_p=specific heat at constant pressure, g=acceleration of gravity, α=coefficient of expansion, K=thermal conductivity, η=viscosity, and ρ=density. Ammonia was selected as representative of water vapor, with a more convenient temperature range at room conditions.

A theoretical and experimental study was made of the effect of radiative transfer on the onset of convection by comparing the effects of air and ammonia contained between horizontal aluminum plates maintained at different temperatures. Detailed knowledge of the physical and optical properties of the gases were required, so that the authors were able to calculate the temperature profiles and heat flux, for all cases. Air does not interact with the radiation flux, and a linear temperature profile results, while ammonia absorbs and re-emits radiation from the plates, giving rise to a nonlinear temperature profile.

Measurements in the convection cell had to be made with great precision (e.g., temperatures were measured to within ±0.01°K), because the heat flux due to conduction and convection between the plates was very small compared to that due to direct radiation. The heat flux was measured by means of the temperature gradient in the cell structure, and the gas temperature distribution by means of an interferometer. In the case of the two gases, two different plate spacings, and several values of heat flux, very good agreement with the theory was obtained. Onset of convection is indicated by an abrupt increase in the heat flux.

It was found that, if the lower plate is at the higher temperature, and if the temperature difference is sufficiently large, the enclosed gas will become unstable to small disturbances, and convection will start. Radiative transfer within the gas tends to stabilize the situation. It appears that the critical Rayleigh number is quite analogous to the critical Reynolds number for forced convection. It is possible to estimate the value of critical Rayleigh numbers and the time constant for instability for many situations. The authors feel that this is the first attempt to determine the critical Rayleigh number of a gas with precision.

Subject Headings: ***Convection, with radiation; Radiation, effects on convection; Rayleigh number, critical.***

J. K. Richmond

Murgai, M. P. and Varma, R. K. (Defence Science Laboratory, Delhi, India) "Radiative Transfer Effects in Natural Convection above Fires—Opaque Approximation," *Quarterly of Applied Mathematics* 22, 345–353 (1965)

This paper is the second in a series of at least three theoretical analyses of radiative energy transfer effects in convection plumes above fires. In the first,[1] Murgai attempted two solutions of the coupled continuity, conservation, and radiative transfer equations within the framework of conventional axisymmetric boundary layer and convection column theory. Approximations of plume transparency and opacity were invoked in the radiative transfer equation and two corresponding solutions attempted. While the former assumption allowed a solution, the latter reduced to the case of no radiative transfer because the author assumed the temperature at the edge of and outside the plume to be the same, resulting in no temperature gradient and loss of the dominant terms in the usual boundary layer approach.

In this paper, the authors have retained the vertical (along flow directions) diffusivity terms usually negligible in boundary layer theory and have modified the values of absorptivity corresponding to the opaque approximation. A table of results is given in which the calculated 50% heights for bouyancy from the opaque model are compared with values the authors previously obtained from the transparent case. The values calculated in this paper for typical fire sizes (10^3 to 10^5 cm) are considerably smaller than those formerly calculated. The large values of the 50% heights of bouyancy in the transparent approximation were an obvious indication of the weakness of the model. The results for this, the opaque case, indicate that 50% heights for bouyancy are independent of fire size at the horizontal boundary of plumes having the same absorption coefficient.

Noteworthy also is the result indicating the existence of a layer very near the horizontal boundary where radiative transfer is dominant. In this region, the radiative Prandtl number is much less than 1 and the thickness of the thermal boundary layer becomes very large and penetrates deep inside the plume. Physically this corresponds to a case in which the plume is losing heat very fast via radiation, with the bouyancy approaching zero immediately and plume size and velocity remaining nearly constant.

For the mathematically minded, the paper also contains an extensive appendix describing the approximate analytical solution of the differential equations involved and a comparison of this solution to results obtained by numerical integration.

Reference

1. Murgai, M. P.: J. Fluid Mech. *12*, 441 (1962).

Subject Headings: *Convection, and radiation in fire; Fire, radiative conduction in; Plumes, radiation from; Heat transfer, radiative, with convection.*

W. J. Miller

VII. Suppression of Combustion

Chandler, S. E. (Joint Fire Research Organization, Boreham Wood, England) "Danger of Explosions in Domestic Back Boilers," *The Municipal Journal* (15 January 1965)

A short discussion is given of the danger of explosion in the boilers used in homes in the United Kingdom.

Subject Headings: *Boilers, explosion danger in; Explosion, danger, in boilers.*

Editor

Davis, J. B., Dibble, D. L., Richards, S. S., and Steck, L. V. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Gelgard—A New Fire Retardant for Air and Ground Attack," *Fire Technology* 1, 216–224 (1965)

Viscous water and gels have been proven to be more effective on forest fires than plain water. In 1963 and 1964, a new member of this family of fire retardants was tested. The authors describe the properties and characteristics of the compound, report the results of laboratory and field tests, and compare its effectiveness to that of plain water and other viscosity agents.

Subject Headings: ***Fire retardants, Gelgard; Gelgard, fire retardant.***

Authors' Abstract

Elkins, G. H. J. (Joint Fire Research Organization, Boreham Wood, England) "Use of Anti-Freeze in Water Extinguishers," *Fire* **57,** 448 and 456 (1965)

The problems and possibilities of using anti-freeze solutions in commercial water fire extinguishers are discussed.

Subject Headings: ***Anti-freeze, in water extinguishers; Extinguishers, anti-freeze in.***

Editor

Lindeken, C. L. and Taylor, R. D. (Lawrence Radiation Laboratory, University of California, Berkeley, California) "High Expansion Foam Fire Control System for Gloved Boxes," *Fire Technology* **1,** 211–215 (1965)

The use of hazardous materials in gloved boxes has resulted in a need for rapid fire detection and extinguishment within the enclosures. Inert atmospheres and reduced atmospheres have been tested but have not yielded the degree of reliability required. An automatic high expansion foam system, which has given satisfactory results, is described.

Subject Headings: ***Suppression, in glove boxes, by foam; Foam, for glove box fire.***

Authors' Abstract

Meldrum, D. N., Williams, J. R., and Conway, C. J. (National Foam System, Inc., West Chester, Pennsylvania) "Storage Life and Utility of Mechanical Fire-Fighting Foam Liquids," *Fire Technology* **1,** 112–121 (1965)

Many foam liquids for use in fire fighting are concentrated aqueous solutions of material of organic origin and their storage life is limited. As yet there is no set of tests that is accepted as giving a good estimate of the useful life of foams. In this paper the authors discuss the various factors which may play a part in influencing storage life and give the results of some tests on heat stability and evaporation effects. The original U. S. Armed Services specification JAN-C-266 required that the sediment accumulated after three years of storage under normal conditions should not exceed 0.2%. The current U. S. Military specification O–F–555 does not indicate a sediment limit but requires at least one year of useful life. The sediment limit which can be tolerated is a function of the nature of the sediment and the method of foam liquid injection into the main stream. However, for the tests which they carried out the authors took 0.2% sediment as a reasonable indication of initial liquid deterioration.

Thermal effects

A series of tests was carried out by subjecting up to 8 samples for each point to temperatures which were varied between 100° and 200°F. The containers were sealed so that the foam liquids were not exposed to the atmosphere, but no other details are given of the method of testing except that the temperature must be controlled to within ±1°F. A log–log plot of time against reciprocal temperature leads to a straight line for the results on the two liquids tested. These results were confirmed by field tests on the same two liquids. The method of testing was not refined and gave only an indication of susceptibility to thermal degradation.

Most of the storage containers used in practice are vented to atmosphere and this can lead to evaporation from the stored foam liquid. In the case of those stabilized by iron salts, a crust of solids can form on the surface which breaks up and sinks when the solution is agitated. Over a period of three months, tests were made in closed and vented containers with two liquids stabilized by a relatively high concentration of iron salts. One of the vented tanks reached 5% sediment for a 3% evaporation loss; sediment was negligible in the other cases. Apart from this particular characteristic, evaporation leads to changes in density and viscosity in the stored foam liquid. This can have very serious effects on the amount of foam liquid incorporated into the main stream where inductor-type devices are used to mix the two streams. The authors carried out tests and give the results for viscosity change with evaporation and the effect on the pickup in an induction-type device due to the evaporation loss.

They also discuss the effects on storage life and utility of dilution and contamination of foam liquids.

Subject Headings: ***Foam, liquids, storage life of; Storage life, of foam liquids.***

M. G. Perry

Murphy, E. E. (Stanislaus National Forest, California) **and Murphy, J. L.** (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Value of a Timber Fuel Break—The Wet Meadow Fire," *Fire Control Notes* 26, 3–4 (1965)

A discussion is given of the value, engineering, and maintenance of fire breaks in relation to the Wet Meadow Fire of July 5, 1962, in the Stanislaus National Forest of Northern California.

Subject Headings: ***Fuel breaks; Timber, fuel breaks; Fire, Wet Meadow.***

Editor

Murphy, J. L. and Schimke, H. E. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Do Wire Fences Stop Ground Fires?" *U. S. Service Research Note PSW 70* (1965)

Five meshes ($\frac{1}{8}$ to 1 in.) of 16-gauge steel wire fences, 3 ft high, were tested as possible ground fire barriers in four fuel types. The $\frac{1}{8}$-in. mesh stopped only one test fire but retarded others; $\frac{1}{4}$-in. mesh retarded some. The results suggest that further trials may be worthwhile.

Subject Headings: *Fences, wire, for fire stopping; Fire, stopping, by wire fences.*

Authors' Abstract

Nash, P. and Fittes, D. W. (Joint Fire Research Organization, Boreham Wood, England) "Further Work on the Compatibility of Dry Powders and Protein Foam Liquids," *Joint Fire Research Organization Fire Research Note No. 564* (July 1964)

An experimental study was made to determine the compatibility of dry powders and protein foam liquids when used in combination as fire extinguishers. Dry powders are rapid and efficient, in terms of fire area capability per pound of agent, but lack the ability to seal the surface of the fire and prevent reignition from hot sources remaining in the fire areas. Foams are slower in action and less efficient but are superior in sealing the fire area until it cools to a safe temperature.

Powders and foams are frequently incompatible in that powders tend to highly accelerate the rate of breakdown of the foam blanket. This is particularly true of powders with metallic stearate water-proofing and flow additives.

Many factors affect the compatibility of a particular combination of a powder, powder additives, and a foam, including the nature of the flammable liquid and the method and order of application.

Conclusions on the compatibility of a powder and foam is dependent upon the type of laboratory test employed. As many as six different tests have been used each of which may yield a different indication of effectiveness of the material under test. Three test methods have been selected by the Joint Fire Research Organization, none of which alone is suitable for a final specification but collectively indicate a relative effectiveness of extinguishing agents.

Briefly, the test methods are:

1. Measurement of time for the fire radiant heat output to drop to one-tenth of its initial value.
2. Agent applied until the radiation drops to one-tenth its initial value, the application stopped and measurement then made of the time required for the fire to recover to one-third its initial intensity.
3. Measurement of the drainage rate from a pan of foam, the upper surface of which is irradiated at a given intensity.

Tests were run by each of the three test methods of various combinations of 20 powders and 5 foams. The order of effectiveness of a combination for each test method was tabulated. The rating of powders by tests (1) and (2) were broadly in agreement but were in disagreement with tests by method (3), particularly for powders having a high content of metallic stearate. The results also showed that the degree of foam breakdown due to powder containing metallic stearate is strongly influenced by the composition of the base powder. The susceptibility of foams to breakdown was correlated to the changes in pH of the foam liquid due to the powder partly dissolving in the liquid. A large pH change was found with foams very susceptible to breakdown. Other factors such as salt concentration and foam shear stress were discussed.

It was concluded that test method (1) was best because conditions were typical of practice, results were not overly sensitive to foam batch variation, and it was a simple test to conduct. The most compatible powders were sodium and potassium bicarbonates, chlorides, and sulphates but their effectivenesses are dependent upon many factors.

Subject Headings: ***Foam, compatability, with powder; Compatability, foams and powders; Potassium bicarbonate; Powders, compatability, with foam; Foam, protein; Sodium bicarbonate.***

R. W. Ziemer

Phillips, C. B. (California Division of Forestry, Sacramento, California) "Fighting Forest Fires with Air Tankers—1963," *California Division of Forestry, Department of Conservation Fire Control Experiments No. 7* (1964)

A summary of experience on fighting forest fires with air tankers is given.

Subject Headings: ***Air tanker, for fire fighting; Fire fighting, with air tanker; Forest fire, fighting, with air tanker.***

Editor

VIII. Model Studies and Scaling Laws

Grumer, J. and Strasser, A. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Uncontrolled Fires—Specific Burning Rates and Induced Air Velocities," *Fire Technology* 1, 256–268 (1965)*

The authors describe a series of experiments with wood fires. Their purpose was to increase the understanding of the fire storm. Their method was to employ model fires in the laboratory. They started with the hypothesis that the fire storm is generated by the nearly simultaneous ignition of a large area of heavy fuel load, and the presumption that a large fire area will by virtue of size alone induce winds which

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* This work was supported in part by the Department of Defense and the National Science Foundation through the National Bureau of Standards.

accelerate specific burning rates into those observed in fire storms. A further implied assumption was that the fire behavior characteristics identified as the "fire storm" are present in measurable, or at least detectible and reproducible form in small "uncontrolled" fires of laboratory scale.

The fires were uncontrolled only in the sense that the fuel consumption rate depended on fuel and ambient conditions. The fuel beds consisted of small wood blocks from 2 to 9 cm on an edge in wire mesh baskets. Tests were run with blocks in random or "unordered" arrangements, and in specific arrangements to test effect of orientation and spacing. The weight of fuel in a basket ranged from 4 to 40 kg. Fuel loading ranged from approximately 15 to 150 kg/sq m. Burning rate was measured by continuously weighing the fuel bed. Air flow velocity was measured by means of motion pictures of dust particles dropped into the air.

The tests showed no significant correlation between horizontal cross section of the fuel bed and induced air velocity for diameters ranging from 33 to 100 cm and fuel weights ranging from 4 to 40.5 kg.

When air blasts into the fuel bed were imposed, the burning rate increased in ratios ranging from 1.6 to 6.6. The average for a 5 mile wind was 1.6. That for a 20 mile wind was 2.8. When the air blast was into the fire column instead, the burning rate did not increase.

When tests were made of the effect of spacing between burning fuels, the maximum burning rate was at a separation of 6 cm.

In ordered fuel beds there was strong evidence that heat transfer by convective energy controlled burning rate to a much greater degree than heat transfer by radiation. The authors reinforced this by introducing the results of experiments by D. Gross[1] in burning cross piles of wood.

Over all, these tests failed to simulate any of the characteristics attributed to a fire storm and were perhaps disappointing to the authors on that account. Yet the data obtained are of valuable reference and are likely to be useful beyond the scope of these experiments.

There are many handicaps in modeling a large uncontrolled fire and even more uncertainty in simulating a fire storm. This is due to several factors. From ignition to peak burning rate, a large intense fire in woody fuels can not be properly described by a smooth curve. Rather the progression represents successive crossing of several thresholds with associated changes in the behavior of the fire and its relation to its environment.

There is good evidence from analysis of forest fire records that superadiabatic lapse rates often lead to so called "blow up" fires, fires which exhibit violent behavior, similar to fire storms. This supports the authors' conclusion that energy from the atmosphere, as well as from the fire, must enter into the phenomena. The temperature gradient measured in the laboratory would have a negative effect in this respect.

Another factor is oxygen access. The test fires were so well ventilated that complete combustion took place close to the fuel bed. As size of the fire and fuel loading increase varying degrees of oxygen lack enter in. This is illustrated by ignition of unburned gases at increasing distances from their source. Fire whirls and development of violent convection, appear to be associated with burning rates that temporarily race ahead of a uniformly available oxygen supply. This phenomenon is not observed in small fires.

The dominant role of convective forces in heat transfer is of special significance in the behavior of forest fires. Experiments by Fons indicated that only about 20% of the energy is radiated outside the fire system. In very large fires heat transfer by convection reaches the proportions of mass transport.

All these relationships are given additional significance by virtue of these experimental fires. Each needs continuing research to eliminate the uncertainties that persist in interpreting and predicting the behavior of a free burning fire in woody fuels.

Reference

1. Gross, D.: J. Research Natl. Bur. Std. *66C*, 99 (1962).

Subject Headings: ***Air, induced, burning rate of; Burning rate, induced air; Fire storm, simulation; Modeling, of fire storm.***

A. A. Brown

IX. Atomization of Liquids

Essenhigh, R. H., Froberg, R., and Howard, J. B. (Pennsylvania State University, University Park, Pennsylvania) "Combustion Behavior of Small Particles," *Industrial and Engineering Chemistry* 57, 32–43 (1965)

Analysis of the equations for boundary-layer diffusion, adsorption and subsequent desorption (as represented by the Langmuir isotherm) has confirmed the conclusions of Hottel and Stewart that the resistances to combustion of small particles in flames are due to the combined effects of diffusion and adsorption—not simply to diffusion alone. The re-examination of the classic data of Hottel, Tu, and Davis[1] in the light of more advanced theory has established that adsorption controls the combustion of particles under 100 microns in diameter. The theory of one of the more important processes of our time—the combustion of carbon—is thus made consistent with experimental observation to an extent not previously known.

Simultaneous consideration of the reaction rate equation for boundary layer diffusion

$$R_s = k_0(p_0 - p_s) \tag{1}$$

with the reaction rate equation along the Langmuir isotherm

$$1/R_s = (1/k_1 p_s) + (1/k_2) \tag{2}$$

yields the following equation for the specific reaction rate (R_s):

$$R_s^2 - (k_0 p_0 + k_2 + k_0 k_2/k_1) R_s + (k_0 p_0) k_2 = 0, \tag{3}$$

where k_0 = velocity constant for mass transfer (B.L.), k_1 = velocity constant for adsorption process, k_2 = velocity constant for desorption process, and p_0 = oxygen partial pressure in the main stream.

For k_2 large, Eq. (3) reduces to

$$1/R_2 = (1/k_0 p_0) + (1/k_1 p_0) = S_0 + S_1 \tag{4}$$

a first-order reaction (at high temperature). For k_1 large, Eq. (3) reduces to

$$(R_s-k_2)\ (R_s-k_0p_0)=0, \tag{5}$$

which implies that k_2 is controlling at low temperatures, k_0p_0 at high temperatures, with a discontinuous change from one region to the other. For k_0 large, Eq. (3) reduces to the Langmuir isotherm of Eq. (2), with p_0 substituted for P_s:

$$1/R_s=S_1+S_2. \tag{6}$$

Application of the above concepts (including the introduction of an effective activation energy) to the empirical data of Tu, Davis, and Hottel permits excellent correlation of the data, which verifies the validity of the empirical methods utilized, tends to confirm the accuracy of diffusion calculations, and establishes the confidence with which the derived equations can be used for calculating mass transfer in a flowing system. The results of the empirical correlation leads to the following conclusions regarding the three-resistance concept:

1. At low temperatures ($<1000°K$), the desorption resistance (S_2) predominates, and the reaction order is zero.
2. At high temperatures, the diffusion and adsorption resistances (S_0 and S_1) are both important, and the reaction is first order.
3. At higher velocities, or small (<100 microns) particle sizes, the diffusion resistance S_0 becomes progressively less important.

The reciprocals of the three resistances are related to the velocity constants of the three processes by:

$$1/S_0=k_0p_0=A_0p_0(T/T_0)^{0.75} \tag{7}$$

$$1/S_1=k_1p_0=A_1p_0 \exp\ (-E_1/RT)=B_1'p_0 \exp\ (-E_1'/RT) \tag{8}$$

$$1/S_2=k_2=A_2 \exp\ (-E_2/RT), \tag{9}$$

where A_0 is velocity dependent and temperature independent, A_1 is temperature dependent and velocity independent, and B_1' and A_2 are both temperature and velocity independent.

Reference

1. Tu, C. M., Davis, H., and Hottel, H. C.: Ind. Eng. Chem. *26*, 749 (1934).

Subject Headings: ***Adsorption, effects on combustion, of particles; Combustion, of particles; Particles, combustion of.***

C. C. Miesse

Peterson, H. B. (U. S. Naval Research Laboratory, Washington, D. C.) "The Measurement of Particle Size of Fire-Fighting Dry Chemicals," *U. S. Naval Research Laboratory Report 6274* (1965)

Four samples of potassium bicarbonate base fire extinguishing powders, "Purple-K-Powder," which had been ground to different degrees of fineness were analyzed for particle size characteristics by several different methods. These were the Blaine

Fineness test, the Roller Particle Analyzer, the Coulter Counter, surface area by nitrogen adsorption, and mercury porosity. Comparisons were made of the results of the procedures. Highest values for specific surface were obtained by the nitrogen adsorption method followed by the Blaine, the Coulter, and then the Roller methods, in that order. No conclusions were made as to which method gave the most accurate result for particle size, but it was found that the mean diameter was a better basis for comparing results than was the median diameter. Although the relationships of specific surface values among methods were nonlinear over wide ranges, calibration curves were made to facilitate conversion. It was also concluded that specific values, as obtained by permeability with the Blaine method, were adequate for describing the desired size of particles for fire extinguishing purposes.

Subject Headings: *Area, specific, of powders; Particles, dry chemical, size of; Particles, size measurement; Powders, dry chemical, size of; Powders, Purple K, size of; Area, surface, of powders.*

Author's Abstract

X. Meteorological Interactions

MacHattie, L. B. (Department of Forestry, Ottawa, Canada) "Comments on the Meterology of Forest Fire Control and Forest Regeneration in Canada," *Original paper presented July 13, 1962, at the Scientific Session jointly sponsored by the Commission for Agricultural Meteorology and the Royal Meteorological Society, Canadian Branch, held in Toronto, Ontario.* (*Paper revised December 1962*)

The long life of the crop, the great and inaccessible surface area it has, and the roughness of the terrain on which it grows make forest meterology much different from agricultural meteorology. The forest meteorologist aims to understand the microclimates of the forest, as well as their relations to the macroclimate and their responses to alteration in the forest itself.

Weather so directly affects fire occurrence and behavior that the application of meteorology has especially large potential economic benefit in the control and use of fire. A system for rating fire danger on the basis of simple weather observations has been developed over the past 30 years and is in use throughout Canada. The number of fires and area burned correlate well with ratings. Two major factors in the danger rating system are moisture content of light surface fuels and rate of drying in depth of heavier fuels. Research is under way on the role of dew in drying, rate of drying during drought, and effects of topography on weather.

A recent study in Alberta revealed lower night minimum relative humidities on lower slopes than in a major valley bottom, although day minima were almost identical. Maxima and minima were essentially the same in young lodgepole pine stands as in the open. Other research deals with the occurrence of lee winds in British Columbia and with specific circumstances under which lightning starts fires.

Temperature and light are perhaps the most important meteorological factors in regeneration. In the special case of jack and lodgepole pine, temperatures adequate to cause the serotinous cones to release seed were found near the surface of the soil, although air temperature was 20°C lower. Similar soil heating frequently causes fatal stem girdling of spruce seedlings in Alberta, and drought is also an important cause of death. At the other extreme, frost due to radiational cooling can kill more than 50% of spruce seedlings in openings such as clear-cut areas. Variation in soil surface temperature depends mainly on soil moisture and ventilation by wind.

Early development of tree seedlings depends heavily on light intensity, which is very hard to measure in forest stands. The light requirement of a species is a major determinant of the cutting method best suited for regenerating it. Heavy thinning is required to appreciably increase light intensity beneath the stand. (26 references, all Canadian.)

Subject Headings: ***Fire control, meteorology; Meteorology, fire control.***

G. R. Fahnestock

Pirsko, A. R., Sergius, L. M., and Hickerson, C. W. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Causes and Behavior of a Tornadic Fire-Whirlwind," *U. S. Forest Service Research Note PSW 61* (1965)

A destructive whirlwind of tornadic force was formed in a 600-acre brush fire burning on the lee side of a ridge near Santa Barbara on March 7, 1964. The fire whirlwind, formed in a post-frontal unstable air mass, cut a mile long path, injured 4 people, destroyed 2 houses, a barn, 4 automobiles, and wrecked a 100-tree avocado orchard.

Subject Headings: ***Tornado, induced by fire; Vortex, induced by fire; Whirlwind, induced by fire.***

Authors' Abstract

XI. Operational Research Principles Applied to Fire Research

Jarrett, H. F. (System Development Corporation, Santa Monica, California) "A Symposium: The Systems Approach to Fire Protection Problems. Part I. The Systems Approach—An Overview," *Paper given before the Society of Fire Protection Engineers, Washington, D. C.* (May 19, 1965). *Fire Technology* 1, 182–187 (1965)

Courses of action determined by investigations of limited scope may create problems outside the area of immediate concern. The systems philosophy provides a broad base for research by considering the effects of individual elements on the over-all system. The author explains the systems approach and relates it to several subjects of interest to the fire protection engineering profession.

Subject Headings: ***Fire protection, systems approach to; Operations research, in fire protection; Systems approach, to fire protection.***

Author's Abstract

XII. Instrumentation

Hill, K., Hornstein, B., and Michaelis, T. (Thiokol Chemical Corporation, Reaction Motors Division, Denville, New Jersey) "Research Leading to the Development of a Hydrogen–Air Fire and Explosion Detection System for Aerospace Vehicles," *Technical Report AFAPL-TR-65-33, Contract AF33(615)-1550 Air Force Systems Command, Wright-Patterson Air Force Base, Ohio* June 1965.

Previous work[1] demonstrated that timely detection of hydrogen–air deflagrations in aerospace vehicle environments is best based upon detection of OH band radiation (UV) from the reaction zone.

The main goal of the present work was to determine to what extent this principle could be applied in a practical system to provide timely, reliable, and useful detection of incipient deflagration hazards in flight vehicles under all hazardous operational conditions. Ideally this system would not only detect a hazardous reaction but also evaluate the degree of hazard through quantitative electronic processing of the early time history of the radiation from the reaction zone.

In this connection a series of simulated leak tests, with ignition occurring in partially mixed, nonhomogeneous hydrogen–air systems proved that the time rate of growth of radiation and pressure were highly variable and depended not upon gross stoichiometry but primarily upon the relative positions of leak and ignition source, leak rate and orientation, and chamber geometry which govern the degree of mixing obtained at the time of ignition.

It was therefore concluded that degree-of-hazard evaluation was not practical for a simple electronic system because the time–radiation characteristics could not be analytically predicted in a generalized form. Therefore, the model detection system fabricated has the practical purpose of positive detection under all conditions plus determination of the location of the incipient deflagration through the use of dual detectors.

As part of this program, commercially available photo-emissive detectors were evaluated for solar-blind operation. None of the detectors tested displayed both an adequate solar blindness and an adequate linearity of response.

Reference

1. Hill, K. and Hornstein, B.: "Detection of Hydrogen–Air Fires and Explosions in Aerospace Vehicles via OH Band and Water Band Emission," *Technical Documentary Report No. ASD-TDR-63-113*, January 1963. (See *Fire Research Abstracts and Reviews 6*, 73–74 (1964).)

Subject Headings: ***Detectors, for fire; Explosion, detection of; Fire, hydrogen, detection of; Hydrogen, fire, detectors.***

Authors' Abstract

Schnizlein, J. G., Brewer, J., and Fischer, D. F. (Argonne National Laboratory, Argonne, Illinois) "Temperature Transducer for Thermogravimetric Studies," *Review of Scientific Instruments* 36, 591–593 (1965)

An instrument has been designed to measure the temperature of a sample suspended in a thermobalance without interfering with the balance operation. Continuous and simultaneous temperature and weight records therefore can be obtained.

The instrument uses the principle of a magnetic amplifier to sense a current caused by the potential generated by a thermocouple in the sample. A d.c. potential linear with temperature is recorded. Precision has been demonstrated to be better than 2° up to 700°C. No measurable effect of the temperature transducer on weight recorded by the analytical balance was detected. Bouyancy and convection effects on weight are discussed.

Subject Headings: ***Temperature transducer, for thermogravimetry; Thermogravimetric studies, temperature transducer for; Transducer, for thermogravimetric studies.***

Authors' Abstract

XIII. Fire-Fighting Techniques, Equipment

"Fire Record of Cities, 1964—As Reported by Municipal Authorities," *Fire Journal* **59** (5) 56–60 (1965)

Fire statistics for a number of cities in the United States and Canada are tabulated by states and provinces. The number of total alarms, total fires, building fires, false alarms, and population are compiled. Another table (Table I) shows a com-

TABLE I *

Comparative statistics, 1963 and 1964

Alarms and Fires	United States 1963	United States 1964	Canada 1963	Canada 1964
Alarms:				
Number of cities reporting	753	740	83	72
Number of alarms	1,469,305	1,480,770	105,399	100,444
Alarms per 1,000 population	19.3	19.5	13.1	13.8
Fires:				
Number of cities reporting	757	739	83	72
Number of fires	813,075	819,198	54,126	49,857
Fires per 1,000 population	10.7	10.8	6.8	6.9
Fire losses:				
Number of cities reporting	623	670	64	63
Amount of loss	$263,236,000	$280,462,000	$40,247,000	$29,540,000
Amount per capita	$5.42	$4.96	$6.05	$4.48
Building fires:				
Number of cities reporting	756	739	83	71
Number of fires	312,720	324,737	28,144	24,065
Fires per 1,000 population	4.1	4.3	3.5	3.3
Building fire loss:				
Number of cities reporting	639	634	71	62
Average loss	$1,290	$1,100	$1,770	$1,277

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parison of the over-all statistics for alarms and fires in the United States and Canada for 1963 and 1964. An encouraging reversal in the recent upward trend of fire losses is noted.

Subject Headings: ***Records, urban fire; Records, urban fire, Canada; Records, urban fire, United States.***

Editor

"A List of Cities and Towns in Texas with Fire Protection and Fire Record Data," *State Board of Insurance of Texas, Austin, Texas* (March 1, 1965)

The fire protection record for the year 1964 is compiled for the State of Texas by the State Board of Insurance.

Subject Headings: ***Fire protection, Texas; Records, fire, Texas; Texas, city and town fire records.***

Editor

"Federal Fire Experience for Fiscal Year 1964," *Federal Fire Council, Washington, D. C.*

The federal fire experience is summarized for the fiscal year 1964.

Subject Headings: ***Fire, federal experience, United States; Fire, on federal property.***

Editor

Ashton, L. A. and Malhotra, H. L. (Joint Fire Research Organization, Boreham Wood, England) "Curtain Walling and Fire Protection," *The Architect's Journal* **140,** 1059–1064 (1964)

This article describes an experiment of a large-scale type, to determine whether it was possible to design curtain walls so that the present British fire requirements could be satisfied without a back-up wall for residential or office occupancies. The tests were conducted in a four-story tower, consisting of single rooms approximately 10×10×8.5 ft high, one above the other. One side of the tower was left open and was filled in by the wall construction to be used. The curtain wall covered the open end of each room on each story. It included fire resistant infill panels and normal glazing. Aluminum mullions were fixed to the floor slabs by means of bolted clamps at each floor level. Each panel consisted of two skins of asbestos insulation board, $\frac{3}{8}$ in. thick with $\frac{5}{8}$ in. of mineral wool. The external face of the panels were finished with an aluminum sheet bonded to the asbestos.

A standard crib fire set at the first floor level and detailed observations and heat measurements were taken on the upper floors. After $6\frac{3}{4}$ min, the windows on the first floor cracked. The windows on the floor immediately above the fire cracked shortly thereafter and combustible materials on the second floor were ignited within the next 3 or 4 min. The test was continued for 45 min, at which time the fire had subsided. While the exterior aluminum panels on the floor directly above the fire were fused, fire did not enter this area except through the broken windows.

It was concluded that curtain walls of this type of light alloy could be designed to meet the standards of fire protection specified in local requirements without a back-up wall when subjected to fire conditions of the severity to be expected in apartments or office buildings.

Subject Headings: ***Curtain walling, fire protection by; Fire protection, by curtain walling; Tests, of curtain walling fire protection.***

J. J. Ahern

Bletzacker, R. W. (Building Research Laboratory, The Ohio State University, Columbus, Ohio). "Impact of New Materials and Construction Systems on Fire Test Technology" *Fire Technology 1*^{6} 205 (1965)

New construction techniques and the growing number of building materials have resulted in the modification of old fire test methods and the development of new ones. Many otherwise useful materials have failed the highly restrictive noncombustibility test that is in use today. The author suggests that tests more basic than the full scale fire endurance tests must be devised to more accurately evaluate the effects of combustible materials under fire conditions.

Subject Headings: ***Building materials, fire tests; Tests, fire, on new building materials; Tests, fire, for construction methods; Construction methods, new, fire tests for.***

Author's Abstract

Carlson, R. E. (California State Fire Marshal's Office, Sacramento, California) "Fire Test Data and Building Design—Some Problem Areas," *Fire Technology* 1, 295–302 (1965)

Some fallacies in strict interpretation of accepted definitions and fire test results are pointed out which limit current methods for classifying the combustibility, fire endurance of structural elements, and the flammability of interior finishes. Since these tests are used as guide lines in designing fire resistance and fire protection into buildings, more comprehensive reporting of data, based on fire tests reflecting more closely the way materials and assemblies perform under actual fire conditions, would be extremely useful in applying sound fire protection principles in the design of fire-safe buildings.

Subject Headings: ***Building design, fire tests; Fire resistance, tests for building design; Tests, of fire resistance.***

Author's Abstract

Hogg, J. M. and Firth, J. M. (Joint Fire Research Organization, Boreham Wood, England) "The Ranking of Some Industries in Great Britain in Accordance with Their Relative Fire Hazard," *Joint Fire Research Organization Fire Research Note No. 558* (June 1964)

The frequency and the spread of fire were analyzed on the basis of six components of industry: (1) industry size, (2) competitiveness, (3) productivity, (4) value of stocks relative to industry, (5) portion of total costs which is spent on administration, and (6) sensitivity to external economic conditions. The first component (size) accounted for 40% of the variation between industries and the six components accounted for 85% of the variation. Size was measured by interrelated and thus weighted factors: (1) number of establishments, (2) purchases of materials, fuels, etc., (3) products on hand for sale, (4) stocks of material and fuel, (5) payments for transport, (6) net output minus wages and salaries, (7) wages and salaries, (8) average number employed, (9) new building work, (10) plant and machinery (acquisitions minus disposals), and (11) vehicles (acquisitions minus disposals). The Census of Production for 1958 furnished the data required to correlate the factors and components of industry. The fire frequency and fire spread were analyzed also from samples of fire reports by fire brigades on fires in buildings from 1957 to 1961. In this analysis, 118 industries were examined and ranked on the basis of fire frequency with allowances made for industry size. From this analysis, 8 industrial groups were obtained which were relatively homogeneous with respect to product of the individual industries (Table I). The ranking of these groups in terms of fire frequency based on average industry size is shown in Table II. The data in Table II show that the fire frequency was highest in the production area regardless of industry group. Other data not summarized in Table II show that (a) regardless of industry size, more fires originate in production than in other areas, (b) the highest increase in frequency of fire occurred with Group 7 followed by Group 1. The other industries paralleled each other roughly and thus maintained the relative positions shown in Table II. At the above-average industry size, Group 7 rapidly approaches Groups 2 to 6 in fire frequency with increase in size.

TABLE I*

Group No.	Industrial group
1	Timber, furniture, etc.
2	Metal, shipbuilding, and vehicles
3	Miscellaneous (which included some 15 standard industrial classifications such as refractory goods, cement, abrasives, brushes and brooms, games and sporting equipment, plastics manufacturing, gas, electricity, and water supply)
4	Textiles and paper
5	Leather, fur, and clothing
6	Chemicals and allied industries
7	Food, drink, and tobacco
8	Engineering and electrical goods

* Group numbers have been entered into this table for later convenient reference.

TABLE II

Fire frequency for each group in one of three fire-source areas

Hazard class	Production		Storage		Miscellaneous	
	Group No.	Frequency	Group No.	Frequency	Group No.	Frequency
High	1	216	1	47	1	36
Medium	2 to 6	68	2 to 7	16	2 to 8	18
Low	7 and 8	27	8	9	—	—

The ranking of these groups based on fire spread (the proportion of fires extinguished by fire brigades using hose-reel jets and pumps versus total fires extinguished) is shown in Table III. The ranking of the industrial groups is the same as the ranking of the industry on the basis of fire frequency. The fire spread did not appear to be a function of industry size or any of the other five industry components mentioned earlier. These data also revealed that although fires are less frequent in storage areas than in production areas, the fire spread is larger, regardless of industrial group, as illustrated in Table IV.

TABLE III

Hazard class	Industry group	Proportion of fires extinguished by fire brigades
High	1	0.92
Medium	2 to 7	0.77
Low	8	0.69

Since it became evident during this study that it was not always possible or convenient to calculate the component of industry which appears to correlate to industry size, the alternative unit of measure, the number of employees, was examined. It was found that the logarithm of the number of employees was related

TABLE IV

Area of fire origin	Proportion of fires extinguished by fire brigades
Storage	0.87
Production and miscellaneous	0.70

TABLE V

Average number of employees	Industry group
882	5
802	2, 3, 4, 8
717	1
631	6, 7

to industry size. In most industry groups the number of employees increased at the same rate with increase in size. Group 5, however, increased at a more rapid rate, apparently because it is less amenable to automation. The ranking of industry groups by the average number of employees is shown in Table V.

Subject Headings: ***Fire hazards, ranking of industries; Industry, fire frequency and spread in.***

R. A. Gorski

Hogg, J. M. and Fry, J. F. (Joint Fire Research Organization, Boreham Wood, England) "The Relative Fire Hazard of Different Industries," *Joint Fire Research Organization Fire Research Note No. 597* (May 1965)

For some purposes, such as fire protection legislation and fire insurance, it is desirable to have some measure of the inherent fire hazard of industries. Experience and knowledge of the materials and processes involved have led to the adoption of fire precautions of various kinds in most industries, but despite this there remains some degree of fire hazard which may be more pronounced in one industry than another and which is reflected both in fire frequency and in fire spread. This study has been made in terms of fire frequency only since there is at present no satisfactory quantitative measure of fire spread available to the Organization.

