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W. G. Berl, Editor; Committee on Fire Research; National Research Council

International Symposium on
THE USE OF MODELS IN FIRE RESEARCH

> "*. . . science is more than an accumulation of facts; . . . it is not simply positive knowledge, but systematized positive knowledge; . . . it is not simply unguided analysis and haphazard empiricism, but synthesis; . . . it is not simply a passing recording, but a constructive activity . . .*"
>
> —George Sarton

International Symposium on

THE USE OF MODELS IN FIRE RESEARCH

Sponsored by
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The Fire Research Conference
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W. G. Berl, *Symposium Proceedings Editor*

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PREFACE

This volume contains the Proceedings of the First International Symposium on Fire Research, sponsored by the Committee on Fire Research of the National Academy of Sciences—National Research Council and held in Washington, D. C. on November 9–10, 1959. The topic of the conference was "The Use of Models in Fire Research."

From its inception the Committee on Fire Research recognized the need for increased emphasis on and support of fundamental studies. Areas in which fruitful work could be done were delineated and brought to the attention of scientists working in these and related fields. Simultaneously, a small periodical, devoted to reviews and abstracts of topics related to the fire problem, was started under the auspices of the Committee. In addition, plans were laid for holding symposia on specific subjects of current interest.

The understanding of modeling principles is of particular importance to Fire Research. Quantitative descriptions of the structure, intensity, and propagation rate of large-scale fires can be made only on the basis of models if all the important scaling parameters are understood and taken into account. The papers of Taylor and Hottel show clearly the difficulties that must still be overcome.

Based on the pioneering study of Blinov and Khudiakov a number of investigations are under way in which the experimental parameters of a fire over a liquid surface are explored in detail. This is probably the simplest case of a controlled and scalable fire situation which can be related to a reasonably detailed theoretical analysis. Here important advances may be expected in the near future.

The intimate interplay between aerodynamics, heat transfer, and chemical reaction rates makes the study of fires the intriguing problem it is. Many situations of practical interest present special cases of those factors and require, therefore, that problems with specific boundary conditions be investigated. The papers dealing with the Aerodynamics of Fires and with Experimental Techniques give some new insights into these problems.

Rounding out the technical presentations, three full-scale investigations were described in an evening session, and are included in condensed form in an Appendix.

The arrangement of the program was in the hands of Mr. A. A. Brown, Director, Division of Forest Fire Research, U. S. Forest Service, supported by members of the Committee on Fire Research and its capable staff. The interest shown by the participants and the general high level of the contributions give encouragement for holding another conference on one of the major Fire Research topics.

W. G. Berl, *Symposium Proceedings Editor*

PROGRAM

Welcome

Dr. S. Douglas Cornell, Executive Officer, National Academy of Sciences—National Research Council

Introduction and Background

Professor H. C. Hottel, Chairman of Committee on Fire Research and Fire Research Conference

SESSION I—MODELING PRINCIPLES

Presiding, Professor H. C. Hottel, Massachusetts Institute of Technology

Fire under Influence of Natural Convection

Professor G. I. Taylor, Cambridge University, England

Fire Modeling

Professor H. C. Hottel, Massachusetts Institute of Technology

SESSION II—LIQUID SURFACE MODEL FIRES

Presiding, Dr. William H. Avery, Applied Physics Laboratory, The Johns Hopkins University

Some Observations on Pool Burning

Dr. Howard W. Emmons, Harvard University

Burning Rates in Liquid Fuels in Large and Small Open Trays

Dr. David S. Burgess, U. S. Bureau of Mines

Tests on Combustion Velocity of Liquid Fuel and Temperature Distribution in Flames and Beneath Surface of Burning Liquid

Dr. Gert Magnus, Technische Hochschule, Karlsruhe, Germany

Effectiveness of Some Powdered Materials in Extinguishing Hydrocarbon Fires
Mr. T. G. Lee, National Bureau of Standards

Commentaries on Session II

Dr. Bernard Lewis, Combustion and Explosives Research, Inc.

Mr. Joseph Grumer, U. S. Bureau of Mines

Dr. Hans Wolfhard, Thiokol Chemical Corporation

Mr. Richard Tuve, Naval Research Laboratory

SESSION III—FULL-SCALE STUDIES AND TESTS

Presiding, Mr. A. A. Brown, U. S. Forest Service

Natural Phenomena Exhibited by Forest Fires
Mr. J. S. Barrows, U. S. Forest Service

The St. Lawrence Burns
Mr. G. W. Shorter, National Research Council, Canada

Operation School Burning
Mr. R. M. Hill, City of Los Angeles Fire Department

SESSION IV—AERODYNAMICS OF FIRES

Presiding, Dr. Howard W. Emmons, Harvard University

Study of Convection Currents Created by Fires of Large Area
Mr. J. Faure, Laboratoire National d'Hydraulique, France

Some Studies of Building Fires Using Models
Dr. P. H. Thomas, Joint Fire Research Organization, England

✓ Upward Convection Current from a Burning Wooden House
Mr. Sizuo Yokoi, Building Research Institute, Japan

✓ Current Research Relevant to Aerodynamics of Fires
U. S. Bureau of Mines—Dr. Michael G. Zabetakis
Stanford Research Institute—Mr. Fred M. Sauer

SESSION V—EXPERIMENTAL TECHNIQUES

Presiding, Dr. Walter T. Olson, National Aeronautics and Space Administration

A Steady-State Technique for Studying Properties of Free-Burning Wood Fires
Mr. W. L. Fons, U. S. Forest Service

Experiments with Model Mine Fires
Dr. J. G. Dawes, Safety in Mines Research Establishment, England

On the Self-Ignition of Wood Materials
Dr. Tosiro Kinbara, University of Tokyo, Japan

Commentaries on Session V

Mr. Frank R. Caldwell, National Bureau of Standards

Dr. Robert Van Dolah, U. S. Bureau of Mines

Professor T. Y. Toong, Massachusetts Institute of Technology

Adjournment
Professor H. C. Hottel

CONTENTS

WELCOME

S. DOUGLAS CORNELL

Executive Officer of the National Academy of Sciences—National Research Council

TO YOU, Mr. Chairman, and to all the participants and guests of this Symposium I extend the warmest welcome on behalf of President Bronk and the officers of the Academy-Research Council.

As science advances, the interests and capacities of its practitioners often become, necessarily, narrower as they become deeper. Fragmentation seems to be a concomitant of the steady evolution of science. We here have long felt that one of our chief purposes must be to bring a counter-influence to bear, to strive for the re-synthesis of science from the complex of its increasingly fertile fragments.

Only thus, we believe, can science reach its fullest satisfactions as a product and a preoccupation of the human mind, and technology find its fullest flower for the material betterment of mankind.

Therefore, we find particular gratification when we can play a part in the holding of a scientific gathering like yours of today and tomorrow, because it represents the bringing together of various scientific disciplines for mutual instruction and stimulation in the interests of eminently worthy technological and human ends.

Such a gathering gives us special satisfaction when it includes our colleagues from other nations who confer upon our program and discussions much additional luster and distinction.

The National Academy of Sciences—National Research Council, as a non-governmental institution for the furtherance of science, has been able, through the years, to draw together the diverse elements of United States science, and often international science, for common ends. The scientific resources for such purposes are supplied by the scientists themselves, the financial sinews by a variety of sources inside and outside the Federal Government.

Our Committee on Fire Research and this Symposium which it has organized, under Professor Hottel's chairmanship, are financed by three agencies of the Federal Government: the Office of Civil and Defense Mobilization, the United States Forest Service, and the Department of Defense.

To them, to our distinguished visitors, to all of you, our gratitude is due for this opportunity to join hands in consideration of a problem of wide scientific and technological interest and of universal human concern.

On behalf of President Bronk I thank you all for being with us and I wish you two full and fruitful days.

INTRODUCTION and BACKGROUND

H. C. HOTTEL

Chairman of the Committee on Fire Research and Fire Research Conference

WE ARE delighted to be the guests of the Academy and hopeful that this meeting to discuss the applications of modeling principles to fire will contribute significantly to the stimulation of interest in fundamental fire research.

A word is in order about the Committee on Fire Research, why it was set up, what progress it has made. The Office of Civil and Defense Mobilization (formerly Federal Civil Defense Administration) and the U. S. Forest Service some years ago asked the Academy for guidance on fire. In response to that request a Committee on Fire Research and a larger Correlation Conference on Fire Research were established. There were almost no terms of reference for the new Committee; we were told to decide what the job was; and the crystallization of our reason for being was rather slow. There ultimately emerged a conviction that, although much vigorous and valuable effort went on in the fire field, that effort showed little influence of the Herculean strides that had been made in the fifteen-year period since the war in physical chemistry, in mathematics, in computational techniques, in fluid mechanics; and the necessarily empirical approach to the solution of pressing fire problems continually arising was not, we felt, properly backed up by fundamental studies to understand fire growth and spread. So our Committee decided to focus attention on one rather small part of the general fire field, that of better understanding fire growth and spread, and to attempt to persuade some of the "purer" scientists that fire presents many challenging problems, and that involvement in fire research can be an honorable estate.

A large conference was held in Washington—larger than this—bringing together representatives of a wide range of disciplines, and including pure scientists on the one extreme and practicing firemen on the other. It was found that although this mixing process had a few salutary effects, there was just too great a spread in background for much development of mutual interests.

The Fire Committee's second large conference was held at the University of California in Los Angeles. That meeting perhaps helped to paint a picture of the problems of forest fires, but it too apparently failed to cause new science-oriented individuals to enter the field of fire research.

In this Symposium we are quite specifically limiting the field to fire research of rather fundamental character and shall not be concerned with ultimate applications to practice. We permit ourselves to wander as far afield as we wish—down various byways in our quest for the ultimate truth about fire.

I might interpolate that although the Fire Committee, in the planning stage of its activity, had no significant funds to spend on fundamental research, it was convinced that the weakness was one of ideas and men, and not of money. We believed then, and still believe, that when enough able scientists and engineers start thinking hard about some of these interesting problems, they will not be stopped long by problems of funds.

From the Fire Committee's deliberations there slowly evolved a proposed program of fundamental research on fire; and after some polishing and repolishing by the larger Fire Research Conference group, it was decided that we were ready to push for action.

The action started in Mr. Macauley's office in the Department of Defense at a meeting with Dr. Killian, Special Assistant to the President for Science and Technology. Representatives of the Fire Research Committee later appeared before Dr. Killian's Research Panel, and then before a group brought together by Dr. Killian representing those civilian and military agencies of the government having an interest in fire. The proposed program of research was presented, together with the recommendation that fire research should be supported in three ways: Some of it would have no difficulty qualifying for sponsorship by the National Science Foundation. Most of it was plainly of an applied character, so plainly of that sort that it would be best administered by directly interested government agencies. A considerable block of the work, no less scientific than that to be sponsored by the National Science Foundation but somewhat more closely controlled as to objective (i.e., coordinated to fill known gaps in our scientific knowledge of fire), deserved to get out from under the direction of the various services where it would otherwise lead a precarious existence budgetwise in competition with those problems showing chance of early pay-off; and the Fire Committee recommended that this third block be coordinated under a single government agency.

At the close of the meeting Dr. Killian appointed a subcommittee of representatives of the various interested government agencies, headed by Mr. Gerald Gallagher of the Office of Civil and Defense Mobilization and charged with replying to our Committee's proposal and formulating a plan of action. The Gallagher Subcommittee in essence accepted the Fire Committee's recommendations, and recommended that the scientific research effort on fire, apart from that which the National Science Foundation would support, should be monitored by the National Bureau of Standards; they added that it was appropriate, however, for the various government agencies to continue support of such fundamental research as was required to back up their ad hoc fire research.

Modest funds for fiscal 1960 will be transferred from the Office of Civil and Defense Mobilization and the Department of Defense to the Bureau of Standards. It is expected that the Bureau of Standards will obtain funds essentially in the same order from Congress in its budget for 1961. This is a small item to those of you who think in terms of military budgets, but it should suffice to get effective work started and, with National Science Foundation support as well, we think some real headway can be made.

Since support of fire research by the National Science Foundation did not need any new action to implement the initiation of projects, our Committee on Fire Research decided this past spring that it was time to start stimulating various individuals and groups to produce some ideas; so we wrote to faculty members of universities with backgrounds of achievement in combustion, to private laboratories (profit and nonprofit), and to government laboratories, asking for presentation of ideas of the type which the proposer believed justified National Science Foundation support. It was carefully pointed out that the Fire Committee itself was in no position to promise this support, and that the National Science Foundation would handle all proposals ultimately through its regular channels; but we did promise to have the proposals assessed by experts known to us and, in consequence of those assessments, to make our own Committee's recommendations available to the National Science Foundation. We received more proposals than we expected, forty or more. Some of the proposers are here in the audience. We are hopeful that a significant number of these proposals will receive favorable action.

An activity of the Fire Committee initiated about a year ago is the publication of a journal, FIRE RESEARCH ABSTRACTS AND REVIEWS, aimed at research people in the fire effort rather than the users of fire research results, and intended primarily to stimulate the fire research effort. Responses have been enthusiastic, laboratories and research groups in the United States, Europe, Asia, and South America showing an enormous appreciation of this activity. Dr. Walter Berl of The Johns Hopkins University Applied Physics Laboratory deserves our special thanks for a fine job in getting this new publication going.

This meeting today represents a return of our Committee, after a period of government committee contacts—too many of which can be rather deadening—to what it conceives to be its main function—stimulating scientists and engineers to think more deeply about the nature of combustion out of control.

Our Program Chairman is Mr. Arthur Brown who deserves our thanks for his fine efforts in arranging this meeting.

MODELING PRINCIPLES

H. C. HOTTEL, *Presiding*

Fire under Influence of Natural Convection
G. I. Taylor

Fire Modeling—*H. C. Hottel*

I NOW COME to the pleasant task of introducing our guest speaker. If this were an audience of specialists in fluid mechanics, the introduction of our speaker would be an incongruous formality; for no one in that field is better known than he. But a meeting like this assembles students of so many disciplines that some of you perhaps need to be given some additional facts.

If I told you that our speaker had been a licensed pilot, a parachute jumper, an oarsman, a Major in the Army, an explorer of the interior of Borneo, an arctic sailor, and a crew coach with Pandit Nehru on one of his crews, you might be inclined to say, "There are so many committees running meetings in this town; I have come to the wrong one."

I could then add that our speaker is the inventor of an improved ship's anchor, the organizer of a successful company to build and market it, and is presently involved as a board member of a company for transporting oil over water in link sausages instead of ships; and I could add that he has been an ardent golfer, a flyer of kites, and a blower of bubbles. You might begin to picture an athlete turned successful businessman and entrepreneur—with an odd taste for relaxation.

The picture could then be corrected by adding that the man you have come to hear was the chief meteorologist on a ship which, after the *Titanic* sinking, went out to study iceberg problems off the Newfoundland shores; that he was present as the Handley Paige representative at the first transatlantic crossing by an airplane—the Alcock–Brown flight; that he was present at the first A-bomb test at Los Alamos in 1945; that his ship's anchors held the famous Mulberry floating dock during our Normandy landings in the Second World War; and that he gave major aid on technical matters to almost all of the British Ministries during the Second World War.

Our speaker is the son of an English painter, from whom he acknowledges the gift of seeing and perceiving. He can look at clouds in motion and see on a grand scale the phenomena of turbulence in action. He is the maternal grandson of the Irish mathematician George Boole, a highly original thinker and inventor of Boolean algebra, about which even those of you who have negligible acquaintance with mathematics have undoubtedly heard. Perhaps by inheritance, perhaps by chance, he adds to his rare gift of being able to see and perceive the phenomena of clouds a capacity for profound and abstruse thought about the quantitative meaning of what he sees, and its application to flow phenomena all about us.

Sir Geoffrey held for over a quarter of a century at Cambridge the Royal Society Research Professorship in Applied Mathematics, during which time his prodigious output ranged over the field of applied mathematics and included such diverse subjects as plastic deformation of metals, dislocation theory of crystal structure, earth waves, the statistical theory of turbulence, fluid atomization in nozzles, torsion in structural members. These are but a few of his fields, with which I have some personal familiarity. Many of you know of many others. Sir Geoffrey retired in principle from his chair at Cambridge in 1951, but no one has been able to detect any effect of that retirement.

I spoke of bubble blowing. This is an example of modeling—applied to the problem of strength in torsion of structural members. Professor Taylor showed that if a soap film is blown from a bubble pipe the edge of which follows the external contour of the cross section of a structural member of any complex shape of interest, the curvature of the bubble is a quantitative measure of the stress concentration; and one thus has an analog computer for handling problems too difficult for conventional analysis.

Concerning another field of modeling, the one that brings us here today, you will hear directly from our speaker. Gentlemen, with the greatest of pleasure I give you one of the great scientists and engineers of our time, Sir Geoffrey Taylor.

Fire Under Influence of Natural Convection

G. I. TAYLOR
University of Cambridge, England

CONVECTION currents are produced whenever air at any point is hotter than the surrounding air. The heated air rises and unheated air must flow in below to take its place. If the source of heating is fixed in space the inflowing air is heated so that a continuous column of rising hot air is formed. The heated column mixes with the air around it and so produces a complex flow pattern of moving air some of which is hotter and some at the same temperature as the surrounding air. These two inter-related parts of the whole pattern can perhaps be referred to as the convection column and the induced flow, though it is not usually easy to define exactly the boundary between the two. It is only possible to construct a scale model of such a field of flow when one has a physical picture of the processes involved, and the best way to test one's theoretical ideas is to apply them to some case for which the geometry is so simple that one can make quantitative predictions based on those ideas and at the same time can make the experiments necessary for comparison with theory.

The simplest examples of this kind are convection currents rising from concentrated sources of heat which, in the analysis, can be taken as a point or as a horizontal line. Mathematical representations of these cases were presented in 1941 by W. Schmidt.[1] Schmidt used Prandtl's mixture length theory of momentum and heat transfer. According to this theory, turbulence is considered as an agent which conveys transportable physical properties like heat, water vapor, and momentum from one place to another. Fixing attention on a small volume of fluid, the simplest physical conception is that this starts from a place where it has the mean temperature or momentum of its surroundings and then travels with velocity v through a distance l (called a mixture length) before it mixes with its surroundings and delivers its load of the transferable property to this new position. This model leads to the assumption that turbulence conveys all transferable properties as though by a virtual transfer coefficient proportional to the mean value of $v \times l$, (written $\overline{vl}$). To apply this idea to any actual case of turbulent flow it is necessary to make some assumptions about how both v and l are related to the mean flow and the boundaries. Prandtl was concerned mainly about cases where the mean velocity is nearly parallel to a straight line, and the transfer at right angles to it. Thus, if u is the mean velocity and y is a coordinate perpendicular to u, Prandtl assumed that the rate of transfer of a property s across unit area at right angles to u is proportional to $\overline{lv}\,\frac{ds}{dy}$; $\overline{lv}$ is the transfer coefficient. He imagined that v would be proportional to $l\,\frac{du}{dy}$ so that he took as his transfer coefficient $\overline{l^2}\,\frac{du}{dy}$. I had used the same idea in a paper which Prandtl had not seen when he produced his theory. In using this form for the transfer coefficient, Schmidt imagined vertical thermal jets from point or line sources as being narrow and only spreading a little way laterally from a vertical line or plane through the source of heat. He, therefore, took l to be proportional to the breadth b of the column so that the transfer coefficient $\propto b^2\frac{du}{dy}$. Thus the rate of transfer of momentum laterally $\propto \rho b^2\left(\frac{du}{dy}\right)^2$ and the rate of transfer of heat is $\rho\sigma b^2\left(\frac{du}{dy}\right)\left(\frac{d\theta}{dy}\right)$, θ being the temperature, ρ the density, and σ the specific heat. Since no heat was supposed to be radiated by the jet, the equation determining θ is simply that for conservation of heat while the distribution of mean vertical velocity is determined by equating the upward force on an element due to its buoyancy to the rate of transfer of momentum out of it by the Prandtl transfer coefficient. Prandtl's assumptions are rather more detailed than would be expected of any purely a priori theory and the equations derived from them are complicated. Nevertheless, Schmidt solved them. He found that the assumptions of Prandtl's theory lead to two kinds of prediction. The first, A, is that the heated column will spread out so that both the distribution of temperature and of upward velocity are similar at all heights (though not the same distributions) and further that the width of the column increases uniformly with height above the source so that the heat is contained within a wedge if the heat source is a line, or a cone if it is a point. The second kind of prediction, B, was that the distributions of temperature and velocity assume the special forms calculated by Schmidt. Schmidt made measurements of the distribution of temperature and velocity at various heights above a concentrated source of heat and found that the predictions A were well verified and that those of class B approximately so. He could not get enough heat into his apparatus to produce a measurable rising column of air from a very concentrated source, so he heated air by means of electrically heated wires coiled in a circular hole, 5.5 cm. diameter, cut in a horizontal sheet. The upward current did not start from a point but the measurements showed that the column behaved as though it had started from a point 11.1 cm. below the sheet.

Since then Hunter Rouse,[2] who had not seen Schmidt's analysis, deduced Schmidt's results of type A using only the assumption that the distributions of temperature and also of velocity would be similar at all heights. Some of Rouse's students measured both the temperature and the vertical velocity above point and line sources of heat. Schmidt's measurements of θ_1, the ratio of temperature at any point to temperature in the middle of the thermal current, are shown in Figure 1. The full curve is Schmidt's theoretical curve and the broken line is a mean curve drawn through Hunter Rouse's experimental points. The abscissa η is the ratio of the distance of a point from the vertical through the source to the height z.

Though Rouse's treatment could not produce results of type B, i.e. could not give information about the distribution of temperature across the thermal jet, it showed that the assumption of similarity of both mean and turbulent velocities leads to

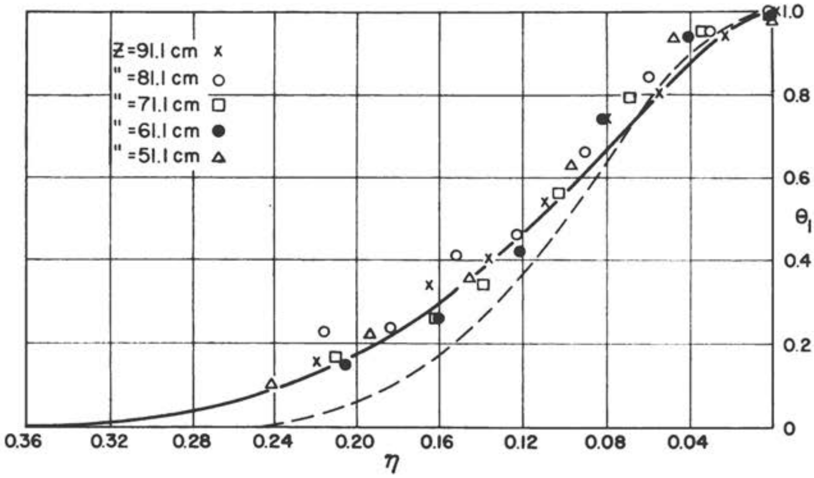


Figure 1. Distribution of temperature above a point source of heat
Full-line—Schmidt's calculation
Broken line—Faired curve through Hunter Rouse's observations
Points—Schmidt's observations

the conclusion that the jet must expand at a uniform rate with increasing height so that the jet rising from a line source will be contained within a wedge and the jet above a point source within a cone. Rouse showed also that the jet above a line source has the same velocity at all heights while at height z above a point source the velocity decreases as $z^{-1/3}$. The temperatures above line and point sources decrease as z^{-1} and $z^{-5/3}$ respectively. These results were verified experimentally by measurements which involved changes in the total heat flow and of the positions of observation points. Rouse expressed his results in terms of the flux of what he called 'incremental weight' and represented by the symbol $\Delta\gamma$. If ρ_0 is the density of the air outside the thermal jet and the density at any point is $(\rho_0 + \rho')$, $\Delta\gamma = g\rho'$. This is the buoyancy force per unit volume and when the buoyancy is due to a small rise in the temperature T' above atmospheric temperature T_0 in degrees absolute, $\Delta\gamma = gT'\rho_0/T$ where ρ_0 is the density of the atmosphere. The measured quantity is T' but when the results are expressed in terms of $\Delta\gamma$ they are applicable to models where other sources of buoyancy are used, such as alcohol discharged into water.

For line sources of heat, Hunter Rouse gave as the best formulae for expressing his experimental results
vertical velocity

$$w = 1.80\left(\frac{-W}{L\rho_0}\right)^{1/3}\exp\left(-32\frac{y^2}{z^2}\right)$$

buoyancy

$$\Delta\gamma = -2.6\left(\rho_0\frac{W^2}{L^2}\right)^{1/3}\frac{1}{z}\exp\left(-41\frac{y^2}{z^2}\right)$$

and for point sources

$$w = 4.7\left(-\frac{W}{\rho}\right)^{1/3} z^{-1/3}\exp\left(-96\frac{r^2}{z^2}\right)$$

$$\Delta\gamma = -11.0\,(\rho_0 W^2)^{1/3} z^{-5/3}\exp -71\frac{r^2}{z^2}$$

Here the velocity is expressed in ft/sec and distance in feet. $-W/L$ is the rate of discharge of buoyancy in pounds per foot per second for the line source in length L feet. ρ_0 is the density of air which must be expressed in pounds per cubic foot if the units are to be consistent.

Induced Currents

The total amount of air crossing a horizontal section of a 2-dimensional jet is proportional to wz while in the axisymmetric case it is proportional to wz^2. The inflow velocity at the edge of the two-dimensional jet is proportional to $\frac{d}{dz}(wz)$ while that at the edge of the axisymmetric jet is proportional to $\frac{1}{z}\frac{d}{dz}(wz^2)$. In the thermal jet above a line source the inflow velocity is therefore constant since w is constant. For the axisymmetric flow induced by a point source w is proportional to $z^{-1/3}$ so that the inflow at the edge of the jet is proportional to $\frac{1}{z}\frac{d}{dz}(z^{-1/3+2})$ i.e. to $z^{-1/3}$. Thus the induced flow at the outer edge of the jet at any level is in both cases proportional to the velocity of the jet at that level.

This leads to a simple conception as to the connection between jets which rise from hot sources and the induced flow, namely, that the jet entrains air through its outer surface at a rate which is proportional to its velocity. In other words the inflow velocity is a certain fraction α of the jet velocity. This is probably an extremely rough approximation but it gives a method for calculating the field of induced flow which is applicable not only to thermal jets but to forced jets, i.e. jets emanating from slits or holes in a pressure vessel. I have, in fact, calculated in this way inflows in three cases of thermal jets and four of forced jets.[3] The three thermal cases were

1) horizontal line source at ground level,
2) point source at ground level,
3) point source in unobstructed free space.