As the ultimate objective of fire prevention would be the total elimination of fires in industry it is not possible to define any specific level of fire frequency as being "acceptable," and the effort has therefore been directed towards deriving a method of comparing one industry with another.

Subject Headings: ***Fire hazards, of industries (United Kingdom); Hazards, fire, in industries (United Kingdom); Rating, of industrial fire hazards (United Kingdom).***

Authors' Abstract

McGuire, J. H. (National Research Council, Ottawa, Canada) "Fire and the Spatial Separation of Buildings," *Fire Technology* **1**, 278–287 (1965)

The spread of fire from one building to another is a serious problem. Spreading may occur by means of flying brands, convective heat transfer, and radiation. Secondary fires from flying brands may be started over distances of at least a quarter of a mile. Practically, many buildings cannot be separated far enough to combat this hazard.

Ignition by convective heat transfer takes place only if the gas-stream temperature is several hundred degrees Celsius, or higher. Usually these temperatures in convective gas streams are found close to the flame issuing from windows of burning buildings.

Nearby buildings can be ignited by radiation from a burning building at distances appreciably greater than those to which the visible flames ordinarily extend. Considering the three ignition mechanisms discussed, it can be seen that ignition by radiation is the dominating factor governing the specification of the spatial separation of buildings from the viewpoint of fires.

The author devotes the primary portion of his paper to the formulation of a technique to prescribe separation distances between buildings with an objective of reducing the likelihood of spread of fire by radiative heat transfer.

Most materials require a pilot flame delivering at least 0.3 cal/sq cm/sec before ignition can occur by radiation. One notable exception is unfinished, untreated fiberboard; it ignites in the presence of a pilot flame at even lower intensities. However, this material is unlikely to be the one exposed in the usual fire situation where radiation is considered.

The mechanism discussed above involves a pilot flame, a local high-temperature source. A building adjacent to one that is burning is exposed to radiation plus sparks and flying brands, which are local high-temperature sources. When the radiation level exceeds 0.3 cal/sq cm/sec, sparks or flying brands are quite likely to pass through the evolved streams of combustible volatiles.

Thus, the criterion is established that spatial separation of buildings should be such that a fire in one building should not subject the facade of another to levels of radiation higher than 0.3 cal/sq cm/sec.

Experiments were conducted to determine the radiation levels expected from various types of burning buildings. The major results are: (1) The nature of exterior cladding (brick or clapboard) had little influence on the radiation level; (2) Peak radiation levels at some distance from the building coincided with those that would result if window openings, at an appropriate hypothetical temperature, were taken to be the only sources of radiation; (3) Peak radiation levels from buildings with highly flammable linings were twice those from buildings with noncombustible linings; (4) Radiation levels were affected by wind direction.

Although the fires were arranged to develop rapidly, radiation levels did not exceed about one-fifth the peak values until at least 16 min elapsed.

Generally it has been assumed that spatial separations based on peak radiation levels will prevent ignition by radiation for an indefinite period. These distances exceed practical limits. A method was devised to obtain tables which give separation distances calculated to prevent ignition by radiation long enough for fire extinguishing operations to begin. Detailed discussions of the tables and their application are given.

From these studies and others, it would appear that much work remains to be done in this area of fire research to place it on a more quantitative basis.

Subject Headings: ***Buildings, separation and fire spread; Fire spread, effect of building separation.***

L. E. Bollinger

Malhotra, H. L. (Joint Fire Research Organization, Boreham Wood, England) "Building Boards and Fire," *Board Practice* **8**, 63–66 (1965)

The article outlines the basic factors concerning the effect of interior finish on the rate at which an interior fire is likely to develop.

There is a complete description of the various tests utilized in the United Kingdom for determining combustibility and flame spread. There is also a discussion of a simple ignitability test which is used on separating hazardous combustible materials from those either completely safe or those improved by the application of fire-retardant treatments. The authors also include a rather complete discussion of flame-retardant treatments covering the various types of surface coating treatments as well as impregnation.

Based upon these tests, classifications have been established and incorporated into the building regulations to provide for the type of interior finish which can be utilized in various situations ranging from that of exit facilities to normal domestic usage.

It is pointed out that the effect of this control, which will be exercised for the first time, will be to increase the demand for fire-retardant treatments for building material and for materials which are available with the required flame-spread properties.

It is pointed out that this has provided an impetus for better and more lasting treatments and has encouraged the manufacture of lining materials with the necessary treatment incorporated into their composition.

Subject Headings: ***Buildings, building boards and fire; Fire, building boards; Ignition, of building boards; Tests, of building materials; Tests, of building materials, for fire resistance (United Kingdom).***

J. J. Ahern

Moore, W. S. (U. S. Forest Service, Washington, D. C.) "The National Fire Coordination Study," *Minutes of Annual Meeting of Federal Fire Council*, p. 15 (May 5, 1965)*

ELEMENTS OF THE COMPREHENSIVE FIRE DEFENSE PROGRAM

Protection Measures

1. TV & Radio kit for citizens' fire extinguishing and prevention program.
2. Fireproof furnishings in buildings.
3. Smoke generation.
4. Window shielding (supplemental to smoke as needed).
5. Shelter fire inspection and rating program.

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6. Infrared mapping of nuclear fires.
7. Study effectiveness of aerial fire retardants for protecting shelters.
8. Study special equipment needed to suppress nuclear fires.

Support Plans

1. Nuclear fire analysis system.
2. National fire defense plan.
3. Guidelines for community planning to minimize fire spread.
4. Professional fire staff leadership.
5. Standard fire service radio operating procedures handbook.
6. Standard fire service terminology for the United States.
7. National fire intelligence system.
8. National fire communications system.

Training

1. National nuclear fire leadership training.
2. Local nuclear fire leadership training.
3. Rural fire defense training.
4. Fire defense support fireman training.
5. Fire technical staff support center.

Subject Headings: ***Fire defense program; Federal Fire Council, fire defense program.***

Nash, P. and Fittes, D. W. (Joint Fire Research Organization, Boreham Wood, England) "Foam Generator for Aircraft Fire Control," *The Engineer* **219,** 537–538 (1965)

This paper proposes an improved foam generator for effective control of major aircraft fires. Since foam has been the only agent capable of maintaining fire control over a lengthy period (necessary for rescue operations to proceed), the experimenters make a strenuous effort to put their work on a somewhat scientific foundation. Foam is defined by four physical properties: (1) "expansion"—the ratio of volume of the foam to that of the aqueous solution from which it is produced; (2) "critical shear stress"—or stiffness of the foam, which is controlled by the energy supplied in forming the bubble structure; (3) "quarter drainage time"—an arbitrary measure of the stability of the foam; and (4) the rate of application of the foam to the fire area, usually expressed in terms of gallons of foaming solution per minute per unit area of fire.

Various groups engaged in aircraft fire fighting have held differing views on the optimum values of these properties, and on the type of equipment and tactics best suited to aircraft fire control. The expressed purpose of this paper is to resolve these differences, since all operational staffs have the same basic problems. Two sets of experiments are cited in which uncertain conflicting results were obtained. In the first series where the main features of an aircraft crash fire were simulated in a 10 ft by 10 ft area, results showed that the rate of liquid application of the foam and critical shear stress were both important, but the expansion was not significant in obtaining quick control of the fire. The second series of tests conducted on fires in an area ten times the size of the small-scale fires again suggested that the rate of application was important, but reversed the roles of expansion and critical shear stress. The weather conditions prevailing at the time of these tests, and the need for different equipment to produce the required range of experimental foam properties made it desirable to repeat the latter series of experiments. A specially designed gas-turbine-operated foam generator capable of producing the whole range of rates of application and physical properties required was developed.

The principal feature of the foam generator is that the air delivered by the turbocompressor is divided into two streams. The first stream drives or displaces a premixed foam solution (3% to 6% of foam liquid in water) from a 650-gal capacity pressure vessel. The second air stream passes directly to a "foam improver" where the foam solution is dispensed into it through a nozzle. The expansion of the foam produced is controlled by varying the ratio of the volume flow rates of the second air stream and the liquid flow.

Experimental aircraft fires were produced using 250 gal of aviation turbine fuel primed with 5 gal of petrol. In an area of 25 ft by 35 ft, a metal assembly representing the essential elements of an airplane was used to facilitate reproduction of the fires. After ignition, the fire was allowed to burn for 45 sec before the application of foam began. The foam was applied continuously until the fire was "controlled." The fire was considered controlled when the intensity of heat radiation was reduced to one-tenth of its initial value at the start of foam application. The time to control the fire was used as a basis of comparison for the effectiveness of foams having various physical properties. The versatility of this equipment can be seen from the wide range of property values available from it: solution rate, 50 to 200 gal/min; expansion ratio, 6 to 20; critical shear stress, 300 to 1500 dyne/cm^2; and quarter drainage time, 10 to 160 min.

The authors suggest that this method of foam generation could quickly and easily be used in future crash fire-fighting vehicles. Large helicopters, for example, could use an air-bleed system from their gas-turbine driving units for foam production.

Subject Headings: ***Aircraft, fire fighting, by gas turbine foam generator; Fire fighting, with gas turbine foam generator; Foam, generation by gas turbine; Gas turbine, foam generator.***

C. O'Neal, Jr.

National Fire Protection Association "Fire and Fire Losses Classified, 1964," *Fire Journal* 59 (5) 31–36 (September 1965)

A discussion is given of the types of fires and fire losses in the United States during 1964. The raw statistics are well summarized in Figure 1 and Table 4 of the

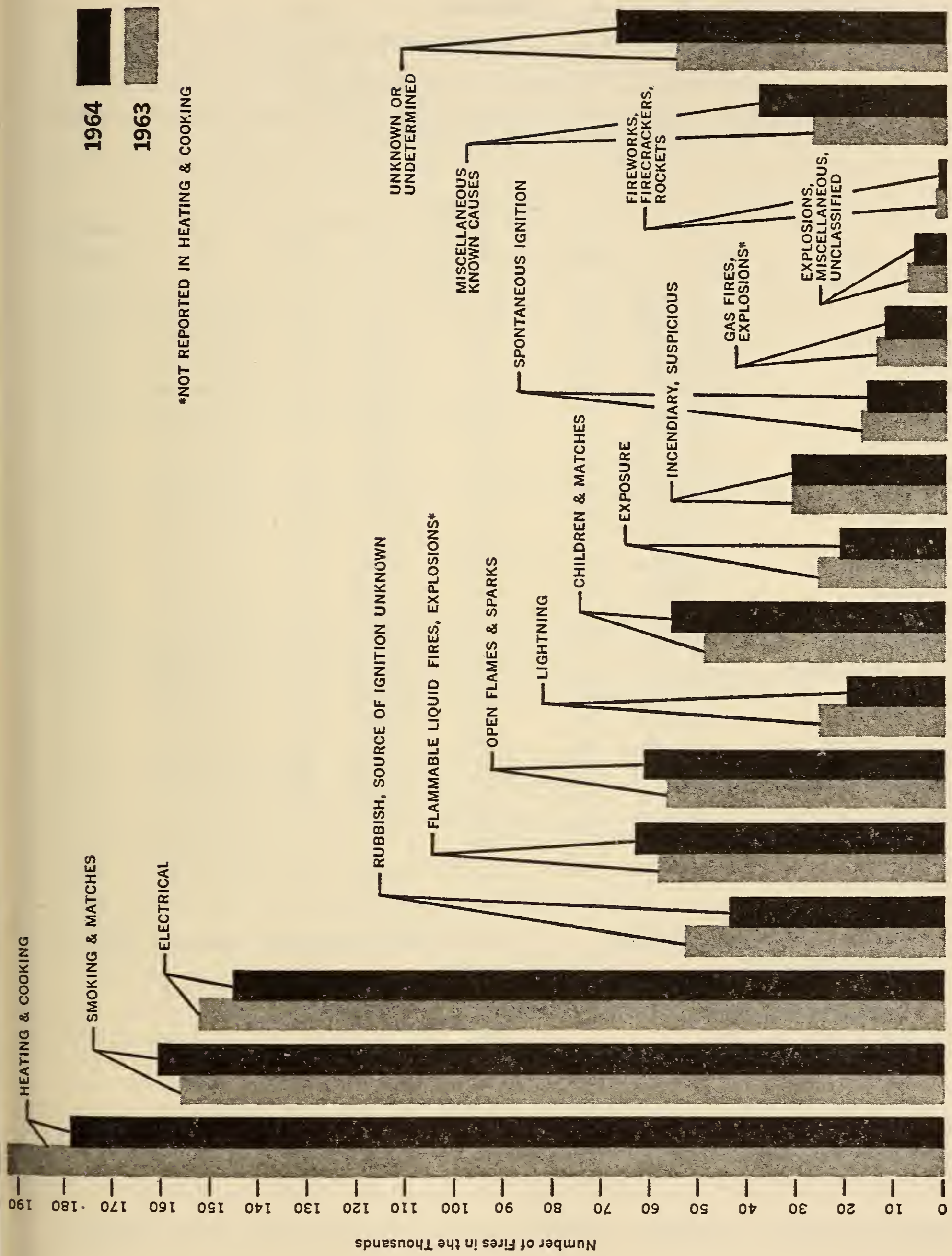

FIG. 1. Fire frequency by causes, 1963 versus 1964.

TABLE 4

Fire statistics, 1964, as reported by 23 State Fire Marshals

Note: Variations among states in frequencies of fires and fire deaths and per capita losses are due in part to differences in methods of compiling fire loss data. For this reason comparisons between individual states based on these figures should not be made.

State	Population	Killed	No. deaths per 1,000,000	No. of fires	No. per 1,000	Fire loss	Loss per person
Alaska[b,c]	250,000	33	132	806	3.2	$4,188,000	$16.75
Connecticut	2,766,000	79	29	2,304	0.8	10,259,000	3.71
Illinois[a]	10,489,000	251[g]	24	21,247	2.0	45,303,000	4.32
Iowa	2,780,000	87	31	3,441	1.2	14,440,000	5.19
Kansas	2,225,000	92	41	3,435	1.5	6,328,000	2.84
Kentucky[a]	3,100,000	237	76	6,306	2.0	18,369,000	5.93
Louisiana	3,468,000	257	74	10,307	3.0	19,030,000	5.49
Maryland[b]	3,432,000	149	43	5,637	1.6	9,067,000	2.64
Michigan[h]	8,116,000	312	38	88,175	10.9	55,065,000	6.78
Minnesota[e]	3,521,000	79	22	4,030	1.1	22,483,000	6.39
Montana	707,000	30	42	2,890	4.1	5,674,000	8.03
Nebraska	1,470,000	37	25	2,413	1.6	6,552,000	4.46
New Hampshire[i]	654,000	23	35	1,378	2.1	4,532,000	6.93
New Mexico[a]	1,018,000	31	30	9,615	9.4	5,387,000	5.29
North Dakota[a,b,c,d]	645,000	37	57	1,060	1.6	4,296,000	6.66
Ohio	10,173,000	261	26	24,092	2.4	48,698,000	4.79
Oregon[b,c]	1,906,000	80	42	12,739	6.7	15,019,000	7.88
South Dakota[a]	737,000	26	35	2,013	2.7	3,953,000	5.36
Tennessee[b,c,e]	3,798,000	203	53	7,633	2.0	20,764,000	5.47
Utah[h]	992,000	16	16	7,654	7.7	4,073,000	4.11
Vermont[a,b,d]	409,000	10	24	776	1.9	2,771,000	6.78
Virginia[b]	4,378,000	193	44			17,015,000	3.89
Wyoming	343,000	6	17	2,599	7.6	3,050,000	8.89

[a] Fiscal year ended June 30, 1964.
[b] Insured losses only.
[c] Number of insurance claims
[d] No loss less than $100.
[e] No loss less than $25.
[f] Includes insurance losses not reported to fire departments.
[g] Includes Chicago for calendar year 1964.
[h] Includes grass and brush fires.
[i] Building fires only.

article, which are reproduced here with the permission of the National Fire Protection Association.*

Subject Headings: ***Fire statistics, of States; State fire statistics; Statistics, fire, in States.***

Editor

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* Reprints of the entire article (identified as FJ 65–15) are available from the National Fire Protection Association, 60 Batterymarch Street, Boston, Massachusetts 02110 (50¢ per copy).

Palmer, K. N. and Wright, C. A. (Joint Fire Research Organization, Boreham Wood, England) "Fire Hazards in Buildings Affected by a Leakage of Domestic Fuel Oil," *The Institution of Fire Engineers Quarterly* 25, 71–79 (1965)

From a study of the fire hazard presented by oil leakage in brick buildings, the following conclusions were reported:

"1. Bricks saturated with kerosine, or similar oil, are easily ignited with matches and present a considerable fire hazard. The hazard persists until at least 50% of the oil is removed.

2. The oil can be removed by allowing the bricks to dry in the atmosphere, but this may take months if the bricks are in a wall. Heating the bricks to above the flashpoint of the oil must be avoided. Washing with detergent solutions removes very little oil.

3. Protection of oil-treated bricks and wood during the drying period can be obtained by painting with fire-retardant paint."

Subject Headings: ***Bricks, oily, fire hazards of; Fire hazards, of oily bricks.***

Editor

Peterson, H. B. and Gipe, R. L. (U. S. Naval Research Laboratory, Washington, D. C.) "A Study of the Gas Turbine Powered MB-5 Aircraft Firefighting and Rescue Vehicle," *U. S. Naval Research Laboratory Report 6309* (1965)

One of the MB–5 series of crash trucks was equipped with a gas turbine engine as a source of power. During the testing of this vehicle the operating characteristics of the engine were monitored under different load conditions, variable road speed, and variable foam pump speed. The turbine powered vehicle was compared to other, conventional engine model, trucks now in operation, both for rapidity of acceleration and for ease of operation.

A standardized simulated firefighting operation called a "scramble" operation was devised for the integration of human engineering with the relative efficiency of each of the three vehicles. Time intervals required to reach a given series of check points during a fixed firefighting procedure were recorded by multichanneled instrumentation or by observation.

The turbine-powered vehicle proved to be superior in acceleration performance and equal in firefighting capability to conventional engines. These factors alone may not justify the higher initial cost of the turbine power plant. Future field studies involving maintenance costs over extended periods of field operation and vehicle performance under severe environmental conditions might alter present considerations.

Subject Headings: ***Aircraft, fire-fighting vehicle; Fire fighting, vehicle for aircraft.***

Authors' Abstract

TABLE I

Some flammability test methods for evaluation of paints

Test method	Sample size and position	Fuel rate	Test duration	Specimen conditioning	Basis of classification	Ref.
			Accepted Standards			
Flame resistance SS-A-118b	36 x 36 in., horizontal	ASTM standard time-temperature curve=1400–1500 Btu/min gas flame	40 min or 20 min	To constant weight at 75±5°F at RH ±5%	Four classifications based on flashing and flaming behavior	(7)
Tunnel ASTM E 84	25 ft x 20 in., horizontal	5000 Btu/min, gas flame	10 min or less	To constant weight 70±5°F at RH 35–40%	Flame spread as per cent of that for Red Oak	(8)
Radiant panel ASTM E 162-T	6 x 18 in., 30° from vertical	1430 Btu/min, 12 x 18 in. gas-fired radiant panel and pilot flame	15 min or less, continuous pilot	Absorption to constant weight at 75±5°F at RH 50±5%	Index based on heat release and ignition sensitivity (approximates above)	(9)
Eight-ft tunnel (before ASTM for acceptance)	8 ft x $13\frac{3}{4}$ in., $13\frac{3}{4}$ in. side at 30°, 8 ft side at 6°	3400 Btu/min 85 Btu/min from pilot flame, gas-fired	18.4 min or less	To constant weight at 80±10°F at RH 30±5%	Flame spread as per cent of that for Red Oak	(10)
Spread of flame BS 476	9 x 36 in., 9 in. edge, vertical	3 x 3 ft gas-fired radiant panel and pilot flame	10 min, or when flames die out; 1 min for pilot	To constant weight at 50 to 70 F at RH 55–65%	Maximum spread of flame	(11)
Cabinet method ASTM D 1360	$\frac{1}{4}$ x 6 x 12 in., 45° to horizontal	5 ml ethyl alcohol	About 1 min	Dried at 120°F for 40 hr	Weight loss and char volume	(12)
Stick and wick ASTM D 1361	1 x 1 x 16 in., vertical	4 ml ethyl alcohol; 8 or 12 ml optional	100 sec; 200 or 300 optional	Dried at 140°F for 72 hr	Index based on weight loss, char length, and flame length	(13)
Inclined panel ASTM C 209	12 x 12 in., 45° to vertical	$\frac{5}{8}$ in. I.D. cup, 1 ml ethyl alcohol	Fuel consumption plus 1 min	Equilibrium 70°F and 50% RH	Char area and flame duration	(14)

Other Methods

Pilot ignition (Australia)	24 x 18 in., 24 in. edge, vertical	1000 Btu/min, 12 x 12 in. gas-fired radiant panel and pilot flame	Time to ignition of specimen plus 2 min	To moisture content in equilibrium with air at 60–80°F at 55–65% RH	Time to ignition	(5)
Vertical spread (Australia)	1 ft 9 in. x 9 ft, vertical	About 6000 Btu/min	Time for flames to reach 9 ft	As above	Time from ignition until spread flames reach 9 ft	(5)
Bowling pin test	Bowling pin, vertical	867 Btu/min	480 gm weight loss or 30 min	Dried as recommended by paint manufacturer	Weight loss and derived estimate of remaining structural strength of charred timber	(16)
Modified Schlyter	Two pieces 12 x 31 in., vertical 2 in. apart	97 or 291 Btu/min, gas flame	3 min	To moisture content 7±1%	Maximum flame spread and time for completion of burning	(6)
New British building board	9 x 9 in., vertical	30 Btu/min for 3 min, then 15 Btu/min; gas and electricity	20 min	20°C and 56% RH	Time to ignition and heat release rate	(19)
Side wall	4 x 8 ft as side wall, 4 x 8 ft on ceiling	2245 gm hard maple crib fire +50 ml ethyl alcohol	About 3 min	Not specified	Rate of flame growth and temperature changes	(6)
Corner wall	Two 2 x 8 ft in corner, 4 x 4 and 4 x 8 ft on ceiling	As above	As above	As above	As above	(6)
Two-foot tunnel	$\frac{1}{2}$ x 12 x 24 in.	Not specified	5 min	Two days or more at 75°F and 50% RH	Flame spread as per cent of that of Red Oak	(18)

Robertson, A. F. (National Bureau of Standards, Washington, D.C.) "Fire Test Methods for Paints," *Building Research*, 48–52 (July–August 1965)

A discussion is given of a number of fire-test techniques used by various groups for evaluating fire resistance of paints. These are summarized in Table 1 of the paper, reproduced on pages 134–135.

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Subject Headings: ***Paint, fire test methods for; Fire tests, for paints.***

Editor

Rosenberg, B. A., Shanovskaya, S. S., Kochan, L. D., Fishilevich, Z. A., and Babin, E. P. "The Problem of Increasing the Stability of Foams Used in Dust Suppression in Coal Mines," *Zhurnal Prikladnoi Khimii* 37, 908–911 (1964)

The use of foams for the suppression of dust during the working of various mining machines and mechanisms is a comparatively new and effective method. This problem has been the subject of a systematic study for a number of years at the Makeevsk Scientific Research Institute on Safety in Mining.

The advantages of the suppression of dust with foam are due to the fact that foam creates a large surface for interaction with the dust with a relatively small consumption of water. The foam method, however, is used only on a limited scale at present due to the absence of foaming agents which give foams with the physicochemical properties necessary for dust suppression.

Testing of foams stabilized with glue show that it is highly effective in the prevention of dust formation in mines. The widespread industrial use of such stabilizers, however, has been discouraged by the short supply and comparatively high cost of these products and also from the instability of glue solutions to fungi and bacteria which decompose glue.

These investigators have conducted a series of tests using small quantities of synthetic high molecular compounds added to solutions of surfactants which led to considerable increase in foam stability.

Foam stabilizers suitable for dust suppression in coal mines should be: (1) Soluble in water, (2) Nontoxic, (3) Stable on storage, (4) As inert as possible to electrolytes.

After tests on a number of potential materials, it was found that only polyvinyl alcohol, polyacrylamide, and methylcellulose and carboxymethylcellulose appeared to be effective foam stabilizers.

It is further shown in their test program that the stability of the foam obtained by addition of these polymers is equivalent to that established by joiner's glue without the basic defects present in the use of glue.

A complete table showing the results of their stability tests is included.

Subject Headings: ***Coal dust, suppression, by foam; Dust, suppression, by foam; Foam, used for dust suppression, stability of; Suppression, of dust, by foam.***

J. J. Ahern

Schaffer, E. L. and Eickner, H. W. (Forest Products Laboratory, U. S. Forest Service, Madison, Wisconsin) "Corridor Wall Linings—Effect on Fire Performance," *Fire Technology* **1,** 243–255 (1965)

Fire tests within a partially ventilated corridor in an abandoned school building were conducted to determine the effects of three types of wall linings on fire performance. The corridor selected was 11 ft wide, 72 ft long, and 13 ft high and was of brick and plaster construction. Modifications were made on the corridor for each of the three tests that were conducted.

The original wall finish and wooden wainscot was left intact in the first test. In Test 2, $\frac{1}{4}$-in. hardboard was used to line the walls of the corridor. In Test 3, $\frac{25}{32}$-in. red oak flooring was used as a wall covering.

Instruments and equipment for measuring temperature, smoke density, and gas concentration were installed at selected points along the corridor. Fire load consisted of two 250 lb Douglas-fir cribs measuring 3×3×2.5 ft. Both cribs were placed on an asbestos pad at one end of the corridor. Ignition was accomplished with pans of ethyl alcohol placed under the cribs.

Four minutes after ignition flames reached ceiling level. Ceiling temperatures directly above the cribs were generally higher in Test 3. In Test 1 the wainscoting ignited between the 5 and 6 ft points after 4 min. In the third test the red oak flooring near the crib ignited after 4 min and spread to the ceiling and for 12 ft along the wall after 4$\frac{1}{2}$ min. The hardboard used in the second test darkened but did not ignite.

Flashover occurred in 6 to 7 min after ignition in all three tests prior to any appreciable flame spread along the walls, and in the case of the second test, without ignition of the hardboard paneling. Crib flaming and flaming of other corridor members were momentarily suppressed immediately after the flashover.

Smoke concentration was greatest in the first test, less in the third, and least in the second. The author attributes the greater smoke density in the first test to the higher moisture content of the corridor material. Dense smoke developed immediately after the flashover. As visibility improved, reignition occurred. During the first test a second flashover occurred 15 min after ignition. This was also followed by the development of dense smoke.

Six minutes after ignition the oxygen levels fell below 10% and the carbon monoxide levels were greater than 10%. Carbon dioxide levels were as high as 12% to 18% in the second test.

Temperatures at 5 ft above the floor exceeded 300°F between 4.3 to 5.6 min after ignition. Ceiling and wall temperatures were generally highest during the red oak test and lowest during the first test. Maximum temperatures recorded on the ceiling and walls exceeded 1300°F before the tests were ended. Minimum wall temperatures of 600° to 800°F were recorded during the first and second tests. These temperatures were exceeded by the minimum ceiling and wall temperatures during the red oak test (Test 3).

The authors conclude that both the gas concentrations and temperatures recorded during these tests would make human occupancy untenable.

Subject Headings: ***Corridor wall lining, fire performance of; Fire performance, of corridor wall lining; Linings of corridors, fire performance of; Wall linings of corridors, fire performance of.***

W. Y. Pong

Thomas, P. H. (Joint Fire Research Organization, Boreham Wood, England) "The Rate of Temperature Rise in a Compartment Fire," *Joint Fire Research Organization Fire Research Note No. 595* (May 1965)

In this note a theoretical analysis of the mean air temperature changes occurring at the ceiling of a room during the initial growth of a fire at floor level is presented. The compartmenting of ceilings to aid in fire detection by ceiling-mounted temperature-sensitive devices is considered.

Two stages of the fire are studied. In the first, hot gases rise to the ceiling and spread sideways in an expanding hot layer. The first stage ends when this hot layer reaches the confining walls. During the second stage, the hot gas layer at the ceiling thickens as burning continues.

Equations are given which permit a calculation of the time-duration of the first stage and also the rate of temperature rise due to fire spreading on the floor. For the second stage, the hot layer temperature and the rate of temperature rise are presented as a function of time. In the derivation of the above relations, perfect mixing within the hot layer is assumed and heat loss to the ceiling is neglected.

In a situation where the fire is spreading and the rate of heat relase $\mathcal{Q}$ is increasing with time in a typical manner, the time-duration for the first stage and the rate of temperature increase is shown to be inversely proportional to H, a measure of height which may be taken as the ceiling height. Hence, as H is increased, it becomes less likely that a detector will operate before the second stage commences. Compartmenting the ceiling to reduce its area A reduces the time-duration of the first stage.

During the second stage, the rate of rise of temperature varies inversely with A. Thus, compartmenting the ceiling to decrease A and also to decrease ceiling heat loss will tend to hasten the operation of detectors.

In the analysis, the following group appears: $\mathcal{Q}/(\rho cAH)$ This group is a measure of the rate of temperature rise of a perfectly mixed air mass of volume AH, where ρ is the density and c is the specific heat. The numerical value of this group for a given situation can be used to determine the applicability of a specific detector. For example, if its value is 60°C/min, then a detector responding to a temperature rise rate of say 30°C/min will be applicable.

For the case of a slowly developing fire, i.e., when the floor area occupied by the fire is small, the time-duration t_1 of the first stage is approximately represented by $t_1 = 10A/[gH^3]^{1/2}$, where g is the acceleration due to gravity. This relation is useful for estimating whether it is worthwhile to compartment the ceiling to hasten the operation of the detector. If it is desired that the detector function before hot gas begins to descend, the operation time (taken equal to t_1) and H may be used to calculate the maximum acceptable value of A.

Subject Headings: *Fire, compartment, temperature rise in; Temperature, rise in compartment fire.*

G. A. Agoston

"Fireproofing from the Dead Sea," TIME p. 33 (December 25, 1964)*

FIREPROOFING FROM THE DEAD SEA

High on the list of Israel's slim supply of natural resources are the brains of its scientists and the chemicals such as bromine that can be extracted from the Dead Sea. Making use of both resources, Chemist Menahem Lewin has developed a wood-fireproofing process that may create a new world market for Israeli bromine.

Bubbles and Salts

There are two conventional ways of fireproofing wood and wood products, including paper and fiberboard. One is to coat them thickly with paint that releases carbon dioxide when heated and forms a layer of protective bubbles. This process serves satisfactorily for mild fires, but the bubble layer cannot resist intense or prolonged heat. The other system is to impregnate wood with various salts, but this weakens the wood and adds as much as 25% to its weight.

Bromine has long been known for its fireproofing qualities, but if it combines with wood's cellulose fibers, it weakens them seriously. Dr. Lewin's process gets around this disadvantage by forcing the bromine to attach itself to the wood's lignin, the cement that causes the fibers to stick to each other. The best grades of paper have no lignin, but the types of wood pulp used to make paperboard and wallboard retain enough of it to make Dr. Lewin's process useful.

Pulp and Chlorine

To brominate wood pulp, Dr. Lewin simply adds sodium bromide, which is as stable as table salt, to the solution in a standard bleaching apparatus, then bubbles chlorine through it. The combination of chemicals releases active bromine in a form that attaches itself to the lignin in the pulp. Treating solid wood is a more complicated process, but the results are spectacular. When a piece of brominated wood is put in a hot fire, it does not burn. After a while, a layer of carbon forms on its surface, but carbonization stops as soon as the wood is taken out of the fire. Any structure of brominated wood or wood products is safe from fire unless it is stuffed with highly combustible contents. "We could fireproof Japan," says Dr. Lewin, who sees no reason for false modesty about his achievement.

For all his studies, Dr. Lewin does not yet know in detail how bromine fireproofing works, but in general the action is connected with the way that wood burns. When heat is applied to natural lignin and cellulose, they give off combustible gases that form flames and spread the fire by heating more wood. Somehow, bromine seems to make those gases nonflammable. And with no flames to spread it, combustion stops as soon as the external heat source, such as a lighted match, is removed.

Subject Headings: ***Bromination, of wood, for fireproofing; Dead Sea salts, used in fireproofing, by bromination; Wood, fireproofing of, by bromination.***

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* Courtesy TIME; © Time Inc. 1964.

XIV. Miscellaneous

Brown, J. K. (Lake States Forest Experiment Station, U. S. Forest Service, St. Paul, Minnesota) "Estimating Crown Fuel Weights of Red Pine and Jack Pine," *U. S. Forest Service Research Paper LS-20* (October 1965)

Crown fuel weights of individual trees varied by d.b.h., site index, and stand density. Site and stand density influenced crown production as they typically affect total wood production of single trees. For both red pine and jack pine, crowns on good sites weighed more than crowns on poor sites, and crowns from low-density stands weighed more than crowns from high-density stands. Graphs and equations are presented for determining the crown weight per tree and per cord of merchantable wood. Both site quality and stand density influenced crown weight per cord. The proportion of live crown weight composed of needles averaged 43% for red pine and 21% for jack pine.

Subject Headings: *Fuel, crown weights, for pines; Fuel, weights of pine crowns; Pines, red and jack, crown fuel weights of.*

Author's Abstract

Chandler, S. E. (Joint Fire Research Organization, Boreham Wood, England) "Fire in Old People's Homes: A Study," *Fire* 57, 539–540 (1965)

Forty-three per cent of accidental fires are caused by smokers and heating appliances; almost half of these incidents involve the ignition of bedding, upholstery, and chairs by carelessly discarded smokers' material. On this basis the Joint Fire Research Organization recommends more careful supervision of elderly people with particular emphasis on the disposal of smoking materials.

Subject Headings: *Fire, in old people's homes; Old people's homes, fire in; Smoking habits, fire, in old people's homes; Heating appliances, fire, in old people's homes.*

Editor

Fairbairn, A. (United Kingdom Atomic Energy Authority, London, England) "The Fire Hazard of Metallic Beryllium," *United Kingdom Atomic Energy Authority Report* (1965)

The author discusses the fire hazards associated with the handling of metallic beryllium.

Subject Headings: *Beryllium, fire hazards of; Fire hazards, of beryllium.*

Editor

Madejski, J. (Politechnika Gdańska, Gdańsk, Poland) "Theory of Nucleate Pool Boiling," *International Journal of Heat and Mass Transfer* **8**, 155–171 (1965)

Nucleate boiling of a superheated liquid on a horizontal submerged flat plate is analyzed. A relationship for the bubble velocity above the flat plate is developed. The heat flux is considered to derive from three components: motion of the bubble columns, molecular heat conduction in the liquid, and turbulent convection. Molecular heat conduction is of no importance, after the bubble leaves the flat plate surface, and was therefore neglected in the analysis. Equations for bubble motion, bubble growth, heat flux associated with bubble motion, and heat flux due to turbulent convection were combined and integrated to provide closed-form solution to the problem. From this solution, a relationship between local bubble diameter and temperature difference was recognized, assuming the bubble population is inversely proportional to the radius of a nucleus. As a result, it was found that

$$\mathrm{Nu} \backsim \mathrm{Re}^{2/3},$$

where Nu = Nusselt number $= \alpha l/\lambda'$, Re = Reynolds number $= ql/\Delta i \rho'' \nu'$, α = heat transfer coefficient for nucleate boiling. $l = [\sigma/g(\rho' - \rho'')]^{1/2}$, σ = surface tension, g = acceleration of gravity, ρ', ρ'' = mass densities of liquid and vapor, respectively, λ' = thermal conductivity of liquid, q = heat flux, Δi = latent heat of vaporization, and ν' = kinematic viscosity of liquid. This relationship has been observed by many investigators.

An analytical expression for the form of the relationship for the first crisis of boiling is developed. The first crisis is taken as the time when bubble flow is stopped, forming a vapor layer near the heated surface. The analysis shows that, for the first crisis

$$\mathrm{Re} \sim \mathrm{Ar}^{1/2},$$

where Ar = Archimedes number $= gl^3/\nu'^2[(\rho' - \rho'')/\rho']$. This relationship has been confirmed experimentally and agrees with other theories.

A precise expression for the first crisis of boiling in water was derived by using the analytical form to correlate experimental data. The result was

$$\mathrm{Re} = 7960 p^{-0.354},$$

where p = pressure, for water at $p < 30$ atm.

The influence of the heated surface on the boiling process was examined using the analytical relationship developed in the paper. Experimental data on the relationship between nucleate boiling heat transfer coefficient and heat flux for different surface materials (aluminum and nickel) were interpreted by the analysis as indicating different bubble contact angles. As experimentally observed by the author, the contact angle of water on aluminum is considerably greater than on copper, brass or nickel, verifying the trend predicted by the use of analysis results.

Subject Headings: ***Boiling, nucleate; Velocity, bubble, in boiling; Heat flux, in boiling liquids; Nucleate boiling, theory of,***

A. E. Noreen

Satterlund, D. R. and Eschner, A. R. (Northeastern Forest Experiment Station, U. S. Forest Service, Upper Darby, Pennsylvania) "The Surface Geometry of a Closed Conifer Forest in Relation to Losses of Intercepted Snow," *U. S. Forest Service Research Paper NE-34* (1965)

On the basis of equations for turbulent heat and vapor transfer, and reasoned application of knowledge about intercepted snow, the authors predicate great differences in the energy and vapor balance between an intercepted "snowfield" and one on level open ground. The differences, resulting from the complex surface geometry of a closed conifer forest, are sufficient to account for considerably greater losses from intercepted snow.