In case (1) the inflow at the outer edge of the jet being uniform is consistent with uniform horizontal induced flow extending to all distances on each side of the jet, and in fact, both Hunter Rouse and Schmidt have drawn the stream lines of the induced flow as horizontal lines both for case (1) and for (2). Figure 2 is taken from Rouse's paper in Tellus (l.c.) and shows the horizontal stream lines for the two cases.

In case (2) it turns out that the stream lines cannot be horizontal. I calculated them from the formulae given in my note (reference 3) and they are shown in Figure 3. The source in each case is represented by the point 0. The outer boundary of the jet is represented by the broken line which is drawn arbitrarily since the calculation does not give the angle of spread of the jet. Lines 1 to 5 represent on an arbitrary scale the total amount of air which has been induced into the jet beneath each stream line.

It will be noticed that of four possible cases involving point and line sources at ground level and in free space, only three have been mentioned. The fourth, namely a line source in free space, has been omitted because there appears to be no solution to this problem. The physical reason for this seems to be that the velocity in the two-dimensional thermal jet does not decrease with height so that any possible solution in which the jet is unbounded above must lead to finite velocities at infinity. This does not invalidate case (1) where the finite velocity at infinity is simply a uniform current, but, when one tries to calculate the

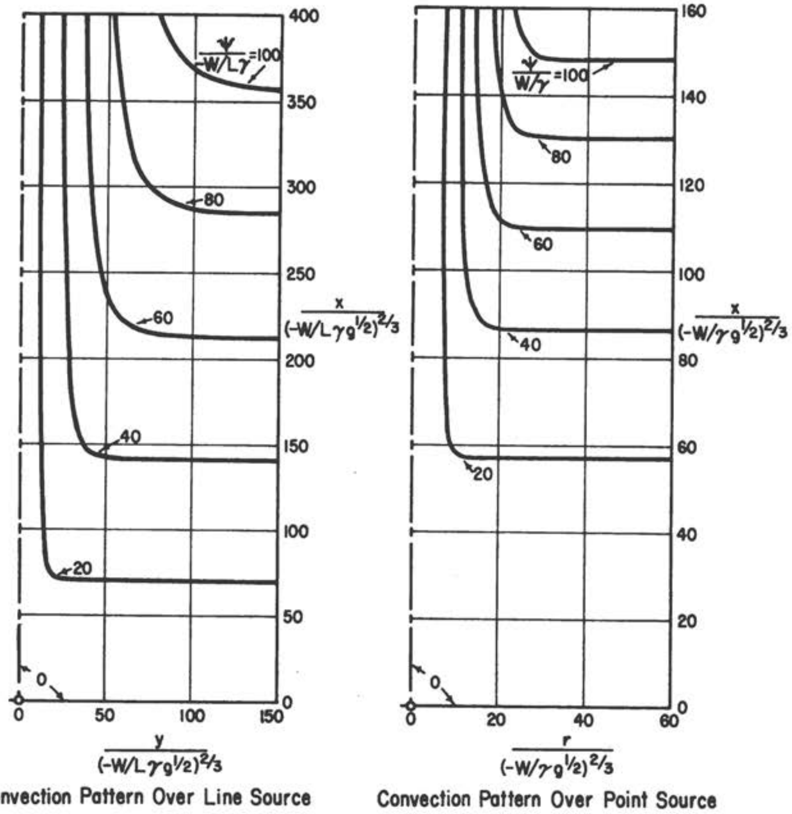
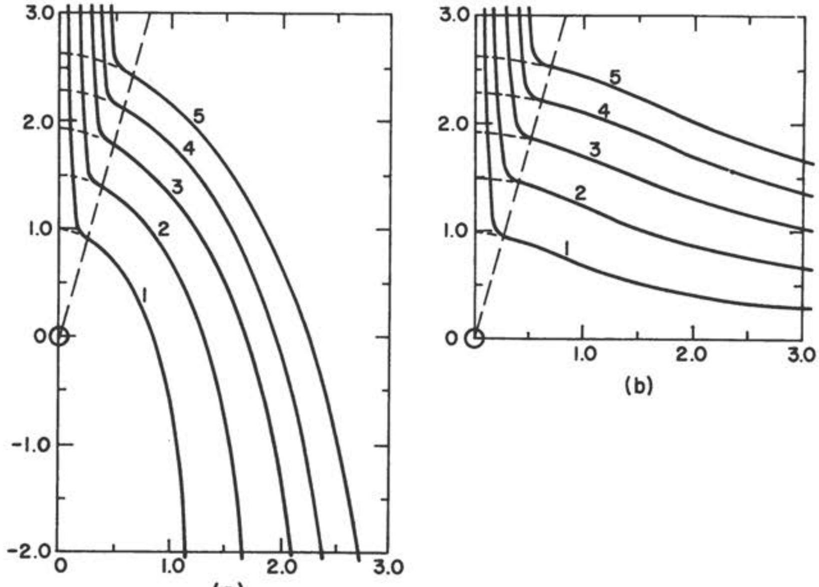


Figure 2. (a) Convection pattern over a line source.

(b) Convection pattern over a point source

flow induced by an unbounded thermal jet, one finds that the effect of the part of the jet which lies at a great distance above the source affects the flow near the source. This is not a trivial mathematical curiosity; it is, I think, merely an example of a difficulty inherent in making two-dimensional models of thermally produced convection currents *in an unlimited atmosphere.* We are accustomed to thinking that all models are rather simpler when two dimensions only are needed to describe the geometry, than when three dimensions are necessary. There is, therefore, a strong tendency to think and model in two dimensions. Where convection currents are involved, this is a mistake in some



(a)

(b)

Figure 3. Stream lines of flow induced by a point source of heat
(a) Source unobstructed by ground
(b) Source at ground level

cases. Suppose that we wish to design a model experiment to represent in two dimensions what happens when a side wind blows at right angles over a long line of fire. We can experiment with a line of small burners laid across the floor of a wind tunnel. The stress in the fluid is due partly to gravity and partly to turbulence. The latter is proportional to ρu^2 and the former to γL where γ is the buoyancy force per unit volume, L a linear scale of the apparatus. Writing suffixes *o* and 1 to represent the model and full scale, similarity is attained when

$$\frac{\gamma_0 L_0}{\rho_0 u_0^2} = \frac{\gamma_1 L_1}{\rho_1 u_1^2}$$

provided the changes in density are small enough to be neglected except for their buoyancy effects. If the total rate of discharge of buoyancy per unit length of the source is Q, $Q \propto Lu\gamma$ so that for similarity

$$\frac{Q_0}{Q_1} = \frac{L_0 u_0 \gamma_0}{L_1 u_1 \gamma_1} = \frac{\rho_0 u_0^3}{\rho_1 u_1^3} \tag{1}$$

While preparing for this talk I unearthed an old report (unpublished), written in 1945 by the late Professor A. O. Rankine and describing experiments made in a wind tunnel 100 ft. long x 30 ft. wide x 12 ft. high. Butane burners were arranged in a transverse line and the temperature distribution was measured downstream when wind of various strengths was turned on. These experiments were primarily designed to test the scaling law when designing burners for the project F.I.D.O.[4] during the war. It was realized that the scaling law represented by equation (1) would only apply in the atmosphere where buoyancy is due to heat if the density changes were small, but this complete similarity both of density and temperature distribution between model and full scale should be attainable if the temperature at similar points were the same. These can be attained if $\frac{u_0}{u_1} = \left(\frac{L_0}{L_1}\right)^{1/2}$ and $\frac{H_0}{H_1} = \left(\frac{L_0}{L_1}\right)^{3/2}$ or writing R = ratio of linear scales of full size to model.

$$\frac{u_0}{u_1} = R^{-1/2} \text{ and } \frac{H_0}{H_1} = R^{-3/2} \tag{2}$$

Measurements of the temperature profile were made at 75 yards from a line of burners laid horizontally on the floor of a large new unfilled reservoir when the wind was 8½ mi/hr and the heat flux 22.4 therms/yard/hour. Temperature measurements were made in the wind tunnel at distances 15′, 7′6″, 3′9″, i.e. on scales of 1/15, 1/30 and 1/60. The heat discharges were 0.38, 0.13, 0.05 therms/yd/hr which are nearly in the correct ratios for complete similarity when the wind speeds were 3.2, 2.3 and 1.6 ft/second. Figure 4 shows the results. It will be seen that the model tests do in fact predict the temperature with considerable accuracy but this result was only attained when both the wind speed and the heat discharge were in accordance with the scaling law.

This is an interesting result because the scaling law is founded on the idea that the turbulence is similar on all scales. The turbulence arises partly from the friction of the wind on the ground (both to windward of the burners and between them and the observation point) and partly because the temperature dis-

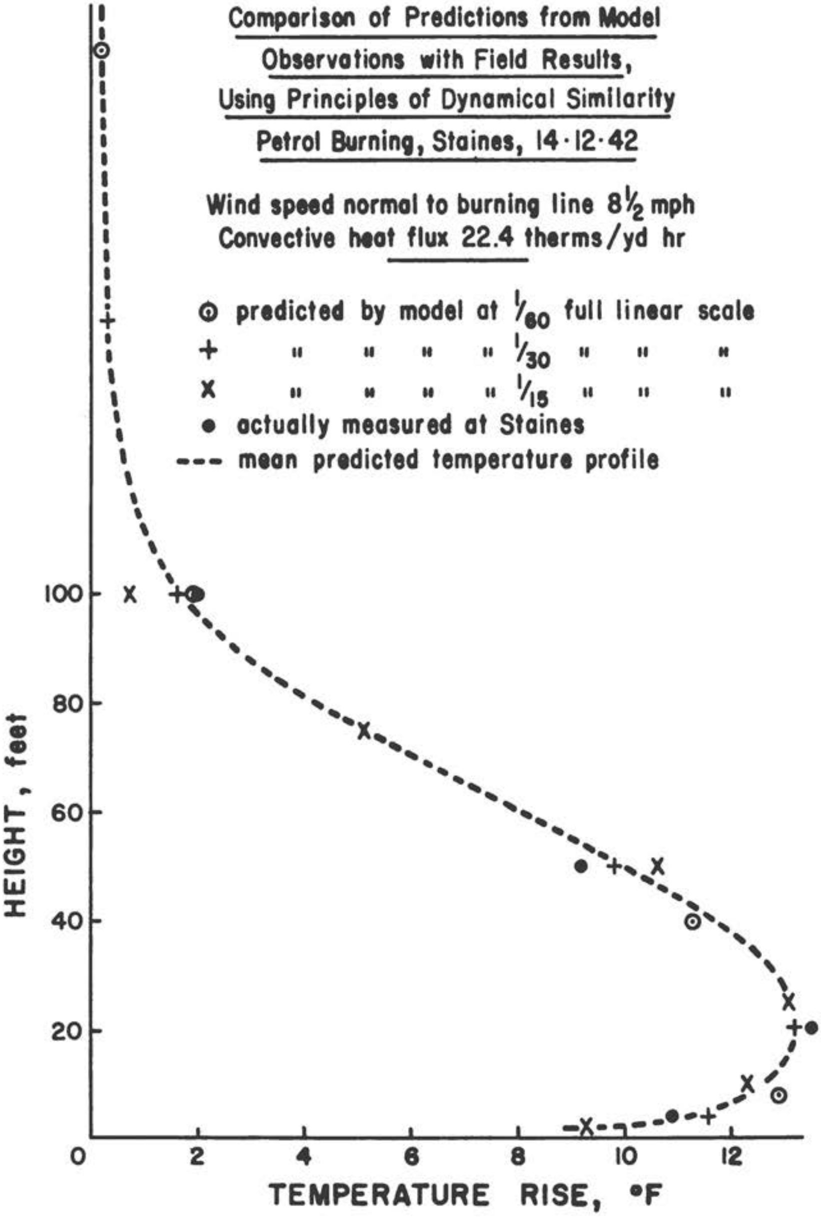


Figure 4. Temperature distribution downwind from line source of heat at ground level

tribution is unstable. Exact similarity could only be expected if the distribution of wind and turbulence upstream of the burners were similar in model and full-scale experiments. In all probability they were not the same, so that one can perhaps infer from the consistency of the results shown in Figure 4, that the effect of the turbulence already in the air stream before it passes over the burners is small compared with the turbulence produced downstream of the burners.

When there is no wind the heated air current rises vertically and produces uniform inflowing convection current at each side. It might be expected that a *very slight* side wind would cause the thermal jet to lean over to one side. If one could imagine that each element of the jet is carried sideways by a wind u while preserving its upward velocity w it would lean over so that its center line lay at an angle $\tan^{-1}(u/w)$ to the vertical and the jet would be bounded by planes lying at angles $\tan^{-1}\left(\frac{u \pm \alpha w}{w}\right)$. Formally the angles $\tan^{-1}\left(\frac{u \pm \alpha w}{w}\right)$ exist whatever the values of u and w may be but when the total induced velocity outside the jet is positive, i.e. when $u > \alpha w$ the air outside the jet is flowing away from it on the down stream side, the air which passes through the jet is hot, so that the conception of a heated column continually increasing in volume as it ascends by entrainment of unheated air is unrealistic. All the cases represented on Figure 4 were ones in which the air to leeward of the burners was moving away from them. Professor Rankine tried to obtain flows in which there was a sufficiently small side wind to ensure that air flowed in from both sides but he was unable to do so because with very small winds the heated column rose to the top of the tunnel and part of it ran along the top against the wind and so recirculated. An attempt was made to do away with the top but the experiments had to be discontinued so that the transition from the upward current type of thermal jet to the type in which the heat is blown downwind was not explored. When there is no wind the side inflow αw is really known so that it would be interesting to find experimentally whether the critical condition under which the rising jet is blown over corresponds with a velocity of the air on the windward side of the jet of $2\alpha w$.

If this critical condition is exceeded, as was the case in the measurements shown in Figure 4, the top boundary of the heat rises at an angle β which Rankine measured. He found empirically (p. 30 of his report) that tan β is proportional to $H^{0.286}$ and inversely to $u^{0.86}$. The fact that 0.86 is so exactly three times 0.286 makes me think that Rankine must have analyzed his measurements assuming, on theoretical grounds, that tan β must be a function of H/u^3. One can perhaps learn something from the measured value of the index when $\tan\beta \propto (H/u^3)^{0.283}$. After giving this result Professor Rankine referred to a letter of mine in which I had expressed the opinion that tan β might be proportional to $(H/u^3)^{2/3}$. My argument is perhaps worth recording. It was that, if the dispersion of heat upwards is due only to thermal currents without assistance from turbulence generated by friction of the air on the ground, the thermal currents in any volume of fluid which is carried along by the wind from a line source might be the same as the thermal currents which would arise if heat were initially distributed uniformly close to the ground and then allowed to disperse upwards. The relationship between the two problems is that the distribution of temperature with height at distance x in the line source problem would be identical with that in the related problem at time x/u provided the total amount of heat spreading upwards in the second problem was $H_1 = H/u$ per unit area. In the second problem, distributions of temperature with height at different times must be similar. If the vertical component of turbulent velocity is v, the similarity law would be that $\theta L/\bar{v}^2$ must be a function of z/L only here L is the height of the heated layer at any time, z the height of the point where the mean square velocity is $\bar{v}^2$. The top of the heated volume is rising at speed $\sqrt{(\bar{v}^2)_{z=L}}$ and θL is proportional to H_1 so that $H_1/(\bar{v}^2)_{z=L}$ is independent of H_1.

In the line source problem $\tan^2\beta = \dfrac{(\bar{v}^2)_{z=L}}{u^2}$

so that

$$\tan^2\beta \propto \frac{H_1}{u^2} \text{ or } \frac{H}{u^3} \text{ so that } \tan\beta \propto \left(\frac{H}{u^3}\right)^{1/2} \tag{3}$$

The unrealistic assumption that was made on this analysis is that the vertical dispersion of heat is due entirely to currents of thermal origin. If the currents had been entirely due to wind friction β would have been independent of H. The fact that the experimentally determined exponent of H/u^3 is 0.283, which is roughly halfway between 0 and ½, suggests that in the range of values of H/u^3 in Rankine's experiments the friction-driven turbulence is roughly of equal importance in the dispersion to the thermal instability.

Three-Dimensional Scale Relations

Schmidt's calculated values for θ_m, the excess temperature, and w_m the upward velocity, in the centre of a jet rising from a point source were

$$w_m = A\left(\frac{Hg}{\rho\sigma T}\right)^{1/3} z^{-1/3} \tag{4}$$

$$\theta_m = 0.924\, A^2\left(\frac{H}{\rho\sigma}\right)^{2/3}\left(\frac{T}{g}\right)^{1/3} z^{-5/3} \tag{5}$$

Here H is the heat discharged from the source per unit time and $H/(\rho\sigma T)$ is of dimensions (l^3t^{-1}). A is a constant arising in the mixture length theory. Other theories involving constant distributions at all heights would be of the same form except that the number 0.924 would be replaced by another number of the same order of magnitude.

When the thermal jet is blown by a side wind of velocity u one condition of similarity between full scale and model is that at similar points u/w shall have the same value, so that equation (4) gives $\dfrac{u_1H_1{}^{-1/3}z_1{}^{1/3}}{u_0H_0{}^{-1/3}z_0{}^{1/3}} = 1$ and at similar points z_1/z is the ratio R of the linear scales of full scale to model scale. For complete similarity θ_m must have the same value at similar points for model and full scale so that equation (5) gives

$$\left(\frac{H_0}{H_1}\right)^{2/3} = R^{-5/3} \text{ or } \frac{H_0}{H_1} = R^{-5/2}$$

and (6)

$$\frac{u_0}{u_1} = \frac{H_0{}^{1/3}z_0{}^{-1/3}}{H_1{}^{1/3}z_1{}^{-1/3}} = R^{-5/6+1/3} = R^{-1/2}$$

Comparing these with equation (2) it will be seen that velocities scale in the same way as for two dimensions. The heat does not appear to scale in the same way but the H of equation (2) has not the same dimensions as the H of equation (6). If the heat from the point source were considered as coming from short lengths L_0 and L_1, the ratio of the heat emission per unit length of these lines would be $R^{-3/2}$ as in equation (2), since for similarity $L_1/L_0 = R$.

The case of a point source in a side wind has been chosen as a simple example of a three dimensional field, but the scaling laws represented by equation (6) seem to be universal in their application.

Models of Convection in an Atmosphere of Variable Potential Temperature

In the cases discussed so far the ambient atmosphere has been considered as of uniform density. In the atmosphere the density decreases with height and the buoyancy of air at any height depends on the difference between its temperature and that of the surrounding air. As the air rises in a thermal current it cools owing to adiabatic expansion as it rises into places where the surrounding pressure decreases. If the atmosphere is in neutral equilibrium, its temperature decreases with height and that of the air in rising current will decrease at the same rate so that its buoyancy is preserved. The atmosphere is then described as having uniform potential temperature. Its actual temperature decreases at a rate of approximately 1°C per 100 meters.

If the potential temperature in the atmosphere increases with height, as it must do if it is to remain stable, a rising thermal current does not preserve its buoyancy because it entrains air which is at a higher potential temperature.

It would be exceedingly difficult to calculate the flow in such a case because similarity would not be preserved. On the other hand, some of the main features of the flow can be described in the case of a point or line source under a windless atmosphere using three simplifying assumptions: (1) the distributions of velocity and temperature are assumed to be similar at all heights (2) the rate of entrainment over the outer surface of the jet is assumed to be proportional to the velocity of the rising current (3) the potential temperature is assumed to rise at a constant rate with increasing height. Solutions of the point source problem subject to these limitations have been given by Morton, Taylor, and Turner[5] and by Priestley and Ball.[6] These solutions differ in detail but the non-dimensional combinations which occur in them are the same.

The two independent measurable quantities which determine the height to which the column or plume of hot air will penetrate into the atmosphere are F_0, the flux of buoyancy at the source divided by ρ_1, the density of the ambient fluid at the level of the source, and $G = -\dfrac{g}{\rho_1}\dfrac{d\rho}{dz}$. The assumption of similarity between distributions of buoyancy and velocity at all heights reduces all cases to the same non-dimensional form. The linear scale is proportional to $F_0^{1/4}G^{-3/8}$ and the velocities to $F_0^{1/4}G^{1/8}$. The calculated non-dimensional radius of plume R, buoyancy Δ and vertical velocity U are shown in Figure 5, as non-dimen-

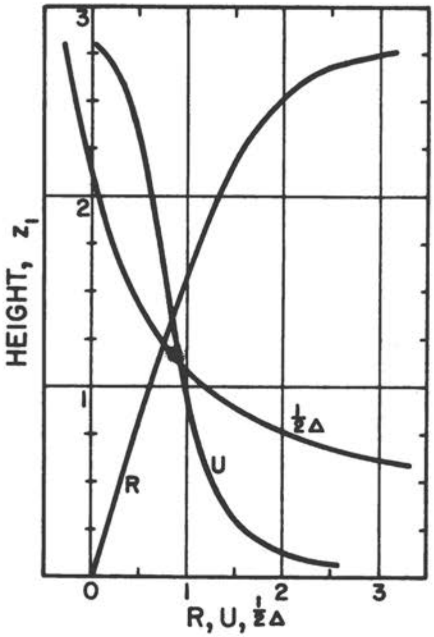


Figure 5. The variation with height of the horizontal extent (R), the vertical velocity (U), and the buoyancy (Δ) calculated for the turbulent plume in a uniformly and stably stratified fluid.

sional functions of non-dimensional height $z_1 \propto F^{-1/4}G^{3/8}$. It will be seen that according to the analysis the thermal column loses its buoyancy at $z_1 = 2.1$ but it still has vertical velocity which carries it up $z_1 = 2.8$ where it spreads out. The simplifying assumptions of the theory break down, however, before this stage is reached.

Model of Plume Penetrating Into Stably Stratified Fluid

Instead of using stably stratified air as the fluid a tank contains, salt solution, of which the concentration decreased uniformly with height, was used and the density gradient measured. This gives G. The thermal plume was represented by discharging coloured methylated spirit of known density at a known rate so that F_0 could be calculated. Figure 6 is a photograph of one of

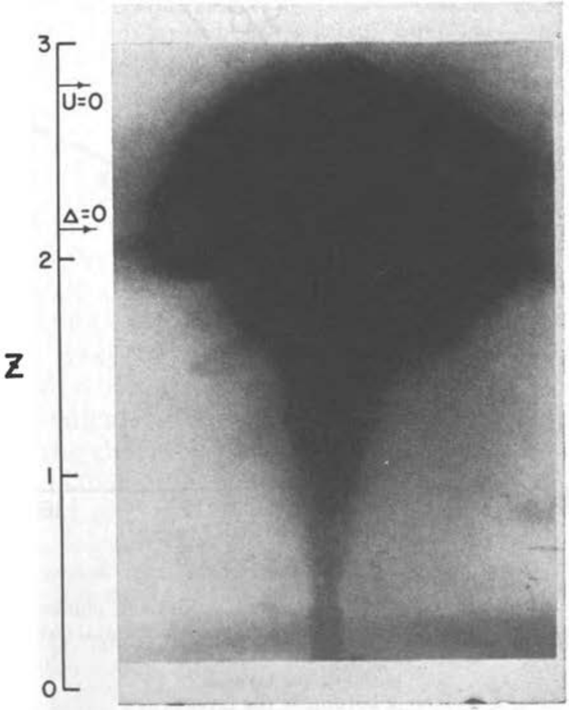


Figure 6. Maintained plume in a stably stratified fluid (methyl alcohol in salt solution)
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the plumes with a scale of z. They spread out and the heights of the top and bottom were measured.

These are plotted against $F_0^{1/4}G^{-3/8}$ for a variety of values of the abscissa ranging from 3.5 to 16 in Figure 7 and it was

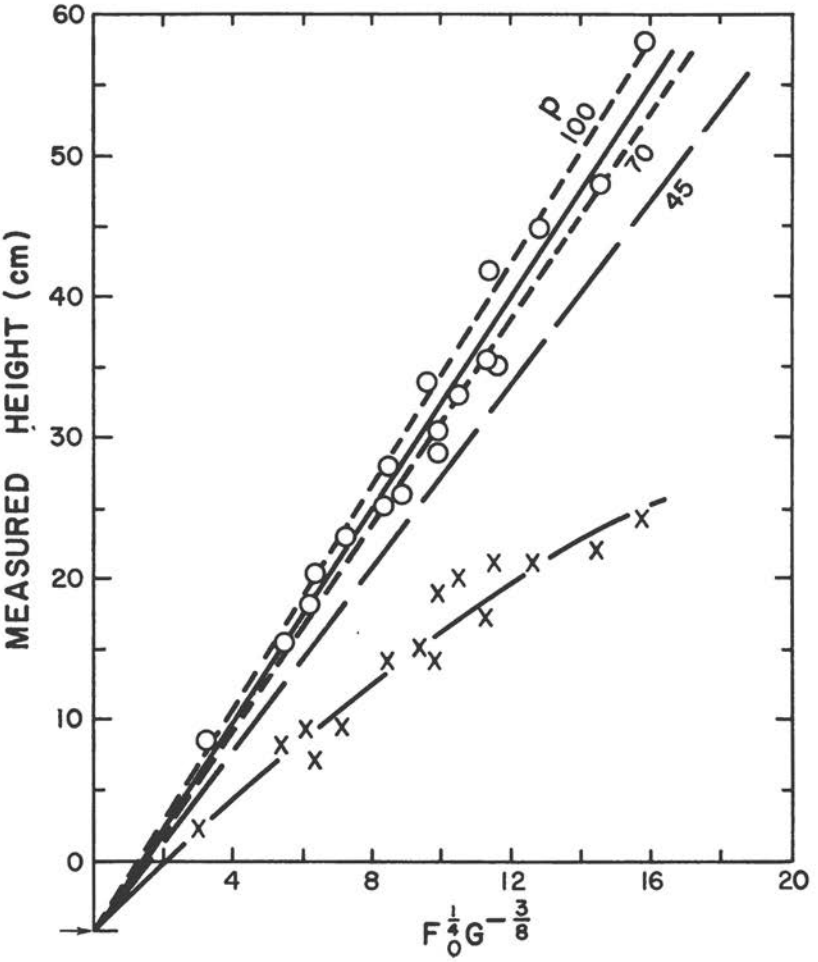

Figure 7. Experimentally determined height of maintained plumes compared with the height prediction made by comparing previous experimental data on unstratified fluids.

o top of the layer
x bottom of the layer

The continuous straight line is the line of best fit with the experimental points for the plume top. It has slope 3.7.

found that the points represented by the top lay near a straight line whose slope was about 3.7. The calculated value of the maximum height to which the fluid could penetrate was $z_1 = 2.8$ in non-dimensional units, but the relationship between these and the also non-dimensional $z/(z_1F^{1/4}G_0^{-3/8})$ depended on the value of α, the coefficient of entrainment. It was found (ref. 5, Table 2) that if α has the same value as that which makes theory agree with Schmidt's experiments, the value of [(height of top of plume) $\cdot (F^{-1/4}G_0^{3/8})$] would be near 3.8 so that the agreement with the data shown in Figure 7 is good.