Subject Headings: ***Forest, conifer, snow loss from; Geometry, effects related to snow loss; Snow loss and geometry; Geometry, surface, snow loss.***

Authors' Abstract

Turner, H. L. (Los Angeles Fire Prevention Bureau, Los Angeles, California) **and Segal, L.** (California State Fire Marshal's Office, Sacramento, California) "Fire Behavior and Protection in Hyperbaric Chambers," *Fire Technology* **1**, 269–277 (1965)

Increasing use of relatively high-pressure environments in medicine has raised questions on the effects of air pressure on combustion and fire protection. Results from tests conducted in the hyperbaric chamber of a Los Angeles hospital are presented.

Subject Headings: ***Fire, behavior, in hyperbaric chamber; Hyperbaric chamber, fire behavior in; Pressure, effects on fire.***

Editor

Tuve, R. L. (Engineering Research Branch, U. S. Naval Research Laboratory, Washington, D. C. 20390), "Fire Research Methodology at the U. S. Naval Research Laboratory and Some of Its 'Fallout'," *Pyrodynamics* **2**, 25–38 (1965)

A continuous program of fire engineering research has been conducted for the past 25 years at the U.S. Naval Research Laboratory along lines of applied science. The care and feeding of such a specialized endeavor has required the adoption of a philosophy of application research methods quite different that that used to promote more sophisticated or more glamorous and instantly useful projects in the world of science. Engineering research results in areas involving the physical chemistry of foams, the free radical quenching action of certain Group I cations and the useful surface chemistry of perfluorocarbons have resulted from this program. The scarcity of fire research support in the United States today suggests some need for introspection of its technical goals and its methods of vindicating and achieving them.

Subject Headings: ***Fire research, U. S. Naval Research Laboratory; U. S. Naval Research Laboratory, fire research.***

Author's Abstract

"Proceedings Third Annual Tall Timbers Fire Ecology Conference," Florida State University, Tallahassee, Florida (April 9–10, 1964)

This two-day annual meeting on fire ecology was held at Florida State University, Tallahassee, Florida. Following are abstracts of the eleven papers presented:

Burning on Private Lands in Mississippi—John W. Squires

The author, who has had a great deal of experience in prescribed burning, made a strong plea for greater use of this technique. In order to find out what was actually going on in connection with prescribed or controlled burning in Mississippi, he contacted the State Forestry Commission, Mississippi Game and Fish Commission, the U.S. Forest Service and several larger wood-using industries. He was very disappointed to find the limited use of prescribed burning in Mississippi.

The author believes that the burning program in the State is at least 10 years late and that efforts should be made to encourage the use of more prescribed fires. He recommends the use of a great deal more fire for rough reduction, game management, disease control, etc., and further study and research in the methods, costs, and application of prescribed burning.

Moose and Fire on the Kenai—David L. Spencer and John B. Hakala

Fires in the boreal forest have a profound effect on the welfare of moose populations. The inadvertent firing of a tract of land dedicated primarily to moose occurred on the Kenai National Moose Range in 1947. Population surveys have been conducted and study plots examined since the fire occurred. The resulting data were used to obtain various moose and fire relationships.

The vegetative change following the burn was recorded. Spruce reproduction is nearly universal over the entire burn. This revegetation now shows dense stocking with dominants 5 ft high. Aspen, prominent throughout much of the original stand in scattered trees or small groves, resulted in heavy and immediate regrowth through suckering and later through seedling stock. Approximately one-fifth of the 1947 Burn has revegetated to birch through reseeding from remaining mature trees.

Moose population data were obtained by aerial surveys. It is apparent that improving forage conditions resulting from the 1947 Burn permitted increasing moose population, whereas the trend prior to the Burn was that of declining population because of deteriorating winter forage.

Fire Ecology and Forest Management in the New Jersey Pine Region—S. Little

Fire has been a major influence on the composition and value of the forest stands of the New Jersey Pine Region. Wildfires have been one of the factors checking succession from the commercially valuable white-cedar stands to relatively worthless hardwoods such as red maple, blackgum, and sweetbay.

Fire as a tool has a varying role in different forest stands. In the swamps it is of value in slash disposal. In the pine lowland sites a relatively deep-burning fire at the end of the rotation can create conditions conducive to the development of seedling pine stands. Light fires during the rotation are difficult to apply there because of the presence of dense, highly flammable shrubs, but are of value in reducing fuel and controlling wildfires. On upland sites periodic burns can be used to reduce fuel and to prepare seedbeds for natural reproduction.

Fire and Management Problems in Ponderosa Pine—Harold Weaver

Over extensive areas of the Ponderosa Pine Region the large, high quality pines have been harvested and the original forest has been replaced by worthless brush fields. Reclamation of these areas will be very expensive. Over even more extensive areas, reproduction stands of ponderosa pine and of associated species are far too densely stocked for optimum growth. There is therefore serious need for expanding corrective programs to solve understocking and overstocking problems. The speaker reviewed some of the ecological relationships that are of primary influence in development of present conditions and suggested measures that may aid in their correction.

Burning in Naval Stores Forest—Norman R. Hawley

The gum naval stores business is the harvesting of oleoresin or gum from standing, living pine trees. The history of this industry was reviewed, leading to the use of fire in the naval stores woods.

In the current management scheme involving gum production, the use of fire is applied in orderly manner. It is applied under exacting conditions in advance of hanging the cups in which the dripped gum is collected. It is then rigidly excluded for a number of years, termed the cycle. If a repeat cycle of naval stores is to follow, the usual procedure is to cut the worked-out timber in the winter and allow the accumulated debris to dry for a season. A prescribed fire is then applied in the fall after which the new timber is hung during the winter and initially cupped the next spring.

The prescribed fire in the naval stores woods makes individual trees accessible through reduction of rough and its use serves to reduce the possibility of unexpected wildfires.

Burning Flint Hills Bluestem Ranges—Kling Anderson

The ranges in the Flint Hills are used for grazing cattle. Many factors which affect range productivity are beyond the control of the range manager. Some of them such as soil moisture and plant populations, however, can be influenced by use and management, and one important practice available to him is the use of fire.

Many experiments have been conducted to relate burning to the behavior of bluestem grasslands. Burning has had some effect on plant population, but the greatest effect seems to be a reduction of soil moisture which is directly reflected in lower yields of vegetation. Burning, when properly controlled, need not result in undesirable shifts in botanical composition in bluestem range.

Fires in Wilderness Areas—Glenn A. Thompson

The fire situation of the Idaho Primitive and the Selway Wilderness Areas was presented.

The causes of wildfires, their complex behavior and their destructive effect were discussed. One of the methods suggested for protection of such areas against wildfires is the use of prescribed burns.

Lightning Behavior in the Yukon—L. E. Requa

The speaker suggested that a study be conducted to determine the rhythm of the fire cycle and the apparent effect of the cycle on the flora and fauna. In remote areas of the Yukon where fires are mostly caused by lightning, this cycle could be observed from the air. The terrain is checkerboarded with all phases of the cycle from fresh burn to stands of mature timber.

Project Skyfire Lightning Research—Keith Arnold

Project Skyfire, a study of meterological problems associated with lightning-caused forest fires, is being conducted by the U.S. Forest Service. The Project's goal is to obtain a better understanding of thunderstorms and lightning, and their relationships to forest fuels.

The research program embraces four areas of study: (1) regional study of thunderstorms and resultant forest fires, (2) study of individual thunderstorms; (3) characteristics and effects of individual lightning discharges; (4) weather modifications.

Large Scale Prescribed Burning—R. J. Riebold

The National Forests in Florida contain about 508,000 acres which are burnable by prescribed fire. About 83,000 acres of forests are burned each year. The average size of prescribed burning blocks is about 1100 acres, so that 83,000 acres represents about 75 separate blocks to be selected, planned, and burned. Prescribed burning consists of planning, plowing, and burning. Planning is divided into two parts: pattern planning and block planning. Cross lines made with tractor plows are essential to controlling fire. Repeated burning of blocks has led to the development of permanent plow lines. The tractor plow, the drip torch, and aerial photos are essential to successful prescribed burning along with a corps of well-trained men.

The Natural History of Lightning—E. V. Komarek, Sr.

The author delved into the natural process of lightning and its effect on vegetation. The natural history of lightning shows evidence that (1) Lightning is ecologically very important; (2) The susceptibility of lightning strikes varies for different species of trees; (3) Lightning is of such frequency and magnitude that there are not many lands that have not been subjected to lightning-caused fires; (4) Plants, animals, and possibly life itself have evolved through a long process of natural selection in an environment where lightning and fires so initiated have been important factors.

Subject Headings: *Burns, forest management; Ecology, of fire; Fire ecology; Forest management, burns; Burns, prescribed, forest management; Moose and fire in Kenai; Project Skyfire.*

K. Sumi

BOOKS, MEETINGS, NEW JOURNALS

Books

Fenimore, C. P. (General Electric Research Laboratory, Schenectady, New York) *Chemistry in Premixed Flames*, Volume 5 of The International Encyclopedia of Physical Chemistry and Chemical Physics, Pergamon Press, New York (1964)

This small book (120 pages) reviews studies of the chemical reactions which take place in premixed laminar flames. Combustion-type reactions which take place at lower temperatures are ignored, consideration being limited to reactions at flame temperatures. The literature is covered through 1962 (283 references) with a few references to work published in 1963. This is a survey rather than a critical evaluation of the present state of knowledge. There is a chapter on flame inhibition, which unfortunately was written before recent work including several papers by Fenimore himself, which led to a much better understanding of the mechanism of inhibition by halogen compounds. The major use of this book to those interested in fire research would be as a summary of information on the chemistry of various flame systems. Although devoted mostly to hydrogen and hydrocarbon flames, systems including hydrazine and nitrogen oxides are also covered.

Chapter 1 describes the techniques of measurements, reviews the observables of a flame—temperature, velocity, and composition—and discusses the equations of flame theory with which they may be correlated. Chapter 2 expounds the concept of quasi-equilibrium, i.e., a pool of radicals (H, O, OH, etc.), equilibrated among themselves through rapid two-body reactions, but of a total concentration much higher than would be expected if they were in equilibrium with the stable species (H_2O, O_2, H_2, etc.). The radicals decay toward complete equilibrium by slower three-body reactions. The experimental evidence for this situation in rich hydrogen-oxygen is discussed. Chapter 3 describes how this concept is used to determine radical concentrations and measure rates of radical recombination in the post-flame gases of such flames. Other reactions may be measured in this region and some involving nitric oxide, carbon monoxide, and boron oxides are discussed.

The important reactions in the hydrogen-oxygen flame are discussed in Chapter 4. Some information about this flame can be gained from low temperature studies of slow combustion and explosion limits. The rates of the major reactions are given and the techniques by which they are determined are discussed. Of particular interest are the varied methods used to estimate the concentration of hydrogen and oxygen atoms. Fenimore has pioneered in the use of chemical additives or tracers to determine the concentration of radicals in flames.

For example if the rate constant for the reaction of $N_2O+O \rightarrow 2NO$ is known, N_2O may be added to a H_2–O_2 flame and the concentration of N_2O and NO measured and the rate of formation of NO calculated. Since $dNO/dt=2k[N_2O][O]$ and $d[NO]/dt$, k, and $[N_2O]$ are known, $[O]$ may be calculated. Similarly $[H]$ may be determined from $H+D_2 \rightarrow HD+D$, $H+N_2O \rightarrow N_2+OH$, or $D+H_2O \rightarrow HD+OH$. (Reactions rates are determined from the underlined species. The difficulties are in being sure that the measured species is only formed by the given reaction and in the determination of the reaction rate constants.)

Going on to hydrocarbon flames in Chapter 5, Feinmore summarizes the state of knowledge with a particularly good discussion of the formation and reaction of the methyl radical. For simple saturated hydrocarbons the initial reaction is $RH+H \rightarrow R+H_2$ or $RH+OH \rightarrow R+H_2O$ depending on whether the flame is rich or lean. (R is a hydrocarbon radical, CH_3 in the case of methane.) The rates of these reactions are known. The hydrocarbon radical is then oxidized to carbon monoxide, $CH_3 \rightarrow ? \rightarrow CO$, but the intermediate steps are not certain. Fenimore presents evidence for CH_3+O. Some workers prefer CH_3+O_2. The final step, $CO+OH \rightarrow CO_2+H$, is well understood and the rate constant is known. Radical concentrations in hydrocarbon flames do not reach the high concentrations found in hydrogen–oxygen flames. In the case of unsaturated hydrocarbons the initial attack is by oxygen atoms and again the rates are known.

Chapters follow on "Ionization and Electronic Excitation in Hydrocarbon Flames," "Soot in Premixed Flames," and "Flame Inhibition." The chapter on "Flame Calculations" refers mainly to the Zeldovich approximation and other simplified correlations. As Fenimore points out, although these determinations of an over-all rate law may have some use in interpolating experimental measurements, they have no fundamental relation to the actual chemistry and kinetics of the flame. The final chapter is devoted to flames involving nitric oxide (NO) either as an oxidizer or an intermediate.

Subject Headings: ***Chemistry, of flames; Flame, chemistry of; Flame, structure of; Flame, premixed.***

W. E. Wilson

Fristrom, R. M. and Westenberg, A. A. *Flame Structure* (McGraw-Hill Series in Advanced Chemistry) New York: McGraw-Hill, 1965. $17.50.

Here is a valuable addition to the literature on flame research. In spite of the widespread use of flames, only few books exist dealing directly with spectroscopy, ionization, optics, aerodynamics, etc. of flames. The main purpose of this book is to provide a better understanding of the chemical kinetics structure of flames. Therefore, special attention is devoted to those flames whose "burning speed" is primarily determined by the rate of chemical reaction, i.e., the book is mainly concerned about the analysis of laminar (and approximately one-dimensional) premixed flames, while turbulent and diffusion flames for which transport phenomena are rate determining are thus mentioned briefly.

The book is divided into 14 chapters that cover the broad categories: (1) mathematical analysis or tools for the exact description of flame structure, (2) experimental techniques for quantitative determination or direct measurement of flame temperature and composition, and (3) interpretation and presentation of results in terms of high temperature gas transport properties and chemical kinetic data.

The reader is well introduced to the scope of the combustion research effort in Chapter I before an introduction, classification of flames, and an outline of the main subject treated in the book, i.e., microstructure of laminar premixed flames is given in Chapter II. In the same chapter, macroscopic flame properties are summarized briefly. Such properties, as opposed to the microstructure properties of flames, are related to the flame as a whole; thus data on flame velocity, quenching distance, propagation limits, adiabatic temperature, minimum ignition "temperature," and energy, etc. are explained and tabulated for some 50 selected fuels. Chapters III, IV, and V are devoted to the mathematical analysis of one-dimensional premixed flame data and basically use the formulation given in the standard work by Hirschfelder, Curtiss and Bird.[1] Under the laminar flame assumption of steady state, constant pressure, negligible effect of viscosity, or radiation, of external forces, and of thermal diffusion, the basic flame equation is derived in Chapter V. This equation is formed by three terms: a diffusion term, a convection (on overall flow) terms, and the chemical reaction term. Steady state requires that the sum of the *transport terms* (diffusion and convection) be equal to the *chemical reaction* term. If this requirement cannot be met for a particular gas flow and burner setup, the flame is either blown off the burner or eventually flashes back. A brief summary of transport coefficient equations is given in Chapters III and V while their experimental determination is discussed extensively in Chapter XII. This chapter is illustrated by examples of experimentally and numerically obtained binary diffusion coefficients for stable as well as for some unstable species, of thermal diffusion coefficients, and of thermal conductivity coefficients which are presented in tables and will serve as handy references for workers in the field.

To be able to give a complete kinetic interpretation of a completely analyzed flame is the final goal of research devoted to uncover the reaction mechanisms of flames. From this viewpoint, the chapters on burner systems (VI), aerodynamic measurements (VIII), temperature measurements (VII), or measurement of stable (IX) as well as of unstable (X) chemical species in the flame reaction zone and on distance measurement and photography in flames (XI) discuss a wide variety of methods and techniques that have been used in the past by the authors and others working toward the mentioned goal. More specifically, in Chapter XIII the authors examine the extent to which "useful" information can be extracted from the data of the preceding chapters.

Lean premixed, laminar methane-oxygen flames at subatmospheric pressure have been extensively studied by the authors and are used often as examples throughout the book. Thus, these flames are also discussed in detail as representative examples in the last Chapter which is on the chemical interpretation of flame structure data. Three distinct zones can be observed in these flames; the first zone or "transport zone" extends from the flame holder (burner-screen) to an approximate height above the burner of $z \approx 0.2$ cm for a flame at 0.1 atm pressure. By then, the flame has reached a temperature of about 1300°K but, below and until this point, all composition and temperature changes are shown to be due only to molecular transport processes, i.e., the second or chemical reaction zone (oxidation of CH_4 and production of H_2O, H_2, and CO) does not start before that temperature is reached. In the third zone, the unstable species recombine and CO is slowly converted to CO_2. Throughout these three zones, the important role of the OH radical becomes evident. Not only is it the most likely reaction partner (especially in lean flames) to initiate the consumption of methane, but it also plays an important role in the oxidation process of the intermediate products as well as in the conversion of CO to CO_2. Besides the methane flame, other flames, like the hydrogen–oxygen flame, the chlorine–hydrogen flame, the bromine hydrogen flame, some hydrocarbon flames, etc. are discussed briefly. They form part of a review and summary of reactions and reaction rates involving the important O, H, and OH radicals in flames.

The book is written with care, richly illustrated, and printed in well-sized print. Together with the list of used symbols and the adequateness of explanatory remarks, it is easy to read from cover to cover even for the nonexpert, although finding of the frequent cross references would have been easier if the chapter numbers had been added to the chapter titles on the top of the pages. There are remarkably few misprints in the text; only a few figures, especially some referring to optical measurements, have some errors which, however, either are obvious or can be checked easily thanks to the well organized bibliography. At the end of the book, not only an author and subject index have been provided, but also a bibliography index on flame structure studies divided into 21 principal topics as well as a very useful selection of combustion bibliography.

An amazing number of facts about flames, experimental techniques, and data of transport properties and reaction rates in flames have been assembled in this book of only 400 pages. Besides the main subject matter, the authors skillfully managed, without inhibiting the clarity of exposition, to cover a vast amount of material in form of compact summaries and/or critical surveys. The extensive and very useful bibliography review which covers papers published before and in the *Proceedings of the Tenth Symposium* (*International*) *on Combustion* (1965), balance out nicely those parts of the book that could be treated only briefly. For all those researchers working on combustion, on peaceful combustion as well as on accidental fires, or for those in need of quick references, this very alive research report, review, and critical compilation of data will be a most welcome addition to their libraries.

Reference

1. Hirschfelder, J. O., Curtiss, C. F., and Bird, R. B.: Molecular Theory of Gases and Liquids, John Wiley and Sons, Inc., 1954.

Subject Headings: ***Chemistry, of flame, Flame, chemistry of; Flame, physics of; Flame, structure of; Physics, of flame; Flame, premixed.***

U. Bonne

Meetings

Technical Meeting on Pyrolysis and Cellulose Chemistry. Committee on Fire Research, National Academy of Sciences—National Research Council

As part of a continuing program of small informal meetings on topics of interest in Fire Research, the Committee on Fire Research sponsored a technical meeting at the National Academy of Sciences in Washington, D. C., on January 7, 1966, covering the topics of "Pyrolysis" and "Cellulose Chemistry." A number of informal papers were presented (see agenda below) followed by discussion of the relationships between the various branches and the state-of-the-art in general. Papers were verbal; those desiring more information should contact the discussers directly.

1. A review of the status of pyrolysis research related to:
   - (A) Heat shield ablation—Dr. T. R. Munson, Avco Research and Development, Wilmington, Massachusetts.
   - (B) Char penetration in wood—Erwin Schaffer, Forest Products Lab., Madison, Wisconsin.
   - (C) Hybrid rocket combustion—R. F. McAlevy, Stevens Institute of Technology, Hoboken, New Jersey.
2. A discussion of aspects of cellulose chemistry that include
   - (A) The production and properties of levoglucosan—Dr. Shafizadeh, Weyerhauser Company, Research Division, Seattle, Washington.
   - (B) The mechanism of primary pyrolysis—A. Broido, Pacific Southwest Forest and Range Experiment Station, U.S. Forest Service, Berkeley, California.
   - (C) The energy relationship in pyrolysis—Herbert Eickner, Forest Products Lab., Madison, Wisconsin.
   - (D) The influence of additives and the pyrolysis process—A. Broido.

Editor

Fourth Annual OCD Fire Research Contractors Conference

On 8–11 March 1966 the Civil Defense Technical Group of the Technical Management Office of USNRDL conducted the Fourth Annual Office of Civil Defense Fire Research Contractors Conference at Asilomar Hotel and Conference Grounds, Pacific Grove, California. Dr. M. G. Gibbons and Mr. R. J. Jenkins were co-chairmen.

The principal subject matter of the Conference was the progress and results of the 29 fire research projects currently sponsored by the OCD Research Directorate. All but three of these projects are managed by the USNRDL Civil Defense Technical Group.

The purpose of the Conference was to allow the contractors to exchange information and assistance and to see how their individual efforts fit into the over-all OCD fire research effort and how that effort fits into the over-all U.S. fire research effort.

The 55 Conference participants included 26 from private contractor organizations, 13 from USNRDL, 3 from the Office of Civil Defense, 6 from other federal agencies or installations, 4 (of whom three were members of the NAS—NRC Committee on Fire Research) from universities, one from the California State Disaster Office, one from the Los Angeles Fire Department, and one from the Scientific Advisor's Branch of the British Home Office.

An agenda of the meeting is reproduced herewith.

Morning Sessions

Session 1—Shelter Habitability
- Firetest Rating System for Shelter Components
- Design of Test for Urban Building Burns
- Shelter Habitability in Existing Buildings under Fire Exposure

Session 2—Rescue and Damage Control
- Rescue Problem Analysis
- Fire Service Capabilities for Rescue
- Fire Service Capabilities for Damage Control

Session 3—Spread of Mass Fires
- Project FIRESCAN
- Preliminary Aerial Fire Mapping Systems Analysis
- Feasibility of Mass Fire Control

Session 4—Fire Fighting Operations and Command
- Fire Department Operations Analysis
- Fire Information for CD Command and Control
- Fire Fighting Communications Analysis
- Design of Tests for Effects of Mass Fire on Shelter Occupants

Session 5—Fundamental Fire Research
- Fundamental Fire Research
- Committee on Fire Research
- Fundamental Research in Limitation and Control of Fires

Session 6—Urban Fire Vulnerability
- Urban Fire Vulnerability Parameters
- Fire Start Capabilities of Nuclear Weapons
- Survey of Fuel Arrays

Session 7—Phenomena in Mass Fires
- Interaction of Mass Fire and Its Environment
- Fire Storm Environment Model
- Fire Storm Exploratory Analysis
- Mass Fire Characteristics and Development

Session 8—Mass Fire Effects on Personnel
- Mass Fire Life Hazard
- Local Assessment of Conflagration Potential
- Evaluation of Nuclear Weapon Thermal Threat

Session 9—Thermal Countermeasures
- Exploratory Development of Thermal Hardening Measures
- Smoke Screen Systems
- Exploratory Development of Thermal Countermeasures

Status Summary of Research on Fire Effects on Shelters and Personnel

Status Summary of Research on Fire Control and Rescue

Status Summary of Research on Fire Phenomena

Status Summary of Research on Fire Vulnerability and Prevention

Afternoon Sessions

Fire Effects on Shelters and Personnel
    Shelter Habitability
    Mass Fire Effects on Personnel

Fire Control and Rescue
    Rescue and Damage Control,
    Spread of Mass Fires,
    Fire Fighting Operations and Command

Fire Phenomena
    Fundamental Fire Research
    Phenomena in Mass Fires

Fire Vulnerability and Prevention
    Urban Fire Vulnerability
    Thermal Countermeasures

Evening Sessions

The OCD Fire Research Program
    The OCD fire research program as a whole
    The relationship of the OCD fire research program to OCD operational requirements
    Relationship of the OCD fire research program to the 5-city study

The DASA Fire Research Program
    The DASA fire research program as a whole
    Relationship of the DASA fire research program to the OCD fire research program
    Operation FLAMBEAU

Fundamental Fire Research
    The Nature of Fundamental Fire Research
    Recent Developments and Implications of Fundamental Fire Research
        Ignition Phenomena
        Growth and Spread
        Burning Rates and Related Physical Phenomena
        Confinement
        Extinguishment

New Journals

Current Papers in Physics, A. Tybulewicz, Editor, semi-monthly beginning January 1966. This abstract journal carries titles of physics research papers from about 100 sources (Institution of Electrical Engineers, Savoy Place, London W. C. 2, England). Surface mail $5.00, Air mail $11.00 for members of AIP member societies; $8.50 surface, $14.50 air mail for nonmembers.

INDEX OF AUTHORS

INDEX OF SUBJECTS

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ABSTRACTS AND REVIEWS

Volume 8 Number 3

Fire Research Abstracts and Reviews

Committee on Fire Research
Division of Engineering
National Academy of Sciences—National Research Council

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
Washington, D. C.
1966

FIRE RESEARCH ABSTRACTS AND REVIEWS is published three times a year by the Committee on Fire Research of the National Academy of Sciences—National Research Council, 2101 Constitution Avenue, Washington D. C. It is supported by the Office of Civil Defense of the Department of the Army, the U. S. Department of Agriculture through the Forest Service, the National Science Foundation, and the National Bureau of Standards. The opinions expressed by contributors are their own and are not necessarily those of the Committee on Fire Research.

Library of Congress Catalog Card Number 58-60075 rev

Available without charge from the
Office of the Committee on Fire Research
National Academy of Sciences—National Research Council
Washington, D. C. 20418

FOREWORD

The issue begins with a review on the molecular transport properties of interest in fire studies. Although the paper represents a joint effort by your editor and Dr. A. A. Westenberg of the Applied Physics Laboratory, the special knowledge is that of Dr. Westenberg who is one of the world experts in this field. This information is useful not only in flame structure studies, but in general heat transfer problems in the fire field. Advances in this field during the past decade have been marked and those whose information is derived from older textbooks will be pleasantly surprised by the new understanding of the processes and the detailed experimental information available in the area of high temperatures.

A second feature is a short article by Mr. Lohneiss, "Observations of a Flame Generated Vortex." He has managed to document this interesting phenomenon photographically in a beautiful series of pictures which appear in a color plate through the courtesy of his sponsor, the Defense Research Corporation. It is fortunate that such a skilled observer was present.

Two meetings are reported. The first was the annual meeting of the National Fire Protection Association in Chicago (May 16–20); the second was a technical meeting on "Inhibition of Combustion by Chemical Means," sponsored by the Committee on Fire Research of the National Academy of Sciences—National Research Council, held at the Applied Physics Laboratory (June 23 and 24, 1966). These meetings offer a contrast in objectives and organization. The first was a national meeting of a large society with over a dozen sessions covering topics from fire-fighting practice through problems of fire technology. Its objectives were manifold and were attacked with vigor. The second was a small meeting devoted to a single topic. Most of the major contributors to the field were present. Interest was high—some of the attendees came from as far away as California and the discussion was spirited.

ROBERT M. FRISTROM, *Editor*

CONTENTS

Volume 8 Number 3

Page

REVIEWS

ABSTRACTS

I. Ignition Phenomena

II. Thermal Decomposition

III. Heat and Material Transfer

IV. Diffusion Flames

V. Combustion Principles

VI. Radiation

VII. Suppression of Combustion

VIII. Model Studies and Scaling Laws

IX. Atomization of Liquids

X. Meteorological Interactions

XI. Operational Research Principles Applied to Fire Research

XII. Instrumentation

XIII. Fire-Fighting Techniques, Equipment

XIV. Miscellaneous

BOOKS, MEETINGS, NEW JOURNALS

Books

Meetings

REVIEWS

Molecular Transport Properties for Flame Studies*

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The transport properties required in the quantitative study of laminar flame structure are ordinary concentration diffusion (most important) and thermal conduction. Thermal diffusion is generally of minor importance except for light gases under special circumstances, and this, in addition to the considerable complication it brings to an already very involved task, means that it is usually left out of consideration entirely. Additional discussion of thermal diffusion is presented in Section 4. Viscosity enters obliquely into the discussion, however, as will be seen. The emphasis throughout this article is on the *practical* measurement or computation of diffusion and thermal conductivity coefficients for use in combustion studies generally and laminar flames in particular. For more detailed treatments the reader should consult the appropriate references.

In considerations of laminar flame structure per se, the thermal conductivity of the flame gases is of the same importance as their respective diffusivities, since it enters into the determination of the thermal structure of the flame in the same way that diffusivities determine the composition structure. From the viewpoint of the information which can be derived from it, however, the composition structure (and hence molecular diffusion coefficients) should be regarded as the more important, since it is from this that chemical kinetic data are obtained without knowledge of the thermal conductivity. Nevertheless, the energies of the flame are of intrinsic interest, and thermal transport is vital in this connection.

The reaction zone in any practically attainable flame contains more than two chemical species, so that rigorously it should be treated as a multicomponent mixture. In the case of diffusion, this means that the diffusion velocity of a particular species depends on a set of multicomponent diffusion coefficients each of which, in turn, depends in a complicated way on the mixture composition and the binary diffusion coefficients of all the pairs of species in the mixture (Ref. 1, p. 487). For use in flame calculations complete rigor would, in this case, also be completely impractical. Fortunately, many common flame systems suitable for study have one component present in large excess, i.e., a diluent. Examples are those flames involving air as oxidant where the mixture is usually mostly nitrogen or those using a deliberate excess of oxygen. In such cases, *each species may be regarded as a trace in a binary mixture with the excess component.* Then the one-dimensional diffusion velocity (neglecting thermal diffusion) is given simply by

$$V_i = -\frac{D_{ij}}{X_i}\frac{dX_i}{dz} \tag{1}$$

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* From FLAME STRUCTURE, by R. M. Fristrom and A. A. Westenberg. Copyright © 1965 McGraw-Hill Inc. Used by permission of McGraw-Hill Book Company.

where D_{ij} is the binary diffusion coefficient of species i with the excess component j. In cases where species i is present *as a trace* in a more general multicomponent mixture, the relation

$$V_i = -\frac{1}{X_i \sum_{j \neq i} X_j / D_{ij}} \frac{dX_i}{dz} \tag{2}$$

may be used, which reduces to Eq. (1) when all the other species except the trace are lumped into one excess component j. In any case, the important quantities to be determined are the binary diffusion coefficients. These are discussed in the following section for stable species. Unstable atoms and radicals are considered separately in Section 3.

For thermal conductivity we shall have to consider multicomponent mixtures, although here again if one species is in large excess, the problem is much simpler. The conduction of heat through a gas is a much more complex phenomenon than mass diffusion, since in the latter only the translational motion of the molecules enters the picture, while in the former the internal degrees of freedom also play a role. In the case of a pure gas, the one-dimensional flux of heat energy due to a gradient of temperature is given simply by

$$q = -\lambda(dT/dz), \tag{3}$$

where λ is the thermal conductivity, while in a mixture with gradients in composition there will be other terms due to diffusion. The rigorous expressions for the thermal conductivity of binary and multicomponent mixtures of monatomic gases are given in Ref. 1, pp. 534–538. They are too complex for inclusion here, nor shall we need to use them. Various approximations are considered later in the article. The important thing is that the starting point for the treatment of mixtures is a knowledge of the thermal conductivities of all the pure components; these are therefore discussed first in Section 4.

SECTION 1. EXPERIMENTAL DIFFUSION COEFFICIENTS OF STABLE SPECIES

Experimental Techniques

The classic techniques of making gaseous diffusion measurements are those associated with the name of Loschmidt[2] and Stefan.[3] These are described in some detail by Jost.[4] Various refinements have been used, but basically the apparatus consists simply of a long tube divided into two chambers by a stopcock or diaphragm of some kind. Initially each chamber contains one of the gases of the pair being measured. At time zero, the stopcock is opened and the two gases mix by diffusion. Analysis of the mixture at some point in the tube at a later time enables the binary diffusion coefficient to be determined. It is, of course, extremely important that opening the stopcock between the two chambers does not disturb the gas so that mixing occurs by other than molecular processes. Most of the refinements introduced since Loschmidt's original work have been concerned with this point. The technique in various forms has been used by Von Obermayer,[5] Boardman and Wild,[6] Klibanov et al.,[7] Boyd et al.,[8] Strehlow,[9] Bunde,[10] and others. It is capable of very good precision (0.1 percent) when used with considerable care. The main disadvantage of the

Loschmidt method is that it requires very careful thermostating of a fairly long column which also contains moving parts, and so it is inherently unsuitable for high-temperature measurements. There is also some ambiguity about the concentration dependence of the diffusion coefficient measured in this way which is important in certain cases.

The method of Stefan[3] has been used for measuring the diffusion coefficient of a vapor in a gas. One component is liquid and is put in the bottom of a vertical tube. The other (gas) component is passed slowly over the open mouth of the tube. The liquid evaporates, the vapor diffusing up the tube and out the end, where its concentration is kept essentially zero by the gas stream. The vapor concentration at the liquid boundary is determined by the vapor pressure of the liquid. From this information and the rate of evaporation determined by observing the liquid level, the vapor-gas diffusion coefficient may be determined. The method has been used by Winkelman,[11] Trautz and Ludwig,[12] Schwertz and Brow,[13] and others. It is a simple technique but not suited for high temperatures and—at least in its original form—only useful for volatile liquids.

A technique developed by Walker and Westenberg[14–19] makes use of a point source. One component (the carrier) is passed through a tube ending in a series of precision screens, so that the flow at the exit is slow, uniform, and laminar. The second component is introduced through a fine hypodermic tube to furnish a point source of trace gas. By sampling the gas mixture downstream of the source with a fine probe and measuring its composition, one may derive the binary diffusion coefficient. The technique is relatively simple, of good precision (1 to 2 percent), and most important, adaptable for fairly high-temperature work since the carrier gas flow may be heated. Since it is a flow technique, difficulties with thermostating are largely avoided, as are stray convection currents. Also, it is a trace technique, and the measured diffusion coefficient is always representative of essentially zero concentration of the point source gas, thus clarifying the concentration dependence problem. By using the burned gas from a flat flame as a carrier, the point source method has been used at temperatures as high as 1700°K.[20]

Other miscellaneous techniques have been used. Waldman[21] has made interesting use of the Dufour effect (reciprocal to thermal diffusion) to determine some diffusion coefficients, while the rate of approach to the steady state in thermal diffusion has been employed by Nettley[22] and Saxena and Mason.[23] These are not precision methods, however, and are not well suited to high-temperature work. For temperature range, precision, and general flexibility of application, the point-source technique would appear to be the best available. Flame structure data (in the transport region where no reaction occurs) have also been used in an interesting way to deduce diffusion coefficients.[79] This is the reverse of the usual procedure, of course.

Experimental Data

Table 1 contains a compilation of the best available values (at 298°K and 1 atm) of binary diffusion coefficients on gas pairs likely to be of use in combustion studies. Two significant figures are given in all cases, which probably reflects the accuracy of most of them. The data were obtained by the various techniques described in the previous section, and unless otherwise stated, the concentration dependence of the diffusion coefficient has been ignored. While many of the common flame constituents are given, it will be apparent that many pairs are not included—especially for the

TABLE 1

Experimental binary diffusion coefficients at 298°K and 1 atm

Gas pair	D_{ij}, cm^2 sec^{-1}	Ref.	Gas pair	D_{ij}, cm^2 sec^{-1}	Ref.
N_2-CO_2(trace)	0.17	15	H_2-H_2O	0.99	13
N_2-CO	0.22	6	H_2-Br_2	0.58	24
N_2-H_2	0.78	10	H_2-C_6H_6	0.34	25
N_2-O_2	0.22	6	H_2-n-C_4H_{10}	0.38	8
N_2-H_2O	0.24	13	H_2-N_2O	0.62	26
N_2-C_2H_4	0.16	8	H_2-C_2H_5OH	0.44	11
N_2-C_2H_6	0.15	8	H_2-$(C_2H_5)_2O$	0.35	4
N_2-n-C_4H_{10}	0.096	8	H_2-$(CH_3)_2CO$	0.43	4
N_2-Ar	0.20	21	CO_2-CO	0.16	5
N_2(trace)-He	0.69	15	CO_2-C_2H_4	0.15	5
N_2-He(trace)	0.73	15	CO_2-CH_4	0.18	5
O_2-CH_4(trace)	0.23	17	CO_2-H_2O	0.19	13
O_2(trace)-CO_2	0.16	17	CO_2-C_3H_8	0.086	27
O_2-CO(trace)	0.22	17	CO_2-CH_3CHO	0.092	27
O_2-H_2O(trace)	0.29	17	CO_2-CS_2	0.074	3
O_2-H_2(trace)	0.82	17	CO_2-C_6H_6	0.061	25
O_2-C_6H_6	0.080	12	CO_2-Ar	0.14	6
O_2-Ar	0.14	6	CO_2-N_2O	0.11	6
H_2-CO	0.75	5	CO_2-C_2H_5OH	0.79	11
H_2-CO_2	0.65	8	CO_2-$(C_2H_5)_2O$	0.062	4
H_2-CH_4	0.73	8	CO_2(trace)-D_2	0.49	23
H_2-C_2H_4	0.60	8	H_2O-CH_4	0.28	13
H_2-C_2H_6	0.54	8	H_2O-C_2H_4	0.20	13
H_2(trace)-Ar	0.85	18	CO-C_2H_4	0.13	5

more unusual flames. There is room for considerably more experimental work in this connection.

The lack of experimental data is, of course, far more pronounced at high temperature. The highest temperature (≈1700°K) at which any diffusion measurements have been made are for the point-source self-diffusion data reported by Ember, Ferron, and Wohl.[20] The data of Klibanov, Pomerantsev, and Frank-

Kamenetskii[7] for H_2O-air and CO_2-air to 1500°K were made by a capillary-leak method closely related to the classical Loschmidt technique. The data were so imprecise, however, as to be of interest mainly from a historical point of view. The moderately high-temperature data of Walker and Westenberg[14–17] and Westenberg and Frazier[18] were obtained by the point-source method. This work covered the nominal range 300 to 1150°K, except for certain gas pairs which underwent spontaneous ignition at somewhat lower temperatures. Some of the gas pairs[17] were specifically chosen for their pertinence to methane-oxygen flame studies. The available high-temperature data are given in tabular form in Table 2. No other published data have extended to temperatures much higher than about 400°K, and even these[9,10] were not on systems of general interest in combustion. Thus, except for the data given in Table 2, there are essentially no experimental data available at temperatures even remotely approaching those in flames.

TABLE 2

Experimential diffusion coefficients at high temperature obtained by the point source method

Pressure = 1 atm. The first gas of each pair is the trace component.

Temp., °K	D_{ij} (cm^{2}sec^{-1})									
	CH_4-O_2	O_2-CO_2	N_2-CO_2	H_2-O_2	CO-O_2	H_2O-O_2	He-Ar	He-N_2	H_2-Ar	CO_2-CO_2
300	0.23	0.16	0.17	0.82	0.22		0.76	0.74	0.86	
400	0.39	0.28	0.30	1.40	0.37	0.47	1.27	1.22	1.44	
500	0.58	0.42	0.44	2.09	0.54	0.69	1.89	1.77	2.14	
600	0.80	0.58	0.61	2.88	0.74	0.94	2.59	2.41	2.95	
700	1.05	0.77	0.79	3.76	0.96	1.22	3.38	3.12	3.84	
800	1.33	0.97	0.99	4.74	1.19	1.52	4.24	3.89	4.80	
900	1.62	1.19	1.21	5.79		1.85	5.17	4.74	5.94	
1000	1.95	1.43	1.45			2.20	6.17	5.65	7.22	
1100		1.68	1.70			2.58	7.24	6.62	8.65	
1200										1.76
1300										2.16
1400										2.50
1500										2.86
1600										3.21
1700										3.57

Sources: CO_2-CO_2 data from Ref. 20. All others from Refs. 14–18.

Experimental data on multicomponent diffusion, especially in systems of interest to flame problems, are almost completely lacking. The rigorous expressions relating the diffusion velocity of a particular species in a multicomponent mixture to the various binary-pair diffusion coefficients and the composition are so complex and unwieldy as to be impractical. The special case noted in Eq. (2), where the species is a trace, has been tested experimentally, however. Comparison of Eqs. (1) and (2) indicates that the *effective* diffusion coefficient of such a trace species in the mixture is given by

$$D_{i\,\mathrm{mix}} = \left(\sum_{j \neq i} \frac{X_j}{D_{ij}} \right)^{-1}. \tag{4}$$

This expression has been verified by Fairbanks and Wilke[28] and by Walker, De Haas, and Westenberg.[19] The latter data were obtained at room temperature on the system CO_2 (trace)-He-N_2 by the point-source method. The agreement indicates that the theory is valid.

SECTION 2. THEORETICAL PREDICTION OF DIFFUSION COEFFICIENTS

Aside from its own intrinsic interest, the general scarcity of experimental data has made the theoretical prediction of molecular diffusion coefficients indispensable in practical applications—especially at high temperature. While there have been many empirical or quasi-theoretical relations proposed for predicting binary diffusion coefficients and their temperature dependence,† these are now of historical interest only. The best results are now all based firmly on the rigorous Chapman-Enskog kinetic theory of dilute gases, as discussed in detail by Hirschfelder, Curtiss, and Bird.[1] The results of the theory which are necessary for its application will now be outlined.

Kinetic Theory Relations

The Chapman-Enskog theory is strictly intended to apply only to gases whose molecules possess spherically symmetric force fields in their interactions with each other. The transport properties all involve molecular collisions; thus it would be expected that the forces which molecules experience during collisions should play a vital role in the theoretical treatment. The requirement of spherically symmetric particles, while strictly fulfilled only by monatomic gases, may be regarded as being approximated nearly enough by most of the relatively simple nonpolar gases or by mixtures with only one polar component.

The first approximation to the binary diffusion coefficient of a gas pair made up of species i and j is given by the theory in general form as

$$(D_{ij})_1 = 3(kT)^2/16P\mu\Omega_{ij}^{(1,1)}, \tag{5}$$

where k = Boltzmann constant, T = temperature, P = pressure, μ = reduced mass of the pair of molecules, and $\Omega_{ij}^{(1,1)}$ is one of a group of so-called collision integrals $\Omega_{ij}^{(l,s)}$, for which the subscript ij indicates interaction between species i and j. This integral is temperature-dependent and involves explicitly (Ref. 1, p. 525) the potential energy of interaction between the molecules.

It will be noted that in this first approximation only the interaction between the unlike species i and j appears. Collisions between like molecules do not enter, and to this approximation, there is no concentration dependence of the diffusion coefficient.

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† These have been reviewed by Wilke and Lee (Ref. 29).

In the second approximation

$$(D_{ij})_2 = (D_{ij})_1 f_D^{(2)}, \tag{6}$$

where $f_D^{(2)}$ is a complicated function of the mixture composition, molecular weights, and various collision integrals for interactions between both like and unlike molecules. This factor can amount to a correction of a few percent in the case of gas pairs with very unlike masses.[15] In most cases of interest in flames it is entirely negligible, and for that reason we shall not consider it further. Methods of evaluating $f_D^{(2)}$ have been summarized to convenient form by Mason.[30] For simplicity, the subscript 1 denoting the first approximation to the diffusion coefficient will be omitted from now on.

Potential Energy Functions

The real potential energy of interaction between two particles which enters into the transport calculations cannot be calculated from first principles (i.e., quantum mechanics) for any but a very few of the simplest molecules. For any progress to be made in this area, the necessary procedure is to assume some functional form for the potential energy—which is expected to approach reality in varying degree depending on the function—and then rely on experiments to fit the adjustable parameters of the function to the data. This gives some basis for interpolation or (more important) extrapolation of data to higher or lower temperatures. It is a semiempirical approach to the problem, in which theory and experiment are mutually indispensable.

We shall discuss five of the classical potential energy functions which have been, and are, the most useful in transport property calculations. The simplest of these considers the molecules to be *rigid noninteracting spheres* with an effective collision diameter σ; that is, the potential energy $\phi(r)$ is zero for any internuclear separation r greater than σ, and infinite for $r<\sigma$.† For this model

$$\Omega_{ij}^{(1,1)} = \sigma^2(\pi kT/2\mu)^{1/2}, \tag{7}$$

and Eq. (5) reduces to the familiar expression of simple kinetic theory

$$D_{ij} = 3\sqrt{2}(kT)^{3/2}/16P\sigma^2(\pi\mu)^{1/2}. \tag{8}$$

This relation is useful for rough estimates of diffusion coefficients, but becomes progressively less reliable as the temperature increases since, as we shall see, the $\frac{3}{2}$ power of temperature is too small a dependence. For this reason we shall make no further use of the rigid sphere model. This is the only one for which the collision integrals may be solved analytically. All the others require extensive numerical computations (which have been done) to arrive at the desired collision integrals.

The next simplest function is the *inverse power repulsive potential*, in which the potential $\phi(r)$ is given as a function of the intermolecular separation distance r by

$$\phi(r) = d/r^{\delta}, \tag{9}$$

where d and δ are adjustable constants. This is a purely repulsive potential in which no allowance is made for the attractive (London dispersion) forces operative at

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† Strictly speaking, quantities like σ, $\phi(r)$, μ, etc., which are characteristic of a particular pair of molecules i and j should carry these letters as subscripts. We shall avoid this whenever there is no danger of confusion, however, for the sake of simplicity.

relatively long range. At high temperatures molecules undergo more penetrating collisions, and it might be expected that in this regime the repulsive forces would be more important than those of attraction, so that a potential like that of Eq. (9) would be especially applicable. For this potential, the binary diffusion coefficient may be written

$$D_{ij}=\frac{3(2k^3/\pi\mu)^{1/2}(k/d\delta)^{2/\delta}T^{3/2+2/\delta}}{16PA^{(1)}\Gamma(3-2/\delta)}, \tag{10}$$

where $A^{(1)}$ is an integral (a function of δ) which has been evaluated (Ref. 1, p. 548) and $\Gamma(3-2/\delta)$ is the Gamma function of the indicated argument. A convenient feature of this potential is that it gives a simple power temperature dependence of the diffusion coefficient, that is, $D_{ij}\propto T^s$, $s=\frac{3}{2}+2/\delta$. Thus in using it to interpret experimental diffusion data, a test of its applicability is given by plotting log D_{ij} versus log T, which should be linear. The slope s yields the value of δ directly.

A closely related function is the *exponential repulsive potential*

$$\phi(r)=A\exp(-r/\rho), \tag{11}$$

with A and ρ as constants for a given interaction. A potential of this form has some theoretical justification[31] and presumably should be somewhat better than the simple inverse power function at high temperatures. The necessary integrals have been evaluated by Monchick[32] and are given in the form

$$\Omega_{ij}^{(1,1)}=(8\pi kT/\mu)^{1/2}\alpha^2\rho^2[I_{(1,1)}]_{ij}, \tag{12}$$

where $\alpha=\ln(A/kT)$ and $[I_{(1,1)}]_{ij}$ is an integral tabulated as a function of α. For this model, the temperature dependence of D_{ij} is complex, as can be seen by combining Eqs. (12) and (5).

The potential function which has been most widely used for transport property calculations is the *Lennard-Jones* (12-6) *potential*

$$\phi(r)=4\epsilon[(\sigma/r)^{12}-(\sigma/r)^6]. \tag{13}$$

The adjustable parameters ϵ and σ have the significance shown, that is, ϵ is the depth of the potential "well" and σ the value of r at which $\phi=0$. This potential has both attractive and repulsive terms to take account of behavior at both large and small separations. The r^{-6} dependence of the attractive term is consistent with the induced dipole–induced dipole dispersion force and has a fairly firm theoretical basis.[33] The r^{-12} repulsive term, however, was originally chosen mainly for mathematical convenience and in most cases represents too strong a repulsion at close distances of approach. The collision integrals for this potential have been evaluated by several different investigators and are well established. They are given in the treatise by Hirschfelder, Curtiss, and Bird (Ref. 1, pp. 1126–1127) in terms of the reduced quantities $\Omega_{ij}^{(l,s)*}$ obtained by dividing the $\Omega_{ij}^{(l,s)}$ by the corresponding integral for the rigid sphere model of Eq. (7). Thus for the $l=1$, $s=1$ case needed in diffusion, the tabulated integrals are

$$\Omega_{ij}^{(1,1)*}=(2\mu/\pi kT)^{1/2}(\Omega_{ij}^{(1,1)}/\sigma^2) \tag{14}$$

and are given as function of the reduced temperature $T^*=kT/\epsilon$.

The last potential to be considered is the *modified Buckingham* (*exp*-6) *potential*

$$\phi(r)=\frac{\epsilon}{1-6/\alpha}\left\{\frac{6}{\alpha}\exp\left[\alpha(1-r/r_m)\right]-\left(\frac{r_m}{r}\right)^6\right\} \tag{15}$$

which contains three parameters, ϵ, α, and r_m, a fact which by itself would be expected to facilitate fitting experimental data. The form of this potential is similar to the Lennard-Jones model except for a somewhat more realistic repulsive term. A theoretical disadvantage of this potential is that it has a maximum at small values of r, although this is generally of no practical importance. ϵ is the well depth, r_m the value of r at the "bottom of the well" (energy minimum), while α is a measure of the steepness of repulsion. (It should not be confused with the α used with the exponential repulsion model.) The collision integrals for this potential have been computed by Mason.[34]

For convenience in calculation, the expressions for the diffusion coefficient in terms of practical units for the various models are as follows:

Rigid spheres:

$$D_{ij}=\frac{1.86\times10^{-3}[(M_i+M_j)/M_iM_j]^{1/2}T^{3/2}}{P\sigma_{ij}^2} \tag{16}$$

Lennard-Jones (12-6):

$$D_{ij}=\frac{1.86\times10^{-3}[(M_i+M_j)/M_iM_j]^{1/2}T^{3/2}}{P\sigma_{ij}^2\Omega_{ij}^{(1,1)*}} \tag{17}$$

Modified Buckingham (exp-6):

$$D_{ij}=\frac{1.86\times10^{-3}[(M_i+M_j)/M_iM_j]^{1/2}T^{3/2}}{P(r_m)_{ij}^2\Omega_{ij}^{(1,1)*}} \tag{18}$$

Exponential repulsion:

$$D_{ij}=\frac{4.65\times10^{-4}[(M_i+M_j)/M_iM_j]^{1/2}T^{3/2}}{P\alpha_{ij}^2\rho_{ij}^2[I_{(1,1)}]_{ij}} \tag{19}$$

where D_{ij} is in cm^2 sec^{-1}; P is pressure in atm; σ_{ij}, $(r_m)_{ij}$, and ρ_{ij} are in angstroms; T is in °K; and M_i, M_j are molecular weights. A general expression for the inverse power repulsion model is not reducible below the form given by Eq. (10).

Potential Parameters from Diffusion

In order to make use of any of the foregoing potential functions for computing binary coefficients and (especially) their dependence on temperature, it is necessary to have available values of the parameters for the potential characteristic of the particular pair of gases being considered. The most reliable way of obtaining these parameters is by fitting the measured diffusion coefficients themselves as a function of temperature. In this sense the whole procedure is somewhat academic, since in order to make theoretical predictions of a quantity, the quantity itself has to be measured. However, for extrapolation of data beyond the range of temperature over which measurements have been made, the interplay of theory and fitted experimental parameters is most useful.

The only diffusion measurements which have been made with sufficient precision and over a wide enough temperature range for meaningful potential fitting are those given in Table 2. Using a least-squares procedure, the data on the nine unlike gas pairs may be fitted about equally well (i.e., with a standard deviation of less than 3 percent) over their measured temperature ranges by any of the four potential functions given in Eqs. (9), (11), (13), and (15). The potential parameters determined in this way are given in Table 3. A word of caution is appropriate at this point. It should be emphasized that, even over a range of measurement of several hundred degrees as in these examples, the individual parameters of a particular potential cannot be very precisely determined in this way. A *particular pair* of parameters—the ϵ/k and σ for the Lennard-Jones (12-6) potential given for O_2-CO_2 in Table 3, for example—are uniquely determined in that $\epsilon/k=213$ must be used with $\sigma=3.36$. But another pair of values may also fit the data within the experimental error nearly as well. For the O_2-CO_2 case, either $\epsilon/k=200$, $\sigma=3.40$, or $\epsilon/k=240$, $\sigma=3.31$ will do nearly as well as the values given. Thus one should be wary of inferring that *the* potential well depth for O_2-CO_2 interaction has a value $\epsilon/k=213$°K. This is only a fitting parameter for use with $\sigma=3.36$ A in calculating $D_{O_2-CO_2}$ by the Lennard-Jones (12-6) model, and it says very little about the "real" interaction potential.[16]

TABLE 3

Potential parameters obtained by fitting experimental diffusion data of Table 2

Gas pair	Inverse power repulsion		Exponential repulsion		Lennard-Jones (12–6)		Modified Buckingham (exp-6)		
	d, erg A^{δ} $\times 10^{10}$	δ	A/k, °K $\times 10^{-5}$	ρ, A	ϵ/k, °K	σ, A	ϵ/k, °K	r_m, A	α
CH_4-O_2	4.56	6.83	8.0	0.491	182	3.37	220	3.61	17
O_2-CO_2	3.75	6.54	6.5	0.520	213	3.36	255	3.62	17
N_2-CO_2	20.6	7.91	24.5	0.432	154	3.52	184	3.78	17
H_2-O_2	1.62	7.13	9.0	0.395	152	2.82	117	3.42	12
CO-O_2	75.6	9.52	105	0.339	91	3.48	110	3.73	17
H_2O-O_2	358	11.41	900	0.261	80	3.33	100	3.57	17
He-Ar	1.81	8.12	26	0.307	125	2.59	150	2.78	17
He-N_2	22.6	10.45	350	0.241	69	2.87	85	3.07	17
H_2-Ar	1.68	7.34	12.5	0.371	155	2.76	112	3.37	12

A comparison of the diffusion coefficients predicted from the potential parameters of Table 3, using Eqs. (10), (17), (18), and (19) and the appropriate collision integrals is shown in Table 4. It is evident that in the range of experimental measurement, the agreement between the different models is excellent. In the range 1500 to

TABLE 4

Predicted diffusion coefficients using various potentials (parameters of Table 3)

Pressure = 1 atm; L-J = Lennard-Jones (12–6); M.B. (exp-6) = modified Buckingham (exp-6); I.P.R. = inverse power repulsion; Exp. R. = exponential repulsion.

Gas pair	Potential function	Temperature, °K						
		300	500	1000	1500	2000	2500	3000
He-N_2	L-J	0.741	1.77	5.65	11.1	17.9	25.9	35.0
	M.B. (exp-6)	0.741	1.78	5.66	11.1	17.8	25.7	34.6
	I.P.R.	0.745	1.76	5.68	11.3	18.3	26.7	36.3
	Exp. R.	0.746	1.76	5.69	11.3	18.5	27.2	37.2
	L-J (viscosity)	0.723	1.69	5.34	10.5	16.9	24.5	33.2
	I.P.R. (scattering)			5.54	11.4	19.1	28.4	39.3
CO_2-N_2	L-J	0.174	0.440	1.45	2.86	4.62	6.69	9.05
	M.B. (exp-6)	0.174	0.439	1.46	2.86	4.60	6.49	8.99
	I.P.R.	0.177	0.434	1.46	2.98	4.93	7.29	10.0
	Exp. R.	0.178	0.433	1.46	3.01	5.04	7.54	10.5
	L-J (viscosity)	0.156	0.389	1.27	2.49	4.02	5.82	7.87
He-Ar	L-J	0.757	1.89	6.17	12.2	19.6	28.4	38.5
	M.B. (exp-6)	0.755	1.90	6.23	12.1	19.7	28.4	38.2
	I.P.R.	0.763	1.86	6.25	12.7	21.0	31.0	42.6
	Exp. R.	0.765	1.86	6.26	12.8	21.5	32.1	44.6
	L-J (viscosity)	0.756	1.77	5.60	11.0	17.7	25.7	34.8
	I.P.R. (scattering)			5.98	12.3	20.5	30.6	32.1
CO_2-O_2	L-J	0.161	0.419	1.43	2.84	4.59	6.66	9.01
	M.B. (exp-6)	0.162	0.418	1.42	2.81	4.55	6.58	8.89
	I.P.R.	0.164	0.412	1.44	3.00	5.04	7.54	10.48
	Exp. R.	0.164	0.410	1.44	3.04	5.19	7.90	11.15
	L-J (viscosity)	0.156	0.389	1.27	2.51	4.04	5.85	7.92
CH_4-O_2	L-J	0.226	0.581	1.95	3.86	6.23	9.03	12.22
	M.B. (exp-6)	0.230	0.593	2.00	3.95	6.38	9.23	12.45
	I.P.R.	0.229	0.574	1.99	4.11	6.88	10.26	14.23
	Exp. R.	0.230	0.570	1.99	4.18	7.11	10.77	15.18
	L-J (viscosity)	0.225	0.554	1.79	3.52	5.67	8.21	11.1
H_2-O_2	L-J	0.821	2.09	6.93	13.7	22.2	32.1	43.4
	M.B. (exp-6)	0.818	2.07	6.99	14.1	23.1	34.0	46.6
	I.P.R.	0.828	2.06	7.06	14.5	24.3	36.1	50.0
	Exp. R	0.830	2.05	7.10	14.9	25.2	38.1	53.6
	L-J (viscosity)	0.830	1.97	6.27	12.3	19.8	28.7	38.8
CO-O_2	L-J	0.224	0.542	1.73	3.40	5.48	7.93	10.72
	M.B. (exp-6)	0.224	0.542	1.74	3.39	5.54	7.88	10.62
	I.P.R.	0.224	0.538	1.76	3.52	5.76	8.44	11.53
	Exp. R.	0.225	0.537	1.77	3.57	5.89	8.70	11.99
	L-J (viscosity)	0.208	0.503	1.61	3.15	5.07	7.34	9.94

TABLE 4—Continued

Gas pair	Potential function	Temperature, °K						
		300	500	1000	1500	2000	2500	3000
H_2O-O_2	L-J	0.288	0.692	2.21	4.32	6.96	10.09	13.65
	M.B. (exp-6)	0.286	0.691	2.20	4.31	6.93	10.00	13.48
	I.P.R.	0.294	0.691	2.21	4.35	7.05	10.24	13.90
	Exp. R.	0.294	0.690	2.21	4.37	7.11	10.38	14.16
	L-J (viscosity)	0.214	0.620	2.08	4.07	6.61	9.6	13.3
H_2-Ar	L-J	0.847	2.16	7.18	14.2	23.0	33.3	45.0
	M.B. (exp-6)	0.851	2.15	7.20	14.5	23.9	35.2	48.3
	I.P.R.	0.861	2.13	7.27	14.9	24.9	36.9	51.0
	Exp. R.	0.861	2.11	7.26	15.1	25.4	38.3	53.6
	L-J (viscosity)	0.821	1.96	6.25	12.3	19.8	28.6	38.7

3000°K, *which represents extrapolation*, the predictions begin to deviate as much as 20 percent in some cases. *Without additional evidence, it is impossible to state which of the predictions is to be preferred.* In a few cases such as He-N_2,[15] and He-Ar,[16] the necessary additional evidence is available in the form of intermolecular potential energy functions derived independently from molecular scattering experiments.[35,36] These potentials, generally of the inverse power repulsion type, are valid at closer distances of approach (corresponding to higher temperatures), and may be used directly to compute diffusion coefficients at higher temperatures than are easily accessible to measurement. Table 4 contains entries for He-N_2 and He-Ar obtained this way. In the two cases cited, both the pure repulsion potential predictions (inverse power and exponential) derived from diffusion measurements agree better with the scattering predictions than do the other two potentials. In view of the extreme scarcity of such scattering data, however, one should not take this as a general rule. At the present time, for lack of better evidence, it is probably best to choose a model on the basis of simplicity for practical computation. The inverse power potential is preferable from this point of view, with the exponential and Lennard-Jones (12-6) models nearly as simple. The modified Buckingham (exp-6) has little advantage to offer and is more cumbersome. For high-temperature work especially, the purely repulsive potentials should be adequate for most purposes, since the existence of an attractive term is less significant at high temperature.

Potentials Parameters from Viscosity

Except for the gas pairs discussed in the preceding section, diffusion data have not been obtained over a wide enough temperature range to enable reliable determination of potential parameters directly as described. As a consequence, when knowledge of diffusion coefficients is desired, the most common situation is that one is forced to use parameters obtained indirectly from other gas properties. The best method is to use potential parameters for the *pure gases* which have been determined from viscosity data, and certain *combining rules* by which the parameters for the interaction of unlike molecules may be estimated from those for the respective species making up the diffusion pair. Experimental measurements of gas viscosity as a function of temperature may be fitted to the various potentials in a manner exactly analogous to that described for diffusion. The only difference is that the potential parameters so determined are characteristic of like molecule interactions (*i-i, j-j*) instead of unlike interactions. Using the general assumption that an unlike potential ϕ_{ij} is related to the potentials for the pure species by

$$\phi_{ij}=(\phi_{ii}\phi_{jj})^{1/2}$$

it may be shown that the following combining rules are obtained:

Inverse power repulsion:

$$d_{ij}=(d_{ii}d_{jj})^{1/2} \qquad \sigma_{ij}=\tfrac{1}{2}(\sigma_{ii}+\sigma_{jj}) \tag{20}$$

Exponential repulsion:

$$A_{ij}=(A_iA_j)^{1/2} \qquad \rho_{ij}=2\rho_{ii}\rho_{jj}/(\rho_{ii}+\rho_{jj}) \tag{21}$$

Lennard-Jones (12-6):

$$\epsilon_{ij}=(\epsilon_{ii}\epsilon_{jj})^{1/2} \qquad \sigma_{ij}=\tfrac{1}{2}(\sigma_{ii}+\sigma_{jj}) \tag{22}$$

Modified Buckingham (exp-6):†

$$\epsilon_{ij}=(\epsilon_{ii}\epsilon_{jj})^{1/2} \qquad (r_m)_{ij}=\tfrac{1}{2}[(r_m)_{ii}+(r_m)_{jj}] \qquad \alpha_{ij}=\tfrac{1}{2}(\alpha_{ii}+\alpha_{jj}) \tag{23}$$

Since the Lennard-Jones (12-6) model is the only one for which extensive viscosity fitting has been done, its combining rules are the only ones we shall have occasion to consider further.

Viscosity parameters for many gases have been compiled by Hirschfelder, Curtiss, and Bird[1] and by Svehla.[38] A selection of gases of interest in combustion taken from these lists is given in Table 5. By using these values for the pure gas parameters in the combining rules given by Eq. (22), one may estimate the values for σ_{ij} and ϵ_{ij} for an unlike pair. These may then be used with the tabulated collision integrals in Eq. (17) to compute D_{ij}. The entries in Table 4 labeled L-J (viscosity) were obtained in this way. It will be noted that these theoretical values are generally low compared with the other Lennard-Jones entries which were fitted from experimental diffusion data and extrapolated. This seems to be generally true of the viscosity predicted diffusion coefficients, the discrepancy being as much as 20 to 30 percent in some cases at high temperature. The room-temperature viscosity predictions are very good—generally within 5 percent—which is true also for the other gas pairs given in Table 1. Thus, for combustion work (where no experimental diffusion data are available) diffusion coefficients can be calculated from viscosity parameters, the Lennard-Jones (12-6) potential, and the kinetic theory. These calculations may be in error by as much as 20 percent in the temperature range below 2000°K, but in many cases they are more precise. At higher temperatures the probable errors increase considerably, so that only rough estimates can be made.

It is often very convenient to make use of an approximate analytical expression for the diffusion coefficient as a function of temperature. Thus *for values of* $T^*>3$, the Lennard-Jones (12-6) collision integral may be empirically fitted to within 2

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† Mason has also derived more elaborate rules for this potential (Ref. 37).

TABLE 5

Lennard-Jones (12–6) potential parameters from viscosity measurements for use in transport property calculations

Gas	σ, A	ϵ/k, °K	Gas	σ, A	ϵ/k, °K
Air	3.69	84	C_6H_6	5.27	440
Ar	3.46	116	C_6H_{12}	6.18	297
Br_2	4.27	520	n-C_6H_{14}	5.95	399
CH_2CHCH_3	4.68	299	Cl_2	4.40	257
CH_3CCH	4.76	252	D_2	2.95	39
CH_3Cl	4.18	350	F_2	3.65	112
CH_3OCH_3	4.31	395	HBr	3.35	449
CH_3OH	3.58	507	HCN	3.63	569
CH_4	3.80	144	HCl	3.30	360
CO	3.71	88	HF	3.15	330
COS	4.13	335	HI	4.12	324
CO_2	3.90	213	H_2	2.92	38
CS_2	4.44	488	H_2O	2.64	809
C_2H_2	4.22	185	H_2O_2	4.20	289
C_2H_4	4.23	205	H_2S	3.62	301
C_2H_5Cl	4.90	300	He	2.58	10
C_2H_5OH	4.53	363	I_2	4.98	550
C_2H_6	4.42	230	NH_3	2.90	558
C_2N_2	4.38	339	NO	3.60	91
Cyclo-C_3H_6	4.81	249	N_2	3.75	80
C_3H_8	5.06	254	N_2O	3.82	237
i-C_4H_{10}	5.34	313	O_2	3.54	88
n-C_4H_{10}	5.00	410	SO_2	4.29	252
n-C_5H_{12}	5.77	345			

percent by the expression

$$\Omega^{(1,1)*} \approx 1.12/(T^*)^{0.17}.$$

When this relation is inserted into Eq. (17), one obtains the relation

$$D_{ij} \approx \frac{1.66 \times 10^{-3}[(M_i+M_j)/M_iM_j]^{1/2}T^{1.67}}{P\sigma_{ij}^2(\epsilon_{ij}/k)^{0.17}} \tag{24}$$

with P in atm, σ in angstroms, T and ϵ_{ij}/k in °K, and D_{ij} in $\mathrm{cm}^2\ \mathrm{sec}^{-1}$. This may be used with the potential parameters of Table 5 and the combining rules to estimate diffusion coefficients in good approximation to the exact use of the collision integral tables. *It should be emphasized, however, that the approximation breaks down rapidly for $T^* < 3$, and it should not be used in such cases.*

Diffusion in Polar Gases

Thus far all the discussion has been strictly applicable only to spherical nonpolar molecules. Fortunately, most of the common stable flame species fall nearly enough into this category that the theory may be applied. There are important exceptions, however, such as H_2O, NH_3, HCl, HBr, and alcohols, which are strongly polar and for which mutual interactions would certainly not be spherically symmetrical. For binary diffusion involving one polar and one nonpolar species, it is possible to use the Lennard-Jones form of interaction potential (or the others discussed), since presumably the polarity of the one species does not strongly influence the interaction in that case, and approximate spherical symmetry may still be assumed. Thus experimental diffusion data may be successfully fitted over a temperature range by the various potentials as illustrated in the case of H_2O-O_2 in Table 4. (It is interesting that the different potential predictions agree with each other for this pair better than for any other in the table.)

To use the viscosity of polar gases to obtain potential parameters is a more complex problem, however, because viscosity is a property which depends on collisions between like molecules where polarity comes into play. The interaction potential is then an angular-dependent function for which the computation of the required collision integrals is a much more difficult problem. The function usually used is the Stockmayer potential, which is just the Lennard-Jones (12-6) potential with a term $(-\mu_1\mu_2\zeta/r^3)$ added, where μ_1 and μ_2 are the dipole moments of the two colliding molecules and ζ is an angular-dependent factor. Monchick and Mason have applied this potential in an approximate way to pure polar gases[39] and mixtures.[40] The approximation consisted of regarding the relative orientation of a pair of molecules as fixed during a given collision, that is, ζ is a constant, and then averaging the resulting collision integrals over all orientations. These averaged integrals were then used to fit viscosity and other data (not thermal conductivity, which is more complex). The success of this procedure was about the same as that experienced with nonpolar data, and the actual potential parameters σ and ϵ/k obtained were not very different from those derived by fitting polar gas viscosities to the nonpolar Lennard-Jones potential, i.e., ignoring polarity effects. On this basis the parameters listed in Table 5 for polar species were obtained by fitting to the nonpolar Lennard-Jones expression in the same way as all the rest. The errors to be expected in using these approximate parameters for computing diffusion coefficients of polar-nonpolar or polar-polar pairs are perhaps somewhat larger. The diffusion coefficient for H_2O-O_2 computed from viscosity parameters as given in Table 4 is a case in point.

SECTION 3. THE DIFFUSION COEFFICIENTS OF UNSTABLE SPECIES

The previous discussion of diffusion has been concerned with stable species, since these are usually present in the highest concentrations in flames and are the species for which fluxes and reaction rates are determined. It is often only the *concentration* of an unstable atom or free radical which is of direct interest rather than its flux profile, so that its diffusive properties may not be needed. However, for flames containing high radical concentrations, or in certain chemical kinetic applications, it may be important to know the diffusion coefficients of the labile species, and this section summarizes our very meager knowledge in this field.

Experimental Techniques and Data

Direct measurements of the diffusion coefficients of unstable atoms and radicals are almost nonexistent, the obvious reason being that it is a very difficult problem to set up experiments of this kind which are not badly obscured by other phenomena—usually chemical reactions. Of the three *direct*, *absolute* techniques which have appeared in the literature, the steady-state flow method of Walker[41] is perhaps the most promising. In a typical study, a diatomic gas at a few millimeters pressure is passed steadily through the tube and dissociated to a small extent by some suitable means, usually a microwave or radio-frequency electrodeless discharge. As the mixture of, say, O and O_2 flows down the tube, the O atoms recombine on the walls (mostly) so that a gradient in their concentration is set up. The magnitude of the gradient is a function of the flow velocity, the reaction rate constant, and the O-O_2 diffusion coefficient. By assuming one-dimensional flow[42] and first-order disappearance of atoms, the appropriate diffusion equation with flow and reaction can be solved analytically. Then a measurement of the atom gradient at two different (known) flow velocities allows the chemical kinetics and the diffusion to be separated. In this way the O-O_2 diffusion coefficient at room temperature was determined (see Table 6) with considerable precision (±3 percent). The atom gradient in this case was determined by the chemiluminescent reaction of O with NO, but other

TABLE 6

Atom-molecule diffusion coefficients obtained by direct experimental methods

All values of D_{ij} at 1 atm pressure.

Gas pair	Temperature, °K	D_{ij}, cm² sec⁻¹	Reference
O-O_2	298	0.30	41
	298	0.31	43
N-N_2	298	0.37	45

TABLE 7

Diffusion coefficients of H-H_2 obtained by indirect experimental methods

All values of D_{H-H_2} at 1 atm pressure. *Italicized* values extrapolated.

Temp. °K	Relative values, Ref. 46	D_{H-H_2}, $cm^2 sec^{-1}$	
		Absolute values (Ref. 46) using viscosity-derived value at 293°K	Values derived (Ref. 50) from H-H_2 mixture viscosity (Ref. 48)
293	1.00	2.01	2.01
400	1.70	3.42	3.42
500	2.30	4.62	*5.02*
600	2.95	5.93	*6.88*
700	3.60	7.24	*8.98*

techniques may be used. Electron spin resonance spectrometry seems especially promising for this purpose.

Two transient techniques for measuring absolute atom-molecule diffusion coefficients directly have been used. Krongelb and Strandberg[43] observed the decay of O atoms with time by means of electron spin resonance in a tube filled with partially dissociated oxygen (no flow) and were able to infer the O-O_2 diffusion coefficient. Their results (Table 6) are in good agreement with Walker's, although less precise. Young[44,45] has used a somewhat similar technique (with spectroscopic detection of the first positive N_2 bands to measure N atom concentration) to get an approximate value for the N-N_2 diffusion coefficient at room temperature. The experimental data were quite scattered, however.

A means of measuring the *relative* diffusion coefficient of H-H_2 as a function of temperature has been reported by Wise.[46] It is a steady-state technique utilizing a (no-flow) heated tube with a presumably constant source of atoms at one end and a movable tungsten filament catalytic recombination probe at the other for measuring relative atom concentrations. By making certain assumptions—mainly that the filament catalytic activity for H atom recombination is independent of temperature—the relative diffusion coefficient for H-H_2 as a function of temperature given in Table 7 was determined. While this technique is not without difficulties,[47] the results are of interest since they represent the only experimental data on an atom-molecule diffusion coefficient at even moderately elevated temperature. In the absence of any quantitative knowledge of the catalytic activity of the probe, however, it is not an absolute technique and must be based on some other reference value.

This reference value has been taken to be an *indirect* measurement of D_{H-H_2} derived from data on the viscosity of H-H_2 mixtures obtained many years ago by Harteck[48] over the temperature range 195 to 373°K. The viscosity data were originally used by Amdur[49] to compute D_{H-H_2} by an approximate procedure. Amdur's calculations have since been superseded by those of Weissman and Mason,[50] using more realistic force laws. The use of mixture viscosity requires, in addition, the viscosities of both pure components and a ratio of collision integrals which is only weakly dependent on temperature and the particular force law assumed. The viscosity of pure H was calculated using accurate theoretical and experimental interaction potentials (more than one is possible and a weighted average was used), while that of H_2 was available experimentally. Values of D_{H-H_2} obtained from the viscosity data in this way, and slightly extrapolated, are given in the final column of Table 7. They are appreciably different from the data of Wise[46] converted to absolute values by using the same reference value at 293°K. It is apparent that there is need for much more experimental work in this area.

Theoretical Calculations

The fact that experimental data on atom and radical diffusion coefficients are generally not available means that one must rely on theoretical predictions in most cases. Here the situation is very complex because of the multiple possible interaction potentials for species with open outer electronic shells. The multiple interaction problem has been shown[51] to be tractable by suitable averaging and weighting. Using this procedure, Yun and Mason[52] have constructed interaction potentials and collision integrals for various pairs, such as $N\text{-}N_2$, $O\text{-}O_2$, and O-O. These were then used to calculate diffusion coefficients and other transport properties.[53,54] The values given in Table 8 were taken from this work. They are the best available data on these quantities, but it should not be forgotten that they are theoretically computed and are unverified experimentally. The value for $O\text{-}O_2$ extrapolated to room temperature agrees well with the experimental data in Table 6, however.

TABLE 8

Atom-molecule diffusion coefficients computed from theory

All values at 1 atm pressure.

Temperature, °K	D_{ij}, $cm^2\ sec^{-1}$		
	$N\text{-}N_2$ Ref. 54	$O\text{-}O_2$, Ref. 54	$H\text{-}H_2$, Ref. 53
1000	2.34	2.40	17.2
1500	4.78	4.80	36.3
2000	7.95	7.87	62.0
2500	11.8	11.6	94.2
3000	16.4	15.9	133
3500	21.6	20.7	178
4000	27.5	26.2	230

The unstable species considered thus far have all been assumed to be in their ground electronic states. For electronically excited species—atoms, radicals, or molecules which may be important in some flames—there is reason to believe[55] that the diffusion coefficients involved would be abnormally small because the effective interaction distance or cross section would be large. There is, also, the possibility of exchange[51] between identical species in different electronic states which would affect the diffusion coefficient of an excited particle. Only crude estimates of these effects can be made at present, however.