Applying these theoretical formulae to an atmosphere stratified so that the actual rate of increase in temperature is a fraction n of the adiabatic lapse rate Γ, then $G = \frac{g\Gamma}{T_1}(1 + n)$ and P, the height of the top of the plume, is found to be $P = 31(1 + n)^{-3/8}Q^{1/4}$ where Q is the rate of heat discharge at the source in kilowatts and P is in meters. Taking $n = -0.66$, which is a normal kind of lapse rate, (6.5°C/km) $P = 4.6Q^{1/4}$ and a few examples are given below.

	Q k.w.	H meters
Fire 2 lb coal/hr	8	80
2 cwt wood/hr	450	200
Large Power Station ½ Mkw	5×10^5	1200
5000 tons/hr	2.5×10^7	3200

These seem bigger than might be expected but it is seldom that the wind is sufficiently low to permit the heat column to rise vertically. A very small wind will very greatly decrease P. Another cause which may tend to prevent the plumes from attaining their calculated height is the neglect of loss of heat by radiation in the theory.

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Discussion

Professor Hottel: In the actual fire, the distribution of temperatures is affected by the fire and the mixing process determines the heat release during the combustion process. The source is a surface, a surface not necessarily horizontal, and perhaps not at ground level, so that the flame poses a complicated question. Sir Geoffrey, will you give us some hints as to how to handle this in terms of the picture which you presented.

Professor Taylor: I fear that the models I have discussed are concerned only with the air currents produced in the surrounding atmosphere by a fire producing a known quantity of heat and do not touch on other questions to which we would like to know the answer, such as how the air currents react on the rate of combustion.

Professor Hottel: I am sure that many of you who are familiar with the general interest in applying models will feel, and quite properly, that we are a long way from being able to model those aspects of flames which we need to consider in fire growth or fire spread. I do not see how we can avoid using pressure as a tool in some of our fire modeling problems. There is nothing miraculous about modeling; it will not let us study a problem by holding constant fewer dimensionless groups than Nature says are significant to the problem.

Dr. Thomas: I would like to ask Sir Geoffrey to interpret some results we obtained in an experiment we have made recently. Most of the experiments on the flammability of fabrics have been made with different thicknesses of one width of fabric. Recently, to study the effect of varying width, we burned strips of fabric of one thickness in widths ranging from ¼ to 4 inches. These strips were hung vertically and were ignited at the lower edge and we measured the flame height and the rate of spread of flame, which is proportional to the rate of loss of weight. We attempted to interpret the results we obtained in the following manner.

Sir Geoffrey has described how the entrainment velocity is proportional to the upward velocity in a plume and we have made the same assumption for the flame. Because the velocity at which the fuel gases enter the flame zone is small compared with the velocities induced by the buoyancy of the flame, we assumed the upward velocity in the flame to be proportional to the square root of the flame height, so that the mean entrainment velocity was also taken as proportional to the square root of the flame height. If one assumes that the flame of height Z is approximately conical, so that its surface is proportional to Z^2, the total air entering the flame is proportional to $Z^2 \times Z^{1/2}$ and for a constant air/fuel ratio the rate of weight loss R and flame height are related by

$$Z^{5/2} \propto R, \text{ i.e., } Z \propto R^{0.40}$$

Our results gave 0.47 for this index. We then assumed that the length of fabric actually producing flammable gases at any instant was a constant fraction of the flame height. This is so if the rate of decomposition per unit area of fabric surface, and the heat transfer to the material ahead of the burning zone, are constant for different widths of fabric. We then write $R \propto ZB$, where B is the width of fabric, and these two equations give $R \propto B^{2/3}$. Our experimental results gave an index of 0.63.

We also tried to apply these two assumptions:

1) A constant ratio between entrainment velocity and upward velocity of gases in the flame.

2) A proportionality between this latter velocity and $Z^{1/2}$ to flames from the cubical enclosures with one side open.

The flames from the smallest cube are the tallest in relation to the cube size. The value of $Z^{1/2}$ is the smallest and the entrainment velocity is lower than for the larger cubes. Accordingly, a relatively larger surface, i.e. a relatively longer flame, is required for combustion. The flames are not conical, they are relatively short, but applying this kind of analysis gives a correlation, which over a small range of scale, viz. from 1 to 3 ft. cube, does not have any systematic scale effect. May I have comments?

Professor Hottel: I find myself unable to comment. I want to look at this derivation on the blackboard a little more slowly.

Perhaps someone else followed it completely enough to make comments.

Dr. Emmons: It occurred to me during the presentation that when you change models, as in this case, you change from a clearly three-dimensional toward a two-dimensional problem. It should be noted that two-dimensional problems and three-dimensional problems are sometimes very different and one or the other may not exist in a steady state. This has already been noted by Sir Geoffrey. Whenever this occurs, there is a real meaning to the non-existence of a solution. The meaning in the case that Sir Geoffrey mentioned is that there would really be infinite velocities. Since infinite velocities cannot really exist, there must be some actual dimension, say width dimension, that is important in local phenomena and important in a major way. Furthermore, the time scale, the time elapsed from the beginning of the fire is important, so that the starting situation never has disappeared completely, even though the fire has been burning for a long period of time, the convection column is still changing in an important way.

Each of these, therefore, would have fundamental effects on the nature of the problem. Conceivably in a case of this kind, if the experiments had been extended to a very broad cloth, they might have tended to a quite different kind of situation. There are problems that one has to watch very carefully in going from a two- to three-dimensional situation—they may be different in kind, rather than just in degree.

Dr. Fristrom: A problem of considerable interest is that of a finite rather than an infinite point source, and I notice that Sir Geoffrey indicated that the Schmidt work was done with a quite finite source (I believe he said five centimeters in diameter) and that it could be well mapped assuming a virtual point source eleven centimeters below the table. I am wondering if he has any comments as to how far one could push the mapping of finite sources assuming a virtual point source of this kind.

Professor Taylor: This problem is somewhat like St. Venaut's problem in elasticity. If one twists or bends an elastic beam by applying loads at the ends the stresses at all points far removed from the ends depend only on the total moments applied there but quite close to the ends the stresses depend in detail on the manner in which the load is applied. The distribution of velocity in an air jet issuing at high speed from a pipe depends only on the rate of discharge of momentum at points which are more than about two or three pipe diameters from the end of the pipe, but near the pipe the distribution of velocity depends on many things such as the shape of the cross section of the pipe and the state of turbulence of the air as it issues from the pipe.

Dr. Blackshear: I could give a quantitative answer to that. We tried an application of a line source solution to a jet of finite velocity and tried to see what was necessary for this to approximate reality. It turned out that if you have a Reynolds number of unity in your jet, you can approximate reality within two jet diameters or jet widths. If you have a Reynolds number of a thousand in your little slot you have to go to 400,000 slot widths before you start approximating reality, so it is a very strong function of Reynolds number.

Professor Taylor: This is a different condition from that which I envisaged. When the Reynolds number of a jet is small it may be non-turbulent and I was only considering turbulent jets. A non-turbulent jet at low Reynolds number of order 1,000 may travel a long distance before spreading out and assuming a typical distribution of velocity in which similarity is preserved.

Dr. Blackshear: This is the infinitesimal slot.

Professor Taylor: Is it a forced jet, or a thermal jet, or what?

Dr. Blackshear: It is a forced jet. In the analysis you have an infinite velocity coming from an infinitesimal source, and if you try to apply this analysis to a finite jet, of finite dimension, and finite velocity, it works to within quite close to the origin if the Reynolds number is small.

Fire Modeling

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SYSTEMS are identified as similar when the quantitative relations describing them can be put in identical form, so that there is a one-to-one correspondence between an event or a property in the prototype and in its model. A model may be incomplete and may reproduce faithfully only those aspects of the prototype considered of primary importance. In fact, the only models of processes of great complexity which are possible are incomplete ones. It is the engineer's task to determine, by experiment and analysis, which variables in the prototype may justifiably be omitted in the model.

The conditions for similarity may be established in one of three general ways. Use of the pi theorem, popular in the 20's, is one of them. As used in practice, it appears to have contributed to a reduction in the level of understanding of modeling; it defines a procedure so formal that it permits variables to be introduced without identification of the physical reason and yields dimensionless groups which may be in a valid but unfamiliar form. A second approach is to formulate the equations applicable to the problem and, without solving them, manipulate them until the dimensionless groups emerge. This has to work, but it gives the impression that the ability to write the rigorous equation is an essential feature of similitude theory, and of course it is not. The third method of establishing the conditions for similarity is the one which, to this author, best permits the welding of similitude theory and a "feeling" for the problem at hand—also the one which has been applied so effectively in the previous paper[1] of this symposium.

Consider a device or process subject to change in space or time. Quantitative statements about the system will be statements about force, matter, or energy. A statement of the existence of a balance of forces, for example, will of necessity contain terms which are dimensionally identical, and division through by one of the terms will produce a set of force ratios. These ratios must be the same in similar systems. Similar statements may be made about conservation of matter and of energy. It thus becomes clear that, by listing all the variables or parameters in each of the three categories—matter, force, and energy—and by taking ratios within each category, one will have established the form of all the dimensionless groups which can be involved in any quantitative statements about the problem except for the effect of general statements about physical property variations or statements of boundary conditions. The former may always be put in non-dimensional form to disclose the new groups* which arise. The boundary conditions are used to convert as many groups as possible into groups containing no dependent variable, by replacing velocity, length, etc., by a characteristic value. If there is more than one dependent variable in the dimensionless groups, all but the one of interest must be eliminated by taking ratios among the groups. The independent-variable groups so obtained suffice to fix the system completely— or as completely as is consistent with the assumptions made as to what kinds of force, matter, or energy terms merit inclusion in the analysis.

Tables 1, 2, and 3 list some of the forces, mass rates and energy rates expected to enter problems of fire modeling. No claim to completeness is made.

TABLE 1. FORCES

(V = volume; u, v = velocity)

1. Momentum, such as $\rho u^2 A$ and $\rho u^2 V/r$	$u^2 \rho L^2$
2. Viscous stress × area, $\mu A(du/dx)$	$\mu L u$
3. Turbulent stress × area, $\rho \bar{v} l A(du/dx)$	$u^2 \rho L^2$
4. Buoyancy, $V(\rho - \rho_a)g$	$L^3(\rho - \rho_a)g$
5. Pressure-area	PL^2
6. Surface tension	σL
7. Friction: various formulations, including $C_d A u^2 \rho/2$	$(C_d)(L^2 u^2 \rho)$

* The price paid is high if a new group does thereby arise. One tries to avoid it by use of suitable mean values; and here is a place where rigorous analysis of a part of a problem simplifies dimensional analysis of the whole.

TABLE 2. MASS RATES

(Applied to component i)

10. Transport by convection or bulk-flow, $uA\rho f_i$	$L^2u\rho f_i$
11. Molecular diffusion rate, $-AD_i\rho(df_i/dx)$	$LD_i\rho f_i$
[Gas diffusion, $D_i \propto T^{3/2}/p$; Pore diff'n, $D_i \propto T^{1/2}$]	
12. Turbulent transport, $-AD_T\rho(df_i/dx)$	$L^2u\rho f_i(Re)^{-n}$
[$D_T \propto \overline{v}l(Re)^{-n}$; $n \ll 1$, and often ignored*]	
13. Chemical reaction rate in a volume, $Vk_i(\rho f_i)^n$	$L^3k_i(\rho f_i)^n$
[$k_i = k'_ie^{-E_i/RT}$; B_i = mass reacted per unit volume and time, per unit mass conc., $= k(\rho f_i)^{n-1}$]	or $L^3\rho f_iB_i$
14. Chemical rate, gas with a surface, $Ak_s(\rho f_i)^n$	$L^2k_s(\rho f_i)^n$
15. Unsteady-state concentration change, $V\rho df_i/dt$	$L^3\rho f_i/t$

TABLE 3. ENERGY RATES

20. Convection or bulk-flow	
a) of sensible energy, $Au\rho c_p(T - T_o)$	$L^2u\rho c_p(T - T_o)$
b) of chemical energy (species i), $Au\rho f_iH_i$	$L^2u\rho f_iH_i$
21. Conduction, $-A\lambda(dT/dx)$	$\lambda L(T - T_o)$
22. Turbulent transport	
a) of sensible energy, $-A\overline{v}lc_p(dT/dx)$	$L^2u\rho c_p(T - T_o)$
b) of chemical energy, $-A\overline{v}l\rho H_i(df_i/dx)$	$L^2u\rho f_iH_i$
23. Unsteady bulk-temp. change, $V\rho c_p(dT/dt)$	$L^3\rho c_p(T - T_o)/t$
24. Burning rate, or heating rate	q
25. Surface-to-surface radiation, $q_{i \to j}$	
a) gray, $\overline{S_iS_j}\sigma T_i^4$, where $\overline{S_iS_j} \equiv L^2f_1(\epsilon\text{'s, shape})$	$L^2\sigma T^4f_1$
b) non-gray, see text	
26. Gas-zone to surface-zone radiation, or vice versa	
a) gray, $\overline{S_iG_j}\sigma T^4$, where $\overline{S_iG_j} \equiv L^2f_2(\kappa L, \epsilon\text{'s, shape})$	$L^2\sigma T^4f_2$
b) non-gray, see text	
27. Gas-zone to gas-zone radiation	
a) gray, $\overline{G_iG_j}\sigma T_i^4$, where $\overline{G_iG_j} \equiv \kappa L^3f_3(\kappa L, \epsilon\text{'s, shape})$	$\kappa L^3\sigma T^4f_3$
b) non-gray, see text	

Radiation

The radiation terms merit discussion for two reasons: they are less generally familiar to the engineer than the other terms; and full allowance for radiation in modeling is often so restrictive as to force a compromise which cannot be made intelligently without full recognition of how much rigor has been sacrificed. Consider a multisurface or multizone enclosure containing a nonabsorbing medium. The radiation from surface S_i which reaches and is absorbed by S_j, expressed as a fraction of black radiation emitted by A_i, is designated by $\overline{S_iS_j}(\equiv\overline{S_jS_i})$. It has been

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* The *Re* function could, with equal justification, be included in items 3 and 18.

shown[2, 3] that $\overline{SS}$ equals L^2 times a dimensionless function of the system shape and of the emissivities of all surfaces forming the enclosure, the function being expressible in determinant form of order equal to the number of zones in the system (see Appendix). If all surfaces are gray the net flux between zones i and j is then

$$q_{i \rightleftharpoons j} = \overline{S_iS_j}\sigma(T_i^4 - T_j^4) \tag{1}$$

The result for a non-gray system is given in the appendix. For application to modeling, where shape is preserved, it is sufficient to note that $\overline{SS}$ is L^2 times a dimensionless function of surface emissivities, where L is a characteristic system dimension.

When the enclosure contains a radiation-absorbing fluid (combustion gases or flame), there is interest in three kinds of radiant interchange, gas zone to gas zone, gas zone to surface, or vice versa, and surface to surface. Formulation of any of these depends on knowledge of κ, the absorption coefficient of the gas defined as the fractional decrease, per unit of path length, of the intensity of a collimated beam of radiation. When κ is constant along the path, the transmittance through a finite path L is e^{-kL} (Beer's Law); and $1/\kappa$, having the dimensions of length, may be visualized as the mean free path of a photon through the gas—the distance it can go with a chance $1/e$ of escape. The emission from a gas volume V, without self-absorption, is $4\kappa V\sigma T^4$ if the volume is gray, $4V\int_0^\infty \kappa W_\lambda d\lambda$ if not. A detailed discussion of the factors influencing κ is beyond the scope of this paper. It is proportional to the concentration of absorbing components and, due to pressure-broadening of spectral lines, is in addition a weak positive function of total pressure. It varies in a complex way with temperature and wavelength, its mean value over a small wavelength interval being expressible as a power function of temperature, with power varying from zero to small positive values. The influence of these facts on radiation modeling must await formulation of the terms appearing in the expressions for radiant exchange involving absorbing gas.

Interchange between a surface zone and a gas zone may be expressed, for a gray gas and a gray surface, as

$$q_{i \rightleftharpoons j} = \overline{S_iG_j}\sigma(T_i^4 - T_j^4)$$

$\overline{SG}$ has the dimensions of area and may be expressed as the square of a characteristic system dimension L, times a dimensionless function f_2 of the emissivities of all enclosing surfaces, of κL, and of the system shape. The case of a non-gray system is treated in the appendix.

The interchange between two surface zones, with enclosed gas and all surfaces gray, is given by

$$q_{i\rightleftarrows j} = \overline{S_iS_j}\sigma(T_i^4 - T_j^4)$$

As before, $\overline{SS}$ has the dimensions of area and is L^2 times a dimensionless function of shape, emissivities of all surfaces, and κL.

Interchange between two gas zones introduces no new principles significant to modeling.

It is clear that radiation modeling can be difficult. The radiative transport is in competition with turbulent transport and conduction, quantities which are linear in temperature. The ratio is proportional to $f_1 \times (T_1^4 - T_2^4)/(T_1 - T_2)$. If T_1 and T_2 are the hottest and coldest surface elements present in the system and differ by no more than a factor of 2, the replacement of $(T_1^4 - T_2^4)f_1/(T_1 - T_2)$ by $4T_{av}^3f_1$, with T_{av} representing the arithmetic mean of T_1 and T_2, represents a reduction of only 10 per cent. Consequently, for systems in which the radiant surfaces are each fairly uniform in temperature and there are but two of them and their temperatures do not differ by more than a factor of 2, the maintenance of equal values of $T_{av}^3f_1$ in model and prototype guarantees that radiation will keep in step with the heat flux that is linear in temperature in the system, even though $T_1 - T_2$ is greatly different in the two devices. If, however, between the surfaces at T_1 and $T_2 = 1/2\ T_1$ there are other surfaces at all intermediate temperatures, it is clear that maintenance of equality of $T_{av}^3f_1$ in model and prototype will not at all produce "modeled" radiant flux, except between the surfaces at T_1 and T_2. The use of $(\sigma T_{av}^3Lf_1/\lambda)$ as a radiation modeling group is old; it is seldom adequate except where allowance for radiation is of the nature of a correction to the analysis.

Application to Natural-Convection Jets

As an example of radiation modeling, the physical system discussed by Professor Taylor in the first paper of this symposium will be used—that of the natural-convection jet rising from a point or line source. The derivation without radiation will first be repeated, following the method outlined here and using Tables 1 and 3.

The problem is to determine how to model temperature and velocity above a prototype heat source of energy rate q_P, by use of a smaller heat liberation rate q_M in the model. Consider what goes on in a plane the distance z above the heat source or fire, and use z as a characteristic dimension. The statements one may make about the problem concern the forces (numbered in accordance with Table 1),

1. momentum due to steady flow, $u^2\rho z^2$,
3. (turbulent stress) (area), $\rho\overline{lv}z^2u/z$ which, on the assumption of $\overline{lv}$ being proportional to zu, becomes the same as "1",
4. buoyancy $z^3(\rho - \rho_a)g$ which, by use of the perfect-gas relation $\rho/\rho_a = T_a/T$, becomes $z^3g\rho(T - T_0)/T_0$,

and the energy rates (numbered in accordance with Table 3),

20. enthalpy flux or convective flux through an area, $z^2u\rho c_p(T - T_0)$,
22. turbulent transport $\overline{lv}\ z^2\rho c_p(T - T_0)/z$ which, on the assumption of $\overline{lv}$ proportional to zu, becomes the same as "20",
24. heat liberation rate at the source, q.

The statement about forces include two forces, from which a single ratio can be formed; and this ratio includes two dependent variables, u and $T - T_0$. The ratio containing them must be identified with a position in relation to the axis through the heat source, expressed in non-dimensional terms. In application to the radial distance r, the force statement then becomes

$$\frac{u^2 T_0}{zg(T - T_0)} = f_a(r/z)$$

Similarly, the energy statement becomes

$$\frac{q}{uz^2\rho c_p(T - T_0)} = f_b(r/z)$$

Either u or $(T - T_0)$ may be eliminated from these to give

$$\frac{q}{\rho c_p}\left(\frac{T_0}{g}\right)^{1/2} z^{-5/2}(T - T_0)^{-3/2} = f_3(r/z) \tag{2}$$

and

$$\frac{q}{\rho c_p}\frac{g}{T_0} z^{-1}u^{-3} = f_4(r/z) \tag{3}$$

Expressing these explicitly in $(T - T_0)$ and u gives

$$T - T_0 = \left(\frac{q}{\rho c_p}\right)^{2/3}\left(\frac{T_0}{g}\right)^{1/3} z^{-5/3} \times f_3(r/z)$$

and

$$u = \left(\frac{q\ g}{\rho c_p T_0 z}\right)^{1/3} \times f_4(r/z)$$

These two relations appear to have been derived without any assumptions concerning profile similarity, but they do depend on the assumption that the velocity v in the transport coefficient $\overline{lv}$ is measured by the local steady velocity u and that l is measured by the distance the jet has risen or, since reference is to point r/z, alternatively by r. The relations are of course of the same form as the relations obtained by Schmidt and by Hunter Rouse, reproduced by Professor Taylor as equations 4 and 5. To obtain Rouse's equations, one uses the definitions of $\Delta\gamma(\equiv g(T - T_0)\rho/T_0)$, $-W(\equiv qg/c_pT_0)$, and $w(\equiv u)$.

Analysis, by the same method, of the performance of a line source is identical in all respects to the preceding except that $(q/L)z$ replaces q in the analysis, where (q/L) is the heat liberation rate per unit of ground length along the line heat source.

Relation (2) states that in the z-plane in two systems having equal values of $(q/\rho c_p)(T_0/g)^{1/2}(z)^{-5/2}(T - T_0)^{-3/2}$, conditions at corresponding values of r/z will be similar; and relation (3) gives a comparison of velocities at corresponding points in the two systems.

Consider now the addition of radiation modeling to the problem of constructing similar hot natural-convection jets. There are two meanings to the term *radiation modeling*: (1) modeling of the interaction of radiation with other energy-transport phenomena, and (2) modeling of the radiating properties while ignoring their influence on the jet temperature pattern. To achieve the first of these, the ratio of hot-jet radiation to convection is formulated:

$$\frac{\sigma(T^4 - T_0^4)f(\epsilon\text{'s}, \kappa z, \text{shape})}{u\rho c_p(T - T_0)} \tag{4}$$

Elimination of the dependent variable u is achieved by combining this with the left-hand group in equation (3) to give

$$\frac{\sigma(T^4 - T_0^4)f(\epsilon\text{'s}, \kappa z, \text{shape})}{(\rho c_p)^{2/3}(qg/T_0 z)^{1/3}(T - T_0)} \tag{5}$$

Full modeling is then achieved by keeping items (2), left, and (5) above both constant from prototype to model. One now sees the difficulties introduced by radiation. Use of any but the prototype fuel and temperature level appears, practically, out of the question. The group κz is better represented by $\kappa' P z$, with κ' approximately a constant characteristic of the fuel. Substituting proportionality of ρ to P and retaining only those terms in (2) and (5) which are subject to control by the experimenter, one has the two groups

$$\frac{q}{Pz^{5/2}} \text{ and } \frac{f(\epsilon\text{'s}, Pz)}{P^{2/3}(q/z)^{1/3}} \tag{6}$$

which must be kept constant from prototype to model. Since the function f is not one of proportionality to the dimensionless groups ϵ and Pz in it, the right-hand group calls for constancy of each of the groups

$$\epsilon,\ Pz,\ P^{2/3}(q/z)^{1/3} \tag{7}$$

in addition to the left-hand group of (6) that would alone have sufficed in the absence of radiation. Setting $P \propto z^{-1}$ from the center group of (7) into the group $q/Pz^{5/2}$ yields the relation

$$q \propto z^{3/2}$$

But setting $P \propto z^{-1}$ into the right-hand group of (7) yields the relation

$$q \propto z^3;$$

and one sees that not enough degrees of freedom are available to model.

One may abandon the objective of allowing for interaction of radiation with other fluxes—an assumption justified if flame energy loss by radiation is small—and be content with modeling the radiation process. This means simulating the space-distribution of radiation over nearby receiving surfaces such as the ground; maintaining a ratio, in the model, of radiation received at a point from two fixed directions into the flame, which is equal to the ratio in the prototype at a corresponding point; etc. This is accomplished, in systems which are temperature-matched, when the two paths from the point into the flame traverse equal ratios of emitters. And this calls simply for $\kappa' Pz$ or Pz to be the same in model and prototype. The conditions for limited modeling are now constancy of

$$q/Pz^{5/2} \text{ and } Pz \tag{8}$$

which leads to the model laws:

$$z \propto P^{-1} \text{ and } q \propto z^{3/2} \text{ or } q \propto P^{-3/2}$$

Specifically, one simulates a large open fire by burning, in a confining tank, say, at 4 atmospheres, one-eight as much fuel; and one makes measurements at one-fourth the prototype distances. The use of pressure in modeling is plainly not attractive.

There is a limiting case: If the prototype flame is so nearly opaque that the model flame can also be considered so, $\kappa' PL$ is infinite for both; and the only condition to be satisfied is the constancy of $q/Pz^{5/2}$. Pressure need no longer be used to gain a new degree of freedom in modeling. One might instead wish to retain P as a variable and use this freedom to satisfy a chemical requirement for producing luminosity. A satisfactory group is formed from Table 2, items 13 and 10, which yield the ratio zP^{n-1}/u (n is the order of the over-all chemical reaction). Combining with the group in (3), again to eliminate u, one has z^2P^{3n-2}/q. Satisfying this together with the original group $q/Pz^{5/2}$ yields the model laws

$$z \propto P^{-(2n-2)} \text{ and } q \propto z^{1/2(5-1/n-1)}$$

which, with $n = 2.4$ in anticipation of the last section, gives

$$P \propto z^{-1/2.8} \text{ and } q \propto z^{2.15}$$

One would be somewhat concerned about the size of a jet above which the thick-flame criterion failed.