SECTION 4. THERMAL DIFFUSION

For most flame species thermal diffusion is a negligible effect, but for very light components such as H, H_2, and He it is definitely not negligible in some parts of the flame. Inclusion of thermal diffusion complicates the data analysis considerably, but when it is necessary for only one species (usually H_2) it is probably practical if the data are precise enough to warrant it.

The thermal diffusion ratio k_T has been measured for a few gas pairs at low temperatures (Ref. 1, p. 584), but is not generally available at flame temperatures. Theoretical calculations must be relied on[1] but may be quite unsatisfactory since thermal diffusion is the most sensitive of the transport properties to the potential function used.

SECTION 5. EXPERIMENTAL THERMAL CONDUCTIVITY

Because of its importance in other applications, especially engineering heat transfer, there has been a good deal more effort spent on thermal conductivity studies than on ordinary mass diffusion. This is particularly true of the situation regarding experimental data, where the amount is considerable—both in the variety of gases and range of temperature covered. As was pointed out, any real flame involves heat transport in a polyatomic gas mixture, but the properties of the mixture depend ultimately on the conductivities of the pure components.

Experimental Techniques

Most of the published data on gas thermal conductivity have been made in steady-state systems subject to simple solutions of the appropriate equation of heat conduction. These are discussed in detail by Jakob.[56] The concentric cylinder technique first used by Schleiermacher[57] has been widely exploited. The apparatus in its simplest form is a cylinder tube containing a coaxial, electrically heated wire (generally platinum). The gas to be measured is allowed to fill the annulus between wire and tube, and the whole system is immersed in a thermostat. Knowing the steady-state heat output of the wire, the temperature of wire and tube wall, and certain geometric factors, one can calculate the thermal conductivity of the gas. In practice, of course, there are a number of corrections which have to be made, e.g., for end effects and radiation heat transfer, so that for really precise work the method is complicated and requires great care. The difficulties all become greater at high temperature as usual, especially those of providing uniform temperature around the cylinder and avoiding free convection effects. This general technique has been used by many investigators, especially Eucken,[58] Keyes,[59] Johnston and Grilly,[60] and Kannuluik and Martin.[61]

Another technique of more recent origin, although based on an old idea,[62] was developed by Westenberg and De Haas.[63] It makes use of a heated wire, i.e., a line source, in a flowing gas. Measurement of the thermal wake downstream of the wire in a slow laminar flow of gas can be used to obtain the thermal conductivity. It is analogous to the point-source technique for diffusion previously described and has some of the advantages of that technique, especially the avoidance of difficult thermostating problems. The method has been used up to temperatures around 1100°K.

A steady-state variant of the conventional hot-wire cell method in which free convection is allowed to occur but is made negligible by use of a very long cell has been reported.[64] Central wire temperatures as high as 2100°K were employed with the walls at room temperature, so that very high gradients existed. These are the highest temperatures at which data of acceptable precision have been obtained. For inert gases the data are probably accurate also, but there is considerable uncertainty about use of the technique for diatomic or polyatomic species since it is quite likely that dissociation would occur on the very hot central (tungsten) wire.

Other schemes have been used to estimate gas thermal conductivities up to very high temperatures (mainly using shock tubes) but are not yet of much precision and will not be discussed here.

Experimental Data

Table 9 summarizes the available data obtained by the foregoing techniques for those pure gases which are likely to be of interest for flame studies. The data listed are those which the authors consider to be the most reliable in each case, and

TABLE 9

Experimental data on pure gas thermal conductivities

Values of λ are in units of cal cm^{-1} sec^{-1} $°K^{-1} \times 10^5$.

Temp. °K	N^2 [63]*	O^2 [65]	CO_2 [63]	CO [66]	H_2 [66]	H_2O [67]	CH_4 [68]	NH_3 [68]	C_2H_6 [69]	Ar [70]	He [71,64]
300	6.1	6.3	3.9	6.0	43.4		8.0	5.7	5.3	4.2	36.1
400	7.6	8.2	5.8	7.7	54.5	6.2	11.8	8.9	8.4	5.3	43.5
500	9.7	9.8	7.8	9.2	65.0	8.5	16.1	12.6	12.6	6.3	50.4
600	10.6	11.3	9.7	10.6	75.2	11.1				7.2	56.2
700	12.1	12.7	11.7		85.5	13.9				8.1	
800	13.5	14.1	13.5			16.8				8.8	
900	14.7	15.5	15.2			20.0				9.5	
1000	15.7	16.9	16.8			23.4				10.3	
1100	16.5	18.3	17.9							10.8	
1200	17.1	19.6	18.6							11.3	99.1
1300										11.9	106
1400											113
1500											119
1600											126
1700											133
1800											140
1900											147
2000											153

* Bracketted numbers indicate References.

some were obtained by smoothing the results of several different investigations. The estimated reliability of the data is generally within 5 percent. Only directly measured data at the indicated temperatures are included.

It will be seen from Table 9 that data on some of the common flame gases are available over a fair temperature range. N_2 and O_2 are especially important since they are often present in large excess. Many species are lacking, however, and the range for the important organic molecules listed is very restricted.

SECTION 6. THEORETICAL PREDICTION OF THERMAL CONDUCTIVITIES

As was the case with diffusion, one must rely heavily on theoretical computation of thermal conductivities for practical applications at high temperature. The situation is unpleasantly complicated by the fact that energy can be carried in the internal degrees of freedom of polyatomic molecules, as will be evident in the following discussion.

Monatomic Gases

For a pure monatomic gas, the rigorous kinetic theory gives for the thermal conductivity in first approximation (the only one we shall consider)

$$\lambda^\circ = 25kTc_v/16m\Omega^{(2,2)}, \tag{25}$$

where $c_v = 3k/2$ is the specific heat at constant volume (per molecule), m is the molecular mass, and $\Omega^{(2,2)}$ is another of the collision integrals. Since we are dealing with a pure gas where only collisions between like molecules are involved, it is unnecessary to include the subscripts for i-i interaction. Note that, for the dilute gases of importance in the flames we are considering, *the thermal conductivity is independent of pressure.*

As with diffusion, the integral $\Omega^{(2,2)}$ is temperature-dependent, and the potential energy of interaction enters explicitly into its evaluation. The same five potential functions may be considered. For *rigid noninteracting spheres,*

$$\Omega^{(2,2)} = 2\sigma^2(\pi kT/m)^{1/2}. \tag{26}$$

Combining Eqs. (26) and (25) gives the expression

$$\lambda^\circ = \tfrac{25}{32}(mkT/\pi)^{1/2}(c_v/\sigma^2). \tag{27}$$

For the *inverse power repulsive potential,* it can be shown that

$$\lambda^\circ = \frac{25c_v(km/\pi)^{1/2}(k/\delta d)^{2/\delta}T^{1/2+2/\delta}}{16A^{(2)}\Gamma(4-2/\delta)} \tag{28}$$

where $A^{(2)}$ is a tabulated integral function of δ (Ref. 1, p. 548). The simple temperature dependence with this model is convenient.

For the *exponential repulsive potential,*

$$\Omega^{(2,2)} = (16\pi kT/m)^{1/2}\alpha^2\rho^2 I_{(2,2)} \tag{29}$$

and the integrals $I_{(2,2)}$ have been evaluated.[32]

Both the *Lennard-Jones* (12-6) *and modified Buckingham* (*exp*-6) *potentials* make use of the integrals tabulated (Ref. 1 and 34, respectively) in the reduced form

$$\Omega^{(2,2)*}=(m/\pi kT)^{1/2}(\Omega^{(2,2)}/2\sigma^2). \tag{30}$$

For convenient practical calculation, the expressions for the monatomic thermal conductivity for the various potentials are as follows:

Rigid spheres:

$$\lambda^\circ=\frac{1.989\times10^{-4}(T/M)^{1/2}}{\sigma^2} \tag{31}$$

Lennard-Jones (12-6):

$$\lambda^\circ=\frac{1.989\times10^{-4}(T/M)^{1/2}}{\sigma^2\Omega^{(2,2)*}} \tag{32}$$

Modified Buckingham (exp-6):

$$\lambda^\circ=\frac{1.989\times10^{-4}(T/M)^{1/2}}{r_m{}^2\Omega^{(2,2)*}} \tag{33}$$

Exponential repulsion:

$$\lambda^\circ=\frac{0.994\times10^{-4}(T/M)^{1/2}}{\alpha^2\rho^2I_{(2,2)}}, \tag{34}$$

where λ° is in cal cm^{-1} sec^{-1} °K^{-1}, M is molecular weight, and σ, r_m, and ρ are in angstroms. Equation (28) must serve as the general expression for the inverse power repulsive potential.

The situation regarding the determination of the potential constants to be used in the various models for computing thermal conductivity differs from that for diffusion in that, generally, the best method does not involve fitting the experimental thermal conductivity data themselves. This can be done in principle, of course (for monatomic gases), but by far the more common procedure is to make use of viscosity measurements as a function of temperature; they are easier and usually more reliable. One of the important results of the rigorous kinetic theory is that viscosity (η) and monatomic thermal conductivity are related by the expression

$$\lambda^\circ=\tfrac{15}{4}(R\eta/M). \tag{35}$$

Thus the same collision integrals apply to both transport properties, and potential parameters determined from viscosity data may be used to predict monatomic thermal conductivity. In the temperature range where the viscosity was measured, of course, Eq. (35) may be used to obtain λ° directly with no need for potential parameters. This relation between λ° and η is well established. An example is given for the case of argon in Table 10, where the measured thermal conductivities and those computed from measured viscosities agree very closely.

Polyatomic Nonpolar Gases

So far the discussion has been confined to pure monatomic gases, for which the theory is relatively simple and clear-cut. All flame gases of interest, however, are

TABLE 10

Comparison of experimental thermal conductivities with those calculated from viscosities using the modified Eucken correction

Values of λ are in units of cal cm^{-1} sec^{-1} $K^{\circ -1} \times 10^5$.

Gas	300°K		500°K		1000°K	
	λcalc	λexpt	λcalc	λexpt	λcalc	λexpt
Ar	4.3	4.2	6.3	6.3	10.1	10.3
N_2	6.4	6.1	9.5	9.2	16.0	15.7
O_2	6.5	6.1	1.00	9.8	17.9	16.9
H_2	45	43	64	65		
CO	6.4	6.0	9.6	9.2		
CO_2	4.0	3.9	8.0	7.8	16.1	16.8
Air	6.5	6.3	9.5	9.7	16.3	16.2

polyatomic (taken to include diatomic species), and, except when one might be dealing with a flame heavily diluted with a noble gas so that the monatomic theory would suffice, the effects of internal degrees of freedom on heat transport must be considered. This involves the so-called Eucken correction[72] to the monatomic thermal conductivity. A particularly illuminating discussion of this problem for nonpolar gases has been given by Hirschfelder,[73] using relatively simple arguments. The whole subject has since been explored with considerably more rigor and elegance by Mason and Monchick.[74] The important features of their work will be referred to at appropriate points later, but first we shall make use of Hirschfelder's simpler approach.

A pure polyatomic gas is considered to be a "reacting" mixture of species representing all the possible internal energy states (i.e., vibrational and rotational, but only the ground electronic state) of the molecule. In order to define a thermal conductivity at all for such a "mixture," i.e., to equate the heat flux to the product of λ and the temperature gradient, two important assumptions are necessary. First, it is assumed that the distribution of "species" among the internal energy states is that characteristic of local thermodynamic (Maxwellian) equilibrium, so that it is a function only of the local temperature. Any situations where vibrational or rotational temperatures are different from the ordinary translational temperature would thus violate this condition. The effect of a temperature gradient may be viewed as setting up concentration gradients in the species in various internal energy states. Therefore, the heat flux carries terms due to the diffusion of these different species, in addition to that due to the molecules with different translational energy which is accounted for by λ°. The second assumption necessary is that all the different internal energy state species have the same self-diffusion† coefficient D_{ii}. This is a good assumption except where different electronic states are involved, which is the reason for excluding electronic excitation from this treatment. If λ is the thermal conductivity of a polyatomic gas and λ° the value the thermal conductivity would have if the molecules had no internal degrees of freedom, then under the foregoing assumptions it can be shown that

$$\lambda/\lambda^{\circ}=1-\delta_f+\tfrac{2}{5}(\delta_f C/R) \tag{36}$$

where C is the molar heat capacity at constant pressure and δ_f is a dimensionless parameter defined by

$$\delta_f=\frac{5R}{2}\frac{ND_{ii}}{\lambda^{\circ}}=\frac{4\Omega^{(2,2)*}}{5\Omega^{(1,1)*}}. \tag{37}$$

The factor $5R/2$ is the value of C for a monatomic gas, so that δ_f may be thought of as a Lewis number for the fictitious gas regarded as monatomic. δ_f depends on the potential function used to approximate the gas behavior, but for all models it has nearly the same value. Thus for rigid spheres $\delta_f=\frac{4}{5}$, while for both the Lennard-Jones (12-6) and modified Buckingham (exp-6) functions δ_f is weakly temperature-dependent and varies from 0.88 to 0.90 in the temperature range of usual interest in combustion. Behavior for the pure repulsion functions is similar. Thus Hirschfelder has assigned an average value of

$$\delta_f=0.885$$

as closely approximating all realistic potentials. Using this value in Eq. (36) gives

$$\lambda/\lambda^{\circ}=0.115+0.178C \tag{38}$$

(where C is in cal mole^{-1} °K^{-1}) as the final expression for the modified Eucken correction. (The original Eucken correction corresponds to $\delta_f=\frac{2}{3}$.) This relation is extremely useful in computations on polyatomic gases.

The essence of the Mason-Monchick contribution[74] to the polyatomic gas problem was to remove the necessity for assuming equilibrium between the internal and translational degrees of freedom. By use of the formal kinetic theory which takes account of inelastic collisions, Mason and Monchick were able to incorporate the rotational and vibrational (only the former is important at ordinary flame temperatures) relaxation times into an Eucken-type correction to the monatomic thermal conductivity. The modified Eucken correction of Hirschfelder described above was then obtained as a first approximation to the more rigorous theory. The nonequilibrium internal energy expressions lead to better agreement with experiment at low temperatures and are most important in this region. At the high temperatures of flame interest the more elaborate theory differs very little from the simple modified Eucken correction for practical calculations. Thus the latter is usually adequate for calculations where direct experimental data on thermal conductivity are not available. But the Mason-Monchick treatment represents an important advance because it puts the simpler theory on a much firmer basis.

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† As Mason and Monchick emphasize (Ref. 74), this is not strictly the self-diffusion coefficient which would be measured in an isotopic tracer experiment, but for practical calculations little error would be incurred by using this value.

To summarize: The most satisfactory method of predicting high-temperature thermal conductivities of pure nonpolar polyatomic gases is to use viscosity data to compute the quantity $\lambda°$ by means of Eq. (35). If no viscosity data are available at the temperature desired, then suitable potential parameters derived from experimental viscosities at lower temperatures (such as the Lennard-Jones parameters given in Table 5) should be used in Eq. (32) to compute $\lambda°$. When parameters are available for another potential function, they would be used in Eqs. (28), (33), or (34), of course. Then Eq. (38), with the appropriate C data at the desired temperature, will yield the value of λ. Table 10 gives some examples of common gases treated in this way. Experimental viscosities and heat capacities were taken from Svehla's compilation.[38] The general agreement with measured λ values is very good.

Polar Gases

The complications due to polarity are worse for thermal conductivity than for other transport properties because of the possibility that internal (i.e., rotational) energy may be transferred in resonant collisions without effecting translational energy. Physically, this may be pictured as a grazing collision being converted to an apparent near head-on collision because one molecule transfers a rotational quantum of energy to the other, so that it *appears* as though the first molecule undergoes a more pronounced distortion in its trajectory than it really does. The net result is to lower the effective diffusion coefficient for internal transfer and thus the thermal conductivity.

This phenomenon has been treated by Mason and Monchick[74] for various types of polar molecules. Actually the resonance correction is rather small except for light linear molecules like HCl, or the nonlinear H_2O, where a rotational quantum represents an appreciable amount of energy. In most cases the necessary data on rotational relaxation times are not available for application of the theory. It must usually suffice to treat a polyatomic polar gas as described in the previous discussion, where the polarity is ignored.

Mixtures

It is likely that most flame computations requiring a thermal conductivity will use values for the pure gas present in large excess as a diluent, as will be evident in the practical examples discussed in Chapter XIII, Ref. 80. Where this is not the case, however, it will be necessary to estimate the thermal conductivity of mixtures as a function of temperature. The theoretical treatment of even monatomic gas mixtures is a formidable and cumbersome exercise in its full rigor (Ref. 1, Chapter 8), although fully developed. For polyatomic gas mixtures, the Mason-Monchick treatment has been formally developed,[75] but is hardly suitable for practical calculation. The most nearly rigorous approximate, but useful, theory for polyatomic gas mixtures is that of Hirschfelder.[76] Assuming full equilibrium of internal and translational degrees of freedom, the mixture relation is

$$\lambda_m = \lambda_m° + \frac{\sum_i (\lambda_i - \lambda_i°)\,(X_i/D_{ii})}{\sum_j X_j/D_{ij}} \tag{39}$$

where λ_m° is the translational thermal conductivity of the mixture—a complex function of composition, molecular weights, diffusion coefficients, λ_i°, and collision integrals.[77] The pure gas conductivities λ_i would presumably be available from experiment or the computation methods discussed previously. It is also necessary to have all the binary diffusion coefficients D_{ij} for the various pairs in the mixture. The hypothetical monatomic conductivities λ_i° can be obtained from viscosities by way of Eq. (35) and the D_{ii} by the relation (37). Thus it is possible to calculate λ_m with all experimental imput data—either direct or by means of well-established kinetic theory relations. This type of calculation has been compared with experimental mixture data for both N_2-CO_2 and H_2O-O_2 (ignoring the polar nature of H_2O) over a range of temperature[63,65] with fair success. While the resonance correction previously noted for H_2O should affect the H_2O-O_2 mixture calculations, the agreement with experiment is good without considering it.

Finally, mention should be made of the so-called "effective" thermal conductivity in a mixture of chemically reacting gases, a term which has come into considerable vogue. A flame certainly falls into such a category. Wherever there are chemical reactions in a flow system, there are gradients in concentration of the various chemical species, so that energy is transported by diffusion as well as conduction and convection. This was discussed in detail in Chapters III and XIII, Ref. 80. We have chosen to handle the heat transfer problem in flames from this fundamental point of view, i.e., regarding the different mechanisms separately, so that at any point (temperature) in a chemically reacting system such as a flame the mixture has a certain thermal conductivity which is a true molecular property of the mixture. In certain applications[78] it has been considered useful to define an "effective" thermal conductivity for a reacting mixture in the sense of a quantity which, when multiplied by the temperature gradient, gives the total heat flux. It should be clearly understood that such an "effective" thermal conductivity can only be defined when the reactions are so fast compared with the diffusion processes that the mixture may be regarded as being in chemical equilibrium at the local temperature. The treatment is quite analogous to that discussed earlier in connection with the Eucken correction for polyatomic gases. The diffusive contributions to the total heat flux are thus contained in the "effective" thermal conductivity. For flames such a concept is not a useful one, since they are definitely not systems for which local chemical equilibrium exists. Thus it should not be construed that a reacting mixture is somehow fundamentally different from a nonreacting system insofar as the basic con cept of thermal conductivity is concerned.

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Subject Headings: ***Transport properties; Diffusion coefficient; Thermal conductivity.***

Observations of a Fire-Generated Vortex

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In March of 1964, after a relatively dry winter, a fire started accidentally in heavy brush northwest of Carpinteria, California, and spread rapidly into one of major proportions. The unique feature of this fire, however, was not its size, but the creation of a fire storm, a vortex which was spawned by the fire but which then became detached from it and spread destruction separately from the fire. The purpose of this short paper is to record observations on the formation and propagation of this vortex and to discuss a series of still photographs made during this part of the phenomenon. Hopefully, these observations and data may assist fire researchers in some small way.

Distances and directions given here were measured from a county map (Fig. 1) and so are reasonably accurate. Time estimates, unfortunately, suffer from a faulty memory, since no data were recorded during the build-up of the twister. The elapsed time associated with the vortex phenomenon, however, is fairly accurate. It is convenient to label the point at which the vortex started. Let it be called Point *P*.

The fire started in the late morning approximately 600 to 800 feet north of Foothill Road along the extension of Nidever Road, in Santa Barbara County. This is at the base of the foothills of the coastal range of mountains. It is in relatively rugged country with steep slopes and a heavy covering of brush. The prevailing wind, as estimated from the photographs, was approximately from the N–W and probably under 10 mph. The fire, however, because of topography and the location of major areas of fuel, spread generally eastward. From the starting point to Point *P* is a distance of about 6000 feet along a true heading of 100°.

Plate 1 was taken 5900 feet from Point *P*, heading 353°, about 30 minutes before the main event. At this time, the center of the hottest region of the fire had progressed to about 1000 to 1500 feet west of Point *P* at the lower and midportion of a steep slope. (Camera heading: 345° true, at 6000 feet from the hot spot.) This slope rises to a rounded hogback running (from high to low) in a SSE direction. (The eastern face of this hill can be seen clearly in Plate 2.) Notice that surface winds along the edge of the fire nearest the camera are crossing at close to a right angle. The upper wind is spreading in a SE direction. The net effect seems to be a healthy forced draft action from left to right even at this early time. In this photo, Point *P* is slightly above and to the left of what looks like a TV antenna at right. Some burning is noted through the smoke near the ridge line of the hill, but is of a lesser intensity than lower down.

The vantage point for Plate 2 (10 to 15 minutes later) is situated 4900 feet from Point *P*, and the camera is aimed along 324° true. Point *P* is almost directly above the second telephone pole from the right.

One of the two essentials of the impending vortex is now formed. The west face is almost entirely aflame from base to hogback with an intense body of fire near the high ground, and a surface wind is sweeping up the same slope with a velocity that increases the higher it comes up the hill. High velocity winds are evidenced by the

Plate. 1. Fire progress from 101, south of Polo Field.

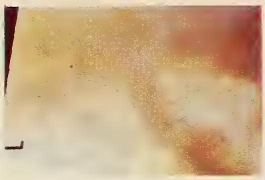

Plate 5. The whirlwind takes form: from Foothill Rd. and Santa Monica Rd.

Plate 2. Fire progress from part way up Santa Monica Rd.

Plate 6. Whirlwind begins movement: left from Foothill Rd. and Santa Monica Rd.

Plate 3. Fire progress from Foothill Rd. and Santa Monica Rd.

Plate 7. Base of the whirlwind.

Plate 4. The whirlwind starts: from Foothill Rd. and Santa Monica Rd.

Plate 8. Whirlwind base rips leftward through trees and homes, under smoke blackened sky.

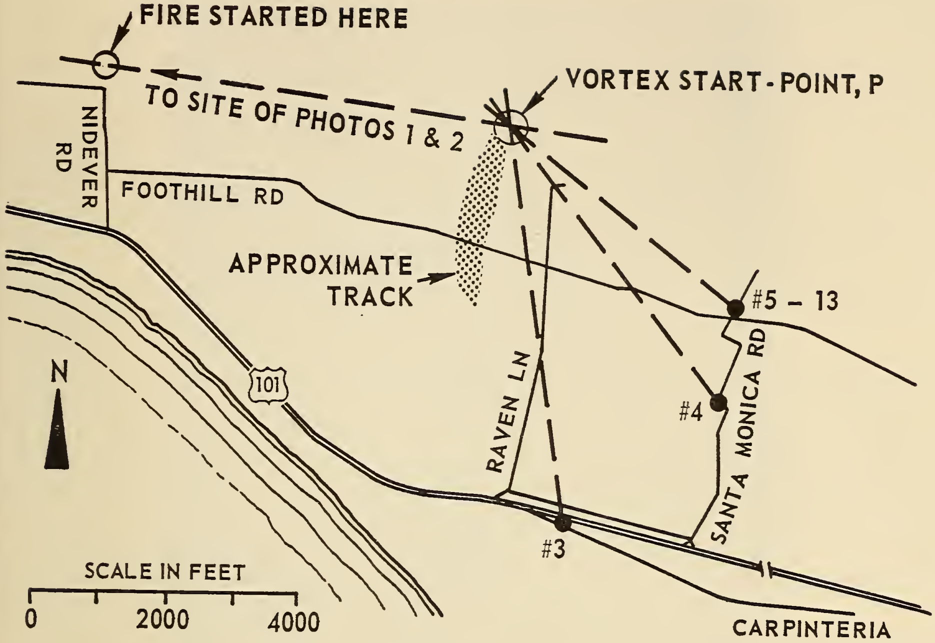

Fig. 1. Fire area map.

strung-out smoke that is mixed to uniform density. The fact that it is not as dense as the black smoke beyond also suggests fast moving flow.

The unburned east face of the hill is thickly matted with brush about head-high with an accumulation of at least a decade of debris. The lower part of the east face of the hill is relatively barren.

Between the second and third pictures (Plates 2 and 3), the camera was moved around northward to a point about 4200 feet from the location of the source of the vortex. All remaining photos were taken from very nearly this same point. All except the last was aimed in the same direction, roughly at Point *P* which was at a heading of 310° from true north.

Memory now enters. The succeeding discussion of events undoubtedly would be of more value if time were accurately known, but only a rough estimate is possible.

Numerous small fires were started on the east slope (Plates 3 and 4) by a spotting process which was instigated primarily as a result of one or two strong gusts of wind from the west. Large numbers of burning chunks rained down and ignited many new fires. A few of these firebrands were visible as they fell, probably from their smoke trails.

Plate 4 shows two things very clearly. The first is the large number of small fires started by spotting. At least a dozen isolated dots of flame are visible, as well as the larger region at the right which was formed earlier by the joining of several smaller ones. The second point to note is the distinct formation of two opposing flows of air and smoke. The flow from the newly created hot-spot at the right is crossing to the left in front of the second, old main flow from the west face. Together they are just beginning the clockwise (viewed from above) rotation of the vortex. The vortex

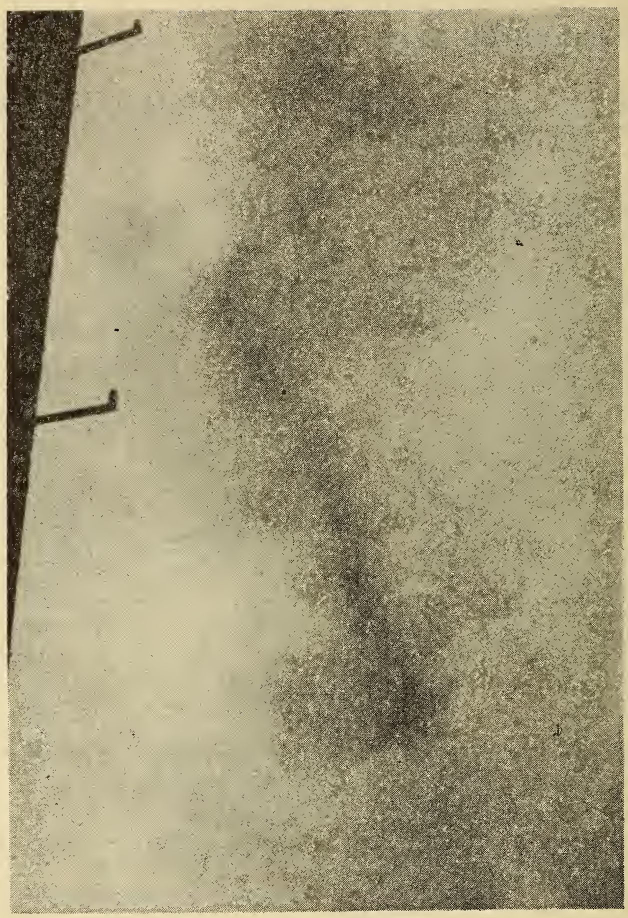

Fig. 2. Whirlwind towers at least 1500 ft, twisting into sky.

is being formed from the outside in, starting with relatively slow moving, large masses of air. The condition is already a destabilizing one, in the sense that it now will tend to fan itself more strongly, force greater drafts through the flames into unburned material at the crest, and progressively increase in (evidently) an exponential manner to higher and higher velocity winds and a concentration of great amounts of thermal and kinetic energy in a relatively small region.

This run-away was evidenced by a sudden huge build-up of flame as the two faces joined in earnest at the crest. Within seconds after Plate 4, a single body of flame rose skyward in a thin spiral to a height of the same order of magnitude as the hill itself (as much as 300 feet). This surge was quite brief, perhaps close to 10 seconds, and it marked the beginning of the actual twister.

Plate 5 shows the early progression of the core into the upper air. Core density, and presumably strength, increases toward the bottom of the picture. The small airplane is a single engine, Cessna-type with a wing span of typically 36 feet. Its altitude was probably between 1500 and 2000 feet, and the full force of the storm has not yet reached its altitude. The picture was taken 10 to 15 seconds after the vortex start time so that the core build-up is approximately 100 feet per second vertically. This after-the-fact calculation seems to bear out my amazed impression at the time. The velocity estimate may easily be low; I doubt that it is too high.

Plate 6 is interesting in that two cores appear, one above the large flaming region on the right (i.e., over Point *P*), and the second at the left in a large smoke filled chunk of sky.

I was not aware of the second core at the time because it was shortlived and overshadowed by the dynamic development of the main vortex, but it appears that the left core is a weak anti-vortex created by the first, with little substance of its own. It formed in a region of abundant smoke. Refer again to Plate 4 which shows a diffuse column of smoke in the proper orientation to feed such an anti-vortex and make it visible.

The short visible life span of the second core is shown by its virtual disappearance in the next picture (Plate 7) which was taken within 1 or 2 minutes of Plate 6. The main vortex is still being fed by the extensive burning area. Flames are still very high where they join together at the top, and high rotational speed is progressing outward from the core center as shown by the lighter smoke trails in Plates 6 and 7.

Plate 8, seconds later. Full development of the core with, very likely, maximum stored rotational kinetic energy. The top of the core stabs the upper smoke cloud, probably 2000 feet above. (The peculiar object at the left is a telephone pole with a climbing rung protruding.)

A high noise intensity was very noticeable during this period, matching the actual power of the twister with frightening sound effects.

Very shortly after (Fig. 2), the twister detached itself from Point *P* and spun across country. By this time, a large percentage of fuel was consumed in the area near the base of the core and the flame intensity appeared more uniform throughout the visibly burning hillside. Translational motion was induced down the hill at first over still-burning regions and then, for approximately 70% of its travel, even over unburned areas. Once translation had started, it continued in roughly a SSW direction, spending its stored energy by ripping through trees, barns and foliage, and spewing cold debris in exactly the same manner as a tornado. A very approximate travel of 1500 to 2000 feet occurred by the time Plate 8 was taken. It continued, beyond Foothill Road, traveling a total of approximately 3000 feet before it dissipated in a puff of wispy, harmless smoke.

Total duration from birth to death was possibly as little as 2 minutes, probably no more than twice that long.

Acknowledgement

I am very grateful for the assistance of Dr. Abraham L. Berlad without whose interest the raw material would have remained forever in the dark vaults of home photo albums.—W.H.L.

Subject Headings: ***Vortex, fire generated; Fire generated vortex.***

ABSTRACTS

I. Ignition Phenomena

Martin, S. B. (U. S. Naval Radiological Defense Laboratory, San Francisco, California) "Ignition-Ablation Responses of Cellulosic Materials to High Radiant Heat Loads," *Pyrodynamics* **2**, 145–150 (1965)

This paper deals with the effect on cellulosic materials of their exposure to very high thermal radiant fluxes for very short times. The subject is of particular interest in view of the character of the thermal radiation from both air bursts of sub-kiloton nuclear weapons and also very high altitude detonations of large yield weapons. Some understanding of the magnitude of the incendiary threat posed by such explosions is gained from an evaluation of the experimental data reported in this paper.

By use of a carbon arc and a very fast mechanical shutter system pieces of cellulosic materials were exposed to irradiance levels as high as 100 cal cm^{-2} sec^{-1} for periods as short as 30 msec. In practice different thicknesses of the material were exposed to 50, 75, and 100 cal cm^{-2} sec^{-1} for various times to establish the threshold of persistent ignition. When ignition did not persist the samples were measured for loss in thickness. Irradiance levels were determined using a radiation calorimeter; times were determined by a phototube circuit with a fast, counter-time readout.

The results showed that for very short pulses the radiant exposures required for persistent ignition were almost independent of exposure duration or irradiance level. The remaining thickness which "just failed" to sustain ignition was found, as expected, to be independent of initial thickness but was inversely proportional to irradiance level. From those samples which failed to sustain ignition, an over-all material loss rate of about 2 mm/sec was found for the maximum irradiance level of this test.

Subject Headings: ***Ablation, by radiation; Cellulose, ignition and ablation of; Ignition, by radiation; Radiation, ignition and ablation by.***

F. Falk

II. Thermal Decomposition

Lincoln, K. A. (U. S. Naval Radiological Defense Laboratory, San Francisco, California)" Flash-Pyrolysis of Solid-Fuel Materials by Thermal Radiation," *Pyrodynamics* **2**, 133–143 (1965)

This paper describes work on the pyrolysis of solid materials with pulsed thermal radiation. Although the main contribution of the paper is a description of the equipment and experimental techniques employed, some useful data on quantity and type of volatile products obtained from pyrolysis of cellulose are presented.

Two different devices, the xenon flashtube and the shuttered carbon arc, were employed as sources of very intense pulses of radiant energy. The xenon flash tube provided a peak irradiance in the order of 3000 cal/cm^2 sec and a duration in the order of 1 msec or less. In the case of heating with a carbon arc, the irradiance level ranged from 1.5 to 11.0 cal/cm^2 sec. The carbon arc beam was appropriately shuttered to provide a pulse duration ranging from less than a tenth of a second to several minutes.

The essential feature of the experimental arrangement employing heating with the carbon arc was an exposure cell in which the sample was heated in a stream of helium carrier gas flowing directly to a chromatograph. In the case of heating with the xenon flashtube, the helical flashtube was positioned coaxially around a segment of glass or quartz tubing which contained the sample. The tubing was connected in series with a stream of carrier gas, thus allowing the volatile products to be swept directly into the chromatography column.

In addition to chromatography, time-of-flight mass spectrometry was used for analyzing the volatile products. When this technique was used the sample was positioned within the ion-source housing and was vaporized by a brief thermal pulse directly into an ionizing electron beam, with the resulting ions being mass analyzed immediately.

The material studied was α-cellulose, specially prepared and formed into sheets of several thicknesses, with 2% of carbon black being added to increase the absorption of radiant energy. A number of decomposition products were found: water, CO_2, CO, about two dozen volatile organic compounds, char and tar.

Whereas slow heating of the cellulose produced primarily water and char, tar was an important product in the case of more rapid heating. A very striking observation was that flash heating with the xenon flashtube volatized the sample almost completely, with no tar and essentially no char being formed. The average molecular weight of the pyrolysis products resulting from flash heating was much lower than that found when pulses of more modest irradiance and longer duration were employed.

Observations of considerable importance to fire research are that the higher irradiances yield much larger amounts of CO and organic volatiles—all of which are quite combustible—and that short lived species are produced from flash-pyrolyzed cellulose.

The author points out that care must be exercised in choosing a flash-heating device for a specific application since the cellulose data obtained in this work show a strong dependence of pyrolysis product composition on irradiance.

Subject Headings: *Cellulose, flash-pyrolysis of; Flash-pyrolysis, of solids; Solids, flash-pyrolysis of.*

J. B. Howard

III. Heat and Material Transfer

Raychaudhuri, B. C. (Central Building Research Institute, Roorkee, India) "Transient Thermal Response of Enclosures: The Integrated Thermal Time-Constant," *International Journal Heat and Mass Transfer* 8, 1439–1449 (1965)

A method has been presented to compute the thermal time-constant of an enclosure which facilitates the assessment, in terms of a single parameter, of the thermal transient characteristics of the entire enclosure when subject to a change in the external temperature. This property of the enclosure is defined as the interval from initial time, when the system is in the steady state, to the instant when the change in the indoor air temperature reaches 63.21% ($=1-1/e$) of its final steady-state value.

The first section of the paper examines theoretically the method of computation for the thermal time-constant for an enclosure, taking into consideration the effects of: the transmission and storage characteristics of exposed and internal walls of homogeneous or composite construction; the existence of internal mass, heat sources, and ventilation; the intersurface radiative exchange; and the surface-air convective exchange.

The characteristics of a single wall are represented by a wall transmission matrix, which, in the case of a composite construction with multilayered fabrics in series, is the product of several individual transmission matrices. The matrix containing hyperbolical functions is obtained by solving the Laplace transform of the unsteady one-dimensional conduction equation for surface temperatures and heat fluxes, and can be expanded in polynomials of the Laplace transform parameter p. The degree of the polynomial depends on the accuracy required.

The mechanism of heat transmission into the enclosure and various heat exchanges in the enclosure is represented by a thermal circuit containing $(n+1)$ nodes, n surface nodes plus one node for the indoor air. In the circuit, the heat flow through the walls is treated as passive quadriples and the wall transmission matrices are used for the conduction flows; the radiative exchanges between the various surfaces and the convective exchanges from these surfaces are represented by their appropriate radiative and convective admittances; and a capacitative admittance is given to the indoor air. The following assumptions have been made: uniform indoor air temperature, constant thermophysical properties of materials and surfaces, and one-dimensional heat flow through the walls which, therefore, have isothermal surfaces.

Considering each node in the circuit in turn, one establishes $(n+1)$ simultaneous linear energy equations in terms of temperature, admittances (including wall transmission matrices) and internal sources, etc. The solution may be expressed by the transfer functions of the system as the ratio between the Laplace transforms of the response (indoor air) and the excitation (outdoor air) temperature functions, both of which may be written as polynomials of p.