Forced Jets or Diffusion Flames

In the spring of 1958 the author made an approximate analysis of the forced turbulent thermal jet to indicate whether buoyancy might lengthen or shorten a driven-jet flame, i.e., to find how the ratio of flame length to nozzle diameter of two jets of identical fuel issuing at identical Reynolds number would compare when their buoyant force-turbulent force ratios were different. The dimensionless group measuring this ratio (items 3 and 4 of Table 1), based on the velocity, diameter and density at the nozzle, is $u_0^2\rho_0/gd_0(\rho_0 - \rho_a)$. Except for the density terms it is the Froude number but with entirely different applicability, and has been called the modified Froude number (Fr)′. It may be identified with $u_0^3 d_0 \rho_0 c_p T_0/qg$. The details of the simplified analysis, based on the conservation equation for mass (or energy; they are of the same form here), the force balance, and the assumption of inflow proportional to axial velocity, are out of place here. The conclusion was reached that at a fixed Reynolds number the more buoyant jet would be shorter, i.e., that a specified molal ratio of ambient fluid to nozzle fluid would be found nearer the nozzle. The implication that buoyancy *shortens* a flame may come rather as a surprise, appearing to go against common sense; the forgotten element in the "common-sense" approach is that buoyancy forces are available to help entrain air into the flame and thereby increase its burning rate.

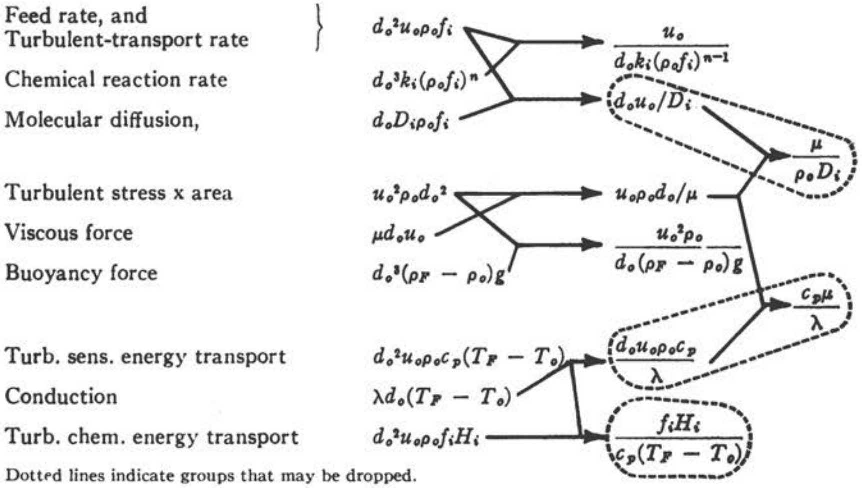
The experimental examination of the forced-jet flame will be presented briefly as an interesting example of the pitfalls of fire modeling. Flames of fuel jets issuing at velocities to several hundred feet per second from vertical burners were being studied. Table 4 summarizes the model analysis, listing the mass rates, forces, and energy rates which were considered of probable importance. Six ratios emerge, but two of them may be dropped with no loss because they combine with others to form the Prandtl and Schmidt numbers, substantially constant for gases; and the sixth is constant for any one fuel. Three are left

turbulent transport/chemical reaction, $u_0/d_0 k \rho_0^{n-1}$
turbulent stress/viscous stress, *Re*, $d_0 u_0 \rho_0/\mu$
turbulent force/buoyancy force, $u_0^2\rho_0/d_0(\rho_F - \rho_0)g$ (9)

Earlier work had indicated that the flame length depended greatly on Reynolds number up to high values of that parameter,

TABLE 4. FORCED-JET FLAMES

(Items from Tables 1, 2, and 3 which appear in the analysis)



Dotted lines indicate groups that may be dropped.

then rose very slowly in a way which was later interpreted as indicating a possible effect of chemical kinetics as velocities approached sonic. This viewpoint was reinforced by studies of gaseous combustion inside perforated spheres, where the mixing achievable by sonic-jet feed was so rapid as plainly to make chemical kinetics controlling. Accordingly, attention was focused on the first two groups of (9), which yield the dimensional groups

$$u_0/d_0P^{n-1} \text{ and } d_0u_0P; \text{ or } u_0 \propto P^{n/2-1} \text{ and } d_0 \propto P^{-n/2} \quad (10)$$

The chemical reaction order was expected from other work to be about 2, indicating that pressure should be varied inversely as nozzle diameter and velocity should remain constant if flame lengths, measured in nozzle diameters, were to stay constant.

Data were taken from experiments planned on the basis of the above expectation—flame lengths versus velocity in combinations of pressure and nozzle size to test the validity of keeping *Pd* constant to achieve modeling. The pressure range covered was 1/3 to 6 atmospheres; nozzles 1/32″, 1/16″, 1/8″; velocities up to blowoff (500 ft/sec). The results, from the doctor's thesis of Mr. C. A. Homsy[4] soon to be published, are shown in Figure 1, as heavy lines. Each heavy line represents flame length versus

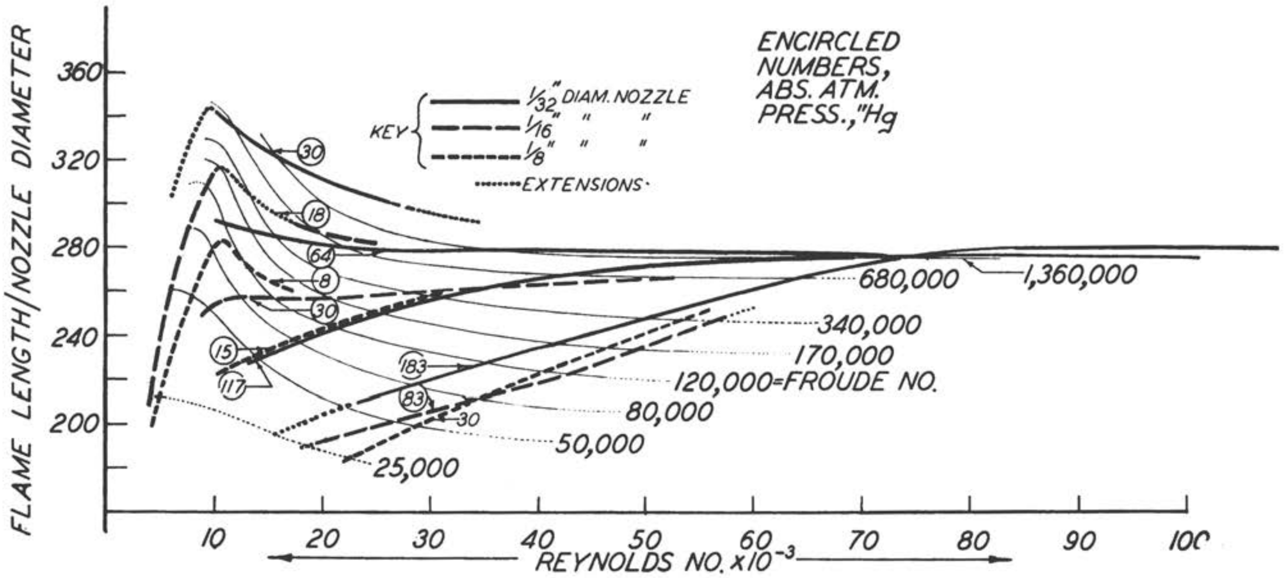


Figure 1. Turbulent flame jet lengths as a function of Reynolds number

Reynolds number, with pressure and nozzle diameter held constant. Flame length is defined as the distance to the axial point where the CO/CO_2 ratio is 0.15. Examination of the figure shows a regular progression, with pressure, of the results for any one size of nozzle; and a regular progression, with size, of the effect of pressure. But the curves appeared hopeless to correlate (partly because incomplete), and did not at all correlate with the chemical group on the basis anticipated. The results suggested, however, that correlation might be obtained by use of a much smaller n than 2.

If one returns now to consideration of the unused buoyancy group in equation (9) and assumes that the Reynolds number and it, rather than the chemical group, control the modeling, then the controlling dimensional groups are

$$U_0^2/d_0 \text{ and } d_0 u_0 P; \text{ or } u_0 \propto P^{-1/3} \text{ and } d_0 \propto P^{-2/3} \qquad (11)$$

Comparison of equations (10) and (11) indicates that, if $n = 4/3$, the model laws are the same. Use of $n = 4/3$ produced a good correlation of the data; and the thin lines on Figure 1 running upwards to the left are lines of constant $(Fr)'$ adequately representative of data at all the pressures and nozzle diameters examined. One could interpret the results as supporting either a low-order chemical reaction or buoyancy. The analytical treatment of buoyancy referred to earlier predicts buoyancy-controlled changes in flame length which are in rough quantitative agreement with the results of Figure 1 at high *Re*, and there appears now to be little doubt that the chemical group is of minor importance here.

Although total flame length was uninfluenced by the chemical group, the luminous portion of the flame appeared to be chemically controlled. Pressure had a profound effect on the soot-luminosity of the flame, and the data on "yellow flame length" supported an exponent n of about 2.4 in the chemical group.

It should be noted from Figure 1 that when the Reynolds number is high, it is without influence on flame length; and only the buoyancy/turbulent transport ratio needs to be modeled. Pressure can then be dropped as a modeling tool or be used to aid in modeling radiation phenomena. It should be clear from this discussion, however, that fire modeling, to be successful, must be associated with research planned to delineate the ranges in which various forces, energy rates or mass rates can either be successfully ignored or combined in a simple way with others. Without such progress modeling is stopped by the existence of too many parameters to satisfy.

Appendix on Radiation

Let $\overline{12}$ designate the product $A_1F_{12}(\equiv A_2F_{21})$, in which F_{12} equals the fraction of the radiation emitted from A_1 which is directed towards A_2. Let all surfaces be gray, and Lambert or diffuse reflectors. Let emissivity be ϵ and reflectivity be ρ $(= 1 - \epsilon$ because gray).

It has been shown that the factor $\overline{S_iS_j}$ of equation (1) is given by

$$\overline{S_iS_j} = \frac{A_i\epsilon_i}{\rho_i}\,\frac{A_j\epsilon_j}{\rho_j}\,\frac{D_{ij}}{D} \tag{1A}$$

where D_{ij} is the cofactor of the i-th row and j-th column of D, and D is a determinant containing direct-view factors F, as follows

$$D = \begin{vmatrix} \overline{11} - \frac{A_1}{\rho_1} & \overline{12} & \overline{13} & \cdots \\ \overline{12} & \overline{22} - \frac{A_2}{\rho_2} & \overline{23} & \cdots \\ \overline{13} & \overline{23} & \overline{33} - \frac{A_3}{\rho_3} & \cdots \\ \vdots & \vdots & \vdots & \end{vmatrix}$$

If the surfaces are not gray, the flux between A_i and A_j is given by

$$q_{i\rightleftharpoons j} = \int_0^\infty (\overline{S_iS_j})_\lambda (W_{\lambda,T_i} - W_{\lambda,T_j})\,d\lambda \tag{2A}$$

where W_λ is the hemispherical monochromatic emissive power of a black body, given by the Planck equation. Note that $\overline{SS}$ is a function of λ, and evaluation of any but a simple geometrical equation is quite tedious. When all surfaces but i and j are black, interchange between the two is due solely to direct radiation, and $\overline{S_iS_j}$ is replaced both in (1) and in (2A) by $\overline{s_is_j}$ or, in the older nomenclature, by A_iF_{ij}.

Interchange between two gray surface zones which are part of an enclosure containing an isothermal absorbing gas involves the factor $\overline{S_iS_j}$, which is obtained as for systems with non-absorbing gas except for a redefinition of $\overline{12}\cdot\overline{12} \equiv A_1\tau_{12}F_{12}$, in which τ_{12} is the fraction of the radiation emitted from A_1 towards A_2 which is transmitted without absorption. If the system is not gray, the expression for interchange becomes

$$q_{i\rightleftharpoons j} = \int_0^\infty (\overline{S_iS_j})_\lambda (W_{\lambda,T_i} - W_{\lambda,T_j})\,d\lambda$$

The approximation of considering the gas to be a mixture of gray and clear gas and the surfaces to exhibit constant but different emissivities for the two spectral ranges involved leads to the expression

$$q_{i\rightleftharpoons j} = \{a(\overline{S_iS_j})_{\substack{\text{based on}\\ \text{gray gas}}} + (1 - a)(\overline{S_iS_j})_{\substack{\text{based on}\\ \text{clear gas}}}\}\sigma(T_i^4 - T_j^4)$$

in which "a" is fraction of the energy spectrum occupied by absorbing gas.

Interchange between the gas zone and a surface zone in a gray system is given by

$$q_{S_i\rightleftharpoons G} = (A_i\epsilon_i - \sum_i \overline{S_iG})\sigma(T_i^4 - T_G^4)$$

If the gas contains temperature gradients and cannot be represented as having a mean temperature, it must be zoned. Methods of handling such a problem are treated elsewhere[3].

Table of Nomenclature

A	area
c_p	specific heat, const. pressure
d_0	nozzle diameter
D_i	diffusivity
f_i	mass fraction of i^{th} component
g	gravitational force per unit mass
H_i	heat of combustion of i^{th} component
k	chemical reaction rate coefficient
L	characteristic length

P	pressure
q	energy liberation rate by combustion, or energy addition rate
r	radius
u	velocity
V	volume
z	vertical distance
ϵ	surface emissivity
λ	either thermal conductivity or wavelength
κ	Beer's law absorption coefficient, length^{-1}
κ'	Beer's law absorption coefficient, (pressure × length)$^{-1}$
μ	viscosity
ρ	density, or reflectivity
σ	Stefan-Boltzmann constant of radiation, or surface tension

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Discussion

Dr. Shipman: The specific problem presented by Professor Hottel shows clearly how to alter the operating variables of a problem in order to make a model. In the case presented, the jet flame, the scale-down can be selected by altering the size of the length parameter of the system, namely the diameter of the jet nozzle. It should be pointed out that such a simple scaling is not possible in a system in which there is no direct geometrical variable. For example, one might consider a grass fire as a fire located in a plane source of fuel of infinite extent. In this case the stated problem has no direct length parameter, and the scaling down must be done in terms of that particular combination of variables chosen for the length parameter, e.g. the square root of the ratio of a characteristic mass transfer coefficient (units: m/lt) to the characteristic volumetric reaction rate (units: m/l^{3}t).

LIQUID SURFACE MODEL FIRES

WILLIAM H. AVERY, *Presiding*

Some Observations on Pool Burning—*Howard W. Emmons*

Burning Rates of Liquid Fuels in Large and Small Open Trays—*David Burgess*

Test on Combustion Velocity of Liquid Fuel and Temperature Distribution in Flames and Beneath Surface of the Burning Liquid—*Gert Magnus*

Effectiveness of Some Powdered Materials in Extinguishing Hydrocarbon Fires—*T. G. Lee*

Some Observations on Pool Burning

H. W. EMMONS
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ABSTRACT

The burning of acetone and methyl alcohol from small open pools has been examined for pool sizes from ¼ inch to 10 inches. The very large influence of the radiant heating of the surrounding area on convective disturbances is noted and the subsequent transfer of some of this heat through the pan rim to the fuel is examined. A method of separating burning rate into more tractable pieces is proposed and is shown to be effective in treating the meager data now available.

Introduction

The free-burning or uncontrolled fire presents a highly complex array of interrelated phenomena. The much publicized three elements—fuel, air, heat—do indeed describe the essential ingredients of every fire. The great present day need is for the quantification of our qualitative understanding of the relationships between these elements.

The burning city, forest, house, crib, or liquid pool differ greatly in many details. The fuel properties and their geometric distribution are vastly different as are also the details of their combustion. However, in each case, there are certain essential steps. The hot burning material (solid or gaseous) releases chemical energy by combustion with oxygen from air. The hot gaseous combustion products rise by natural convection and thus induct air for further combustion. At the same time various mechanisms of heat transfer return heat to the fuel to maintain an active combustion temperature or to gasify additional fuel for further combustion. While the details of these processes differ considerably among the different types of fires named above, we must recognize that in no case, even the simplest, can quantitative estimates of the burning rate be made. It seems desirable as an immediate goal to attain a predictive understanding of some simple case of uncontrolled burning rate.

Simplification of the Experiment

In Figure 1 is pictured a fuel structure (E-G) in partial glowing combustion and partial gasification with flame combustion above (A). The solid combustion is maintained by radiative, conductive, and convective heat transfer within the structure (F-G) and radiative and perhaps some convective heat transfer from above (A). The buoyant gases at (A) and (B) induct new air (D) and drive convections within the structure (E). Radiant heat transfer from (A) goes in part directly to the fire (J). The larger part however is lost above (I) or is distributed over the fire surroundings (C). This latter radiant energy partially heats adjacent, as yet unignited, fuel structures and partially passes indirectly into new air (D) thus returning indirectly to the fire. Some heat is lost by conduction into noncombustible materials such as the ground at (H).

An initial test structure should strive to eliminate every possible complication from this picture. The minimum essential elements are

1) A fuel structure

2) A heat transfer mechanism from flames or products of combustion to the fuel structure

3) A natural convection mechanism

One would also add, (4) a combustion chemistry, if there was any possibility of selecting a really simple chemistry. At the present time all practical uncontrolled combustion systems have chemical kinetics too difficult to unravel and of uncertain importance. It is often believed, perhaps correctly, that the real burning rate control is a diffusive control rather than chemical. While this seems to be correct for a simple diffusion flame, there is some doubt about it for the uncontrolled fire as will be discussed later.

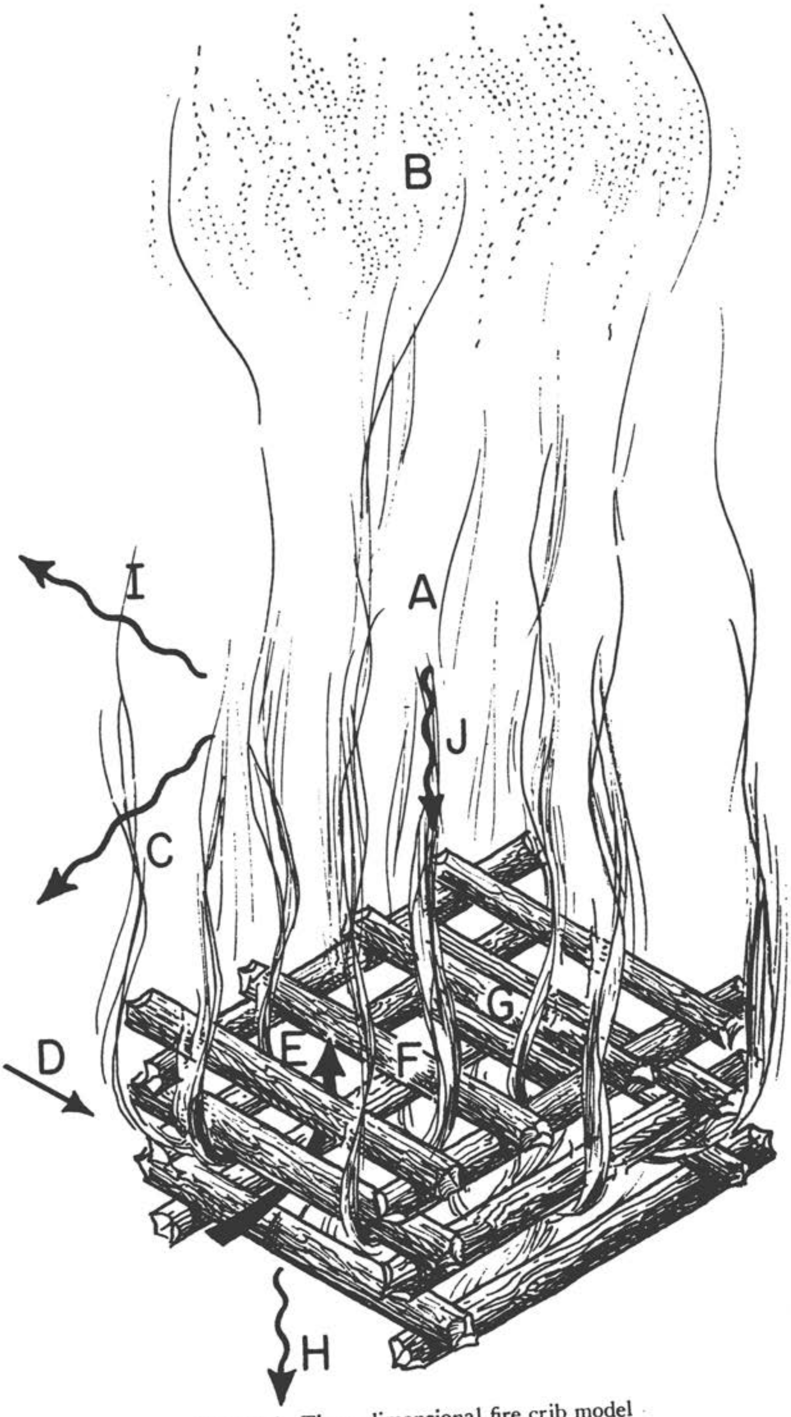

Figure 1. Three-dimensional fire crib model

There appear to me to be three cases of fires in which, with some effort, the number of contributing effects can be minimized. These are

1) A simple geometric structure of a relatively non-gasifying fuel having gaseous products of combustion. A crib made of charcoal is perhaps the best although the production of CO as an intermediate product is an undesirable complication.

2) A simple geometric structure made of porous noncombustible material impregnated with a liquid fuel. The continuous supply of liquid fuel would be necessary.

3) A liquid pool fire.

Since the liquid pool appeared to provide the simplest possible geometry and a fairly wide range of fuel properties, it was chosen as the basis of the present fire study at Harvard.

Simplification of the Analysis

The computation of the rate of burning of an uncontrolled fire based upon the basic laws of physics and the properties of fluids can be accomplished for the simplest cases only (the semi-infinite flat plate, the horizontal cylinder, the sphere). Various special partial problems have been solved such as laminar or turbulent natural convection above fires, the diffusion flame front with infinite or finite reaction rate, laminar flame height, etc.

It does not appear feasible to carry out such a detailed analysis of fires of interest here. One thinks then in terms of less exact and less detailed analyses. A dimensional analysis is the usual minimum analysis which together with experimental results yields useful and general results. However, many complex systems have so many independent variables that some simplification is necessary before a dimensional analysis is useful.

Often it is possible to divide a complex system into independent or semi-independent parts. A simple heat exchanger is not usefully treated by dimensional analysis until after the over-all thermal resistance is broken down into the resistances of individual parts. So with a fire, it is desirable to separate the phenomena into separately treatable parts and a first effort of this kind will be attempted in a later section.

Experimental Study

The Apparatus

The pool burning apparatus was designed to minimize the problem of miscellaneous heat transfer. Figure 2 shows the arrangement. Each pan was made of a flat brass plate with a brass rim ¼ in. deep, sharp at the top, and set flush with the table top. Thus, hopefully, heat transfer by conduction through the rim is thereby eliminated. Pans were made of 12 sizes,

$$D = \tfrac{1}{4}, \tfrac{1}{2}, 1, (1), 10 \text{ inches.}$$

Although continuous fuel supply with steady burning is desirable, it was decided, in view of simpler apparatus, to make initial non-steady tests. Most tests reported here were made by filling the dish ¾ full (i.e. to a fuel depth of $\tfrac{3}{16}$ in.) and noting the time T to burn all the fuel.

Since natural convection tests to be made concurrently with the fire tests were contemplated, it was desired to control miscellaneous room drafts. After some months of experimentation the arrangement shown in Figure 3 was found satisfactory. This did not, however, give a truly "undisturbed" flame. The flame was, of course, turbulent but still randomly leaned badly one way or another, or occasionally swirled partly off the dish.

The cause of these disturbances was traced to the (radiant) heating of the table top adjacent to the pool. Thus heated, the table top heats a boundary layer of slow moving air inducted by the fire. As this thin layer becomes hot enough it becomes unstable and natural convection columns rise adjacent to the fire and are gradually pulled into the fire.

These extra convection columns can be eliminated by cooling the surface around the flame. In our most recent tests, a cooled copper plate surrounds the pool, but in most of the tests reported here the need for this refinement had not yet been discovered.

Two fuels were chosen, acetone and methyl alcohol. These pure compounds were selected because they have moderately low and definite boiling points, are reasonably cheap, and differ considerably from one another in radiation from the flames (acetone burns with a luminous flame while methyl alcohol burns with a faint blue flame).