Once the integrated transfer functions for the system are determined, the response of the enclosure for any given external excitation is obtained by first multiplying the transfer function by the Laplace transform of the excitation function and thereafter obtaining the inverse Laplace transform of the end product, using partial fraction expansion. In the present work, a "unit step function" has been used as an excitation function. The thermal time-constant for the enclosure is determined as the time required by the response function to attain 63.21% of the steady-state value as mentioned above.

In the second section of the paper, results illustrating the use of the method for some simple cases are presented.

Subject Headings: *Enclosures, thermal response of; Thermal transients, of enclosures; Time constants, thermal of enclosures.*

A. S. C. Ma

Swann, R. T., Pittman, C. M., and Smith, J. C. (Langley Research Center, Hampton, Virginia) "One-Dimensional Numerical Analysis of the Transient Response of Thermal Protection Systems," *National Aeronautics and Space Administration Technical Note NASA TN* D2976 (1965)

This report treats the transient response of charring ablators, using numerical methods. While the analysis is developed for the thermal protection systems of re-entry bodies the methods should be applicable for the combustion of solid materials. Of particular interest are the assumptions made in the analysis which result in a set of equations which are solvable and the numerical methods used in obtaining solutions.

The solid material is divided into two parts, the outer char layer and the uncharred material. At the outer surface of the char material heating takes place from the gas by conduction, convection, and radiation. Radiation from the char surface is considered. The char material may be removed by sublimation, oxidation, or spalling. The production of heat at this surface by oxidation reactions is considered. Gas-phase reactions are not included in the analysis. The heat passing through the char layer is partially absorbed by pyrolysis at the interface between the char layer and the uncharred material, and the remaining heat is conducted into the uncharred material. The gases generated by pyrolysis transpire through the char layer and are injected into the surrounding atmosphere. It is assumed that the pyrolysis takes place at the interface between the char layer and the uncharred material at a temperature which may be a constant or a function of the rate of decomposition.

The governing one-dimensional, unsteady equations are derived. These equations are expressed in finite difference form and and are solved using fixed points in a moving coordinate system. The principal difficulty encountered in the numerical analysis is the extensive computer time required to obtain solutions. Provision is made in the numerical equations to introduce options which reduce computer time. Comparison is made with the exact solutions for a homogeneous nonablating heat sink subjected to suddenly applied constant heating and for steady-state ablation. Reasonably good agreement is obtained between the numerical results and the exact solutions.

Subject Headings: *Ablation; Heat transfer, in ablators; Thermal protection, by ablation; Thermal transients.*

D. L. Turcotte

IV. Diffusion Flames

McLintock, I. and Rasbash, D. J. (Joint Fire Research Organization, Boreham Wood, England) "Soot Production by Diffusion Flames. Part 2. Effect of Various Diluents on the Smoke Point of Laminar Ethylene Diffusion Flames," *Joint Fire Research Organization Fire Research Note No. 582* (March 1965)

McLintock, I. and Miller, A. R. M. (Joint Fire Research Organization, Boreham Wood, England) "Soot Production by Diffusion Flames. Part 3. Rates of Soot Formation in Flames," *Joint Fire Research Organization Fire Research Note No. 592* (March 1965)

The investigations reported in these papers were undertaken in order to obtain further quantitative information concerning the effects of additives and diluents on soot formation in diffusion flames which, as outlined in the first paper of this series,[1] are needed in the field of fire research.

Although soot formation is more difficult to control and thus represents a more severe problem in solid and/or liquid fuel combustion, it was felt that studies should be initiated with the simpler homogeneous systems where the fuel flow rate does not depend on the heat transfer from the flame and thus on the fuel evaporation rate; thus in these two research notes measurements are reported of soot formation limits and over-all rates in ethylene diffusion flames stabilized on concentric tube burners. Both the ethylene flowing through the inner tube as well as the oxygen were diluted with nitrogen (which in some runs was saturated with water vapor at room temperature), argon, helium, and carbon monoxide in consecutive experiments.

The following dimensions of the concentric diffusion flame burners were used: For the outer tube, 1 cm inner radius (IR); for the inner tube of 0.1 cm wall thickness, 0.29 cm IR (burner A) or 0.40 cm IR (burner B).

The oxygen and diluent flow velocities were varied between 3.5 and 11 cm/sec while the fuel and diluent flows ranged from 3 up to 20 cm/sec which, together with the burner dimensions resulted in diffusion flames of the order of 10 cm high. Although all flames showed the typical more or less continuous "carbon particle" luminosity, smoke (soot) emission at the flame tip was only observed if the flow rate of ethylene was increased above a certain critical value. This critical flow rate of ethylene was defined as smoke point and was determined by visual observation of the exhaust gases against a white background.

The results are given in a series of diagrams where the smoke points are plotted versus the oxygen concentration of the oxygen and diluent mixtures flowing through the outer tube or versus the flow rate of the added diluent (to the fuel or to the air). Two representative systems are reproduced in Figure 1 that show, respectively, the effect that addition of CO_2, H_2O, and N_2 to the air and of CO_2, N_2 or Ar, and He to the ethylene has on the smoke point of ethylene–air diffusion flames.

A. Dilution of the Oxidant

From Fig. 1, it is evident that the effect of dilution alone on the visual determination of the smoke point cannot explain the observed steep decrease in smoke formation tendency upon addition of CO_2 or H_2O; for example, addition of 10% CO_2 to the air flow shifts the critical ethylene flow by a factor of 1.3, while the same

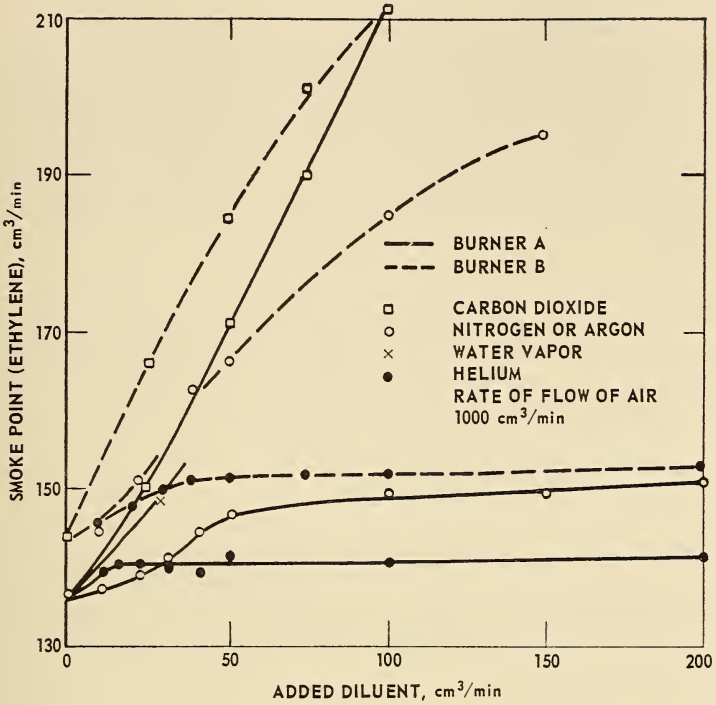

FIG. 1. Effect of adding CO_2, H_2O, and N_2 to air on the smoke point of ethylene–air diffusion flames.

addition of N_2 only shifts it by a factor of 1.01 in that range of the oxygen concentration. Whereas no smoke formation could be observed for any CO_2–O_2 mixture (without nitrogen) in the investigated oxygen concentration range between 17% O_2 (diffusion flame burning limit) and 40%, the smoke formation pattern for N_2–O_2, Ar–O_2, and He–O_2 mixtures was more complex: at small oxygen concentrations, further dilution decreased the smoke formation tendency (increasing the smoke point, as defined above); at O_2 concentrations above 30% the effect of dilution was influenced by the oxidant flow velocity in such a way that increasing the velocity reduced the smoking tendency and even reversed the effect of dilution.

Comparison of flames burning on the two different size burners A and B, with other conditions of flow rates and O_2 concentration being constant, indicate that the decrease in fuel jet diameter (with subsequent doubling of the fuel flow velocity) tends to increase smoke formation at small O_2 concentrations and to decrease it at higher O_2 concentrations.

B. Dilution of the Fuel

The results presented in Fig. 1 show that the effect of fuel dilution is essentially the same as found for oxidant dilution; the efficiency in reducing the smoke formation going in the order CO_2, N_2 = Ar, He.

C. Rates of Soot Formation

In part 3 of this series, results of experiments are reported in which soot from flames with oxygen-nitrogen mixtures was collected by glass fiber filter discs and weighed. The obtained results agree well with the smoke point determinations. In fact, plots of the over-all sooting rate versus the oxygen concentration show the same pattern in terms of soot formation tendency as explained in Sec. A for oxygen–nitrogen mixtures. Also, as it should be, extrapolations to zero sooting rates originate the same curves.

Comparison of the results obtained for different gases indicate that their influence on the smoke formation cannot be understood in terms of diffusion effects alone (CO_2 is much more effective than argon, their diffusion coefficients not being very different) or by the effect of their specific heats alone (as shown by the different results obtained for Ar and He). On the other hand, as stated by the authors themselves, before kinetic aspects of the results can be brought into the discussion, it is felt that data on temperatures and on the concentration of at least some stable species in the various diffusion flame zones are needed. Furthermore, recirculation of combustion products should be ruled out or controlled in order to reduce the number of unknown parameters. However, in the reviewer's opinion, these preliminary studies have shown that a continued effort in this direction can further considerably our understanding of the effects that recirculation of flue gases are known to have[2,3] on the suppression of smoke and even of luminosity in combustion of a variety of fuels.

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Subject Headings: ***Diffusion flame, soot in; Flame, ethylene, smoke point of; Smoke point, of hydrocarbon flame; Soot, formation by diffusion flame.***

U. Bonne

Tsuji, H. and Yamaoka, I. (University of Tokyo, Tokyo, Japan) "The Counter-Flow Diffusion Flame in the Forward Stagnation Region of a Porous Cylinder," *Paper presented at Third Symposium on Combustion in Japan, December 11, 1965*

Experimental studies were made with a laminar, two-dimensional, counter-flow diffusion flame established in the stagnation region on the windward of a porous cylinder, from the surface of which fuel gas was ejected uniformly into the uniform air stream. The effects of the aerodynamical and chemical parameters such as air stream velocity V, fuel ejection velocity v_w, cylinder radius R, fuel composition, etc., upon the position where the flame stands, blow-off limit, temperature distribution across the flame and the flow pattern in the flame were observed in detail.

The uncooled porous cylinder, 3 cm long (sintered bronze), was mounted in a rectangular combustion chamber of 3 cm × 12 cm cross section. The experiment was conducted using four kinds of such cylinders whose diameters were 1.5, 3.0, 4.5, and 6.0 cm, respectively. The fuels used were propane and city gas.

For favorable conditions of V and v_w, a thin, laminar, two-dimensional blue flame stabilized at a distance y^* from the cylinder surface in the forward stagnation region. As v_w/V was decreased, the flame approached the cylinder surface, and finally blew off at a certain critical distance y^*_{crit}. This blow-off is caused mainly by the thermal quenching of the cylinder. There existed a critical value in the stagnation velocity gradient, $(2V/R)$ crit., beyond which the flame can never be stabilized, however large the fuel ejection velocity. This critical value depends on the fuel composition, and may be used as a measure of over-all reaction rate or flame strength, for each combination of the reactants.

The measured location of the flame, designated by a non-dimensional distance η^* $[=(y^*/R)(2\text{Re})^{1/2}]$, was found to be correlated with the nondimensional ejection parameter $-f_w$ $[=(v_w/V)(\text{Re}/2)^{1/2}]$ for a given combination of reactants (Re: the Reynolds number). It was also confirmed that (1) η^* for propane–air was greater than that for city gas-air, (2) as the flame approached the cylinder surface, the flame temperature decreased while the surface temperature increased, (3) fine particles (MgO_2) introduced in the air stream never failed to pass through the flame and their stagnation point was on the fuel side of the flame. These observed results were shown to be consistent with the theoretical results obtained by a simplified analysis of the boundary-layer approximation.

As the flame is very stable and the flow field rather simple, the authors suggested using this flame in studies of flame kinetics, by structure analysis, and of the over-all reaction rate or apparent flame strength.

Subject Headings: *Blowoff, cylindrical counterflow diffusion flame; Counterflow cylindrical diffusion flame; Cylindrical diffusion flame; Diffusion flame, cylindrical.*

T. Kinbara

V. Combustion Principles

Burke, R. and van Tiggelen, A. (University of Louvain, Louvain, Belgium) "Kinetics of Laminar Premixed Methane–Oxygen–Nitrogen Flames," *Bulletin des Societes Chimiques Belges* **74**, 426–449 (1965)

The authors compare their own theory of flame propagation and associated kinetics with that of Zeldovich, Frank-Kamentskii, and Semenov. The former theory stresses the importance of the diffusion of radicals into the fresh gas, while the latter emphasizes the importance of heat conduction. More recent developments have resulted in somewhat of a compromise, involving evaluating mean values of the transport parameters, so that the apparent differences between the two theories has been minimized.

The authors chose to study in detail the reaction between methane and mixtures of oxygen and nitrogen. An expression was derived, in which the burning velocity is a function of the partial pressures of oxidant and fuel, the partial and total reaction orders, and the Ahrennius factor. An important parameter was used in the present method—the mean temperature of the flame front, having been previously derived. The parameters to be determined experimentally were the power-law dependence of the partial pressure relationship (depending on which radical reactions were important), the burning velocity, the final flame temperature, and the flame-front thickness.

The experiments were conducted on burners, with nozzle shapes and sizes adjusted so that the flame was always conical in shape, for a wide range of gas mixtures, and the above values determined. Some 300 flames were examined, and good agreement was obtained between the measured values of flame temperature and theoretical values, except for the richer flames.

Using the above mentioned theoretical relationship, a mean value of 48 kcal/mole for the activation energy was determined. Likewise, the partial orders of methane and of oxygen were determined, as a function of the mole ratio. For a mole fraction of fuel, varying between 0.33 and 0.15, the partial order with respect to oxygen varied from 1.88 to 0.23, and of methane from −0.88 to 0.23. Also, there was some evidence for the role of radicals such as CH_3, HO_2, OH, and HCO in the process.

Subject Headings: ***Diffusion, of radicals and flame propagation; Flame, theory of radicals and flame propagation.***

J. K. Richmond

Lask, G. and Wagner, H. Gg. (University of Göttingen, Göttingen, West Germany) "Influence of Additives on the Velocity of Laminar Flames," *Eighth Symposium (International) on Combustion*, pp. 432–438, Baltimore, Williams & Wilkins Company (1962)

The most significant aspect of this paper is the demonstration that many chemical agents exist that are 10 to 100 times more effective than the common halogen compounds in reducing flame speed. In Table I the effectiveness of the various additives are reported as the volume per cent of the total mixture needed to reduce the flame speed of an *n*-hexane–air flame by 30%. Some of the heavy metal compounds are much better flame inhibitors than the halogens, their effectiveness increasing with increasing atomic weight. In some cases extremely small solid particles of (presumably) metal oxides or hydroxides were observed to form in the flame zone. Phosphorous compounds are also effective flame inhibitors.

Another interesting study reported was a measurement of the effect of Br_2 on the

TABLE I

Effectiveness of various additives as volume % of total mixture needed to reduce the flame speed of *n*-hexane air flame by 30%

Substance	Volume %
N_2	8
CO_2	6.8
$n\text{-}C_6H_{14}$	1.05
Cl_2	3.3
Br_2	0.7
CCl_4	1.38
$CHCl_3$	1.87
$PSCl_3$	0.13
$PSBr_3$	0.15
$(CH_3)_3PO_4$	0.46
$Fe(CO)_5$	0.017
$Pb(CH_3)_4$	0.015
CrO_2Cl_2	<0.024

flame speed of a $CO\text{–}O_2$ flame as a function of added H_2. The flame speed of the $CO\text{–}O_2$ flame increases as H_2 is added showing quite clearly the effect of H and OH in promoting chain and chain branching reactions. The effectiveness of Br_2 in reducing the flame speed also increases with the addition of H_2 showing that its mechanism involves interference with chain reactions by removal of H and OH.

Subject Headings: *Additives, effect on burning velocity; Burning velocity, effect of additives on; Inhibitors.*

W. E. Wilson

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de Graaf, J. E. (Technology University, Delft, The Netherlands), **Callenfels, G. W., van Stein, C., and Beers, J. M.** (International Flame Research Foundation, IJmuiden, The Netherlands) "Flame Research at IJmuiden: 15 Years Past and Prospects," *The Future of Fuel Technology, Proceedings of a Conference held by the Institute of Fuel at the Invitation of, and in Collaboration with, The Royal Institution of Engineers in the Netherlands, Amsterdam, 31–48 (May 1963) Edited by G. N. Critchley. Pergamon Press, The Macmillan Company, New York* (1964)

The history of the International Flame Research Foundation is told and the research work carried out during the past 15 years is reviewed. Highlights of the

IJmuiden experiments on gas flames, blast atomized oil flames, pressure jet-oil flames and pulverized fuel flames are discussed together with some of the results of the more fundamental theoretical and laboratory scale investigations on the aerodynamics and physical chemistry of combustion and on the radiation from luminous flames. Future plans of the extension of the research work are outlined and prospects of possible applications of the results given.

Subject Headings: ***Flame, research at IJmuiden; IJmuiden, research at; International Flame Research Foundation, history of.***

Authors' Abstract

Foster, P. J. (University of Sheffield, Sheffield, England) "Carbon in Flames," *Journal of the Institute of Fuel* **38**, 297–302 (1965)

In the pyrolysis of paraffinic hydrocarbons above 1140°K the equilibrium yield of carbon exceeds 95% of the input. Since the reaction rate is slowed down progressively by the release of hydrogen such equilibrium yields are difficult to obtain. In practice, yields of 50% have been obtained, compared with about 5% from diffusion flames burning with a deficiency of air. The yield of carbon from the pyrolysis of methane decreases with increasing pressure and is increased by dilution with inert gas. In premixed flames, the addition of oxygen to the system reduces the equilibrium yield of carbon since the gas can carry carbon in the form of its gaseous oxides. An empirical rule for partial oxidation with air is that carbon can only exist in equilibrium when the oxygen:carbon atom ratio in the gas phase is about 1.0 or less, which is less than one third of the stoichiometric air for paraffinic fuels. In fact, soot formation has been observed at O:C atom ratios greater than 1.0 so that the soot must not be in equilibrium. Deviations from equilibrium are also observed in fuel-rich flames indicating that the decomposition of hydrocarbons to carbon has a faster rate than the oxidation reaction.

It is found that carbon is deposited on a surface at a lower temperature than that at which it appears as a dispersed phase. It is probable that the precipitation of carbon is a two-stage process, during the first stage the formation of new particles and their growth proceed in parallel and in the second stage, no new particles are formed but existing particles continue to grow. Agglomeration of particles can lead to a type of soot found outside the flame zone but not found in the flame itself. It is evident that the course of the nucleation period determines the particle size distribution of a system of particles which otherwise have similar histories.

The growth of a carbon surface may take place by the surface catalyzed decomposition of the parent hydrocarbon or reaction with the surface of the products of the homogeneous decomposition of the parent hydrocarbon. Data, of several workers, for the rate constant for the deposition of carbon from hydrocarbon gases are presented in an attempt to differentiate between these two schemes. Data are also presented for the oxidation rate of soot.

The optical properties of dispersed particles of soot are considered in relation to the particle size. The thermal balance of the soot particles which receive energy by collision and reaction and lose it by radiation can lead to a difference between the temperature of the particle and that of the gas.

It is concluded that much further work will be necessary before it will be possible to predict the size, number, and constitution of carbon particles formed in a given set of conditions.

Subject Headings: ***Carbon, in flame; Flame, carbon in; Soot, in flame.***

G. L. Isles

Kuznetsov, I. L. and Malanov, M. D. "Measurement of the Velocity of Turbulent Flame Propagation by the Inverse Cone Method," *Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki* No. 4, 132–134 (1964) Translation No. 1677 by W. R. Blake.

This article contains a description of an ingenious experimental technique for determining turbulent burning velocity. There are many difficulties in making such measurements and there is no universally accepted technique (Ref. 1, p. 164). The technique of these authors is to use an inverted flame whose outline is recorded photographically. With such a flame the streamlines diverge significantly due to the expansion of the burned gases. Therefore, it is necessary to measure not the cone angle, but the angle between the local streamline and the flame front. To determine local streamlines a very fine (20 μ) capron (carbon?) filament is suspended in the stream close to the flame front to act as a flag. The fidelity of the flag was checked against particle track measurements[2] using aluminum dust tracers. As a test of the method a number of measurements of turbulent burning velocity were made for several propane air mixtures at varying levels of turbulence. As originally suggested by Damkohler (Ref. 1, p. 174), they relate the ratio of turbulent to laminar burning velocity with the ratio of eddy diffusivity to molecular diffusivity. A linear relation is obtained with a slope of 2, i.e., turbulent burning increases twice as rapidly as the turbulence level. This agrees with measurements made in this country (Ref. 1, p. 173). The authors feel that this nonunity slope requires explanation. They ascribe it to the fact that a photograph of a turbulent flame is a map of the maximum rather than the average excursions. Other explanations are possible. Turbulence levels represent calculated values and may contain a systematic error.

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2. Fristrom, R. M. and Westenberg, A. A.: *Flame Structure*, McGraw Hill, New York (1959).

Subject Headings: ***Flame velocity, turbulent, measurement of; Inverse cone method, for measuring turbulent flame velocity; Turbulent flame velocity measurement.***

R. M. Fristrom

Lawver, B. R. (Aerojet-General Corporation, Sacramento, California) "Some Observations on the Combustion of N_2H_4 Droplets," *AIAA Paper No. 65-355, American Institute of Aeronautics and Astronautics Second Annual Meeting, San Francisco, California* (July 26–29, 1965)

The combustion of hydrazine droplets burning in N_2O_4 vapor was investigated using a suspended droplet technique. Mass transfer history and unit area burning rate data were obtained by measuring the temperature and diameter of the burning droplets.

It was found that the hydrazine droplet temperature remained at the boiling point during steady state burning. It was also found that hydrazine droplets burn with two flame regions, an inner decomposition flame, and an outer oxidation flame. The unit area burning rate of hydrazine droplets burning in N_2O_4 vapor was found to be significantly higher than that reported by other investigators for hydrazine droplets burning in oxygen/nitrogen mixtures. Random droplet shattering was observed to occur with hydrazine droplets burning in 100% N_2O_4 vapor, as well as oxidizer-limited combustion gases.

Subject Headings: *Droplets, burning of; Droplets, hydrazine, burning in N_2O_4.*

Author's Abstract

Smith, R. W., Jr. and Cook, E. B. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "The Thermodynamics of Combustion Gases," *Bureau of Mines Report of Investigations* 6672 (1965)

The equilibrium compositions of product gases for mixtures of air with methane, propane, or ethylene at the around flame temperatures are reported. For each hydrocarbon, compositions are given for five fuel-to-air ratios—two lean, two rich, and one stoichiometric at five pressures, from one to twenty atmospheres, and an ambient temperature of 25°C.

Subject Headings: *Composition of flame gases; Flame, temperatures of; Thermodynamics, of flame.*

Authors' Abstract

Zabetakis, M. G. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Flammability Characteristics of Combustible Gases and Vapors," *Bureau of Mines Bulleitn* 627 (1965)

This is a summary of the available limits of flammability, autoignition, and burning-rate data for more than 200 combustible gases and vapors in air and other oxidants, as well as of empirical rules and graphs that can be used to predict similar data for thousands of other combustibles under a variety of environmental conditions. Specific data are presented on the paraffinic, unsaturated, aromatic, and alicyclic hydrocarbons, alcohols, ethers, aldehydes, ketones, and sulfur compounds, and an assortment of fuels, fuel blends, hydraulic fluids, engine oils, and miscellaneous combustible gases and vapors.

Subject Headings: *Ignition, limits of; Flammability, limits of; Limits, of flammability; Limits, of ignition; Burning velocity.*

Author's Abstract

VII. Suppression of Combustion

Hay, P. M. (J. P. Stevens & Co., Inc., Central Research Laboratory, Garfield, New Jersey) "Flame-Retardant Cellulose: A New Method of Evaluation," *American Dyestuff Reporter* 53, 23–26 (1964)

Reduced flammability of cellulose has been obtained by many kinds of chemical additives and treatments, developed by numerous workers over the last hundred years or more. New treatments, especially treatments which are wash-fast, are reported frequently, but further advances are still needed to achieve a more economical finish which does not impair desirable physical properties in cellulosic fibers and fabrics. One possibility for meeting these requirements is the development of a more efficient finish; that is, one providing adequate flame retardancy when present in smaller amounts.

The efficiency of flame-retardant treatments is usually determined by applying them to a fabric at various concentrations and performing a burning test on the samples. The lowest concentration sufficient to impart a standard degree of flame retardance is then taken as a measure of the efficiency of each flame retardant.

A wide variety of flame tests have been developed for testing the fire safety qualities of fabrics, and some might be used in comparing the relative effectiveness of different flame retardants. Most of them have been described by Little in his ACS monograph on flame-proofing.[1] One of the tests commonly used for control and acceptance testing, the vertical flame test (AATCC 34-1952), has been extensively used in the evaluation of new flame retardant finishes,[2–4] but unfortunately it lacks sensitivity. A heavily over-treated fabric usually undergoes some charring in this test, as a consequence of exposure to the heat of the gas flame. As the amount of flame retarding chemical is reduced, the length of the charred area remains constant until a "break point" is seen, at which point a small reduction in add-on causes a large increase in char length. The determination of the break point with any degree of accuracy often requires the preparation of many samples in the critical range of concentration. During research on new flame retardants it became obvious to us that improvements in test methods are desirable for efficient screening of new flame retardant treatments.

It is also well known to those working in this field that the efficiency of a flame retardant is affected by variations in the weight and physical structure of the fabric to which it is applied. This means that all tests must be run on the same fabric to determine the relative efficiency of various treatments. We needed more information on the effects of the structure of the cellulose.

This paper is a report of a study of the influence of the physical structure of the cellulose on the effectiveness of two standard flame retardant formulas and the development of a more sensitive flame test method. Cellophane, 80×80 cotton, and 8-ounce cotton twill were the substrate materials, and the new flame test proved to be applicable to the cellophane as well as to various types of fabric.

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4. Reeves, W. A., Drake, G. L., Jr, Chance, L. H., and Guthrie, J. D.: Textile Res. J. *26*, 260 (1957).

Subject Headings: ***Cellulose, flame retardant; Flame retardants, cellulose; Test, flame retardance.***

Author's Abstract

VIII. Model Studies and Scaling Laws

Countryman, C. M. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Mass Fire Characteristics in Large-Scale Tests," *Fire Technology* **1**, 303–317 (1965)

It is generally agreed that the prediction of large-scale fire behavior is full of difficulties and uncertainties: complete modeling is impossible, certain aspects of natural boundary conditions are not simulatable, etc. It is therefore necessary that some experiments be carried out on a scale comparable with the natural phenomena in order to investigate the features not present in laboratory models and to conclusively establish the scale-up principles for those which are. The cost of these critical experiments must be relatively high, the time and effort involved in preparation great, and the job of digesting the data rather formidable. Good planning and efficient execution are essential for a high yield of useful information.

The tests reported in this paper, described as the preliminary members of a series, represent a genuine beginning on this problem of the experimental elucidation of the special characteristics of large fires. The results so far obtained are fragmentary and the interpretation given centers around supporting or discounting commonly held notions about mass fires and pointing out the extremes of temperature, wind, noxious gas concentration, etc. Presumably as further tests are carried out a quantitative treatment of some aspects will become possible. It is said that one of the chief aims of the tests is "to identify and describe, both qualitatively and quantitatively, various fire behavior characteristics and the conditions under which they occur."

In the first set of tests wildland fuels consisting of brush and logs were piled or spread uniformly (apparently on level ground) over areas of 2500 ft^2 to 180,000 ft^2 and burned en masse. Fuel loading ranged from 1.3 lb/ft^2 uniform to 40 lb/ft^2 in piles. Air velocities were measured at 7 ft and 20 ft above ground and colored smoke and no-lift balloons were used for flow visualization. The fires tended to behave like obstacles in the path of the ambient wind, with a well-formed turbulent wake on the lee side. On the windward side the air flow 100 ft from the fire appeared to be unaffected.

The convection column above a mass fire is multiple-rooted; in fires as small as 2500 ft^2 a number of convection columns issue from the burning area, apparently from hot spots which may develop, move around, and subside unpredictably. Between these hot spots clear combustion air enters the fire from the sides and from above.

Radiation intensities were measured around the fires. Peak temperatures of 2500° F were recorded in the flame zone. The concentrations of CO and CO_2 were measured at a number of points in and around the fires. The maximum CO content was 5%, and oxygen depletion was frequently evident.

In a second set of tests the burning of blocks of city houses was simulated with wildland fuels arranged in ordered piles having the fuel loading characteristics of one-story wooden dwellings. The largest plot consisted of 10 city blocks (50 acres). In one sub-set of plots the houses were spaced 25 ft apart, and in another, 115 ft. Gas velocities were considerably affected throughout a plot of burning "blocks," but at the plot edge the effects were small. The gas flow patterns in and around large mass fires appear to be very complex.

These tests, and also, observations of large wildland fires, are said to suggest the following picture of the gross structure of a large mass fire: (I) the fuel bed; (II) the combustion zone, usually under 100 ft high; (III) a transition zone extending 100 to 200 ft above the combustion zone; (IV) a thermal convection zone (the well-developed convection column) ending at an altitude between 1000 ft and 20,000 ft; (V) a smoke fallout zone in which smoke drifts out of the base of the convection column cap in thin layers; and (VI) a condensation–convection zone in which the convection column broadens abruptly to form a "cap." It is said that subsequent tests will be aimed at determining the characteristics of each of these zones, but particular attention will be paid to zones II and III since they are primary in determining the course of events on the ground.

To the reviewer the most interesting characteristic of mass fires described in this paper is the multiple-rooted structure of the convection column at its source in the fire zone, with clear combustion air flowing into the fire around the "hot" spots throughout the burning area. This mechanism of the supply of fresh combustion air in depth is of central importance and fundamental studies of it should be made, by theory and by suitable laboratory models which must yet be devised.

Subject Headings: ***Fire, mass, characteristics of; Mass fire, characteristics of; Model fires.***

H. A. Becker

IX. Atomization of Liquids

Asset, G. and Phillips, D. (Chemical Research and Development Laboratories, Edgewood Arsenal, Maryland) "Note on the Lateral Displacement of Solid Particles and Gas in Shear Turbulent Flow," *Journal of Applied Meteorology* **3,** 480–483 (1964)

This note describes an experimental study of the turbulent diffusion of polystyrene particles ranging from 125 to 150 microns in diameter and of ammonia gas in the turbulent boundary layer on the wall of a wind tunnel. The polystyrene powder was slowly introduced into the boundary layer using a tube. The particles were collected downstream using a single petroleum-coated steel wire 0.015 in. in diameter stretched normal to the flow. The distribution of particles was obtained by counting the number of particles on the wire after a given length of time using a microscope. The ammonia was also injected through the tube and the distribution downstream was obtained using a probe and a chemical analysis.

The measured distributions were Gaussian. The spread of the distribution for ammonia was in agreement with previous measurements. The spread in the distribution of the polystyrene particles was an order of magnitude larger than previous measurements. This difference is attributed to a greater intensity of turbulence.

Subject Headings: *Particles, in turbulent flow; Turbulent flow, particle; Turbulent flow, two-phase.*

D. L. Turcotte

Golovkov, L. G. (U. S. S. R.) "Distribution of Drops According to Size in Atomizing Liquids by Means of Centrifugal Atomizers," *Inzhenerno-Fizicheskiy Zhurnal* **7,** 55–61 (1964) (Russian) Translated by Foreign Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio

Proceeding from the Second Law of Thermodynamics, the validity of Tresh's assumption[1] for the derivation of the function of droplet size distribution is shown.

$$\psi(\delta) = dn/n_0 d\delta = (\delta^3)^{-1}\exp(-\beta/\delta) \Big/ \int_0^1 \exp(-\beta/\delta)\,(d\delta/\delta^3). \tag{1}$$

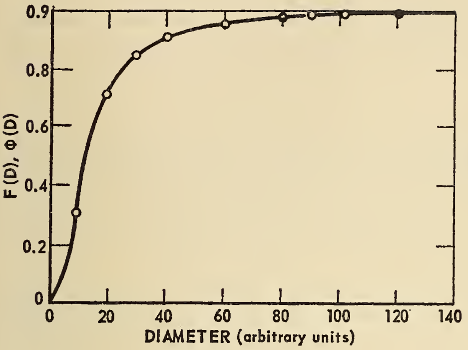
The mathematical statistic methods are used for obtaining the analytical relations between the parameters of this function. This allowed very simple predicting formula

$$\beta = \{1 - b + [(1+b)^2 + 8b]^{1/2}\}/2b, \tag{2}$$

and

$$\beta = \alpha/(1-\alpha). \tag{3}$$

for the determination of the parameter spectra of the pulverized liquid. From the



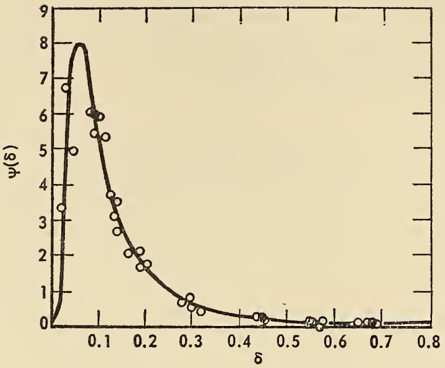


Fig. 1. Graph of the experimental $F(D)$ and theoretical Φ (D) of the integral functions of the distribution of the drops of one centrifugal atomizer.

Fig. 2. Graph of the generalized function of the distribution of the drops in accordance with sizes ψ (δ) for centrifugal atomizers.

treatment of the experimental data the value of $\beta=0.19$ for centrifugal pulverizers was found.

Figures 1 and 2 show how distribution functions (1) and (4) agree with the observation data.

$$\Phi(D) = \int_0^D \phi(D)\,dD$$

$$= \int_0^D \frac{\beta^2 D^2_{\max} \exp(-\beta D_{\max}/D)}{D^3(1+\beta)\exp(-\beta)}\,dD$$

$$= \frac{\beta D_{\max} \exp(-\beta D_{\max}/D)}{(1+\beta)\exp(-\beta)}\left[D^{-1}+(\beta D_{\max})^{-1}\right] \qquad (4)$$

Reference

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Subject Headings: *Atomizer, centrifugal; Centrifugal atomizer; Drop size, distribution from centrifugal atomizer.*

Author's Abstract

Hedley, A. B. and Leesley, M. E. (University of Sheffield, Sheffield, England) "Burning Characteristics of Pulverized Coal," *Journal of The Institute of Fuel* **38,** 492–500 (1965)

This review paper covers over 60 of the more fundamental papers concerning the combustion properties of pulverized coal. The four primary categories into which the papers are classified include (1) the single particle, (2) the theoretical approach to dust-cloud combustion, (3) the experimental approach to dust-cloud combustion, and (4) the combustion-rate-control mechanism of pulverized coal.

Study of the burning of a single particle as a microcosm of a coal-dust-cloud flame has attracted many researchers. However, attempts to extrapolate results from a study of relatively large single particles to predict the behavior of small particles in a burning cloud have not met with much success. Nusselt's original equations, for the combustion of single carbon particles freely suspended in air, contained the difficulty that they gave an infinite burning time for stoichiometric coal–air ratios. This problem was solved by Traustel who modified Nusselt's isothermal burning time equation to give an adiabatic burning time.

Spalding made modifications to the equations pertaining to the combustion of particles in order to relate these to the burning of oil droplets, which is a special case of particle combustion. His theoretical model is similar to that found experimentally by Hottel and his co-workers.

The primary objection to using results from single-particle studies is that the particle is not burning under conditions as met in a real flame.

Many investigators have studied dust-cloud combustion theoretically. In one of the theories, developed by Beer and Siddall, an equation was developed to predict the burning away of a dust cloud at any instant of time. They assumed that the system was adiabatic, that the size distribution followed the Rosin–Rammler law, and that all of the carbon burnt to give carbon dioxide. They neglected the relative motion of the particle and the atmosphere. The resulting equation was integrated numerically and the predicted times agreed rather well with experimental results when certain values were chosen for the indices in the equation. These values are in agreement with those predicted by Hottel and Stewart to give the best fit to Sherman's data.

Only a modest discussion is given to the experimental approach to dust-cloud combustion. The authors indicate that the Controlled Mixing History Furnace, in which the flame is considered to be one-dimensional, can be regarded as a bridge between experiments using large industrial flames and small laboratory-scale flames.

For the heterogeneous reaction of the combustion of coal, it has been assumed by most previous workers that the diffusion resistance, at normal flame temperatures, is the rate-determining step. Recently, however, other researchers have shown that chemisorption processes may be much more important than was realized earlier.

Sufficient practical data are not available to substantiate existing theories of rates of combustion. More research is needed to determine which interdependent variables can be examined separately.

Subject Headings: *Burning characteristics, of coal dust; Coat dust, burning of; Dust coal, burning of; Review, burning of coal dust.*

L. E. Bollinger (Deceased)

X. Meteorological Interactions

Briggs, G. A. (The Pennsylvania State University, University Park, Pennsylvania) "A Plume Rise Model Compared with Observations," *Air Pollution Control Association Journal* **15**, 433–438 (1965)

Schmidt, F. H. (Royal Netherlands Meteorological Institute, De Bilt, The Netherlands) "On the Rise of Hot Plumes in the Atmosphere," *International Journal Air and Water Pollution* **9**, 175–198 (1965)

These two papers consider the same problem, the rise of hot plumes in the atmosphere; however, in solving the problem their approaches are quite different. Briggs used entirely dimensional arguments to predict plume rise, Δh, for buoyant plumes in both stable and neutral air, for both calm and windy conditions. He considered wind speed $\bar{u}$, buoyancy flux F, and a stability parameter S (proportional to potential temperature gradient) as dominant factors. The momentum flux term, which is defined as the product of the efflux velocity, and the mass efflux at the chimney has been discussed by Briggs, but it is considered to be negligible and does not get into final results. On the other hand, Schmidt's theory is based on some previous papers.[1,2] With a few additional assumptions, he established a relationship between the rise of the plume and various parameters. Schmidt considered the diameter of the stack D, potential temperature difference θ_1, wind speed, and the vertical temperature gradient as dominant factors.