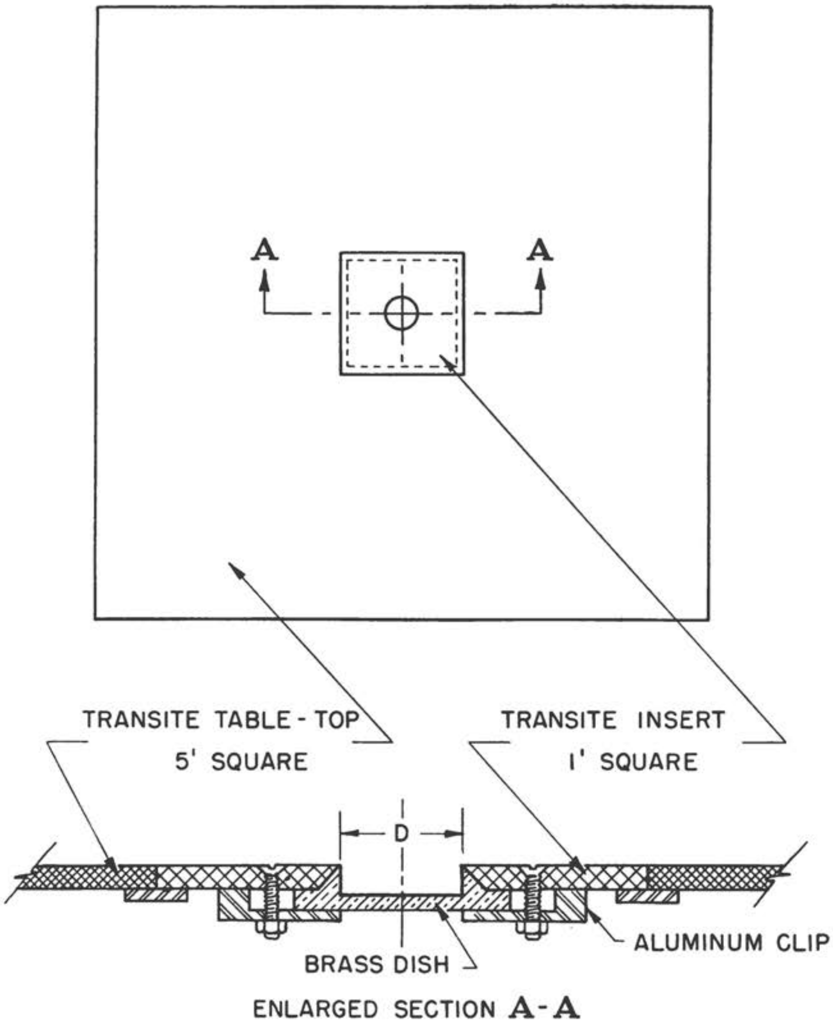

Figure 2. Installation of brass dish

Test Results

Some of the initial results expressed as mean burning velocity $v_l^0 = t/\tau = \dfrac{\text{depth}}{\text{burning time}}$ are shown in Figure 4. We note immediately the agreement with the results of Blinov and

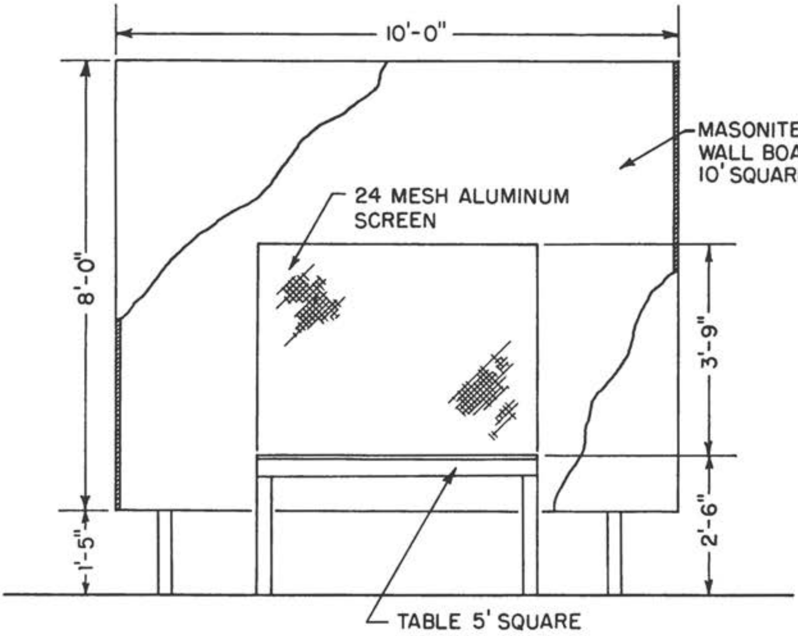

Figure 3. Combustion chamber

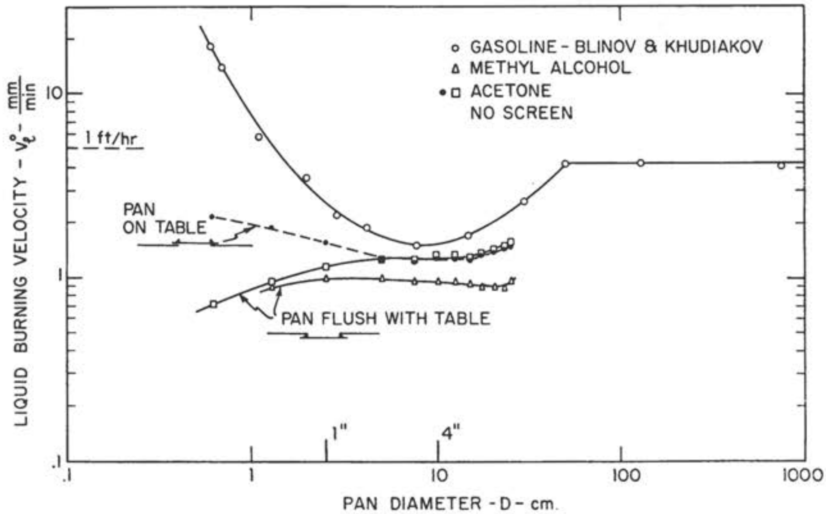

Figure 4. Effect of pan diameter on liquid burning velocity

Khudiakov[1] for the pan sizes 4 inches through 10 inches but complete disagreement for the small sizes. The cause for the diagreement was found when tests were run with the pans placed on top of the table. Results are shown by a dashed line in Figure 4.

One might suppose that radiation directly from the flames to the exposed rim with subsequent heat conduction to the liquid to be responsible for the increased rate of burning. However, placing a radiation shield over the exposed rim had no effect on the burning rate. Thus we see that the heat transfer path from flames to the liquid is (1) radiation from flames to the whole table top (2) convection transfer from table top to inducted air (3) convection transfer from inducted air to pan rim (4) conduction through the rim to the fluid. This four-step mechanism takes the place of the simple conduction term assumed by Hottel.[2] We note, however, that it is proportional to the dish circumference and hence, per unit area of pan, its contribution to evaporation is proportional to $1/D$. It appears then that Blinov and Khudiakov[1] must have had pools with large exposed rims which contributed greatly to the burning rate for small diameters. Furthermore, it is clear that at least for small sizes, there is great variability of burning rate possible by variations of any step in the above four-step mechanism.

A series of tests of a semi-quantitative nature were performed to get a feel for what is important

1) The effect of blackening the pans. Lampblack from a kerosene fire was coated on the inside of the pans and then acetone and methyl alcohol were burned. The results are shown in Figure 5. Except for the smallest pans ($D \leq 1$ inch) radiation to the pan is responsible for only about 7 per cent of the burning rate. This does not imply that the resultant radiation transfer to the liquid is so small.

2) The effect of screens around the table as mentioned under *Apparatus*. The first pan burning tests showed in addition to the expected turbulence some large disturbances in which the flame appeared to periodically slip part way off the pan—by 2 or 3 inches in the worst cases. These were believed to be caused by room turbulence since walking about or opening laboratory doors seemed to make things worse. The placement of a 24 mesh screen around the table made the flame appear somewhat steadier but did not appreciably affect the mean burning rate as shown in

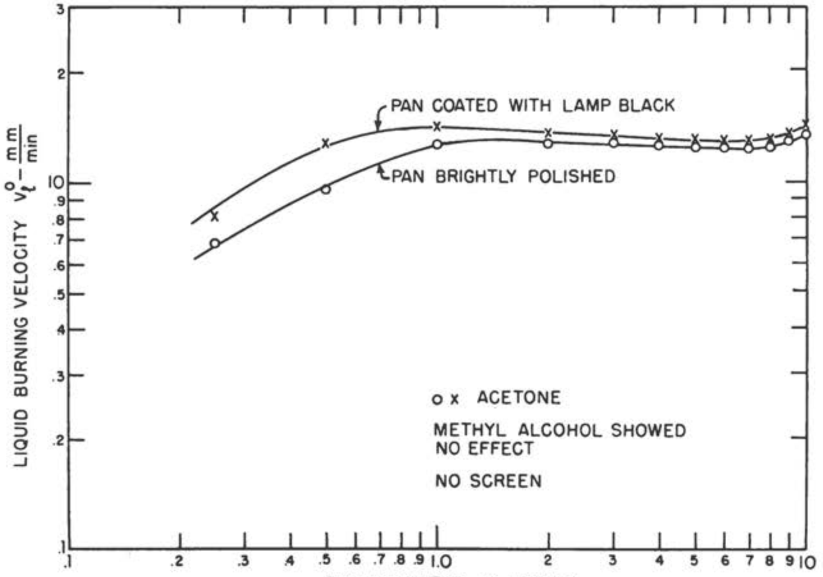

Figure 5. Effect of radiation to pan on burning rate

Figure 6. That a screen is not necessarily any improvement is also shown in Figure 6 where the use of a 70 mesh screen definitely increases the mean burning rate. It was visually obvious that the 70 mesh screen was not sufficiently porous since the flame convection column reacted with the "enclosure" causing a strong eddy which made the flame lean to one side.

3) The effect of partial filling. Tests were made of burning rate as affected by partial filling of the pan. Figure 7 shows the results for two different size pans. The open points show the mean burning velocities as measured. The falling burning rate at low filling is, as will be shown later, caused by the absorption of heat by the pan and the room temperature fuel.

Analytical Considerations

Since, as noted above, a dimensional analysis is popularly resorted to for highly complex problems it is presented here for discussion purposes.

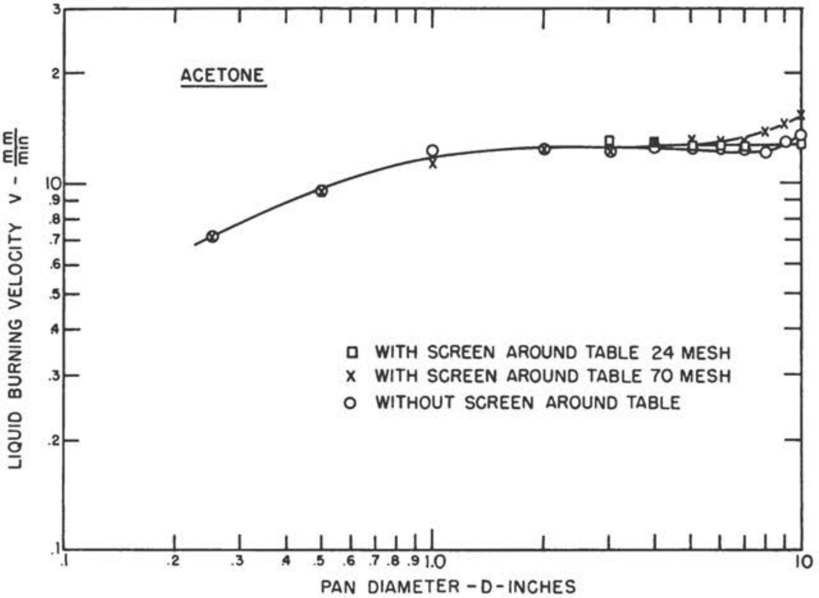

Figure 6. Influence of screens on burning velocity

$$\frac{v_l}{\sqrt{Dg}} = f\left(Gr, Pr, B, Sc, \gamma, D_1, D_2, \frac{\epsilon\sigma Q^3 D}{c_p{}^3 k}, \frac{g\beta D}{c_p}, \frac{c_p T_{cr}}{Q}, Re_{\text{wind}}\right) \quad (1)$$

Gr	modified Grashof number	$\frac{\rho^2 D^3 g\beta Q}{c_p\mu^2}$
Pr	Prandtl number	$\frac{c_p\mu}{k}$
B	$\frac{\text{heating value per unit mass of air}}{\text{effective latent heat of vaporization of fuel}}$	$\frac{\lambda_e}{Q_0 Y_{0_2}}$
Sc	Schmidt number	$\frac{\mu}{\rho D}$
γ	isentropic exponent	$\frac{c_p}{c_v}$
D_1	Damköhler's 1st number	$\left(\frac{Dc_p}{g\beta Q_f}\right)^{1/2}\frac{1}{\tau_r}$
D_2	Damkohler's 2nd number	$\frac{Q_f}{c_p T}$

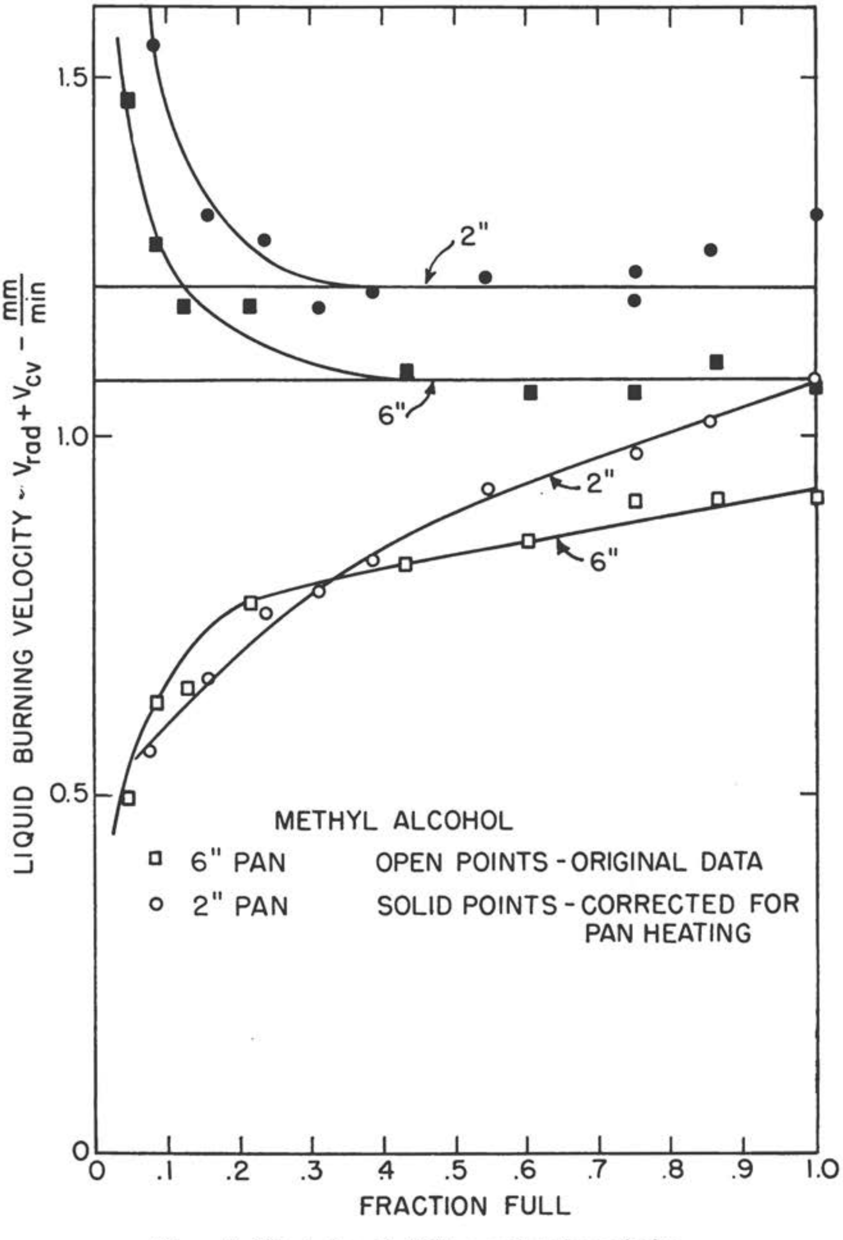

Figure 7. Effect of partial filling on burning velocity

Re_{wind} Reynolds number of wind $\frac{\rho w D}{\mu}$

ϵ emissivity of flames

Q_0, Q_f heat of reaction per unit mass of oxygen and fuel respectively.

τ_r time constant for the controlling reaction.

In problems as complex as an uncontrolled fire the dimensional analysis has effected a reduction from 15 to 11 independent variables. This small reduction is of almost no practical value. A further reduction can be effected by the elimination of those groups whose effect might be expected to be small. In this way we might assume

$$\frac{v_l}{\sqrt{Dg}} = f\left(Gr,\ B,\ \frac{\epsilon\sigma Q^3 D}{c_p{}^3 k},\ Re_{\mathrm{wind}}\right) \tag{2}$$

to be adequate. In spite of the meagerness of presently available data the attempt to use this grossly simplified formula soon made it clear that the function f would have to be a hopelessly complex one. An over-all dimensional analysis is probably useless in the fire problem.

A more fruitful, if still very preliminary, approach follows by separating the observed burning rate into pieces. In Figure 8 the fuel in a pan is schematically shown receiving heat by radiation (Q_{rad}) and convection (Q_{cv}) from the flames, by conduction (Q_{cd}) through the sides and losing heat Q_0 to the pan to raise its temperature. The actual burning velocity v_l^0 of the liquid is thus determined by a heat balance.

$$A\rho_l v_l^0 \lambda = Q_{rad} + Q_{cv} + Q_{cd} - Q_0 - Q_{int} \tag{3}$$

A liquid surface area

λ latent heat of evaporation of the liquid

Q_{int} heat used to heat the liquid from its supply temperature to its boiling point.

This expression can be put in the form

$$v_l^0 = v_{rad} + v_{cv} + v_{cd} - v_0 - v_{int} \tag{4}$$

where

$$v_{rad} = \frac{Q_{rad}}{A\rho_l\lambda},\ v_{cv} = \frac{Q_{cv}}{A\rho_l\lambda},\ v_{cd} = \frac{Q_{cd}}{A\rho_l\lambda},\ v_0 = \frac{Q_0}{A\rho_l\lambda},\ v_{int} = \frac{Q_{int}}{A\rho_l\lambda}.$$

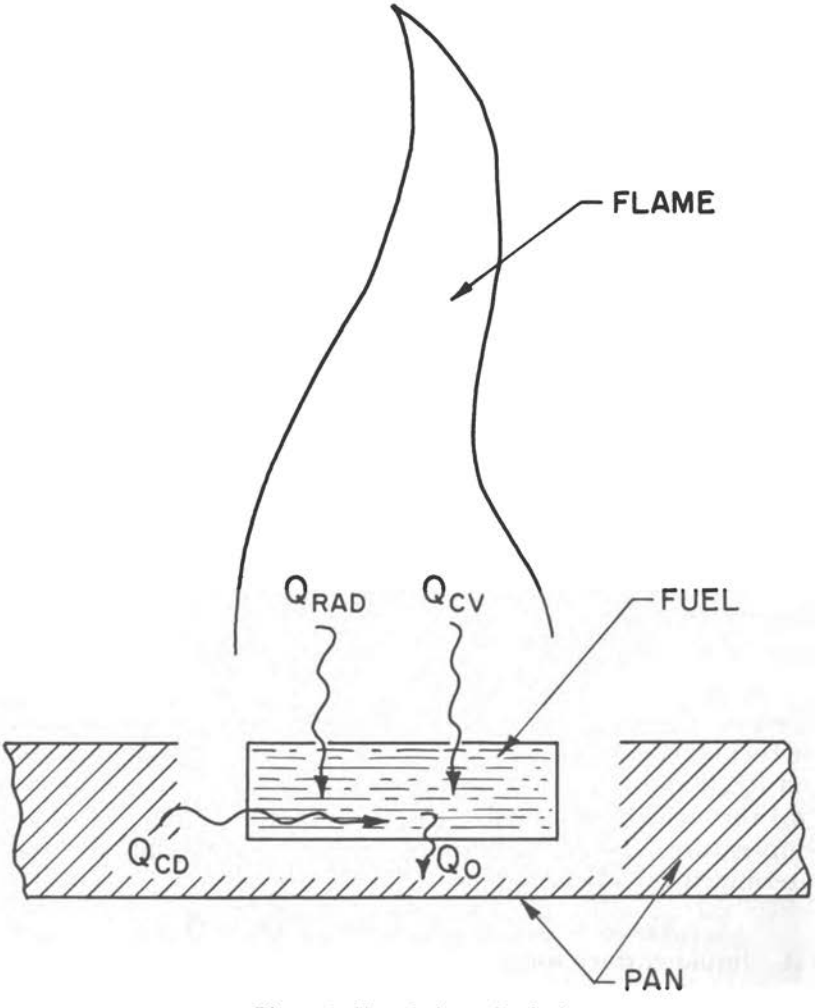

Figure 8. Heat balance for fuel

If the actual burning rate v_l^0 could be decomposed in this manner, each of the pieces could be either computed from basic data or related through a dimensional analysis to a relatively few essential groups.

An attempt to test this separation approach with the present meager data gives hopeful results. In the first place, the data of

Figure 4 strongly suggests that for the pan set flush with the table top, the heat conduction to the pan rim is eliminated. Thus the conductive burning rate v_{cd} can be experimentally reduced to zero. In the second place one is tempted to treat heat used to warm the fuel from the supply temperature to its boiling point Q_{int}, and heat lost to the pan Q_0 as simply a change of "effective" latent heat. That such a point of view is indeed correct can be shown as follows.

$$Q_0 = \frac{c_0 w_0 \Delta T_0}{\tau},\ Q_{int} = \frac{c_l w_l \Delta T_l}{\tau} \tag{5}$$

c_l, c_0	specific heat of liquid and of pan, respectively
w_l, w_0	mass of liquid and of pan, respectively
ΔT_l	temperature rise from initial liquid temperature to boiling point
ΔT_0	temperature rise from initial pan temperature to final pan temperature.
τ	total burning time.

By introducing the burning rate $\overset{0}{M} = w_l/\tau$ and, through equation (3), the burning velocity, we get

$$v_0 = v_l^0 c_0 \Delta T_0 \frac{w_0}{w_l},\ v_{\mathrm{int}} = v_l^0 c_l \Delta T_l \tag{6}$$

and thus, by equation (4),

$$v = v_{\mathrm{rad}} + v_{cv} + v_{cd} = v_l^0 \frac{\lambda_e}{\lambda} \tag{7}$$

where $\lambda_e = \lambda + c_l \Delta T_l + \frac{c_0 \Delta T_0 w_0}{w_l}$ = the heat required to produce a unit mass of fuel vapor, i.e. the "effective" latent heat.

A first test of equation (7), for the separation of the effect of solid and liquid heat capacities is shown in Figure 7. The solid points, and upper curves show the burning velocity corrected for the effective latent heat λ_e. In computing λ_e, it was assumed that the pan was heated by the fire up to the fuel boiling point. Figure 9 shows the data of Figure 4 similarly corrected. It will be noted that for acetone there is one set of data in which correction was made for an effective latent heat based upon actual measured pan temperature (which was measured by a single thermocouple held against the underside center bottom of the pan). Figure 10 shows the measured maximum pan temperatures. For pans larger than

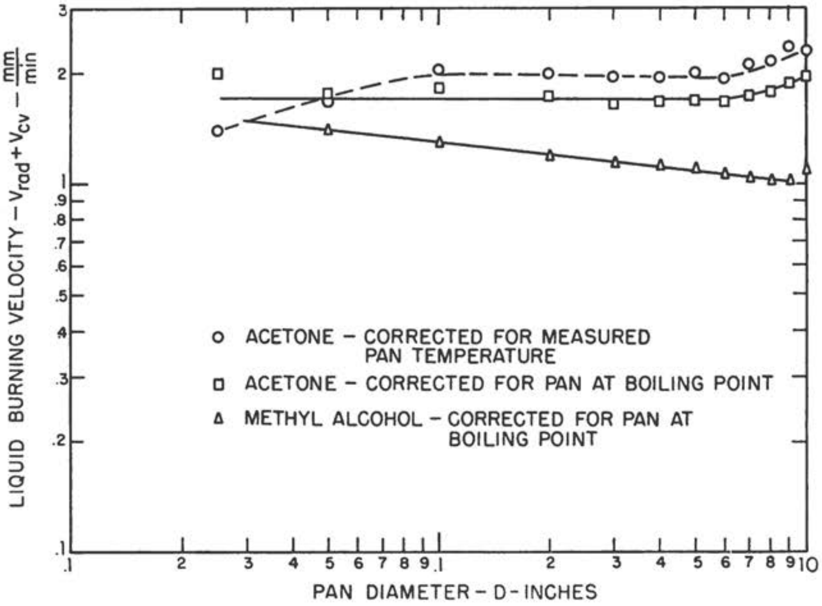

Figure 9. Liquid burning velocity as influenced by convection and radiation

2 inches, the temperature is well above the fuel boiling point during much of the burning time. This suggests (in agreement with Figure 5) that radiation direct to the pan bottom with subsequent heat transfer to the liquid is important. For small pans the heat capacity of the pan is too great to ever be heated up to the boiling point. It is believed that failure to heat the pan up to the boiling point is the primary reason for the rapid rise of the corrected burning velocities for pans less than ¼ full (in Figure 7).

So far no progress has been made with the further separation of the burning velocity into radiative, convective, and conductive components. Much additional data at steady burning rates will be required for this separation and subsequent correlation. A few observations seem pertinent.

By proper pan design and cooling of the surrounding surface, the rim conductive contribution can be eliminated from test equipment. By cooling coils in the burning liquid, the heat loss Q_0 can be controlled and hence (v_{cv} and v_{rad}) determined as above.

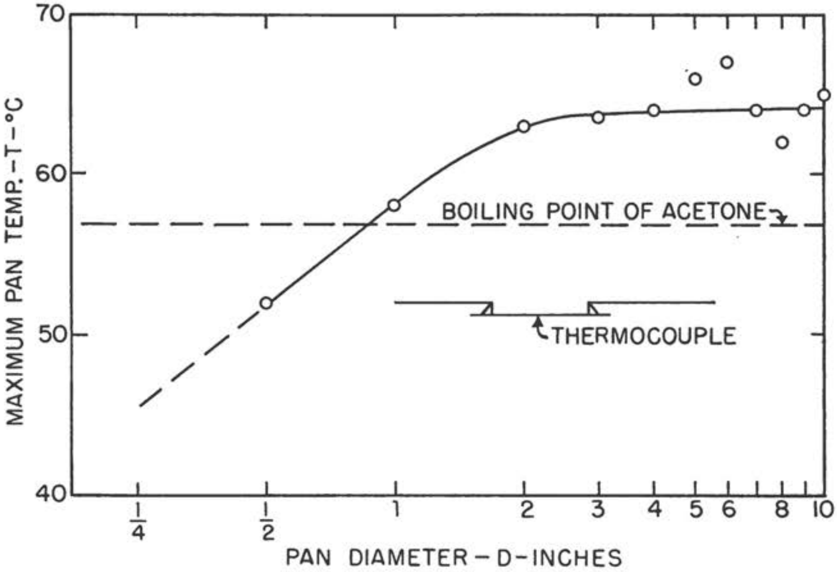

Figure 10. Pan temperatures when burning acetone

Finally, it is believed that considerable careful work will be required to separate and understand v_{cv} and v_{rad}. In particular, v_{cv} is affected by room currents and erratic convective stability phenomena in the laboratory (or field). v_{rad} is affected by the luminosity of the flames and the complex flame geometry. Eventually it seems desirable to reduce v_{cv} to a convective heat transfer coefficient U and v_{rad} to appropriate radiation parameters. However, these both introduce the difficulty of a temperature difference, flame to fuel. As is well known, diffusion flames do not reach the adiabatic flame temperature. In fact, the actual flame temperature is so low that chemical reaction rates probably cooperate with turbulent mixing rates rather than either being controlling. The theoretical work by Zeldovich[3] while on a rather crude model nonetheless shows that if chemical rates were too fast to exert any rate control, the flame temperature should be the stoichiometric adiabatic flame temperature and the flame should be a region separating a region devoid of oxygen from another devoid of fuel. In fact, however, flame temperatures are well below that expected and there is fuel and oxygen in measurable amounts on both sides of the flame. So far no explanation of these experimental results is available except chemical kinetic control.

Some work now in progress appears to indicate that flame radiation heat loss, laminar and/or turbulent diffusion, and chemical reaction rates all contribute in some manner to the final equilibrium condition which exists in a diffusion flame.

Conclusions

The results presented in this paper are too limited to confirm any universal conclusions. Yet some tentative conclusions seem warranted.

1) Further careful experimental burning studies of pan fires and analysis and correlation of results should yield very valuable insights into the mechanisms of uncontrolled fires.

2) The separation of the burning rate, expressed as rate of liquid surface removal, into parts caused by conduction, convection, radiation, and other heat transfer mechanisms is an essential preliminary to a correlation of experimental burning rates.

3) More work is required to understand the diffusive burning process. The production of carbon particles and their rate of burning (or failure to burn) has a large effect on the flame radiation and hence exerts some control in a still obscure manner on the equilibrium flame temperature.

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Discussion

Dr. Wise: I would like to ask Dr. Emmons on what basis he assumes that the surface temperature is the boiling point of the liquid. I believe there is very good indication, both theoretical and experimental, that the surface temperature is below the boiling point of the liquid.

Dr. Emmons: The assumption that the surface was at the boiling point was not made. The surface of the liquid did not enter at all into my discussions. The only use of boiling point that I made was to say that I assumed, where I did not have actual pan temperatures on which to base calculations, that the pan temperatures reached the boiling temperature. The experimental data that I showed you indicate that this is the right order of magnitude, but is not correct to eight or ten degrees, the pan being at higher temperature; I made no assumption about the liquid surface temperature at all.

Dr. Wise: We actually have measured this surface temperature of burning liquids and it turns out to be definitely below the boiling point.

Burning Rates of Liquid Fuels in Large and Small Open Trays

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ABSTRACT

Measurements have been made of the consumption rates of six single-component liquid fuels when burned in open trays. Tray dimensions ranged up to 8 feet in diameter, the ambient atmosphere was very quiet, and the liquid level was adjusted to be nearly flush with the rim of the container. Results with butane,n-hexane, benzene, and methanol are formally similar to those reported by Blinov and Khudiakov for gasoline and for less volatile blended hydrocarbons. Burning rates of liquid hydrogen and of unsymmetrical dimethylhydrazine are consistent with, though too meager to be confirmatory of, the same trends.

The usefulness of Hottel's semiquantitative analysis of heat transfer is demonstrated with new data on burning rates; heat transfer is predominantly radiative in most cases. When burning rates are extrapolated to large tray dimensions, these extrapolated values are inversely proportional to the fraction of the flame's heat of combustion which is fed back to the liquid to maintain a steady evaporation rate.

Interest of the Bureau of Mines in this area was prompted by recognition of the hazards created by the accidental spillage and ignition of volatile liquid fuels. Spill fires were simulated in Bureau laboratories by burning such fuels in shallow trays. The paper by Blinov and Khudiakov, together with a commentary by Professor Hottel,[1] were directly applicable to our study. The present paper represents an extension of the work of Blinov and Khudiakov to six single-component fuels, three of which are not hydrocarbons. Using these new data, we infer burning rates at large tray diameters. These burning rates support a semiempirical law connecting the burning rate with the heat of combustion and the heat of vaporization of the fuel.

A portion of the measurements reported by Blinov and Khudiakov are shown in Figure 1, where the ordinate represents the burning rate of the fuel and the abscissa the diameter of the tray. The appropriate experimental conditions are that the tray should be flush-filled with the liquid fuel, that wind should be absent or negligible (these are primarily important at small tray diameters), and that the burning rates should be measured only after the fuel has attained a steady state of burning. The plateau of burning rate, or the level of burning rate that the experimental values approach asymptotically with increasing diameter, is of first importance. This carries the implication that significant work can be done with tray diameters of the order of 3 feet. Such trays can be handled without a special installation. We can assume that when the tray diameters are such that burning rate is independent of the diameter, the percentage of heat that is radiated to the surroundings and the temperature profile in the liquid phase also will be independent of increasing diameter.

Blinov and Khudiakov discussed the distribution of heat transfer from flame to liquid surface by the expected modes of conduction, convection, and radiation; this is shown across the top of Figure 1, using the symbolism of Professor Hottel:

$$\frac{q}{\pi d^2/4} = \frac{k_1(T_F - T_B)}{d} + U(T_F - T_B) + \sigma F(T_F^4 - T_B^4)(1 - e^{-\kappa d}) \qquad (1)$$

Radiation per unit of liquid surface, expressed as $\sigma F(T_F^4 - T_B^4)$ $(1 - e^{-\kappa d})$, is the term of principal interest because it dominates the heat-transfer picture at large tray diameters and because it provides an explanation for the shoulder of the burning-rate curve shown in Figure 1. In this expression, σ is the Stefan-Boltzmann constant, F a shape factor, T_F the flame temperature, T_B the boiling point of the liquid, and κ an extinction coefficient such that at large values of d, the tray diameter, the exponential term goes toward zero.* In this latter case, the term within the

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* The term $(1 - e^{-\kappa d})$ should be comparable to the measured flame emissivity $E = (1 - e^{\alpha L})$ used by Rasbash *et al.*[2] It is noted that L is a measured flame width while d is the tray diameter. These are roughly equal in large flames.

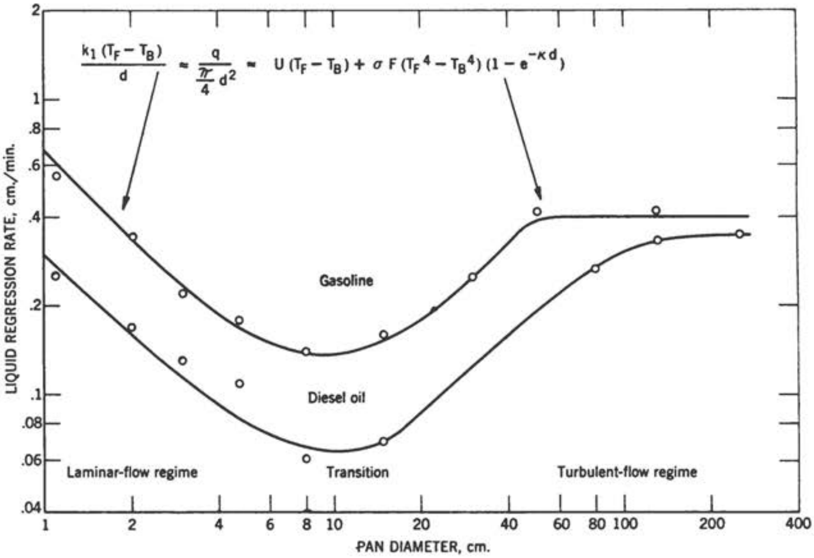

Figure 1. Rates of diffusive burning of two liquid hydrocarbon blends

parentheses approaches unity, giving a maximum value of radiative heat transfer to the liquid surface, that is, a maximum value of the evaporation rate.

We found that the above equation conforms to measured burning rates under the following simple assumptions: the flame temperature, shape factor, and extinction coefficient are constant for diameters beyond perhaps 12 inches, and conduction and convection given by the first two terms in equation (1) are negligible. Figure 2 shows the data obtained by us with methyl alcohol, unsymmetrical dimethylhydrazine, benzene, n-hexane, liquid n-butane, and liquid hydrogen. The curves in Figure 2 are on a regular coordinate plot to stretch out the data between diameters of 1 and 4 feet. To improve appearance, we have omitted a point on the methyl alcohol plot at the 8 foot diameter and many points at very small tray diameters. The horizontal straight lines represent values of burning rate at very large diameter, as we have inferred them from a log-log plot of these same data. Each of the curves shown in Figure 2 was obtained by assuming such a value of the ultimate burning rate and comparing it with the burning rate at the 1 foot diameter. The ratio of these rates

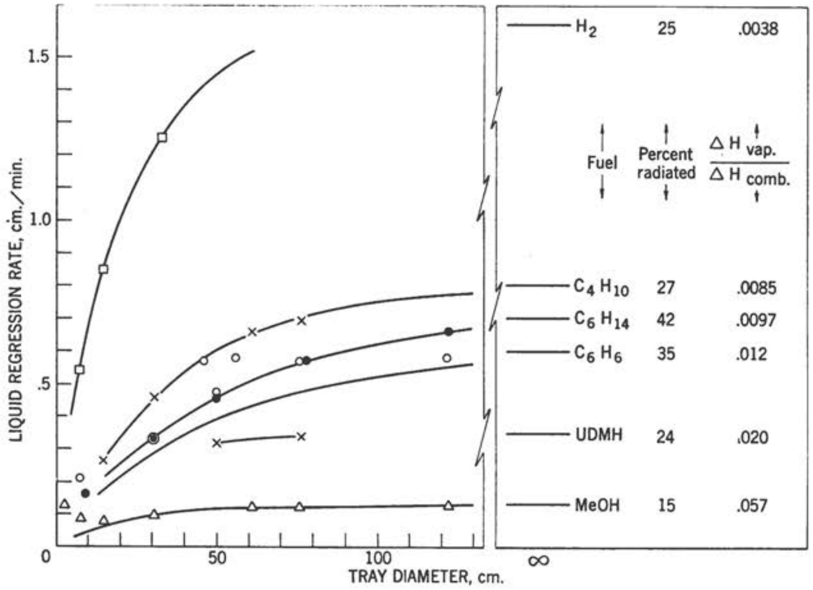

Figure 2. Test of Hottel analysis of liquid burning rates on assumption of exclusively radiative heat transfer

was then equated to $(1 - e^{-\kappa d})$ to calculate κ, the only variable being the tray diameter. The curves therefore represent predicted evaporation rates from the tray due exclusively to radiative heat transfer.

The calculated curves and the experimental points are generally in good agreement. However, there is an obvious exception in the case of benzene, particularly at small diameters. The burning rate of this fuel is unusually susceptible to any casual environmental disturbance that ruffles the flame and increases its opacity. Even at a diameter of 4 feet, nine burning-rate measurements with benzene gave an average rate of 0.58 cm/min. However, the individual rates ranged from 0.52 to 0.62 cm/min, the worst experimental scatter among the measurements reported. With such a range of burning rates, there is some question whether the significant value is the average value or the minimum value, which would correspond to the minimum disturbance of the environment. Likewise, at the 1 foot diameter, where our average burning rate was 0.32 cm/min, we chose to accept a value of 0.29 cm/min from Rasbash *et al.*[2] on the grounds that their work was done indoors and should reflect better controlled conditions than did our outdoor experiments. This accounts for the placement of the line for benzene in Figure 2. As regards the experimental points (open circles) at 3, 12, 20, 30 and 48 inch diameters, it can be seen that they define a rudimentary plateau between 30 and 48 inches. This plateau can better be appreciated if one considers also the points given at 17 and 22 inches, which were obtained with steel drums of 30 and 55 gallon capacity rather than with trays. As far as we know, these experiments were identical in other respects with those in trays, except that the liquid surface was raised about 3 feet above the ground, thereby making it easier for a convection current to sweep upward around the flame. It is not surprising that this arrangement increased the burning rate. What we do find striking is that the burning rates increased exactly enough—55 per cent in one case, 35 per cent in the other case—that their values nearly approximated the plateau rate. We have gone further, burning benzene in small Petri dishes in the laboratory, and again obtained rates of 0.5 to 0.6 cm/min by placing a small chimney above the flame.

Significantly, we have never obtained burning rates with benzene that were much in excess of 0.6 cm/min except when burning in small trays under a clearly observable condition. In this case the flame zone was torn from the rim of the tray by the incident draft, premixing of fuel vapor and air occurred near some point of stabilization, and the flame temperature was several hundred degrees higher than with free-burning diffusional flames. Thus one may argue that drafts accelerate burning by increasing the opacity factor $(1 - e^{-\kappa d})$ in the Hottel equation; however, as long as the flame remains full (unbroken) this acceleration can only be important when d is small. The same type of behavior has been observed with hexane and with methanol.

Concerning the other fuels, measurements with butane were terminated at the 2½-foot diameter because butane flames tend to "walk" or spread to cover a larger area than that represented by the fuel tray. This brings about transitory increases in burning rate, presumably the result of increasing shape factor. Therefore the hazard of handling butane is considerably greater than would be indicated by the extension of its burning-rate curve.

The reason that butane flames tend to spread in this way must be that the vapors are particularly dense. Thermocouple measurements in the vapor zone close to the liquid phase showed that the vapor is only at the boiling point or very little elevated, whereas, for example, in benzene or methanol flames the vapor zone in close proximity to the liquid is very hot. The vapor zone in liquid hydrogen flames is also cool. Therefore, for liquid hydrogen and butane fires, convective and conductive heat transfer appears negligible, and we have extended the radiative-heat-transfer type of curve to small burner diameters. It should be pointed out that the measurements with liquid hydrogen were quite crude by comparison with those reported for the other fuels; each point represents only one burning, and the burnings were conducted in Dewar vessels instead of trays. A correction was made to each measurement for the normal heat loss of the vessel. At the smallest diameter this correction represented nearly one-half of the reported burning rate; therefore, the slope of the burning-rate curve could be considerably in error, and the value suggested for burning rates in large trays could well be in error by as much as 50 per cent. Concerning the burning rates in methanol, the trend with increasing diameter is so flat that small satisfaction can be taken from the agreement between experimental points and the curve calculated for radiative heat transfer. This leaves open the possibility that heat transfer in methanol may be largely convective. An attempt was made to resolve this point by using a differential thermocouple at the liquid surface in a 1 foot tray. The best estimate is in the order of 30 per cent radiative heat transfer at this tray diameter, the remainder presumably being conductive and convective. The shapes and periodic movements of the largest methanol flames suggest that convection is still important.

It is perhaps surprising that the percentages of energy radiated to the surroundings (Figure 2) are so nearly equal for all fuels. These figures assume a spherical symmetry of radiation. They also assume that the fuel has completely burned to carbon dioxide and water and that absorption by atmospheric moisture is negligible, an assumption that is least tenable for hydrogen and methanol flames. Since the percentages of heat radiated outward are so nearly equal, it might be assumed that the percentages of heat radiated to the liquid surface are also comparable in all flames and that the burning rate is proportional to the heat of combustion, $\Delta H_{\text{comb.}}$. A few measurements at low ambient temperature also showed that the burning rate is inversely proportional to $\Delta H_{\text{vap.}}$, the effective heat of vaporization, which is the heat of vaporization at the boiling point plus the integrated heat capacity of the fuel from ambient temperature to the boiling point. This being the case, the burning rates should be inversely proportional to the values of $\Delta H_{\text{vap.}}/\Delta H_{\text{comb.}}$ shown in Figure 2. This is an old concept which may be found more elegantly expressed in reports of the Fire Research Station at Boreham Wood, England. Our present contention is that this correlation is best made using burning rates obtained by extrapolation to large tray diameters. The available data are shown in Figure 3.

The approach to linearity in Figure 3 is somewhat disconcerting in view of the crude reasoning on which the correlation is based. Perhaps the addition of data for other fuels will introduce a greater degree of scatter. However, the merely qualitative adherence to this correlation of maximum burning rates by dif-

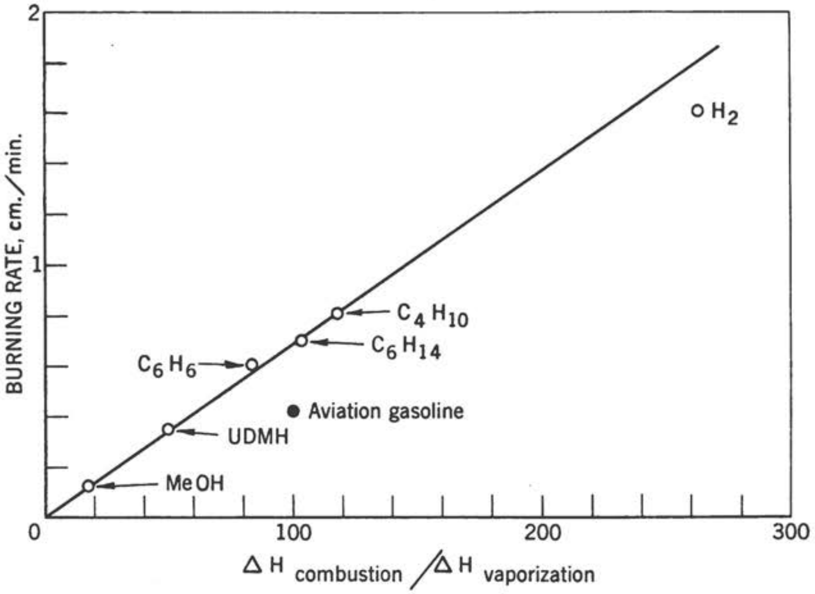

Figure 3. Relationship of liquid burning rates at large tray diameter to two physical properties of fuel

fering fuels (methanol, unsymmetrical dimethylhydrazine, benzene, hexane, butane, and hydrogen) would seem to deny any critical importance to certain other fuel and flame properties. We have considered fuel volatility; the opacity of liquid phase and/or of vapor zone to flame radiation; flame emissivity; molecular weight (therefore diffusivity, density, and Reynolds number in the vapor stream); and air-fuel ratios at stoichiometric burning and at the limits of flammability. None of these parameters has correlated with the observed order of burning rates. Second-order effects are possible, however.

In conclusion, we find that the Blinov and Khudiakov description as refined by Hottel can be applied fruitfully to fuels other than hydrocarbon blends. All of our present reservations to the treatment, as for example with regard to the role of turbulence, emphasize the simplicity of the problem and its amenability to further study.

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Tests on Combustion Velocity of Liquid Fuels and Temperature Distribution in Flames and Beneath Surface of the Burning Liquid

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THE FORSCHUNGSSTELLE für Feuerlöschtechnik in Karlsruhe has undertaken many studies on the behavior of fire. One of the most critical current problems concerning fire behavior is the fuel storage tank fire.

In view of the current practice of using large tanks for the storage of liquid fuels, and the present trend to use even larger capacity tanks, it appeared to us that study was necessary for the development of a more complete understanding of fires involving liquid fuels in storage in order that we might develop techniques to meet the demands for greater fire protection in liquid fuel storage. In the following discussion, we report the results of a study using model fire test tanks to study fire behavior.

In past experience, not much information has been gained from full-scale accidental fires in liquid fuel storage tanks. Since in the accidental fire the first consideration is given to prompt extinguishment, the research investigator has not been given an opportunity to arbitrarily alter the conditions of the fire environment, or even to make a scientific record. From the study of these accidental fires, we conclude only that extinguishment becomes more difficult with increase in the burning area, and to a degree exceeding in direct proportion to the increase in area.

Requirements For Model Study

Since the research investigator cannot use the accidental fire or the full-scale as a satisfactory investigative tool and planned tests on the full-scale are prohibitive in cost, the only remaining alternative is the development of a modeling technique. Early studies in Great Britain[1] showed that correlation between model and full-scale fire configuration could be made. Because the character of similarity between the full-scale and model tank fire could be maintained quite simply, particularly in a geometrical sense, we concluded that such a model study showed considerable promise, and a program was initiated[2] and is still being pursued. It is hoped that larger scale test tanks may be used later. In order to extrapolate model fire behavior to the full-scale, we cannot confine our study to small diameter tanks but must show by the employment of a progression of sizes in the test configurations that the relationships we develop are completely capable of anticipating characteristic fire behavior.

Parameters For Model Study

One of the prime characteristics of a fire of particular practical interest is the rate of heat release. To study this characteristic, which we take as a measure of fire intensity, we chose to measure temperatures in and above the flame zone, and to make note of the rate at which fuel was consumed by the fire.

We investigated fires in tanks of various diameters, and with fuel levels at various heights within the tanks. Other conditions such as wind velocity, air temperature, humidity, and barometric pressure were noted so that their effects could be studied. With the smaller test tanks, studies were made indoors to eliminate insomuch as possible changes in test conditions (particularly in wind and local air currents). Figure 1 shows one of the test setups, with thermocouples installed for measurement of the burning temperature profile in the model configuration.

Experimental Tank Models and Procedures

In the first series of tests we used model tanks with a ratio of diameter to height of 3:4 as shown in Table 1.

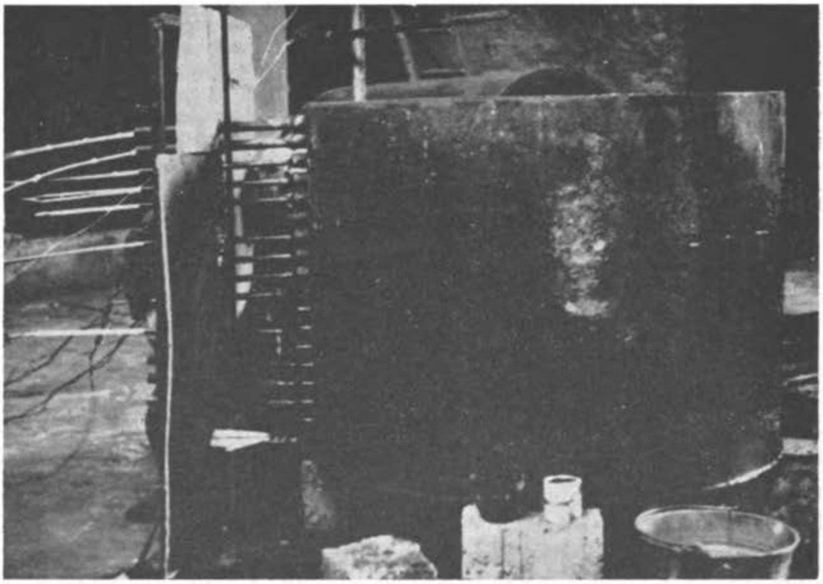

Figure 1. Location of thermocouples on 120 cm. diameter tank

TABLE 1. SIZES OF TANKS

Model No.	Diameter (cm)	Height (cm)
1	12	16
2	18	24
3	25.5	34
4	30	40
5	60	80
6	120	160.5

Subsequently, we have initiated tests using tanks having a diameter to height ratio of 4:3, of 30.5, 60, and 120 cm. diameter.

In the smaller tanks we measured the rate of burning dw/dt or dh/dt by means of a hydraulic balance composed of a hydraulic cylinder upon which the test tank was located, communicating hydraulically to a manograph, thus continuously giving instantaneous weights of the burning fuel. In the larger tanks (more than 60 cm. diameter) the liquid level was observed at specific time intervals to note the rate of burning, dh/dt. Burning characteristics were determined using the model tanks cited in

Table 1 with gasoline and ethanol as the fuels. The progress of the fire was followed with initial levels at the top and intermediate points in the test tanks and, in the case of gasoline fuel, samples were withdrawn from the burning liquid at successive intervals and measurements of the boiling point and density measurements of the samples were made. The characteristics of the fuels are shown in Table 2.

TABLE 2. TEST FUEL CHARACTERISTICS

		Ethanol	Gasoline
Boiling point	(°C)	78.0	40–220
Density	(g/cm^3)	0.8	0.72
Specific heat	(kcal/kg/°C)	0.58	0.4
Heat of vaporization	(kcal/kg)	210.0	72.0
Lower heat content	(kcal/kg)	6390	10200
	(kcal/cm^3)	8	14.15
Theoretical amount of combustion air	(m^3/kg)	7.0	11.6
Thermal conductivity	(cal/cm sec °C)	0.00035	0.00035

Air currents, temperature, humidity, and barometric pressure in the test environment were measured and recorded.

Test Results

Figure 2 shows the results of fire tests using tanks No. 1, 2, and 3 described in Table 1. Table 3 summarizes the maximum burning rate data (specific fuel consumption rate per unit surface area: cm^3/min/cm^2) in cm/min fuel consumption. The effect of increase of the test tank diameter and the increased rate of heat liberation potential is shown. The data also suggest a transition in relation to the dependency of burning rate on surface area between tank diameters of 18 and 25 cm.

Figure 3 shows the burning characteristics of gasoline and alcohol fires in the 30 cm. diameter tank and Figure 4 shows the same characteristics for the 120 cm. diameter tank. In Figures 2, 3, and 4, the effect of the tank freeboard over the surface of the burning liquid is shown.

In order to make a comparison of the data, we expressed height of fuel in the test tank as a function of burning time. As

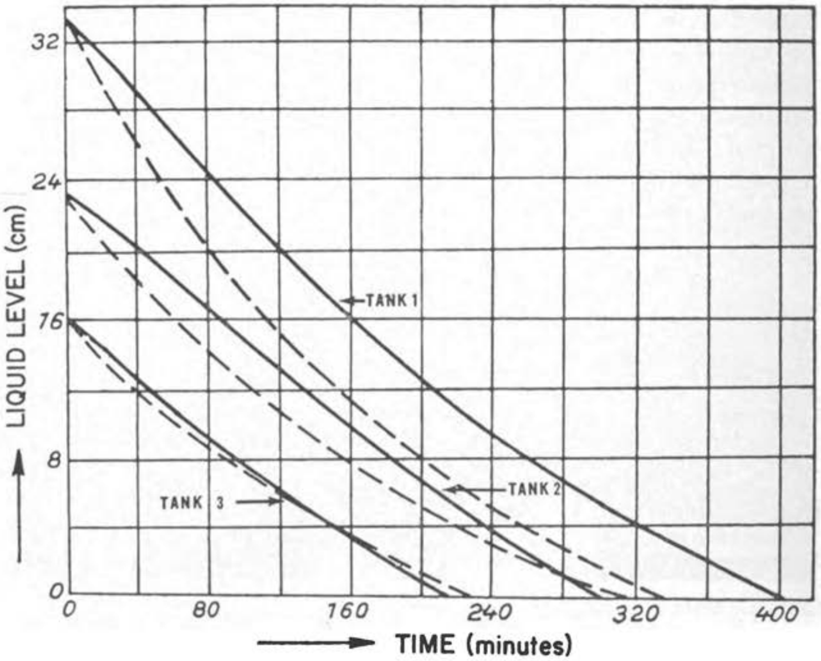

Figure 2. Burning-rate of ethanol (—) and gasoline(--) for various tank diameters and heights.