Briggs' results can be summarized as follows:

transitional rise	$\Delta h = 2.0 F^{1/3} \bar{u}^{-1} x^{2/3}$
rise in stable, calm air	$\Delta h = 4.7 F^{1/4} s^{-3/8}$
rise in stable, windy air	$\Delta h = 2.6 (F/\bar{u}s)^{1/3}$
rise in neutral air	$\Delta h > 400 (F/\bar{u}^3)$

The transitional rise formula which agrees reasonably well with observed data applies to all bent-over plumes before they approach their final height. The constant 4.7 in the second formula is a compromise of previous papers.[3,4] The constant 2.6 in the third formula is estimated from some previously observed data.[5,6] Only the formula for the rise of the plume in a neutral atmosphere lacks the support of observed data.

With the use of the above plume rise formulas, the maximum ground concentrations of plumes for two cases, neutral windy and calm with fumigation, are carried out by Briggs. In the neutral case the highest concentration was found to be

$$\chi_{\max} = 0.007 (\mathcal{Q} / F^{1/3} h_s^{5/3})$$

which occurs as the wind speed at plume level approaches 12.6 $(F/h_s)^{1/3}$, where $\mathcal{Q}$ is the mass efflux of pollutant and h_s is the height of the stack. In the fumigation case it was assumed that the concentration is a function of $\mathcal{Q}$, F, and s, yielding

$$\chi_{\max} \doteq 0.05 [\mathcal{Q} / F^{1/2} s^{-1/4} (h_s + 4.7 F^{1/4} s^{-3/8})]$$

The coefficient of proportionality was determined from very limited data, hence the author feels that more observations are needed to prove the validity of this model.

Schmidt's paper begins with a report of a survey of previous literature related to the rise of hot plumes in the atmosphere. His conclusions may briefly be drawn as follows:

1. Only Morton's theory explicitly contains the influence of atmospheric stability, i.e., the vertical temperature distribution in the atmosphere.
2. All theories result in a well defined plume rise. The intensity of turbulence is completely fixed by the meteorological parameters such as the wind speed and the vertical temperature gradient in the atmosphere.

Schmidt studied the problem in three different cases, the rise of a hot plume in a stable calm, stable windy, and neutral windy atmosphere. The results are written as follows:

stable calm $\Gamma_\theta H^* = [2\theta^* - \Gamma_\theta H^*](1+H^*)^{-5/3}$

stable windy $H^*[(mH^*+1)^{(2-m)/m}+1] = 2\theta_1^*/\Gamma_\theta$

neutral windy $H(Y) = (4D/m)(Y^m-1)$

where $H^* = (H'-4D)/4D$, H' is the ultimate equilibrium height of the plume above the virtual point source, D the diameter of the chimney orifice, $\theta_1^* = (\theta_1 - \bar{\theta}_1)/4D$, $\theta_1 - \bar{\theta}_1$ is the potential temperature difference between the plume and the surrounding air in the level of the orifice, $\Gamma_\theta = \partial\bar{\theta}/\partial Z$ the vertical gradient of potential temperature, m a turbulence parameter which depends on Γ_θ, on the wind speed, and on the roughness of the terrain, H the height gain of a hot plume when its horizontal displacement is ΔX, and $Y = (X_1 + \Delta X)/X_1$.

The formula for the rise of the plume in a stable calm atmosphere has been checked with Morton's result; they are in fairly good agreement. The second formula for the stable windy atmosphere has been plotted out and compared with the observed data. Unfortunately a curve with a definite value of m can never fit a set of observed data. Hence Schmidt tried to relate m with the atmosphere parameters, such as Γ_θ, u, and $\bar{\theta}$ etc., but he has difficulty determining a constant involved in his assumed relation.

Based on the observed data Schmidt assumed the minimum plume rise to occur with a value of the turbulence parameter m equals zero. The formula for the rise in the stable windy atmosphere then becomes

$$H[1+\exp(H/2D)] = 2\theta_1/\Gamma_\theta,$$

which gives the minimum plume rise as a function of D and θ_1.

An attempt was made by the reviewer to compare the results of the above two papers. The formula for the case of stable calm atmosphere in Schmidt's theory is converted into Briggs' notation

$$\Delta h \doteq 4D^{-1/8}[F/ws]^{3/8}$$

which does not quite agree with Briggs' result. Hence, no further attempt was made to compare their results.

The above two papers certainly reveal the authors' efforts and give good approximations to estimate the rise of hot plume in the atmosphere for various conditions, yet, to the reviewer, some additional factors must be considered for further development of this problem. The rise of hot plume in the atmosphere depends on the buoyancy force which depends on the density difference between gases in the plume and the atmosphere. In other words, the composition of gases in the plume plays an important role; and the growing of the plume depends on diffusion and turbulent mixing processes. Therefore, in order to get a more precise theory, these factors must be considered explicitly in the future.

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Subject Headings: *Atmosphere, plumes in; Plumes, hot in the atmosphere; Plume rise, theory of.*

S. J. Ying

Calder, K. L. (U. S. Army Biological Laboratories, Fort Detrick, Frederick, Maryland) "On the Equation of Atmospheric Diffusion," *Quarterly Journal of the Royal Meteorological Society* **91**, 514–517 (1965)

The equation for turbulent diffusion in the atmosphere expresses the equality between the local and convective changes in the mean concentration C, and the gradient of a turbulent flux vector **F** where it is postulated that the flux vector is related in a simple homogeneous linear fashion to the components of the gradient of the concentration. The coefficients of proportionality, or eddy diffusivities, may be expressed in the form of a matrix

$$\begin{pmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{pmatrix}$$

The linear assumption requires that the eddy diffusivities be independent of the concentration if any physical interpretation is to be attached to their value.

The common form for the equation for diffusion

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(K_{xx}\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial C}{\partial z}\right)$$

therefore has the implicit assumptions that the eddy diffusivity matrix is symmetrical and, furthermore, in order for the nondiagonal terms to vanish, the axes must correspond to the principal axes. A special subcase is independent of the choice of axes, or isotropic, and in this case $K_{xx}=K_{yy}=K_{zz}$. Alternatively, it may be postulated that a preferential orientation of the axes does indeed exist. As an example, if only a velocity parallel to the ground is considered, $w=0$, and the equation becomes

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial C}{\partial z}\right)$$

However, since this implies rotational symmetry with respect to the z axis it must follow that $K_{xx}=K_{yy}$.

Subject Headings: ***Atmosphere, diffusion in; Diffusion, in atmosphere.***

T. P. Anderson

Csanady, G. T. (University of Waterloo, Ontario, Canada) "The Buoyant Motion within a Hot Gas Plume in a Horizontal Wind," *Journal of Fluid Mechanics* **22,** 225–239 (1965)

The problem of the dispersal of pollutants in the atmosphere from chimneys reduces to the problem of the behavior of the buoyant plumes which are formed when the hot gases are injected into a moderately strong wind. Theoretical work by Sutton[1] and by Priestley[2] was based on the assumption that such plumes could be treated as vertically rising plumes which are "sheared over" by the wind. Although the development of the two theories differed in other respects, both predicted an asymptotic mean plume path of the form

$$z=\text{const. } x^n,$$

where z is the height above the chimney top and x the horizontal distance along wind. The exponent n has a value of $\frac{2}{3}$ in Sutton's treatment and $\frac{3}{4}$ in Priestley's. These results appear to depend strongly on the assumption that the diameter of the growing plume is proportional to z.

It is doubtful that a vertical plume is simply "sheared over" by the wind where the inclination angle of the plume is small. A more realistic view of most smoke plumes is to regard them as nearly horizontal but having a slow upward drift caused by buoyancy. The approach of Bosanquet et al.[3] is based essentially on this viewpoint and they also assume that the plume diameter is proportional to x rather than to z. Their theory gives for the relationship between z and x

$$z=\text{const. } \log x. \tag{1}$$

However, for large values of x, the theory becomes invalid because the plume no longer grows linearly with distance. None of the three approaches accounts for the effects of ambient turbulence.

There are three separate regions, or phases, of plume behavior. In the initial phase near the source the plume resembles a sheared-over jet and is little affected by ambient turbulence. Next is an intermediate phase of accelerated plume diameter growth where the effects of environmental turbulence are large. It is in this stage that the plume tends to a quasi-asymptotic height. In the final phase, the plume is large with a small constant slope for the mean path. However, its relative growth rate is slower than in the intermediate phase.

The analysis applies primarily to the intermediate and final phases of plume growth. In the first part of the analysis, a theory is developed for slow buoyant movements (in laminar flow) which would take place in a fluid, initially at rest, following the instantaneous release of heat along a line source (the x axis). It is assumed that the atmosphere is neutrally stable and that the weakly buoyant plume is at a considerable distance above the ground. By neglecting squares and products of velocities and excess temperatures, the equations expressing continuity of mass, momentum, and energy are expressed in linearized form. The solutions show that the weak line-thermal, or plume, is a symmetrical vortex-like structure with a maximum velocity at the plume center. Downward flow occurs on the two sides of the plume at distances from the plume center for which the mean excess temperature is 28% or less of the excess temperature at the plume center.

From reasoning based on the fundamental similarities between the mechanisms of molecular and turbulent diffusion and from the assumption that vorticity should behave like a transferable scaler property in turbulent flow, the solutions of the equations for laminar flow are extended to describe the growth and movement of a weak line-thermal in turbulent surroundings. These results are then readily extended to a chimney which is idealized as a continuous point source of heat in a steady uniform wind on which there is superimposed a homogeneous field turbulence. In the initial phase the equation for z is identical to Eq. (1). In the intermediate stage of rapid plume growth, the equation for z becomes

$$z-z_1=(9\alpha F/8\beta^3\epsilon)[(x_1-x_0)^{-1}-(x-x_0)^{-1}], \tag{2}$$

where z_1 is the height of the plume at the beginning of the intermediate phase, and x_1 and x_0 are effective origins for the intermediate phase such that

$$x_1-x_0=Ut_b$$

in which U is the mean, or uniform, wind speed and t_b the characteristic time scale of the turbulence. α and β in Eq. (2) are constants and ϵ is given by the relationship

$$\epsilon=u^3/L,$$

where u is the root mean square of the turbulent velocity and L is the length scale of the turbulence. The variable F in Eq. (2) is

$$F=gQ/\pi\rho C_pT_a$$

in which Q is the rate of heat output, g the acceleration due to gravity, and ρ, C_p, and T_a are the density, specific heat at constant pressure, and temperature, respectively, of the environmental air. The quasi-asymptotic height z_a is given by

$$z_a-z_1=\zeta F/u^3,$$

where

$$\zeta=9\alpha/8\beta^3\phi G^2,$$

in which ϕ is a constant and the gustiness G represents the ratio u/U.

In the final phase the slope of the plume approaches the small constant value

$$dz/dx=\alpha h_a/\zeta GL.$$

However, the perturbation theory ceases to apply for very large plumes, so the form of the mean plume path is uncertain for very large values of x.

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Subject Headings: ***Plumes, rise in atmosphere; Rise, of plumes.***

G. M. Byram

Foster, K. W. (Meteorological Branch, Department of Transport, British Columbia, Canada) "An Analysis of the British Columbia Fire Danger Tables for the 1961 Fire Season," *Report CIR-3827*, *TEC-464* (April 10, 1963)

"The aims of this report are, on the basis of 1961 records, to demonstrate the reliability of the Federal Fire Danger Tables as an index of the probability of fire starting and to compare the reliability of B. C. Provincial Forestry Stations and D.O.T. Meteorological Stations." For the Kamloops, Prince George, Prince Rupert, and Nelson Forest Districts, both objectives are attacked by graphic analysis of per cent of all fires vs per cent of all days falling in each of five fire danger classes. Most of the graphs suggest that number of fires per day increases with fire danger. Exceptions can be explained either rationally or as indicating a need for more stations. Histories of seven large fires show a correlation between fire behavior and the Danger Index.

For the Vancouver Forest District, reliability of the Danger Tables and comparability of stations are subjected to statistical tests. Results show that a few Meteorological Stations represent rather large forest areas rather well, although certain Forestry Stations do better for their immediate localities. With a few more years' records, the method may be suitable to indicate areas of applicability for the various stations, hence, ultimately, the number and locations of stations required for an adequate fire danger network.

The Federal Fire Danger Tables and the Intermountain Model 8 Fire Danger Meter (U.S. Forest Service) are compared for the Nelson Forest District. The suggestion is made that the "Extreme" range of the Danger Index and the Drought Index be extended upward, as in corresponding parts of the Model 8 Meter, to reflect more realistically the effect of long dry periods.

The conclusions of the study are:

1. The Federal Fire Danger Index is a fairly reliable index of fire occurrence throughout most of British Columbia.

2. A network including representative Forestry and Meteorological Stations will give the best fire danger coverage; stations should not be in dry valley bottoms, on mountain tops, or near the sea coast.

3. Detailed study of certain weather phenomena, (e.g., diurnal wind patterns) based on long Meteorological Station records should be undertaken, and further analysis of fire experience in relation to the Fire Danger Tables should be made as more years' records become available.

Subject Headings: *Fire, danger index; Fire, and weather; Weather, and fire.*

G. R. Fahnestock

Gwinner, M. W. (Southern Forest Experiment Station, U. S. Forest Service, New Orleans, Louisiana) "Forest-Fire Danger as Related to Airmass in the Ouachita Mountains," *U.S. Forest Service Research Note SO-21* (1965)

The conclusion most important for fire control is that, in polar air, 24-hour burning conditions are definitely more severe on ridgetops than in valley bottoms even though afternoon fire danger ratings differ little between the two locations. In tropical air, differences in burning conditions due to topographic situation are small at all hours, except for differences in wind speed.

Polar air predominates during the periods of greatest fire occurrence and highest danger in late fall and early spring. Therefore, fire danger measured at the usual valley-bottom locations may result in serious under-estimates of general burning conditions just when accurate estimates are most needed. Cool, moist air at night over valley fire danger stations can completely hide high-danger conditions at higher elevations.

Wind amplifies the topographic difference in severity. It blows throughout the night at higher elevations, but usually calms in the valleys. When valley winds do blow at night, valley and ridgetop have similar temperature and humidity conditions.

The relatively higher temperatures of maritime polar air make it potentially more dangerous from a fuel moisture viewpoint than continental polar air.

Fundamentally the most important conclusion is that the inherent differences between airmass types make them a meaningful and significant basis for stratifying certain types of climatological data. Recognition of this fact can be helpful both to fire-weather forecasters and fire-control personnel.

Subject Headings: *Air circulation, fire danger; Circulation, of air, fire danger; Forest fire, air circulation.*

Author's Conclusions

King, A. R. (Chemical Research Laboratories, C.S.I.R.O., Melbourne, Australia) "Characteristics of a Fire-Induced Tornado," *Australian Meteorological Magazine* **44,** 1–9 (1964)

A fire whirlwind associated with a hot Australian "bushfire" is described. Observations are based primarily on 16 mm movie footage taken for a Melbourne TV station. Using the film with a known interval between frames and surveyed distances, the author has determined speeds and dimensions of a flaming vortex and rotating smoke column associated with the whirl. Prevailing weather conditions are not described in this article.

The "tornado" designation is slightly misleading by U.S. terminology. Although the phenomenon described is a whirlwind, it was not associated with a thunderstorm, nor did its surface effects approach a tornado in violence despite apparent great speeds in its upper portions. It apparently lasted only a few seconds.

On January 16, 1962, a fire in the Dandenong Range in Victoria, Australia, having burned quietly for 2 days, "rapidly and unexpectedly developed severe violence." For a few hours, its size increased from 8000 acres at a rate of 1000 to 3000 acres per hour. Spotting was serious.

The fire burned in an open forest of poor "messmate stringy-bark" trees (*Eucalyptus obliqua*) 40 to 60 ft high. Ground fuels "consisted of dead leaf (about 6 tons per acre), fully cured grass and some fine-leaved scrub." These fuels are light to average for forest areas in eastern Australia.

The "tornado" occurred in a narrow point of forest between two intersecting roads. The apex pointed along the contour of the 40% to 45% slope and out of the wind. The forest was about 265 ft wide (between roads) where the whirl occurred, some 660 ft from the road juncture. Incidentally, the fire did not cross the roads at this point. Fire fighters on the road within 1½ to 3 chains of the "tornado" said that they did not see it but that the fire was burning "very violently" with a "rushing noise." Though the map provided with the article extends only a mile from the whirl, it shows the whirl to have been located on the side of a spur ridge to the lee of higher country.

The first photograph shows an amorphous whirling column of smoke that broadens with height, extending upward at least 1000 feet. Measurements from separate frames in the sequence showed cyclonic rotation at 15 to 30 rpm 200 to 500 ft above the ground. This corresponds to a horizontal speed of about 90 mph 70 ft from the axis.

Very shortly, a thin flaming tube developed in the axis of the whirling column where it was visible for some 4 seconds. Measurements from the sequence of frames showed that the flame top ascended at rates of 170 mph during the first half second and 205 mph after 2 seconds reaching a maximum height of 260 ft. By comparison, a puff of dark smoke 150 to 200 ft from the whirl axis rose vertically at 90 to 110 mph without spinning, or about half the speed of the top of the flaming tube. Vertical speed of debris rising in the relatively small Dallas tornado was computed at 152 mph.[1]

The author attributes the speed of the rising flame tip to vertical motion in the column. He points out that detonation-type burning would have produced much greater speeds—3,000 to 10,000 ft/sec—while normal flame progagation in combustible gas would be only 1 to 3 ft/sec or 2 mph. He proposes "that combustible gas, unmixed with air but burning by the usual diffusion process, or burning solid fuel was sucked up by the vortex to form the column of flame observed." Sudden lowering of the flame top was attributed to depletion of the supply of combustibles.

The author suggests that actually the flame tip was burning downward into the upward flowing "combustible gas, unmixed with air." Hence the vertical observed speed of the flame tip should be increased by the downward rate of burning to more closely approach true vertical speed in the vortex. Based on Byram's[2] laboratory experiments with fire whirls, it would seem that the flame spout is composed of an inner core of unburned gas within a long thin flaming tube representing the surface at which sufficient oxygen is mixed to permit flaming combustion. In a wild fire such a supply of uniformly combustible mixture is unlikely for any length of time, and the rapid dying out and fluctuation of the fire spout results.

Measurements made from scale diagrams of the flaming spout at $\frac{1}{12}$-sec intervals indicate that it was about 15 ft in diameter at its base and extended upward from the side of a broader base of flame some 25 ft in diameter and 45 ft high. This might imply that only part of the central tube was occupied by flame. The author mentions a lateral motion of "20–30 mph at its midheight," but suggests it is not due to "rotation of an irregularly shaped flame eccentric to the axis of rotation."

Assuming a structure of a central tube some 30 ft in diameter at its base surrounding the visible flaming spout, the greatest rotational speeds would be expected in this tube collar. If the structure was similar to that of the Dallas tornado, speed would increase from the outer whirling smoke to the tube wall according to the relation:

$$\text{Speed} \times \text{radius} = \text{a constant}$$

This would imply speeds considerably greater than 90 mph (at 70 ft) closer to the tube. By comparison, a horizontal speed of 170 mph was observed close to the tube of the Dallas tornado 150 ft from its axis and 220 ft above ground. The short life of the fire whirl may have prevented its reaching full intensity even above the surface.

Despite the implied and observed speeds, inspection of the area where the whirl occurred showed no evidence of unusual wind except that in "one area of about 50 ft radius, all twigs less than $\frac{1}{8}$ to $\frac{1}{4}$ in. in diameter were burned away. Apparently the swirling on the ground was nonexistent or slight . . .," indicating that the base of the circulation was generally above the forest canopy.

Beneath the whirlwind, partial combustion apparently occurred at an accelerated rate in the presence of super ventilation. The vertical winds within the vortex quickly distributed the combustible gases along the column much more rapidly than the flame could consume it. The flaming spout resulted when the whirlwind passed over appropriate kind and quantity of burning fuel. The flaming spout possibly contributed to the circulation while it lasted, but the extremely transient nature of the whirlwind indicates its initial formation must be attributed to a momentary fortuitous combination of random local vorticity and a column of rising hot gases. Another possibility is that the whirl might initially have been of the pendent type descending from the main connective column overhead.

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Subject Headings: ***Fire, vortex formation in; Vortex, formation in fire.***

O. P. Cramer

Kuo, H. L. (Massachusetts Institute of Technology, Cambridge, Massachusetts) "On Cellular Convection and Heat Transfer," *Proceedings of the International Symposium on Numerical Weather Prediction, Tokyo, Japan,* 453–468 (1962)

The nature of cellular convection in a rotating compressible fluid has been analyzed. It is shown that the most preferred horizontal scale of motion in an unstably stratified atmosphere is of the same order of magnitude as the depth of the unstable layer. The effect of a stable stratification in the descending region in the case of conditionally unstable stratification is to narrow the ascending region and to weaken the descending motion and make it widespread. Another effect is to increase the critical lapse rate and make it become proportional to the factor f^2k/ν for large Taylor numbers.

Quantitative results on the convective transport of heat and modification of the temperature distribution have been obtained by solving the nonlinear equations for a two-dimensional nonrotating model. This solution converges rapidly for a large range of the imposed temperature difference. It reveals that when the actual Rayleigh number is greater than twice the critical Rayleigh number, a layer of isothermal (adiabatic lapse rate in a gas medium) mean temperature develops in the middle of the fluid layer. The thickness of this layer increases as the actual Rayleigh number increases, and at the same time the temperature gradient increases in the boundary layer so that an increase of the heat transport is accomplished.

The nonlinear solution reveals further that the large temperature gradients are concentrated in the region where the cold descending current approaches the lower boundary and where the warm ascending current approaches the upper boundary. It is also shown that these ascending and descending currents spread out in mushroom-like patterns, a characteristic feature of the convection of isolated hot bubbles, but which never has been considered as the form of finite cellular convection.

The heat transport given by this solution fits a power law of exponent 1.24, which is very close to the observed power law of exponent 1.25 for laminar flow.

Subject Headings: *Cellular convection, in atmosphere; Convection, in atmosphere; Heat transfer, by convection.*

Author's Abstract

Myrup, L. O. (University of California, Los Angeles, California) "The Structure of Thermal Convection in the Lower Atmosphere," *Part II of Final Report under U.S. Forest Service—University of California Contract No. A 5fs-16563 under Office of Civil Defense Contracts OCD-OS-62-143 and OCD-PS-64-24* (February 1965)

This report contains an experimental study of the structure of thermal convection in the lower atmosphere. The measurements were carried out over a desert dry lake so that the heating was maximum and wind conditions very light. Most of the measurements were made using an instrumented light aircraft. Measurements of temperature fluctuations and atmospheric vertical velocity fluctuations were obtained and from these the convective flux of heat was calculated.

The author summarizes the literature on the free convection problem. The opposing theories based on similarity and the Malkus[1] theory of turbulent convection are discussed. Careful laboratory measurements by Townsend[2,3] are in agreement with the theory of Malkus and do not correlate with the similarity theory. A characteristic of the Townsend experiments was the presence of warm air containing large amplitude temperature fluctuations and cool regions with practically no temperature fluctuations. This was interpreted as resulting from convective plumes rising from the lower heated plate. On the other hand most atmospheric measurements are in quite satisfactory agreement with the similarity theory. However, some measurements indicate that the Malkus theory may become applicable under conditions of strong surface heating and light winds. It was the purpose of the atmospheric measurements reported here to carry out experiments under conditions most favorable to the Malkus theory, i.e., strong heating and light winds.

Measurements were carried out over the El Mirage Dry Lake and the Harper Dry Lake in the Mojave Desert of California. The lakes were flat over distances of about 8 km. The primary measurements were carried out using an instrumented light aircraft. The vertical velocity fluctuations were obtained from pitot tubes and accelerometers. The temperature fluctuations were obtained from resistance temperature sensors. The turbulent vertical flux of heat was obtained from the product of the temperature and the vertical velocity fluctuations. In addition conventional ground measurements were carried out.

Both the temperature and vertical velocity fluctuation measurements were in excellent agreement with the similarity theory. The observed $-\frac{1}{3}$ power law for temperature fluctuations disagreed strongly with the -0.6 power law found by Townsend in laboratory experiments. The disturbed-quiet structure obtained in the laboratory was apparent in all the measurements. On the other hand the nondimensional heat flux was not found to have the constant value predicted by the similarity theory.

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Subject Headings: *Atmospheric convection; Convection, thermal, in atmosphere.*

D. L. Turcotte

Taylor, A. R. (Northern Forest Fire Laboratory, U. S. Forest Service, Missoula, Montana) "Lightning Damage to Forest Trees in Montana," *Weatherwise* **17**, 61–65 (1964)

A study was made of the types and severity of damage by lightning strikes to Douglas fir trees in Montana. In addition, an attempt was made to relate characteristics of the damage to features of the tree.

A search over 10,000 acres of timberland disclosed about 1000 trees with evidence of lightning damage. Of these, 53 of recent strikes were examined in detail.

Visible damage of the 1000 trees was distributed as follows: Most of the 1000 had continuous scars about 5 in. wide along the boles; 250 had two or more scars; 100 had severed tops; and 10 were completely demolished.

A lightning strike produces a discharge of electrical current of about 30,000 amperes along the bole, or trunk, of the tree. The actual damage is caused by the intense localized heating of the wood, usually resulting in an explosive rupture from the pressure of the steam and vapor generated within the wood.

Damage to the closely examined trees disclosed the following features. The scars were quite uniform in width and depth from 10 ft above the ground to the top of the scar. The scars were predominantly spiraled, many make more than a complete revolution around the trunk. The lengths extended to the tip. Half of the scars extended to the ground, the remainder to about 6 ft above ground level.

When lightning tore wood from a tree it usually was in two long parallel slabs. On 38 trees the removal was slabs of bark and on the other 15 the gouge extended into the wood and was wider and longer. The scars were usually 5 to 10 in. wide and some as deep as 3 in. Generally, bark loss occurred in trees that were 22 in. or less in diameter and younger than 170 years. Larger diameter and older trees generally exhibited deeper wood loss.

Subject Headings: ***Lightning, damage in forests; Forests, lightning damage in.***

R. W. Ziemer

XI. Operational Research Principles Applied to Fire Research

McMasters, A. W. (University of California, Berkeley, California) "Wildland Fire Control with Limited Suppression Forces," *Operations Research Center, College of Engineering, University of California, Berkeley, California Report ORC 66-5 (March 1966) Contract A5fs-16565(40) U.S. Forest Service*

This study analyzes the influence of limited suppression forces on the attack and control of wildland fires. The allocation of these suppression forces is examined under an event-review schedule where allocations may be made or modified when either a new fire is detected or a current one is controlled. Two classes of strategies are considered: a) forces for a new fire can only come from reserves, and b) forces for a new fire can come from reserves and may also be transferred from existing fires. The latter class includes two principal strategies; one allows transfers only at the end of an existing fire. The strategies are examined under the assumption of the Parks-Jewell fire growth model with no acceleration. The optimality criterion is minimization of the total suppression plus damage costs of all fires considered. Because of the analytical complexity of studying multiple fire situations, except when they occur simultaneously, only the case of two nonsimultaneous fires is analyzed. The analyses begin with the development of a deterministic model of each strategy. From each model the optimal number of initial attack and transferred forces to send to a new fire are determined. The results of the deterministic analyses are used to develop a model of the dispatcher's risk problem: the determination of the optimal initial attack force to allocate to an existing fire under the threat of additional fires when both the detection time and growth characteristics of each new fire are random variables. The procedure for determining the optimal initial attack force for an existing fire is then described by use of the risk model for two-stage programming under uncertainty. A computer example is analyzed to illustrate the salient features of the risk problem including a comparison of the different strategies. Parametric variation of the constraint on available forces, the inter-fire transportation cost, and the expected value of the inter-detection time allows the explanation of a large region of possible behavior of the strategies. In hedging against the possibility of future fires, it is shown that, under the optimal policies, the size of the suppression force to send to a current fire decreases as the inter-fire transportation cost increases. The general strategies allowing transfer of forces between fires are shown to be better than those allowing no transfers, and, as is expected, the total expected costs are shown to increase as the size of the available suppression forces decreases.

Subject Headings: *Fire, control, with limited forces; Fire, strategy; Fire, risk.*

Author's Abstract

XII. Instrumentation

Hirsch, S. N. (Intermountain Forest and Range Experiment Station, U. S. Forest Service, Missoula, Montana) "Airborne Infrared Mapping of Forest Fires," *Fire Technology* 1, 288–294 (1965)

This paper briefly describes the development of an airborne infrared mapping system which promises to be an extremely valuable tool for fire suppression and fire behavior studies. The system can generate aerial thermal photographs of a fire and the local topography which show clearly and accurately the location of the fire and its relative intensity over the burning area. These photographs can be taken at any time of day or night and even when the fire is completely obscured by smoke.

Initial tests were made in 1962 using an obsolete military sensing device set for the 4.5- to 5.5-micron range of the infrared spectrum. Successful photographs were obtained of a 300-acre controlled slash fire which was obscured by a dense smoke layer, approximately 2000 ft thick. Photographs of this fire and several others are included in the article and illustrate the quality of the results.

Continuing development and modification of sensing apparatus and photographic equipment has taken place over the three-year period from 1962 to 1965. The present sensing device was constructed by HRB–Singer and the Polaroid printer was designed and built by the Forest Service. The complete system is presently installed in an Aero Commander aircraft owned by the Forest Service and is undergoing detailed appraisal. The system is expected to be operational by the start of the 1966 fire season.

Briefly, the sensing device consists of an infrared scanner with a rotating scanning mirror mounted in front of the objective mirror of a Cassegrainian telescope; the rotating mirror causes the optical system to scan a line perpendicular to the aircraft flight path. The forward motion of the aircraft causes adjacent scan lines to form an image of the thermal patterns of the scanned terrain. An infrared detector (indium antimonide for the 4.5- to 5.5-micron range) is placed at the focal point of the telescope; the detector output is amplified and displayed on a cathode ray tube; the tube picture is photographed using a Polaroid printer containing two film backs and a flipping mirror to provide sequential imagery while retaining the simplicity of the Polaroid process.

The problem of transmitting pictures to the ground for use during the suppression of a fire has yet to be completely resolved. Pictures dropped in special containers from the aircraft appear satisfactory for small fires while a telemetering capability appears to be the answer for large fires. The report implies that the telemetering capability has not been developed as yet.

During the developmental period, 42 fires ranging in size from 10 to 60,000 acres were mapped; 27 of these were wild fires. These missions showed that the mapping system provides a means of obtaining a fast and accurate appraisal of the state of a fire in spite of darkness or smoke. The complete location of the fire including associated spot fires with respect to various local topological features including roads and fuel-type variation can be obtained. Finally, the pictures provide an indication of the relative intensity of various portions of the fire and a means of measuring perimeter rates of spread. Such information will allow a more efficient deployment of suppression forces on a fire than is generally possible at present.

Subject Headings: *Aircraft, infrared fire detector in; Fire, detector, infrared; Forest fires, detection, by infrared; Infrared fire detector.*

A. W. McMasters

Mills, R. M. (National Bureau of Standards, Washington, D. C.) "New Radiofrequency Mass Spectrometer Having High Duty Cycle," *Journal of Research of the National Bureau of Standards* **67C**, 283–290 (1963)

A new type of time-of-flight mass spectrometer has been developed which, unlike most other such instruments, utilizes a large fraction of the nonpulsed stream of ions. The ions are accelerated through a d-c voltage and then pass into a drift tube. A radiofrequency voltage is applied at the exit and entrance gaps of the drift tube in such a way that the field at the entrance is the negative of that at the exit. The number of ions which pass through the drift tube with such a velocity that the energy change from the rf fields is a minimum, is measured by placing an electrical barrier in front of the collector and differentiating the cutoff curve. Velocity modulation of the beam resulting from the rf field at the first gap limits the instrument to moderate resolution. However, the instrument has a 60 percent duty cycle, a value significantly greater than that achieved by most other time-of-flight mass spectrometers. It also has the advantages of electrical and mechanical simplicity. Due to the nature of the instrument's output, it will be most useful in applications requiring the analysis of a simple mass spectrum and where high duty cycle is of real value. The instrument has resolved the isotopes of rubidium at masses 85 and 87, and has identified one component ion beams ranging in mass from helium to cesium.

Subject Headings: *Mass spectrometer, radiofrequency; Radiofrequency mass spectrometer.*

Author's Abstract

Schwenker, R. F., Jr., Beck, L. R., Jr., and Zuccarello, R. K. (Textile Research Institute, Princeton, New Jersey) "Applications of Differential Thermal Analysis and Dynamic Thermogravimetric Analysis in Textile Research," *Proceedings of the American Association of Textile Chemists and Colorists, American Dyestuff Reporter* **53**, 30–40 (1964)

The suitability of differential thermal analysis (DTA) and dynamic thermogravimetric analysis (TGA) for supplying a continuing need for faster, more versatile and efficient methods of identifying and characterizing textile fibers and fiber assemblies is considered critically. Fifty-seven publications are cited. New data for DTA, mostly in apparatus previously described,[1] and for TGA by the method of Gordon and Campbell[2] are presented for cotton cellulose, Nylon 6, Nylon 66, Dacron, polypropylene, Orlon, Creslan, wool, cotton–Dacron blend, cyanoethylated cotton, tosylated cotton, thioacetylated cotton, disulfide cotton, cotton grafted with polyacrylonitrile, acetate blue dye DG, polyester blue GLF, and latyl blue BCN, both in air and in nitrogen atmosphere.

DTA yields unique curves that rapidly and unambiguously characterize textiles. The curves obtained define the temperature at which changes occur, show whether the changes are exothermal or endothermal, and reveal glass transition, crystallization, melting, crosslinking, oxidation, depolymerization, new product formation, and other reactions. DTA data can be used to estimate quantitatively the crystallinity of synthetic fibers and the heats of transformation for a variety of reactions. Sometimes the degree of saturation of chemically modified cellulose can be determined by DTA. In time, DTA may take a place with infrared spectroscopy and X ray as a basic analytic method.

TGA can provide quantitative data on the thermal stability, rates of decomposition, kinetics of thermal degradation, and on the volatilization reactions of textiles and other polymeric materials. A good correlation was found between DTA and TGA data showing that the two methods are complimentary with TGA data amplifying DTA results.

These dynamic methods of thermoanalysis are now limited by lack of standardization of techniques and instrumentation. An interlaboratory program is suggested as a first step toward establishment of standard methods for characterizing textile materials.

References

1. Schwenker, R. F. Jr. and Zuccarello, R. K.: J. Polymer Sci. C, No. 6, 1 (1964).
2. Gordon, S. and Campbell, C.: Anal. Chem. *32*, 271 (1960).

Subject Headings: ***Differential analysis, thermal, of textiles; Thermogravimetric analysis, of textiles.***

F. L. Browne

Wessels, H. R. A. "The Observation of Reed Fires with Weather Radar," *Hemel en Dampkring*, The Hague **62,** (6), 134–137 (June 1964) In Dutch.

On March 6, 1964, there was an extensive fallout of soot over Amsterdam. This was caused by two large fires in the polder Ijsselmeer which is being readied for cultivation and was covered by a large crop of reeds. The great distance over which the smoke plumes were carried was due to the combination of a strong wind and a temperature inversion which occurred between 1 and 2 km altitude and prevented the rise and dissipation of the plumes. These smoke plumes were detected by the weather radar located at DeBilt almost 50 km away. The outlines of the plumes were as easily seen as those of a "smart" rainfall around Debilt which occurred at the same time. The plumes were well-defined from the polder to Amsterdam some 30–40 km away, but disappeared beyond the city some 50–60 km from the source. One centimeter wavelength was used, as is common for weather radar. The particles in the smoke plumes were of the order of 1 cm with a concentration of the order of one particle per cubic meter. The author points out that this fire and smoke plume were easily observable while much more intense forest fires show up only slightly or not at all in weather radar. He attributes the intensity of reflection to the large particle size pointing out that radar return varies with the sixth power of the dimension of the target. Large particle size is a characteristic of reeds as a fuel. They burn with the production of large light filmy particles in the form of carbonized sheets and flakes which can be carried aloft by the hot gases. Forest fires in which the principal fuel is wood produces dense brands which drop to earth early and are not carried long distances by the smoke plume.

The reviewer suspects that some of the unusual reflectivity may have been due to the approximate coincidence between the particle dimensions and the wavelength of the radar. Such a coincidence produces strong resonant echoes. For example, metallic shards of resonant lengths called "window" were much used for radar countermeasures during World War II.

Subject Headings: ***Detection, of fire, by radar; Radar detection, of fire; Radar detection, of plumes; Plumes, detected by radar; Smoke, plumes detected by radar.***

R. M. Fristrom

XIII. Fire-Fighting Techniques, Equipment

O'Dogherty, M. J. and Nash, P. (Joint Fire Research Organization, Boreham Wood, England) "Suspended Translucent Ceilings—Effect on Operation of Automatic Sprinklers," *Industrial Architecture* **9**, 76–79 (1966)

Tests were performed on perforated and unperforated suspended ceilings made of various materials to determine the effect of these ceilings on overhead sprinkler operation.