	Tank 1	Tank 2	Tank 3
Diameter	12	18	25.5
Height	16	24	34
Fill Height	16	24	34

TABLE 3. MODEL TANK FUEL BURNING CHARACTERISTICS

Model Tank No.	Fuel	Maximum Burning Rates	Ratio of Burning Rates	Equivalent Stoichiometric Heat Release kcal/cm^2/min	Ratio of Stoichiometric Heat Release Rates
1	Ethanol	0.0887	0.683	0.71	0.386
	Gasoline	0.130		1.84	
2	Ethanol	0.908	0.665	0.726	0.377
	Gasoline	0.1365		1.93	
3	Ethanol	0.122	0.640	0.975	0.365
	Gasoline	0.190		2.685	

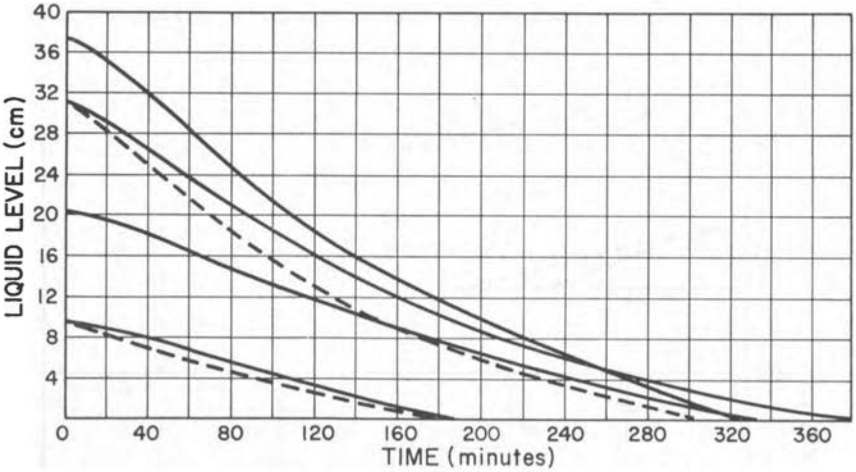

Figure 3. Burning rate of ethanol (—) and gasoline (---) as a function of fill height
Tank diameter 30 cm.
Tank height 40 cm.

indicated in Figure 4, for the larger tanks we could not conveniently obtain a characteristic burning curve from zero freeboard above the burning fuel surface, to freeboard equal to the height of the tank wall (zero fuel level height from the tank bottom as plotted in Figures 2, 3, and 4). As an alternate we burned for periods up to 400 minutes, with the initial fuel level at various selected values (Figures 3 and 4). As noticeable in some of the characteristics curves, there is an initial burning period during which the burning rate increases until a steady-state regime is attained. Following establishment of the steady-state regime, the burning rate decreases gradually, as evidenced by the change in slope of the burning characteristics curves, from those obtained with low freeboard heights (highest level of fuel above the tank bottom) to those with the greater freeboard heights (lowest level of fuel above the tank bottom as plotted in Figures 3 and 4). As a result of the initial period required to attain a steady-state regime, we cannot use the information as shown in Figures 3 and 4 to reconstruct a continuous burning characteristic function.

The effect of freeboard height on the burning rate was found to be a complex function, dependent not only on the freeboard

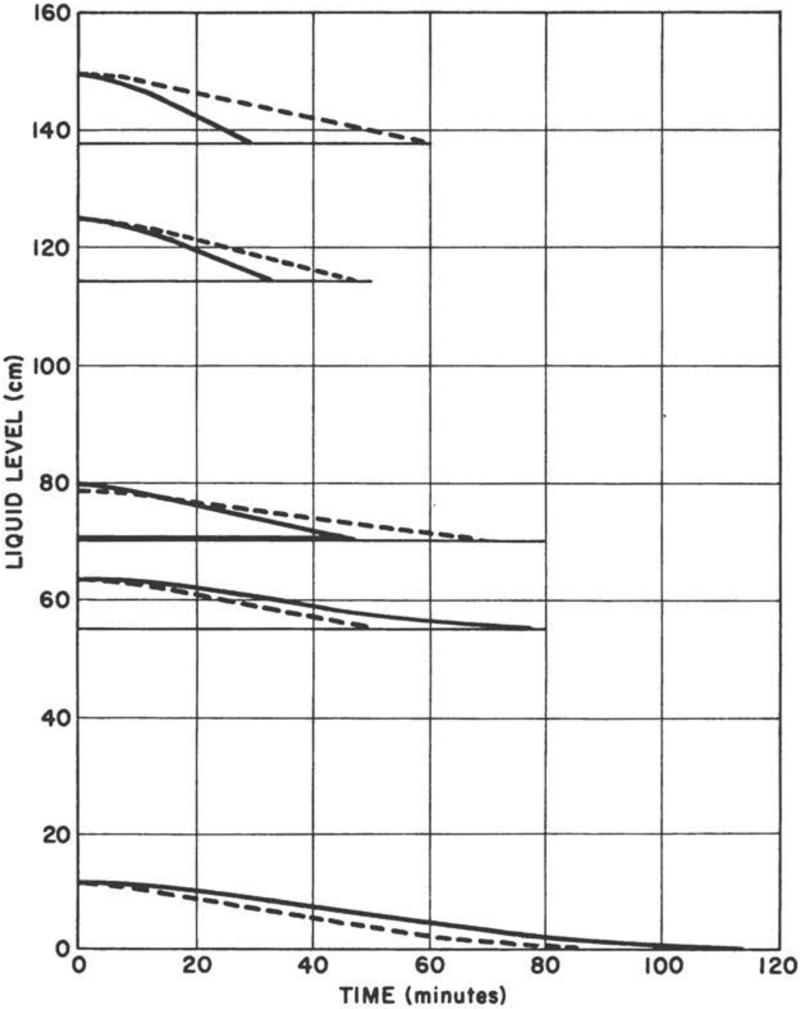

Figure 4. Burning-rate of ethanol (—) and gasoline (---) as a function of fill height
Tank diameter 120 cm.
Tank height 160.5 cm.

height, but also on the test tank height to diameter ratio and fuel composition. We found that ethanol burns more slowly than gasoline with lower tank freeboards, and as the freeboard above the burning liquid surface increases, the rate of burning for gasoline decreases to the extent that, at freeboard heights greater than one-half tank height, ethanol burns more rapidly than gasoline.

The effect of ambient air temperature and humidity on the burning characteristics curves in the test tanks was also investigated. Figure 5 shows characteristics curves for alcohol burning in the 12 cm. diameter tank at 5 and 20°C. The fact that ambient air temperature exercises no significant effect on the burning characteristic is shown in Figure 5 and similarly, negligible effects were noted for ambient air humidity and barometric pressure. On the other hand, wind velocities of less than 0.5 m/sec exerted a perceptible influence on the burning rate, and as a consequence altered the burning characteristic curve. Reradiated (or reflected) heat was found to alter the burning characteristic curve, so precautions were taken to eliminate this effect from our experimental data.

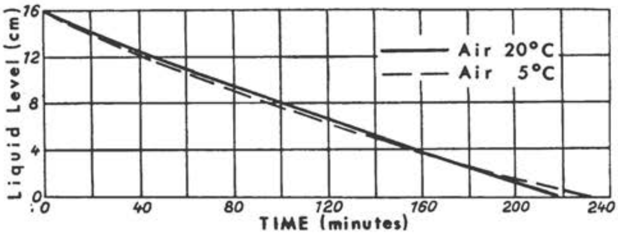

Figure 5. Influence of the air temperature on the burning of ethanol
Tank diameter 12 cm.
Tank height 16 cm.

Figures 6–11 show temperature profiles from the tank bottom to some distances above the top of the tank at incremental burning times as determined by thermocouple temperature measurement, using the various test tank configurations at selected fuel filling heights. It is interesting to note that, although the burning rate was altered by the presence of wind, little effect was noted on the maximum temperature recorded in the temperature profile. It is seen that the maximum profile temperature for gasoline is 10 to 15 per cent higher than that for ethanol.

In the analyses of gasoline fuel samples taken at intervals in the course of the period of burning, the high boiling components increase in concentration with burning time, as evidenced

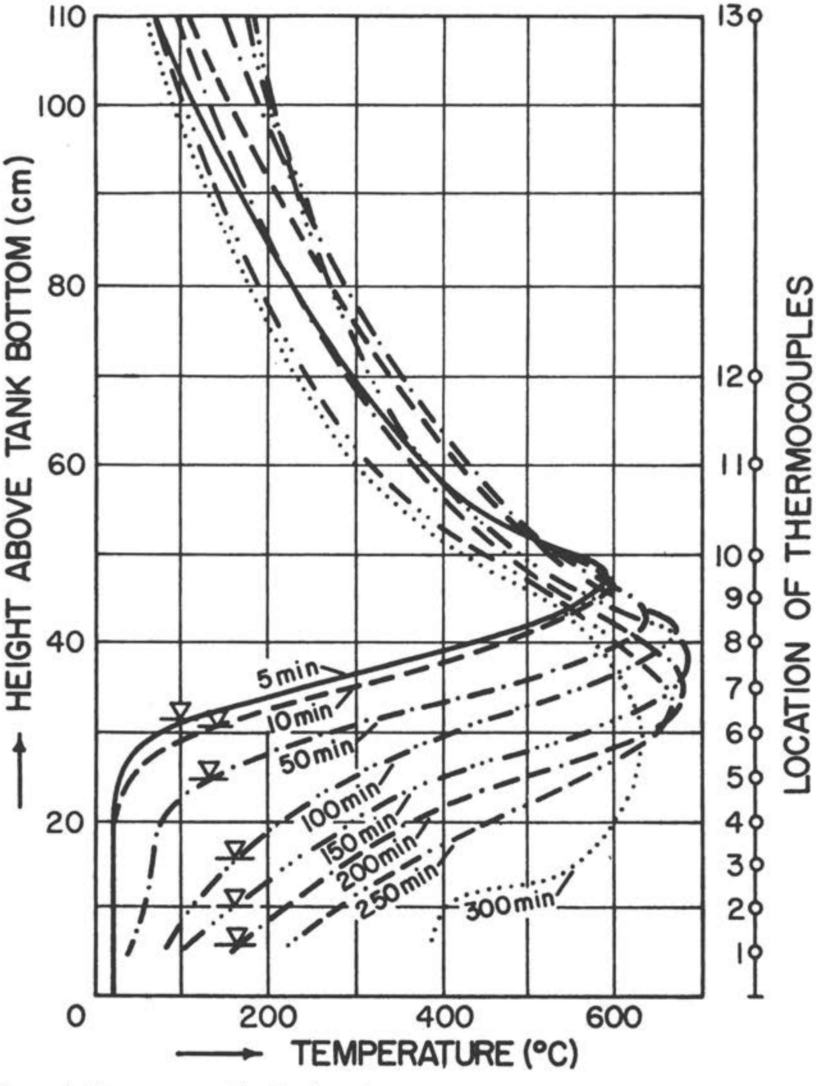

Figure 6. Temperature distribution above tank bottom as a function of time for gasoline
Tank diameter 30 cm.
Tank height 40 cm.
Fill height 31.2 cm.

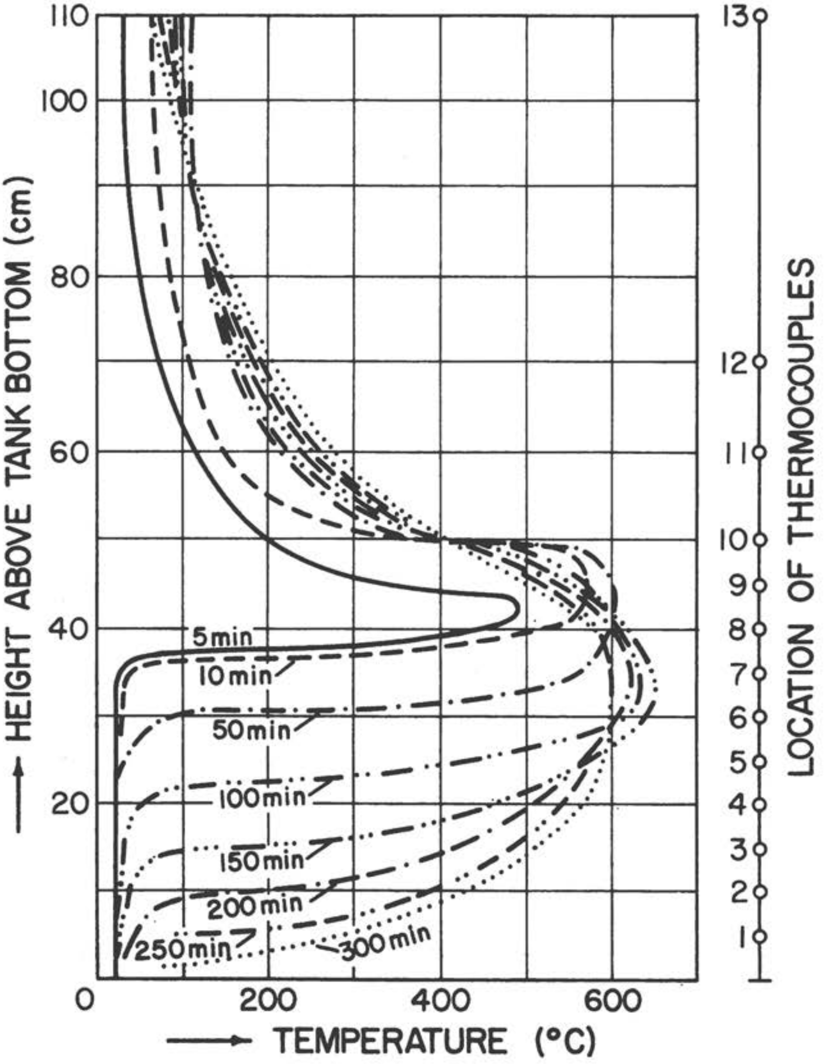

Figure 7. Temperature distribution above tank bottom as a function of time for ethanol
Tank diameter 30 cm.
Tank height 40 cm.
Fill height 37.5 cm.

in the progression of heating into the liquid body under the burning surface with increase in burning time (Figure 6). With ethanol as a fuel, the burning surface temperature was essentially constant, and little subsurface heating was effected (Figure 7). The figures presented are selected as examples of the data developed to the present time in this study.

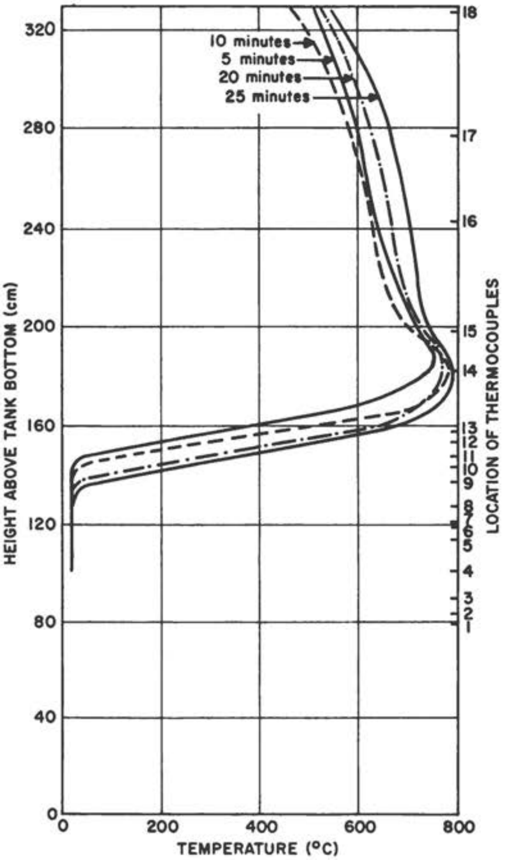

Figure 8. Temperature distribution above tank bottom as a function of time for gasoline
Tank diameter 120 cm.
Tank height 160.5 cm.
Fill height 149 cm.

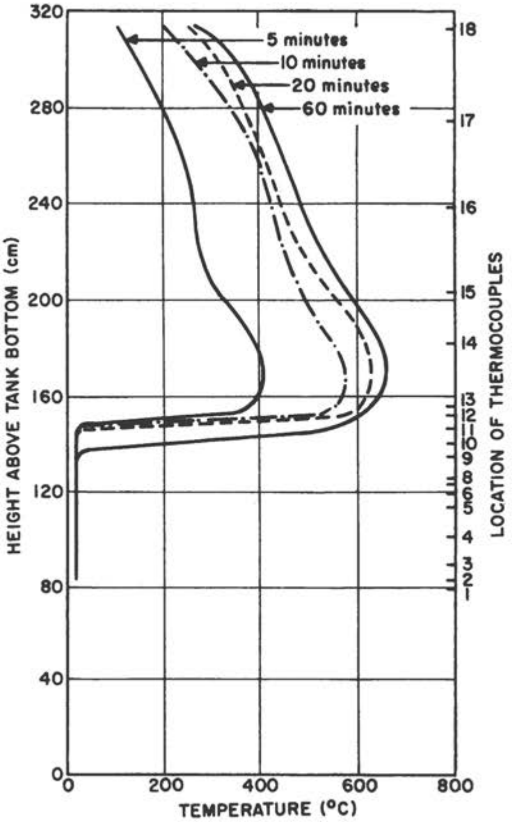

Figure 9. Temperature distribution above tank bottom as a function of time for ethanol
Tank diameter 120 cm.
Tank height 160.5 cm.
Fill height 149 cm.

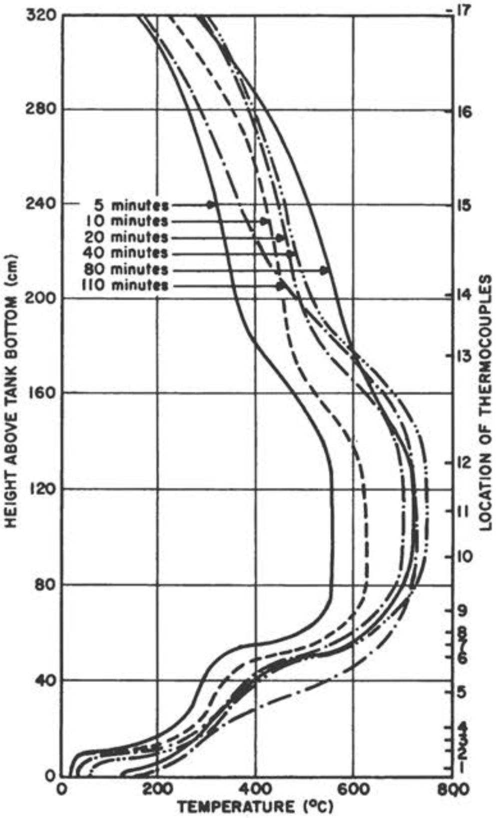

Figure 10. Temperature distribution above tank bottom as a function of time for gasoline
Tank diameter 120 cm.
Tank height 160.5 cm.
Fill height 11 cm.

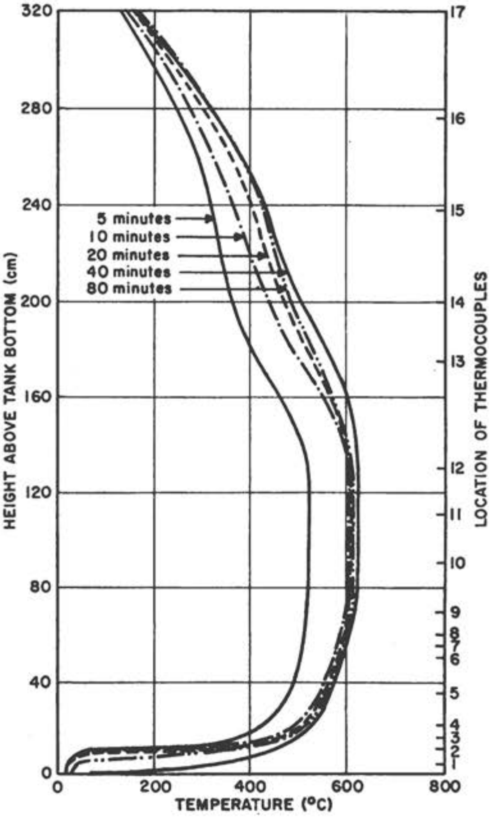

Figure 11. Temperature distribution above tank bottom as a function of time for ethanol
Tank diameter 120 cm.
Tank height 160.5 cm.
Fill height 11 cm.

Findings and Conclusions

Difficulties in carrying out the fire model tests were:

1) Provisioning for complete burning out of fuel, or improvisation of the burning characteristic curve by a series of tests starting at selected fuel levels in the model tanks.

2) Maintaining constant test conditions during the period of test, in particular free from the influence of wind or air currents.

From the tests we conclude that:

1) Burning rate may be taken as a measure of fire intensity, although, because of incomplete combustion, particularly with gasoline, it does not precisely represent the rate of heat release.

2) Wind and air currents are the most critical ambient conditions for model tests as compared to temperature, humidity, and barometric pressure.

3) The specific burning rate of the liquid fuels (unit volume per unit time-unit area) increases with burning area.

4) The variation of fuel burning rate with freeboard over the burning fuel surface concerns the stoichiometry of the combustion reaction and the ratio of freeboard height to burning surface area as it characterizes facility of air feed to the combustion zone.

5) The effect of heat conduction from the tank freeboard wall to the fuel is only perceptible very close to the tank wall at the fuel surface.

6) The effect of increasing tank freeboard over the burning fuel surface is reduction in the maximum flame temperature and a decrease in burning rate.

7) In fire tests with the fuels studied, the liquid is heated by the burning above its surface only in a thin layer beneath the surface and with ethanol, the surface temperature remains essentially constant.

8) The maximum flame temperature is noted at nearly the same distances over the burning liquid surfaces in the test configurations studied.

Discussion

Dr. Wolfhard: I did not understand the experimental arrangement of your temperature measurement. Did you move the thermocouple along the axis of the flame? If the flame is turbulent one would expect stronger temperature fluctuations than indicated in your pictures. In case of a laminar flame I would have expected the maximum temperature to be some distance from the burning surface. Are you in fact measuring over the center of the drum?

Dr. Magnus: Yes, we did, but we did not move the thermocouple. We used various fixed couples.

Dr. Wolfhard: And these temperatures are steady; they do not vary from cold to hot?

Dr. Magnus: No. We worked in an enclosed space, and so we carefully avoided any influx of an air stream.

Dr. Wolfhard: Do you observe your maximum temperature where you visually see the flame?

Dr. Magnus: Yes. The thermocouples are mounted on the axis of the drum (Figure 1) at 5 cm. intervals. The temperature in our diagrams are averages of three or more readings. There are maxima and minima but the differences are not too large. Any flicker of the flame would affect a series of thermocouples, so that any disturbance of the uprising column of hot gases could easily be seen if it would occur. The temperature did not change between hot and cold, the thermocouple was always inside the convection gas column. The fact that the temperature readings are smothered by the heat capacity of the insulation, the mounting, and the material of the thermocouples, was advantageous. By working in an enclosed space we avoided the influx of wind causing turbulence. It is certain that a natural fire is influenced by wind, but we wanted to find out the general behavior of the burning process.

As to your question about the temperature maximum in the flames, consider that though we see the outside of the flame zone, the thermocouples are situated in the center. The distance between the level of the burning fuel and the temperature maximum depends on tank diameter and the fuel. The luminous flame zone is not necessarily the zone of maximum temperature effect, as we are accustomed to assume.

Mr. Grumer: Were the flames of ethyl alcohol and gasoline pretty much the same; that is, did the flames stand about equally high above the liquid? Was as much flame inside of the barrel when the level of the liquid was quite low as when the barrel was nearly full? If the flames were entirely atop the barrel, should one be concerned about convection currents and other effects due to the column of hot gas inside the barrel between the liquid and the flame surface? If the alcohol flame burned at least partly inside the barrel and the gasoline flame burned all outside the barrel, perhaps this difference explains the fact that as the liquid level fell the alcohol burned faster and the gasoline burned slower.

Dr. Magnus: We do not know the amount of energy that was returned by radiation or convection. We tried to avoid these influences by placing the tanks far away from walls and other radiating objects, with the one exception I mentioned in my paper. There we put water-containing tanks near the burning tanks and observed the temperature rise of the water in the tanks. The influence of the flame has not yet been studied and therefore Mr. Grumer's suggestion may give an explanation for the different burning rates.

Effectiveness of Some Powdered Materials in Extinguishing Hydrocarbon Fires

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ABSTRACT

Laboratory methods are described for measuring the effectiveness of powdered materials intended for extinction of flammable liquid fires. Special methods were used for application of several powder materials to fires varying in size from about 1⅛ to 22¾ inches in diameter. The powders used had mean diameters within the range of 6 to 40 microns. The effectiveness of the powders was measured in terms of the minimum application rate required for extinction. This was found to depend on (1) chemical nature, (2) specific surface, and (3) particle size of the powders used. On a surface-area basis, the most effective materials studied, potassium oxalate monohydrate and potassium iodide, were about four and two-and-one-half times, respectively, as effective as sodium bicarbonate, the commonly used extinguishing agent.

With the exception of data for one dense material, the relative effectiveness of different powders did not change appreciably from one fire model to another. For a given powder and method of application, minimum application rate (surface-area basis), required for extinction of diffusion fires appears to be very roughly proportional to the liquid burning rate of the fire model. Limited extinguishment data on large-scale fires by other workers seem to confirm the usefulness of the model method for evaluating powder effectiveness.

Introduction

In the search for a better understanding of the mechanism of action of powder-type extinguishing agents when used on burning liquids, a method has been needed to evaluate the effectiveness of various powders. This paper describes methods that have been developed for such evaluation, and presents results on several powdered agents, some of which were found superior to the "dry chemical" powders now commonly used. The latter usually involve powders consisting of about 96–98 per cent sodium bicarbonate in the form of a crystalline powder (less than 50 micron particle size), and a coating agent to improve free flow characteristics.

A review of the literature in the field of combustion and flame extinction indicates the possibility of improving the effectiveness of powdered extinguishing agents. Although the mechanism by which powders extinguish flames is not well understood, it apparently involves breaking of chemical chain reactions by ions, and quenching by cold surfaces, as well as possible inhibiting by inert gases formed through decomposition of the powder. The ability of alkali halides to suppress gas explosions and to change the explosion-limit pressures of hydrogen-oxygen reaction has been studied by Hinshelwood and Willbourn.[1, 2] Work by Jorissen, Snidders, and Vink,[3] and more recently, by Dolan and Dempster,[4] on ignition and explosion suppression of the methane-air system showed that the specific chemical nature as well as the specific surface of the salt determines its effectiveness. Dufraisse, LeBras, and German[5] observed wide variations in the extinction effectiveness produced by different salts when applied to flames of premixed gases. Excellent reviews of the problem with literature compilations are given by Fryburg[6] and by Friedman and Levy.[7, 8] In general, the alkali salts with low decomposition temperatures were the most effective powders reported for inhibiting combustion reactions in laboratory studies.