Each suspended ceiling was mounted at a distance of 2 ft below a true ceiling which was 20 ft square. For each test, a controlled fire was ignited, designed to operate the sprinklers in about 5 min with no suspended ceiling in position. The water distribution pattern was measured by collecting the water in 8 in. diameter buckets placed on the floor on a 2 ft by 2 ft matrix. The distribution patterns for the various types of suspended ceilings were compared with the pattern for no suspended ceiling.

In the tests on perforated ceilings, there was no significant delay in sprinkler-operating times because the hot gases from the fire were able to pass freely through the ceiling. The perforated ceiling did reduce the throw of the sprinklers. It was found that this could be corrected by increasing the clearance between the sprinkler deflector plates and the ceiling, by using sprinklers with a wider horizontal throw, by increasing the water pressure, and by reducing the sprinkler spacing.

In the tests on imperforate ceilings, the hot gases did not enter the void above the suspended ceiling until a portion of the ceiling had melted. In some cases the hot gases caused the suspended ceilings to separate from their supporting framework well before the sprinkler operated. Other ceilings with slower-melting, thicker panels had a serious effect on the operating times and distribution of the water from the sprinklers.

In the design of imperforate ceilings it is recommended that the softening temperature and thermal capacity of the panels be minimized and that the panels be freely mounted so as to facilitate convective heat transfer.

Flame-retarding materials are recommended for all suspended ceiling construction.

Subject Headings: *Sprinklers, automatic, interference by ceilings; Ceilings, translucent, interference with sprinklers.*

A. L. Goldstein

Rodden, R. M. (Stanford Research Institute, Menlo Park, California) "Significant Primary Fires from Nuclear Detonations," *Final Report for Office of Civil Defense under Contract OCS-OS-63-149* (January 1966)

Thermal radiation from a nuclear detonation can ignite kindling materials over wide areas. Some ignitions will result in significant fires, or fires which, if not controlled, will destroy one or more compartments or structures. On the basis of data ignition point surveys in 1953 and 1956, the study identifies important kindling fuels; their frequency distribution and likelihood of exposure to nuclear detonations; and the probability of significant primary fires developing from exposed kindling fuels. Important kindling fuels are selected from among materials that can be readily ignited and, upon ignition, have a high probability of resulting in a significant fire. Limited available evidence indicates that frequency of occurrence and probability of exposure of kindling fuels to nuclear bursts will be high in most urban areas. Techniques are presented for estimating the range and incidence of significant primary fires. Such techniques can be used when data are lacking or when limited time or resources prevent the expenditure of the effort required to assess a potential fire problem in detail.

Subject Headings: *Fire, from nuclear detonation; Detonation, nuclear, primary fire from.*

Author's Abstract

Stoll, A. M., Chianta, M. A., and Munroe, L. R. (U. S. Naval Air Development Center, Johnsville, Pennsylvania) "Flame-Contact Studies," *Journal of Heat Transfer* 86C, 449–456 (1964)

Standard flame tests of fabrics are directed toward determination of characteristics such as glowing, flaming, and charring of the material. They do not provide measurements of resistance to heat transfer through the fabric before destruction. Heat-transmission measurements are normally made only with conduction or radiation heating and at relatively low temperatures. This paper presents a description of an apparatus designed for utilization in flame-contact studies of heat transfer by a method especially developed for use with fabric but which is readily applicable to a wide range of materials.

Subject Headings: *Fabrics, testing, by flame contact; Flame, contact testing of fabrics; Testing, of fabrics, by flame contact.*

Authors' Abstract

Williams-Leir, G. (National Research Council, Ottawa, Canada) "A Fire Problem in Aircraft Accident Investigations," *Canadian Aeronautics and Space Journal* 12, 7–10 (1966)

In the wreckage of crashed aircraft, fragments are often found to show signs of fire, and it may be of great importance to determine whether fire preceded or followed the crash. If a certain number of fire-marked fragments should be found to fit onto one another, this may be due to chance or to marking before fracture. This study provides a means of estimating the probability of given configurations on the hypothesis of random distribution of the marked pieces.

Subject Headings: *Aircraft, fires; Fire, in aircraft.*

Author's Abstract

XIV. Miscellaneous

Crain, J. L., Meister, R. K., Thomas, L. G., and Spurlock, A. M. (Stanford Research Institute, Menlo Park, California) "Supplemental Analysis—Civil Defense Rescue," *Analytical Report (Phase 1b) through U.S. Naval Radiological Defense Laboratory for Office of Civil Defense under Contract OCD-PS-64-55* (August 1965)

The Office of Civil Defense (OCD) initiated a research program in the fall of 1963 under Contract OCD-PS-64-55. Phase Ia of this program required a year of research and provided a detailed formulation of the problem. A parametric study was made of attack conditions leading to preliminary conclusions of the magnitude and character of the problem, including time constraints and the major contingencies on rescue feasibility. The effort produced a working paper entitled *Civil Defense Rescue Requirements Following a Nuclear Attack.* This phase of the research was not intended to produce system solutions to the problem.

The four chapters and their authors are:

Development of Personnel Casualty and Trapping Functions—Robert K. Meister
Relationship between Fire and Rescue—Robert K. Meister
Postattack Rescue System Criteria—Lacy G. Thomas
Location of Trapped Survivors by Acoustical Methods—Eugene M. Spurlock

Relationship between Fire and Rescue

The outer radius of initial ignitions from thermal energy is highly sensitive to visibility. Outer ignition radii also vary greatly between surface and air bursts. In the former case, the angle from the fireball to the outside radius of ignitions is 2° to 3°. Tops of houses are the only residential material assumed visible and subject to ignition by thermal energy. With air bursts, however, interior kindling fuels are assumed to be exposed to direct thermal energy through windows, and thus to be the principal causes of structural ignition.

The outer radius of secondary ignitions generally extends well beyond that for direct thermal energy—out to the 2.5 psi overpressure range. These ignitions occur in 1.5% of residential structures, and, within the postulated fire-spread conditions, ultimately grow until 50% of the structures in the given area are destroyed.

In comparing the survivor functions (i.e., percentage of survivors in various categories vs distance from ground zero) with the fire spread history, seriously injured or trapped persons are not found beyond the outer fire perimeter. Thus, their rescue can only be conducted prior to the time when the fire prevents further rescue operations or after the fire had died and the area has cooled. The early rescue period lasts three to four hours after the burst.

After the fire has cooled, a portion of the original rescue area may still contain survivors since only 50% of the structures have been destroyed in the area. Rescue, however, depends upon whether any lethal fallout has occurred over the area; if so, further rescue operations are useless (except in special instances). Therefore, effective rescue operations must generally be completed prior to the buildup of the fire.

During the first hours of the initial rescue period, significant numbers of uninjured and lightly injured survivors will be fleeing the fire area. It is very likely that directing these fleeing persons to safe areas will be the principal concern of any general rescue force. Rescue of the seriously injured and trapped may be completely preempted in many cases by more urgent demands on available manpower.

For surface bursts, stem fallout also creates a rescue time constraint that must be considered in the same context as the rescue time constraints resulting from the fire. In general, stem fallout extends much farther downwind than the fire and comcompletely prevents any rescue activities. Upwind and cross-wind fallout are of no significance except under low visibility conditions, whereby it—and not the outer edge of primary ignitions—determines the inner radius of possible rescue operations.

In proceeding through each of the steps of this analysis and in selecting appropriate and practical input parameters, the decision was always to limit the fire spread and to increase the time of spread. As a result, the best possible case for rescue is developed, i.e., as large a portion of the survivors as possible are left in a rescuable location, and the rescue time is maximum.

It should be emphasized that there are natural variations in the input parameters, such as distance between houses and rows of houses, the amount of shading by trees, the effect of seasonal changes in atmospheric visibility, cloud coverage, tree foliage, and effective window openings. There are also variations in the methodology for analytically determining probabilities of ignition, fire, and fire spread. Finally, there are uncertainties about the actual effects of high yield nuclear detonations. All of these possible uncertainties can cause a very large variance in the fire picture and hence in the feasibility of civil defense rescue operations.

This research attempts to present the best case for rescue, however, while using practical, correlated, average U.S. city inputs. Nevertheless, it is possible to postulate a practical case where rescue would generally be infeasible (i.e., by using high visibilities, close spacing of houses, and other conditions that do exist within some cities at certain times of the year).

Subject Headings: ***Civil Defense, fire problems; Fire, problems of Civil Defense; Rescue, fire problems in Civil Defense.***

Authors' Summary

La Mer, V. K. (Professor Emeritus of Chemistry, Columbia University, New York, New York) **and Healy, T. W.** (University of California, Berkeley, California) "Specification of Materials for the Retardation of Evaporation of Water—The Spreading of Hexadecanol Monolayers," *Proceedings of the National Academy of Sciences of the United States of America* **52**, 679–683 (1964)

Field studies on the control of evaporation by monolayers have progressed to a stage where detailed specifications and treatments of the monolayer-forming material are required. The Columbia University surface pressure–evaporation balance (Evaporimeter), as now operating, is suitable for delineating such specifications. Previous investigations in these laboratories had not included the rate of spreading of the monolayer. Monolayers have been spread by various means and left to approach equilibrium. A time of 200 sec is sufficient to attain this state. A survey of the spreading rate behavior of the alcohols therefore became necessary in order to utilize fully the resistance-pressure balance as a tool for specifying suitable materials for field work.

Subject Headings: ***Evaporation, retardance by monolayers; Monolayers, retarding evaporation.***

Authors' Abstract

BOOKS, MEETINGS, NEW JOURNALS

Books

Shchelkin, K. I. and Troshin, Ya. K. (Academy of Sciences, Moscow, USSR) *Gasdynamics of Combustion* Translated by Boris W. Kuvshinoff and Lester Holtschlag (Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland) Mono Book Corp., Baltimore, 1965 222 pages.

A concise and coherent account of combustion problems from the viewpoint of the aerodynamicist is provided with a broad coverage including detonations, deflagrations, non-Hugioniot combustion, accelerated flames, and combustion instability. The book is necessarily brief and the reviewer, a physical chemist, had difficulty in following many of the arguments. This is a result of the Russian affinity for brevity and to differences between what English and Russian scientists consider obvious. Despite this, the conclusions were generally understandable and the illustrative problems with solutions enhances the usefulness to the nonspecialist.

Two weaknesses seem worth commenting upon. First, there is a complete neglect of laminar-flame theory and the chemical aspects of combustion and secondly, there is a lack of recent Western literature. The neglect of the chemical complexities is certainly defensible in a book of gasdynamics of combustion, but it is unfortunate that a short chapter was not added to indicate the nature of these problems and the progress which has been made in the field. The attitude that chemical complexities preclude a compact, coherent treatment seems overdrawn, since flame theory is well developed and the chemistry of many common flames are understood quantitatively.

The book is short of Western literature. No reference is made to Western theoreticians or experimental studies on flame structure and flame instabilities. The treatise of Hirschfelder, Curtiss, and Bird (*The Molecular Theory of Gases and Liquids*, John Wiley and Sons, 1954), for example, is not mentioned. This is hardly due to chauvanism since older literature is referenced and a discussion is given of the turbulent flame structure work of Summerfield. It probably indicates that the effective time lag for English studies to penetrate Russian thinking is at least five years. An indication of this lag is that selected parts from the Sixth Combustion Symposium held in 1956 (*Proceedings, Sixth Symposium* (*International*) *on Combustion*, Reinhold Publishing Co., New York, 1957) appeared in Russian translation in 1961 and was just missed by the authors who published in 1962. It is not a bad showing, however, since it is only twice the information lag found in most English (and Russian) monographs due to the finite time taken to write and publish books.

It is a smooth translation into idomatic English and a credit to the translators. The principal trace of Russian is the Cryillic alphabet in the illustrations. This provides an interesting contrast to the Greek letters common in this country. A good table of nomenclature more than makes up for the slight confusion which the unfamiliar characters may introduce.

The book offers a representative sampling of the Russian literature and the translators have done a commendable job in listing existing English translation. This should become standard practice with Russian translations because many research workers seem unaware of the availability of recently translated Iron Curtain country scientific literature.

In summary, the book can be recommended both as a survey of Russian work and thinking and as a concise treatment of combustion gasdynamics in its own right. Typography and general appearance are good.

Subject Heading: *Combustion, gasdynamics.*

R. M. Fristram

Meetings

70th Annual Meeting of the National Fire Protection Association—Chicago, Illinois, May 16–20, 1966

Nearly 3000 members and guests registered at the 70th Annual Meeting of the National Fire Protection Association in Chicago held at the Palmer House Hotel, May 16 to 20, 1966. The NFPA is generally recognized as the international clearinghouse for fire matters. By membership in NFPA, no one is pledged to any course of action, and people from all walks of life may and do join. Insurance people, who started the Association in 1896, have been successful in getting others to join with them; they are now outnumbered in NFPA both by representatives of industry and by public fire departments. Membership includes 23,000 persons professionally concerned with fire matters in industry and commerce and in government agencies, federal, state and local, in addition to fire departments.

Features of the Meeting included an Aviation Seminar devoted to fire problems of aircraft and airports, a Case Study of Industrial Fire Protection, a Fire Service Forum covering public fire department matters, and a Fire Prevention Education Session on the problem of loss of life and injury due to fires in clothing. In sessions ancillary to those of the NFPA, four organizations, which operate as sections of the NFPA, held their annual meetings. These are the Fire Marshals Association of North America, the Society of Fire Protection Engineers, the Railroad Section, and a new Industrial Section. Membership in NFPA sections carries with it the need to be members of NFPA, but each section sets its own membership requirements.

The week devoted to NFPA meetings also prompts convocations of groups concerned with fire matters but not directly associated with NFPA. For example, the managers and engineers of the fire insurance rating boards and bureaus held a meeting of their Advisory Engineering Council. Also, about a dozen technical committees of the NFPA held meetings during the week, taking advantage of their members' presence in Chicago.

Paul C. Lamb, Safety Administrator, Lever Brothers Company, New York, was elected president, and Elmer F. Reske, Manager, Illinois Inspection and Rating Bureau, Chicago, was re-elected vice president. A new second vice president was elected, John J. Ahern, Director of Security, General Motors Corporation, Detroit. Vice President Reske served as Chairman of the local committee for the NFPA Meeting, and the Chicago Fire Department was a cordial host. Chief Fire Marshal Curtis W. Volkamer welcomed the delegates and fire department attendance was conspicuous at sessions.

Action on Standards

The chief business of the NFPA Annual Meeting was action on proposed standards which will affect fire laws and regulations as well as practices in commerce and industry. At the 1966 Meeting, 36 committees recommended action on 41 standards. The NFPA will formally compile a record of action on technical committee reports in *Proceedings* to be issued later in the year. Copies of papers presented at the Annual Meeting will be processed for reproduction appropriately in the NFPA periodicals, the six-times-a-year *Fire Journal*, the quarterly magazine, *Fire Technology*, and the monthly, *Firemen*. Others will be published in NFPA *Meeting Papers*.

Since 1913, an NFPA Committee on Safety to Life has prepared recommendations dealing with exits which should be provided from buildings and related matters. These have been embodied in a Building Exits Code. Regardless of other provisions in state laws and city ordinances, the NFPA Building Exits Code has come to be the last word in determination of the reasonableness of requirements in buildings for life-safety from fire. The 1966 Annual Meeting adopted a 20th edition of this code, renaming it "Life Safety Code," believing that this new name most accurately defines its purpose. Since the code is used primarily as a supplement to building codes, the current revision has been editorially arranged so that the content is in the same general order as that of building codes.

Among items debated in connection with the adoption of the 1966 edition of this code was the extent to which automatic sprinkler systems should be applied to hospitals, nursing homes, and residential–custodial care facilities. Debate on this matter showed that the Committee was pressing for complete automatic sprinkler systems in residential–custodial care facilities regardless of height or type of construction. The Committee's position is that sprinkler protection for these occupancies is essential because the people concerned, as a practical matter, cannot normally use exit facilities even if they are provided and that fire resistive construction alone does not assure life safety. The enforcing authorities, however, saw enforcement difficulties, and the action of the Annual Meeting supported their recommendation that automatic sprinkler protection be provided throughout all hospitals, nursing homes, and residential-custodial care facilities except those of fire resistive or one-hour protected, noncombustible construction.

A significant debate was involved in approval of a 1966 edition of a recommended system for the identification of fire hazards of materials. This system, in development since 1957, provides readily recognizable and easily understood markings which can be used in industry to give, at a glance, a general idea of the inherent hazards of any material and the order of severity of these hazards as they relate to fire prevention, exposure, and control. The system identifies the hazards of a material in terms of three principal categories—health, flammability, and reactivity, and indicates the order of severity numerically by five divisions ranging from 4 to 0. This has been a very popular identification system. At the NFPA Meeting strong representations were made by state fire marshals and similar authorities that this system should be extended to materials in public transportation, to replace or augment what is at present offered by ICC identifications. The committee responsible for the system has taken the conservative position that it could not yet go so far as to recommend its application to materials in transportation. The Annual Meeting voted for the fire marshals' proposal. The NFPA Board of Directors subsequently referred this difference of judgment back to the committee for further consideration before finally committing the Association.

Aviation Seminar

In one session of the Aviation Seminar, the NFPA Sectional Committee on Aircraft Rescue and Fire Fighting reported with technical movies a series of tests in October 1965 aimed at evaluating the perfluorinated surfactants used in conjunction with potassium-bicarbonate-based dry chemicals as compared with other protein foams and the use of dry chemical alone. Film footage was also shown from a series of tests conducted at the National Aviation Facilities Experimental Center (NAFEC) in 1964 on crash fire-fighting techniques. The impact of future aircraft (including the so-called "stretched" jets, the "jumbo" jets, and SST's) on rescue and fire-fighting requirements was considered. A series of new tests underway at NAFEC to define "adequate" fire protection for crash-fire situations was reported as was an approach to the problem of rescue operations based on protecting "evacuation zones."

A second session of the Aviation Seminar had as its theme research to advance aircraft fire safety. One paper dealt with experiments on gelling of aircraft fuels to reduce their hazard; a second, on tests of aircraft cabin interior finishes which have as their purpose studying and evaluating the flame spread and smoke contribution characteristics of existing materials; the third research project reported on new methods of facilitating egress from aircraft by the use of explosive charges to blast a hole in the side of the fuselage to permit rapid evacuation; the fourth, some work on utilizing high-expansion foam for fire-suppression purposes on-board aircraft. The session was concluded by a detailed report of the lessons learned from the Salt Lake City 727 accident which caused the loss of forty-three lives, attributable to fire after impact.

Fire Marshals Association of North America

The Fire Marshals Association of North America organized in 1906 is made up of state, provincial, county, and municipal fire marshals. These men are charged with investigation of fires in their respective jurisdictions and the administration of laws relating to hazardous chemicals and explosives and safety measures to prevent loss of life due to fire. Since 1927, it has operated as a section of NFPA. The

Fire Marshals Association of North America provides a particularly valuable means by which the experience of public authorities responsible for fire safety may be fed into the deliberations of the Association on its codes and standards. The Fire Marshals group accepts the responsibility for naming certain of its members specially qualified in the respective subjects to membership on NFPA technical committees. Part of its Annual Meeting was devoted to review of recommendations of NFPA technical committees in 1966, which discussion was reflected when recommendations of the various committees were acted on by the main sessions of NFPA.

Society of Fire Protection Engineers

The Society of Fire Protection Engineers, with 1300 members, operates as a section of NFPA. It is a member of the Engineers' Joint Council and sets membership standards that are comparable to those of the other engineering societies. Among papers presented to the Society meeting were "Studies of Building Fires with Models," by Fred Salzberg of the IIT Research Institute, and "Secondary Ignitions in Nuclear Attack," by Kendall D. Moll of Stanford Research Institute. Three papers dealt with building construction matters: "Factors Influencing Fire Resistance of Concrete," by Armand Gustaferro of the Portland Cement Association, "Fire Protection of Structural Steel," by Richard Wildt, Bethlehem Steel Corporation, and "Fire Hazard of Interior Finish Materials," by Norman S. Pearce, Underwriters' Laboratories of Canada. A paper, "Fire Protection for Restaurant Kitchen Hoods and Ducts," was presented by S. E. Auck, Underwriters' Laboratories Inc.; another, "Developments in Fire Alarm Systems and Devices," was presented by Keith Dix, Schirmer Engineering Corporation.

Fire Prevention Education

The things that motivate the actions of people have been found to be relatively more important than technical details of fire protection. The NFPA originated about 1913 the first of the "weeks," Fire Prevention Week. It has been supplemented by Spring Clean-Up Campaigns and by sponsorship of Sparky the fire dog, a symbol for use in the education of children in fire safety.

At a session on Fire Prevention Education at the Annual Meeting, Louis Segal of the California State Fire Marshal's Office and Chairman of the NFPA Committee on Wearing Apparel, estimated approximately 2000 fatal incidents occur annually in the United States due to combustible wearing apparel and that there are another 250,000 cases of nonfatal clothing fire burns severe enough to require medical attention. Mr. Segal reviewed possible solutions: restrictive legislation, technical breakthroughs, and public education. He expressed the opinion that of these, education offers the greatest prospect for effective results in the forseeable future. Education of the public to want safer clothing offers the best means of getting such clothing on store shelves was an observation by Thomas L. Rusk of Sears, Roebuck & Company, which maintains a laboratory to keep it informed on textile flammability.

At this session William V. White of the U.S. Public Health Service, and Dr. Edward Press of the Illinois Department of Public Health discussed programs of their respective departments and experience with legislation. The lively interest of manufacturers in safe products was described by Wallace P. Behnke, Textile Research Laboratories, E. I. du Pont de Nemours Company, in a description of his Laboratories' research approach to the problem of protection from heat exposure.

An International Note

Members from England, France, Australia, and New Zealand were among those attending the Chicago Meeting. In his Annual Report, NFPA General Manager Percy Bugbee announced that a permanent Conference of Fire Protection Associations has been formed. This conference is made up of the fire protection associations of Australia, Belgium, Denmark, Germany, Spain, Finland, France, Holland, Japan, Norway, Austria, Switzerland, Sweden, United Kingdom, and United States. [At the time Mr. Bugbee reported, a meeting of the respective staff directors of these associations was scheduled for Weisbaden, Germany, June 4–5, 1966. This conference was subsequently held, attended by representatives of all 15 of the associations except one (Japan).]

Subject Headings: *Meeting, National Fire Protection Association; National Fire Protection Association, meeting.*

H. Bond

Conference on the Properties and Uses of Plasmas, Moscow 1965

Among the papers presented at this Conference were the following:

"Ionization by Electron Reactions in Hot Gases at Atmospheric Pressure" by A. von Engel

"New Evidence for Excessive Electron Temperature in Torch Flames" by J. R. Cozens

Both von Engel and Cozens are at Oxford University, Oxford, England. For additional report on their work, see *Fire Research Abstracts and Reviews* 8, 104 (1966).

Subject Headings: *Electron temperatures, in flames; Electron temperatures, in flames, excessive; Flame, electron temperatures in; Ionization, in flames; Electrons, in flames; Chemi-ionization. Meeting, Conference on Properties and Uses of Plasmas.*

Editor

A Symposium on Fire Testing—Armstrong Cork Company, Lancaster, Pennsylvania, June 24 and 25, 1965

"Structural Fire Protection Requirements of Building Codes"—J. C. Spence, American Iron and Steel Institute, New York, New York

The building codes of the major cities in the United States and the four model codes have been surveyed to determine the existing structural fire protection requirements for buildings. A comparison is made of the protection requirements for the fire resistive types of construction and the requirements as they would apply to buildings of unlimited height and area for occupancies including apartments, office buildings and institutions. The study also includes information on the existing regulations in codes relating to the acceptance of modern methods of structural fire protection. Requirements relating to special limitations and interpretations have been surveyed.

"Determining Performance Requirements"—H. E. Nelson, General Services Administration, Washington, D. C.

Considerations of factors of construction and occupancy that determine the intensity levels reached in fires and the maximum expected fire severity and the relationship of these and other factors to fire propagation as they affect the development of reasonable performance requirements. Also the relationship of variation in firesafety needs or objectives of an organization to variations in performance requirements.

"Problem Areas in the Application of Fire Test Data in the Design of Fire Safe Buildings"—R. E. Carlson, Office of California State Fire Marshal, Sacramento, California

Safety to life and property from fire in fire-resistive buildings begins on the architect's drawing board, not with the sounding of an alarm and the question of how much equipment and manpower is available for rescue purposes or to combat the fire. A firesafe building incorporates many features of a design and protection among which are fire-resistive construction and a restricted use of combustible finish material. Three fire test procedures enter into the classification of materials essential in the design of a fire-resistive building. First of these test methods are those that establish the classification of combustible or noncombustible materials. Next are the fire test methods that establish the fire-endurance ratings of materials or the assembly of materials. Last is the test method determining the surface flammability of interior finishes. In order that the fire protection engineer may provide a firesafe building and satisfy the design criteria established by the architect he must properly apply the fire test data developed by the above fire test methods. Each of these fire test methods incorporates some inherent deficiencies which the fire-protection engineer must recognize and take into consideration in the design of a firesafe building.

"Heat Contribution Rates by the F M Construction Materials Calorimeter Procedure and Typical Results"—J. A. Wilson, Factory Mutual Engineering Division, Norwood, Massachusetts

The rate of heat contribution is a significant factor in evaluating the fire hazard of materials. A method is presented for measuring this property including a description of the test equipment, the key steps of the method, and typical results. These results are compared with those derived by other known test methods and possible applications for their use are presented.

"Fire Test Methods for Interior Finishes"—C. H. Yuill, Southwest Research Institute, San Antonio, Texas

Fire test methods are discussed in terms of (1) building elements evaluated, (2) the characteristics measured, (3) the test methods in use, and (4) questions yet to be resolved. Particular emphasis is placed upon the differences in the test methods, the ever-widening application of the tests and questions relating to test operation that as yet have not been resolved satisfactorily. While commenting on several test methods, the author primarily discusses the 25 ft tunnel furnace test with which he is most familiar. Among items covered are: the effect of substrates, configuration, misapplication of the test (other types of tests more suitable), correlation of results with building fires and use of the test in defining a noncombustible material.

"Construction of an ASTM E 119 Furnace"—Z. Zabawsky, Armstrong Cork Company, Lancaster, Pennsylvania

An ASTM E 119 Furnace was constructed by the Armstrong Cork Company to evaluate its materials and to predict time-design ratings. Since this apparatus is used to evaluate materials and not building constructions, some of the elaborate controls and construction features were redesigned to make an apparatus that was simple to operate. The design, construction and operation of such an apparatus is presented.

"Significance of ASTM E 119 Floor-Furnace Tests"—R. F. Bellman, Underwriters' Laboratories, Inc., Northbrook, Illinois

Many fire tests are conducted every year to establish ratings on floor or roof, wall, and column assemblies. To be meaninfgul all aspects of each proposed assembly must be considered so that the test results can be representative of the performance that can be expected in the field, since the size of the test sample is limited to the size of the furnace dimensions. The Laboratories' engineers, in working with test sponsors, consider many factors such as the formulation and physical properties of proprietary fireproofing materials (e.g., acoustical tile, spray-on materials, precast-concrete units, wallboard, etc.); arrangement of components in suspended ceilings; and layout of structural members to achieve typical spans and loading to stress these units to maximum design stresses. This is necessary to develop results that will be meaningful to architects, building officials, and rating bureau personnel.

"The Effect of the Building Frame on the Fire Resistance of Floor and Ceiling Assemblies"—R. W. Bletzacker, Ohio State University, Columbus, Ohio

The structural performance of floor and ceiling assemblies as an element of a completed building under fire conditions is discussed. It is assumed that the fire resistance is determined by the load-carrying criterion rather than the temperature transmission criterion. Analyses of the thermal moments developed in the floor structure due to fire exposure are presented. The distribution of thermal forces to the adjacent building frame is evaluated, and the resultant reaction of the structure is derived. Expressions for the change in modulus of elasticity and yield stress as a function of temperature are used in iteration techniques to determine the onset of structural collapse.

"Doors as Barriers to Fire and Smoke"*—H. Shoub and D. Gross, National Bureau of Standards, Washington, D.C.

A study was made of means for improving dwelling unit entrance doors as fire and smoke barriers. Existing combustible doors and frames could be modified to enhance their fire resistance, but it did not appear practical to raise them to the level of rated commercial fire door assemblies. Fire retardant paints, except those consisting of heavy, reinforced, intumescent-type coatings, provided little or no increase in fire resistance. Several modifications of existing doors were not effective in preventing the transmission of smoke. However, controlling the pressure levels on both sides of a door, as by suitable venting, appeared to offer a means of reducing smoke penetration into an area. It is recommended that current methods of fire tests of doors, and criteria relating to their fire and smoke transmission be improved.

Subject Headings: *Building codes; Fire-smoke barriers, doors; Fire testing, of materials; Furnace, for fire testing; Meeting, Symposium on Fire Testing.*

Authors' Abstracts

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* Issued by National Bureau of Standards, Building Science Series No. 3 (March 25, 1966). Available from Government Printing Office, Washington, D.C. 20402

Technical Meeting on "Inhibition of Combustion by Chemical Means"—Committee on Fire Research. Applied Physics Laboratory, The Johns Hopkins University, June 23 and 24, 1966

An informal discussion on "Inhibition of Combustion by Chemical Means" was held on June 23 and 24 at the Applied Physics Laboratory of The Johns Hopkins University, sponsored by the Committee on Fire Research of the National Academy of Sciences—National Research Council. The intent of the meeting was to survey the current understanding of inhibition in flames and in detonations. Presentations were made in four half-day sessions on the following topics: "Inhibition of Homogeneous Premixed Flames" (Chairman: C. P. Fenimore, General Electric Research Laboratories); "Inhibition of Homogeneous Diffusion Flames" (Chairman: R. Friedman, Atlantic Research Corporation); "Heterogeneous Inhibition" (Chairman: U. Bonne, Honeywell Research Center); and "Pertinence of Inhibition Research to Fire Technology (Chairman: H. Emmons, Harvard University). Approximately 70 persons from research establishments, industry, and universities participated. After the first day's discussions, R. Tuve (Naval Research Laboratory) demonstrated impressive advances in the extinguishment of large gasoline fires with a combination of active dusts (potassium bicarbonate) and a low-density water-containing surfactant foam. Merle Lowden, Director of Fire Control, Department of Agriculture, summarized his experiences in Brazil where he was called as a consultant during a disastrous epidemic of plantation fires in 1963.

Inhibition of Homogeneous Premixed Flames

The detailed analysis of flame structure by the Fristrom–Westenberg sampling technique has been applied to a methyl bromide-inhibited lean flame of methane–oxygen (W. E. Wilson, APL/JHU).[1] From the analysis of net reaction rates it was suggested that chemical reactions involving methyl bromide and responsible for "inhibition" are taking place prior to the beginning of the methane-oxygen reaction. Because of their low activation energy, they compete with the chain-branching reaction $H+O_2 \rightarrow OH+O$, thereby postponing the initiation of the main hydrocarbon reactions until a higher temperature level is reached than in an uninhibited flame. It was pointed out that, although homogeneous inhibition decreases, the integrated reaction rates as indicated by burning velocity, the peak rate may reach a higher maximum value, but at a later time or position in the reaction zone.

The interesting empirical observation (W. Creitz, National Bureau of Standards)[2] that inhibition power and electron attachment of halogen-containing additives correlate rather well is being supplemented by an experimental study of ion and electron concentrations by W. J. Miller (AeroChem Research Laboratories, Inc.) using direct sampling in inhibited flames. Flame ions do not appear to be directly responsible for the inhibiting effect due to their low concentrations. However, their chemistry may be directly related and may provide useful information on radicals and molecular fragments which, as neutral species, are below the limits of sensitivity of available detection devices.

Flammability limit measurements (M. Gerstein, Dynamic Science Corporation) leave no doubt that inhibitors must be effective via chemical mechanisms, although the nature of this interference cannot readily be deduced from such data. However, in the case of hydrogen–oxygen detonation limits, the details of the kinetic steps and rate constants are sufficiently well known (R. S. Brokaw, NASA)[3] so that the effect of inhibitors (and promoters) can be predicted quite satisfactorily. R. H. Essenhigh (Pennsylvania State University) suggested that the "Homogeneous Reactor" blow-out limits should serve as effective means in the evaluation of potential inhibitors on a quantitative basis.

J. F. Wehner (University of Notre Dame) reported on a theoretical analysis of an A B C model flame, where, for certain reasonable values of reaction rates of the individual steps, the relevant flame equations had no rational solutions, thereby predicting the existance of fundamental flame propagation limits in one-dimensional premixed flames.

Inhibition of Homogeneous Diffusion Flames

A. E. Potter (NASA)[4] described the development of the "opposed jet" technique for measuring reaction rates in diffusion flames. This method has been improved by better aerodynamic controls of flow by H. Tsuji (Aeronautical Research Laboratory, Tokyo)[5] and should lend itself admirably to a rapid, quantitative study of inhibition effectiveness. In the only reported study (R. Friedman, Atlantic Research Corporation)[6] where this method was applied (the potential inhibition of alkali metals), no effect was noted where the metal vapor was added to the fuel. It was speculated that this lack of effectiveness may occur because the active specie is the hydroxide rather than the metal atom and that the former is not produced in the fuel-rich part of the flame. It was pointed out (H. Wise, Stanford Research Institute)[7] that combinations of halogen-containing compounds and alkali metal salts are less effective than the individual components due to the formation of stable gaseous alkali halides, which do not then interfere with a rate-determining chain-branching reaction. It should be noted that the detailed sampling methods that have proved successful with premixed flames have not been applied to diffusion flames.

Heterogeneous Inhibition

The experimental difficulties of evaluating and characterizing heterogeneous inhibitors are very great. Effectiveness of dusts added to diffusion flames is most likely due to evaporation of an active material from the dust, since the particle sizes and spacings of inhibitive dusts would appear to be too large to permit diffusion of gaseous species to the surface. Surface recombination of radicals could be the dominant process if particle surfaces were increased by fissioning in the flames. Recombination may also be important with heterogeneous precipitates, generated *in situ* in the flame by a chemical reaction (as in the case of iron pentacarbonyl—a most effective reducer of flame speeds) may act by surface inhibition. No definitive conclusions can be drawn as yet.

H. Wise (Stanford Research Institute) discussed problems and possible mechanisms of inhibition by powders. U. Bonne (Honeywell Research Center)[8] reviewed measurements on flames inhibited by $Fe(CO)_5$, a very powerful inhibitor, in which iron oxide particles are produced *in situ*. The particles appear to be produced late in the flame. Measurements of OH profiles indicate that the peak concentration and flame temperatures were essentially unaffected by amounts of $Fe(CO)_5$ which reduced burning velocity markedly. The formation and recombination rates were affected. J. M. Singer (U.S. Bureau of Mines) discussed the ignition of coal dust–methane mixtures. M. Vanpée (Thiokol Corporation) demonstrated the effectiveness of potassium compounds in preventing ignition of hot rocket exhausts containing CO and H_2.

It was pointed out by U. Bonne (Honeywell Research Center) that a most desirable research project would be to subject a single flame system to the various available techniques (chemical sampling of stable species, absorption spectroscopy of free radicals, etc.). The separate methods of analysis are sufficiently complementary so that their simultaneous employment should lead to a substantially better understanding of the dominant processes in inhibited flames.

Pertinence of Inhibition Research to Fire Technology

The status of the understanding of the elementary chemistry of flame inhibition was summarized by R. Fristrom (Applied Physics Laboratory).[9] The chemistry of several simple flames is understood quantitatively and many flame reactions have been identified and possess reliable kinetic constants. A few inhibition reactions have been studied and scattered data is available on their rates and kinetic constants. Machine programs are available which could be modified to use data of this kind in cases where it is available; thus in principle it is possible to attack practical inhibition problems on the fundamental level. The present potentialities of this approach are limited by a scarcity of reliable rate data, but within the coming decade sufficient information should become available to make the basic approach practical.

A substantial part of the final session was devoted to an informal discussion of the role of research and its potential benefits and interactions with the practitioners engaged in actual fire prevention and extinguishment.

The problems of supporting basic fire research, particularly in this area, were discussed. The present situation is less than satisfactory since much of the research in the area is a by-product of studies with other objectives, and, as a result, many crucial pieces of information are lacking. The largely nonproductive nature of fires (i.e., unexpected losses rather than creation of new values), their widespread but relatively small-scale occurrence and the complexity of the events, have conspired to prevent an active and fruitful research program from being organized and having a beneficial effect on the technology of fire prevention and extinguishment. Problems are generally attacked on an ad hoc basis and are solved with specific aims in mind. As new problems arise a vigorous effort is put into practice but as soon as an immediate solution is in sight the development effort is stopped without inquiry into the underlying causes and generalizations. This pattern almost automatically isolates the field from the benefits of modern technology and prevents it from reaching more effective and sophisticated levels of practice.

In the particular instance of "Inhibition of Combustion by Chemical Means" only a handful of projects are being pursued at the present time, with funds earmarked for fire research. Therefore, there is little prospect of significant results and advances in the years ahead. This is, unfortunately, not an isolated instance. Other areas of interest (ignition, fluid dynamics of fires, thermal degradation of materials, etc.) are equally devoid of fire research funds. Thus, progress will come about only indirectly from work funded from other sources and undertaken for other purposes. It was the concensus of the discussion that, in contrast to other technological endeavors, the research base in the fire field is poorly supported. As a consequence, the number of people who spend time and effort to think about and act on fire-related research projects is small. This cannot fail but give concern since the increasing complexity of technology and social organization will cause the threats and losses from unwanted fires to increase substantially.

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Subject Headings: ***Chemical inhibition; Inhibition, chemical; Inhibition, meeting, Committee on Fire Research; Meeting, Inhibition of Combustion by Chemical Means.***

W. G. Berl and R. M. Fristrom

INDEX OF AUTHORS

INDEX OF SUBJECTS

CUMULATIVE INDEX OF AUTHORS

CUMULATIVE INDEX OF SUBJECTS

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