If these conclusions are applicable to field-scale (greater than 9 square feet) gasoline fires, an improvement in the effectiveness of the present-day "dry chemical" ($NaHCO_3$) extinguisher by a factor of four or five is a distinct possibility. However, additional factors are involved in extinguishing large-scale, free-burning liquid hydrocarbon fires, as compared to small laboratory flames of premixed gases on which most data are based. For example, the problem of dispersing the powder and maintaining a sufficient concentration of powder in the flame zone is a critical one. Only limited data are available on the influence of such factors as chemical composition, particle size, discharge rate, and discharge pattern of powders on extinction effectiveness.

McCamy, Shoub, and Lee[9] have reported the use of salts other than $NaHCO_3$ on field-scale fires. They indicate, qualitatively, that for a heptane fire burning on a 4-foot square area, particle size and dispersibility of the powders influence their effectiveness. The powders used were mainly inert and poorly dispersible. Neill[10] recently reported that $KHCO_3$ is about twice as effective as "dry chemical" on 3-foot square fires when applied at minimum critical rates. For fires up to 10 feet square, with powder application at a given constant rate, similar orders of effectiveness were observed on the basis of fire area extinguished.

Obviously, even a slight improvement in extinguisher effectiveness may provide the difference between success and failure in controlling a fire. Thus, a reliable laboratory method is needed to measure the extinguishment effectiveness of powders and to evaluate the factors upon which this effectiveness is based. A good method should be a small-scale one but should give reproducible results that can be correlated with those of much larger fires. The methods described in this paper appear to meet these requirements. These involve the extinguishing of liquid heptane fire models of 1⅛, 6, and 22¾ inches in diameter.

A measure of the effectiveness of any extinguishing agent can be obtained from (1) the minimum rate of application required to extinguish a standard fire, or (2) the time required for extinction under a given rate of application to a standard fire. The first method forms the basis of reporting efficiency here although both types of measurements were made.

Materials Investigated

Table 1 lists the powdered materials that were tested and the preparatory treatment they received. All powder samples, with the exception of glass beads and "dry chemical", were made from reagent-grade chemicals by grinding in a pebble mill. Two per cent of zinc stearate was added, before grinding, to most samples to improve their free-flow properties and to reduce moisture absorption. For the studies reported, narrow fractions of particle sizes were selected from the ground powders by sieving and air elutriation. Beyond this, no definite tolerance was placed on particle size distribution. Measurement of particle-size distribution of some samples by microscopic method showed that the cutoff was sharp on the large particle side of the distribution curve. Mean particle size was measured with a Fisher subsieve sizer based on the air permeability principle. The glass beads used were spherical and had a very narrow particle-size distribution.

TABLE 1. MATERIALS AND PREPARATION PROCEDURES USED FOR POWDERS

Sample	Source	Treatment
$NaHCO_3$, $K_2C_2O_4.H_2O$ KI, $KHCO_3$, $KTiC_2O_4$ RbI, CsI	Reagent-grade crystalline chemicals	2% by wt. zinc stearate added, ground in ball mill, size separation by sieving and air elutriation
Glass beads	Commercial glass microbeads	2% zinc stearate added, mixed and heated to 100°C
Glass beads	Commercial glass microbeads	No treatment
Mixture	Combinations of above components after treatment	Proportion based on wt., thorough mixing
"Dry chemical"	Surface-treated $NaHCO_3$ from commercial extinguisher manufacturer; 98% sodium bicarbonate	Size separation by sieving and air elutriation

Experimental Procedures

Fire Model of 1⅛ Inch in Diameter

The procedure used with the 1⅛ inch in diameter fire model was simple in principle and required only about 0.5g. of powder for each determination. Powder was dispersed in the air at a controlled rate while a small diffusion flame, supported by n-heptane liquid in a cup, was slowly introduced into the freely falling powder stream. Various rates of powder discharge were used to determine the minimum effective rate that would cause extinction.

Figure 1 shows the essential features of the apparatus. The dispenser consisted of a cylinder containing a stainless steel screen at mid-height to support the powder. The rate of discharge of powder was controlled by adjusting the amplitude of an electromechanical vibrator. A brass cup with an inside diameter

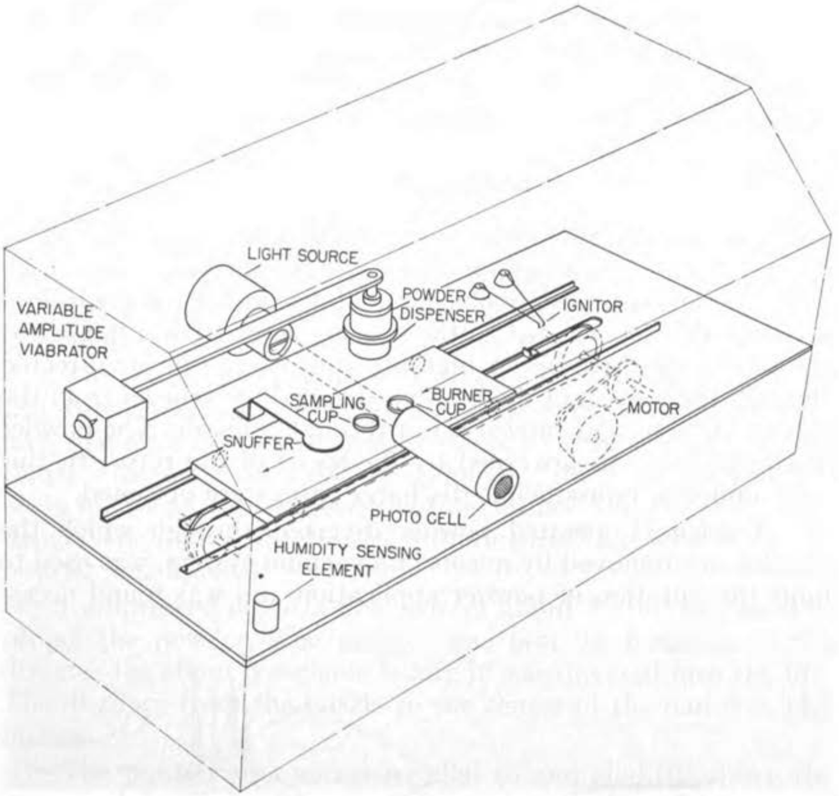

Figure 1. Apparatus for evaluating the fire extinction efficiency of powders using the $1\frac{1}{8}$-inch fire model

of $1\frac{1}{8}$ inches was used as a burner. In use, the cup contained 1.0 ml. of n-heptane floated on 3.0 ml. of water, with the fuel surface initially about 1/32 inch below the rim.

The burner was placed on a flat carriage which moved at a uniform velocity of 1.9 in/sec toward the powder stream. An identical but empty cup was placed on the carriage 2 inches ahead of the burner cup. The weight of powder collected in this cup served as a measure of discharge rate. A recording densitometer monitored the discharge stream for variation in the rate of discharge. The entire apparatus was enclosed in a draft-free cabinet.

The fuel was ignited by a spark discharge and the flame was allowed to burn 35 sec. before the carriage moved it into contact with the falling powder stream. At least 20 determinations were made with each powder sample.

Fire Model of 6 Inches in Diameter

For the 6-inch diameter fire model, powder was propelled by air into a flame burning in a circular, stationary pan (Figure 2). The powder dispenser involved use of a serrated rotor within a housing. Powder was fed to the moving rotor from a hopper at the top of the housing. A high-pressure stream of air directed through the bottom of the housing stripped the powder from the rotor serrations and carried it out through a nozzle. The powder discharge rate was governed by the speed of the rotor. In this way, uniform, reproducible discharge rates were obtained.

A solenoid-operated powder diverter, through which the powder was removed by means of a vacuum system, was used to limit the duration of powder application and was found neces-

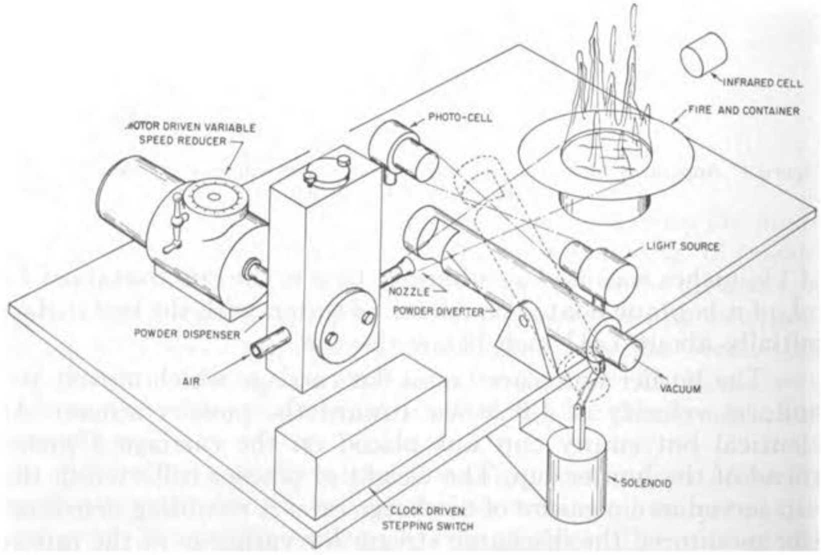

Figure 2. Diagrammatic illustration of apparatus for evaluating extinction efficiency of powders using the 6- and 22¾-inch fire models

sary to reduce the effect of starting and stopping transients. The time of removal and return of the diverter was controlled by a stepping switch.

For the purpose of calibrating the rate of powder discharge, the diverter was fitted with a cellulose filter thimble and used to collect powder for a measured period of 2 to 3 seconds. The average discharge rate for a given dispenser speed was then calculated from the weight of powder collected in the filter and the time period of collection. The diverter was located close to the nozzle and it was assumed that powder which was collected by it would otherwise be effectively applied to the fire.

The flame was supported by 30 ml. of n-heptane floating on water in a brass cup having an inside diameter of 6 inches. A 12-inch diameter horizontal flange attached to the rim of this container was found desirable in stabilizing the flame. A distance of ⅛ inch was left between the fuel surface and the top of the flange. The flame was allowed to burn for 45 seconds before the powder was applied.

Compressed air at a flow rate of about 1 cfm. was used to propel the powder. The powder was first discharged into the diverter for about 3 seconds before it was directed into the fire. The distance from the nozzle to the center of the pan was 14.5 inches.

The powder was aimed parallel to and slightly above the surface of the pan and flange. The nozzle provided a horizontally flat and diverging discharge pattern. The cross section of discharge was about 6 inches wide and 1 inch thick at the region near the center of the fire. In reporting powder application rates for the two large fire models no correction has been made for powder which did not enter the fire zone during application.

During each series of runs, the discharge rate was varied stepwise from one run to the next and the time for extinction was determined in each case. As the discharge rate was decreased, the extinction time increased until a minimum discharge rate was obtained, below which extinction did not occur. Extinction time was taken as the period between arrival of powder at the flame and the time when the flame had decayed to 20 per cent of its initial value as recorded by a lead sulphide infrared detector located behind the fire.

Fire Model of 22¾ Inches in Diameter

The apparatus and procedure for the 22¾-inch diameter fire model were similar to those used with the 6 inch model except that:

1) The distance from the nozzle to the center of the fire was 36 inches.

2) The air flow rate was about 7 cfm. providing a discharge cross section of about 26 x 4 inches located adjacent to and just above the center of the fuel pan.

3) A flange of 37 inches in diameter was used around the top of the fuel pan.

4) A freeboard of ½ inch was used above the fuel surfaces.

5) Three hundred ml. of practical heptanes (Eastman Kodak P-2215) was used as the fuel.

6) A preburn period of 30 seconds was used.

Figure 3 shows the equipment being used for extinguishment of this large fire model. The photometers were not used when this photograph was made.

Results

Fire Model of 1⅛ Inch in Diameter

Figure 4 presents data on minimum rate of powder application for extinguishment of the smallest fire model by various powders as related to mean particle size. Each point is plotted as a cross in which the vertical line represents the region of overlap where both extinction and nonextinction results occurred during the 20 determinations. All runs at discharge rates above the top of the vertical line resulted in extinction; only nonextinctions occurred below the lower end of the line. A circle is used to replace the horizontal bar of the cross for materials on which only one particle size result was obtained. The point at which the horizontal line or circle and vertical line intersect indicates the best value for the minimum effective rate as determined by a statistical formula developed by C. S. McCamy.[11] This formula may be stated as follows

$$W_m = a + \frac{x}{x + y}(b - a)$$

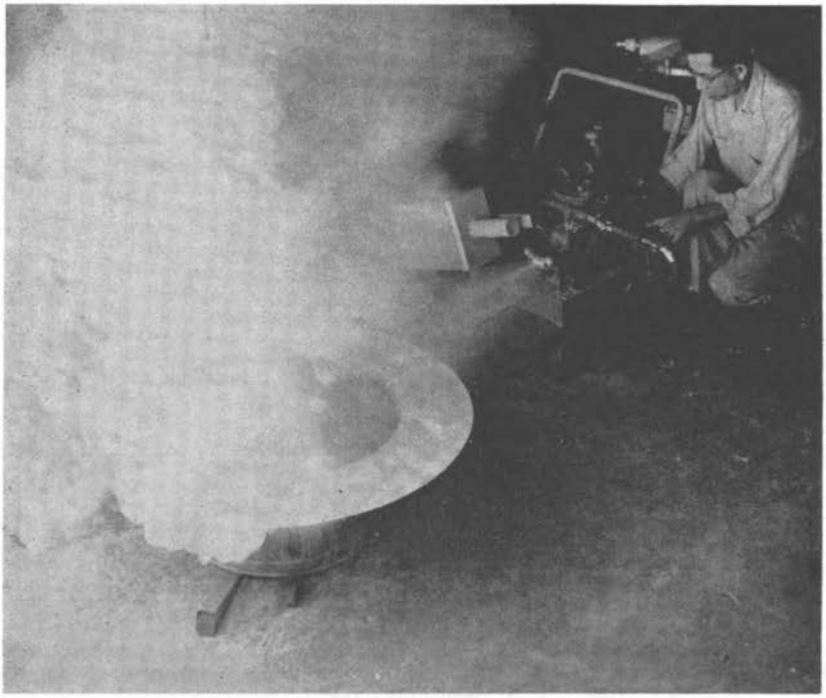

Figure 3. Extinguishment of 22¾-inch fire model. Photometric equipment is not shown. Appearances to the contrary, the extinguishment process is not one of simply blowing the fire out

where

$x = \sum_{n=1}^{j} (N_n - a)$ for $a < N_n < b$

$y = \sum_{n=1}^{k} (b - E_n)$ for $a < E_n < b$

W_m = minimum effective rate

E_n = rate at which extinction occurred

N_n = rate at which non-extinction occurred

a = rate at or below which there were no extinctions

b = rate at or above which there were no non-extinctions

j = number of non-extinctions in interval between a and b

k = number of extinctions in interval between a and b

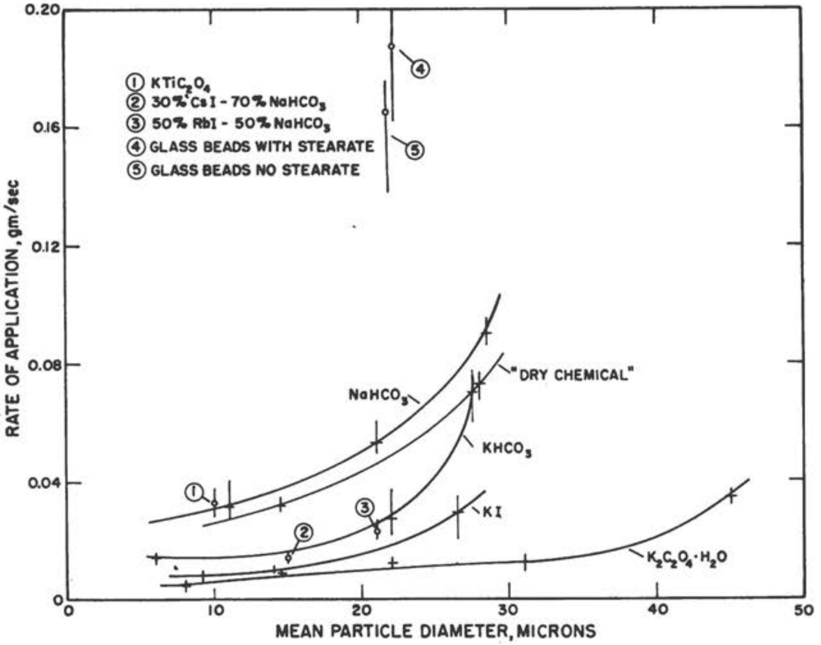

Figure 4. Effective application rate for extinguishment in terms of weight for the 1⅛-inch fire model

The values of *a* and *b* were experimentally determined and, in this case, were based upon at least 20 determinations. All data were on a weight basis. The two points for 22 micron glass beads were displaced relative to each other to avoid overlapping of the two lines on Figure 4. The curve marked "Dry Chemical" was drawn through the two experimental points. Its shape was estimated on the basis of the data for sodium bicarbonate.

Hird and Gregsten[12] have shown that better correlation of data can be achieved for powder of different particle sizes when application rate is expressed in terms of surface area of the powder particles. Accordingly, the curves of Figure 4 have been converted to a surface area basis on the assumption that the particles are spherical in shape and the Fisher subsieve sizer measurements are applicable. The resulting curves are presented in Figure 5.

During the experiments it was observed that particles on the order of 5 micron or less were lifted by the hot gases above the fuel, and in some instances, this effect prevented extinguish-

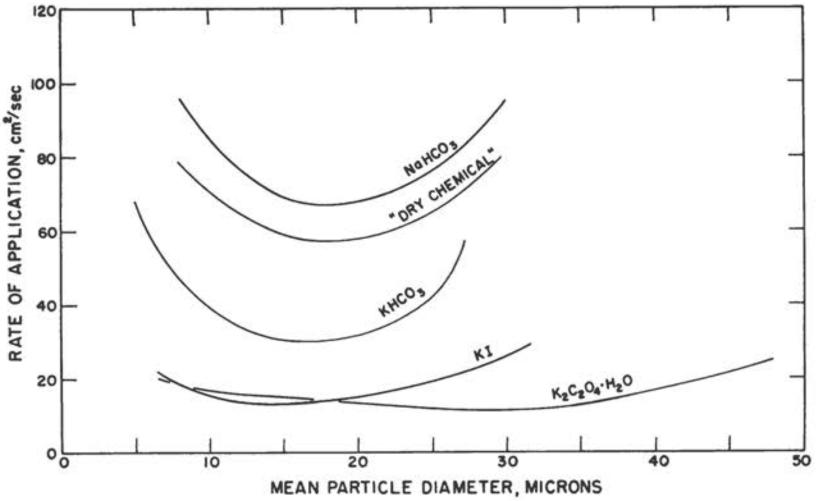

Figure 5. Effective application rate for extinguishment in terms of powder surface area for the 1⅛-inch fire model

ment from taking place. For particles of greater than 25 micron size, the increase in the effective application rate may result from differences in residence time which affect heat absorption capacity and decomposition behavior of the particles in the reaction zone. The differences observed between the $NaHCO_3$ and "dry chemical" curves may be a result of dispersibility and particle shape differences perhaps resulting from different preparation techniques.[13]

Figure 6 shows the effectiveness of mixtures of 22 micron glass beads and 8 micron potassium oxalate monohydrate at various weight ratios. The experimental results are plotted as crosses in which the horizontal and vertical lines have the same significance as in Figure 4. These plotted results may be compared with the curve shown, which was calculated from the minimum effective extinguishment rate observed for 100 per cent 8 micron oxalate (data from Figure 4) on the assumption that the glass beads have no effect in extinguishing the fire. (Thus, for example, the calculated minimum effective rate for the 50-50 mixture is twice that for the 100 per cent oxalate). These results seem indicative that an inert carrier with larger mass could be used to introduce a finely divided and chemically effec-

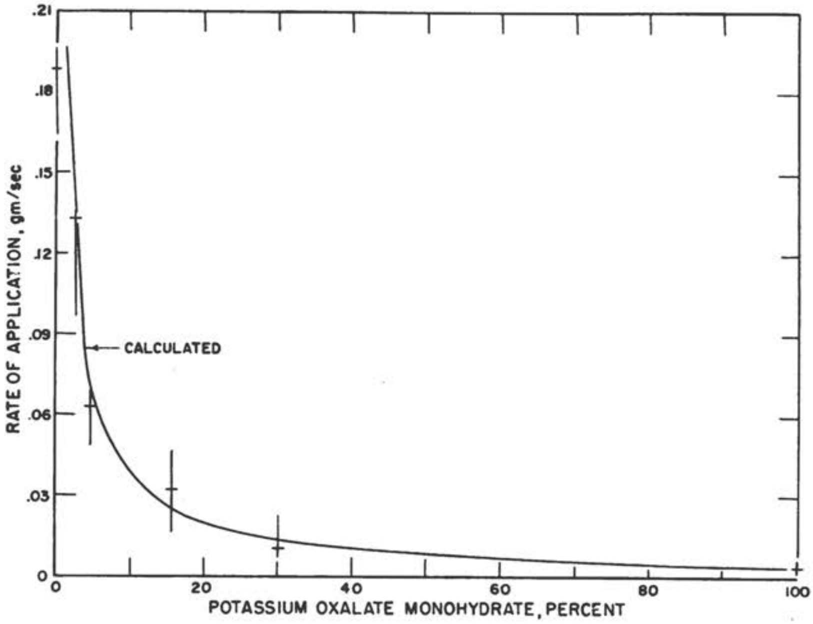

Figure 6. Effective application rate for extinguishment of mixture of 22 micron glass beads and 8 micron $K_2C_2O_4 \cdot H_2O$, for the 1⅛-inch fire model as influenced by the percentage of $K_2C_2O_4 \cdot H_2O$ present in the mixture

tive agent into the desired zone of the flame. Due to surface forces, the fine particles adhere firmly to the carrier, at least prior to its introduction into the flame. The higher momentum acquired by the much larger mass of the carrier would be able to overcome the buoyant forces created by upward draft above the combustion zone.

Fire Models of 6 and 22¾ Inches in Diameters

Figures 7 and 8 show the time to extinguishment as a function of application rate expressed on a surface-area basis. These figures show results respectively for the 6- and 22¾-inch fire models. To avoid overcrowding, a typical set of data points for $NaHCO_3$ only are shown in Figure 7. In general, these data seem similar to those of Hird and Gregsten[12] and show that for a given powder, extinction time increases as the discharge rate decreases.

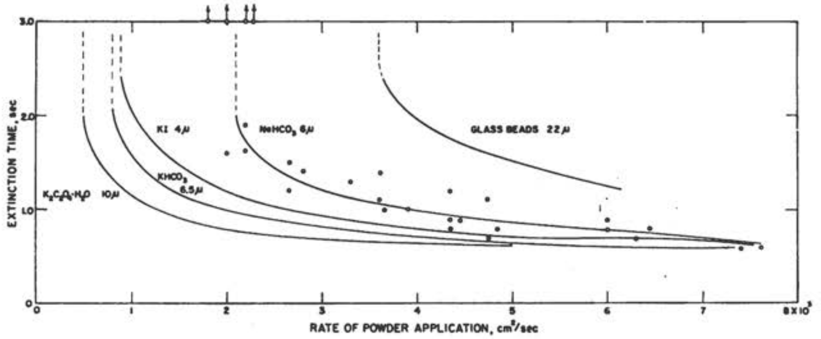

Figure 7. Fire extinction time as influenced by rate of powder application for 6-inch fire model. Dashed lines represent minimum application rate for extinction. A typical set of data points for *NaHCO₃* is shown. The data with arrows represent trials in which no extinction was achieved

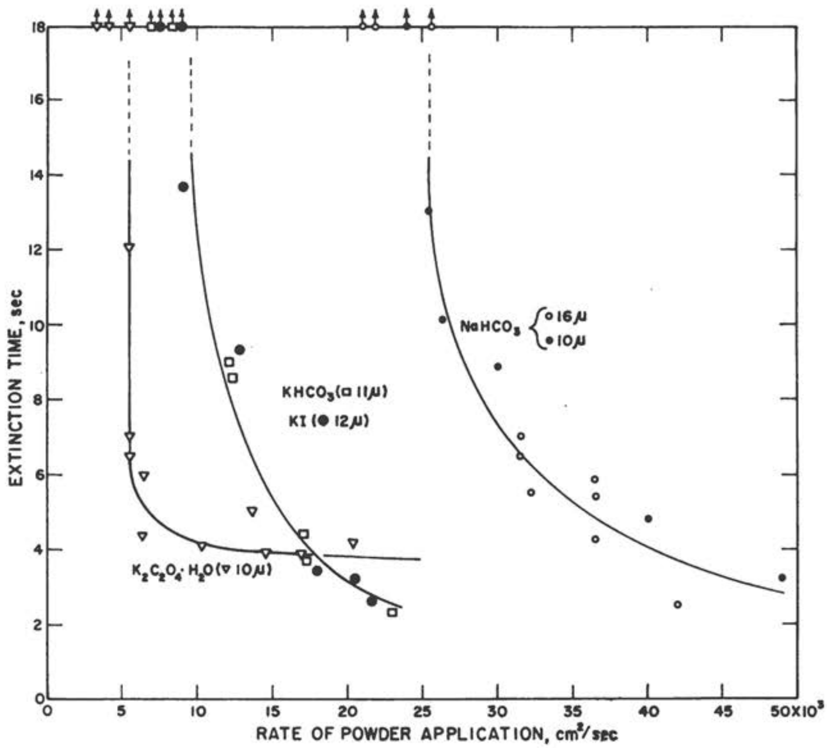

Figure 8. Fire extinction time as influenced by rate of powder application for 22¾-inch fire model. Dashed lines represent minimum application rate for extinction. The data with arrows represent trials in which no extinction was achieved

Eventually, the point of nonextinction is reached. At very high discharge rates it appears that the extinction time approaches a constant.

Tabulation of Summarized Results

Table 2 presents summary results for the three fire models studied and each of the four powders tested. The results are presented in terms of minimum powder application rate on a surface-area basis, as well as in relative application rates with respect to $NaHCO_3$ as a reference material. Also shown is the average fuel burning rate for each of the fires used. This latter shows fuel consumption rates roughly 60 per cent of those reported by Blinov and Khudiakov[14] for gasoline burning in deep fuel pans. When minimum $NaHCO_3$ application rates are divided by fuel consumption rates, the quotient is found to vary by a factor of 2.7 over the very wide range of fire sizes.

Discussion

The results show that the fire extinguishing effectiveness of the powders tested depends on the physical and chemical nature of the powder. Thus, potassium oxalate monohydrate was more effective than sodium bicarbonate or potassium bicarbonate in all three models and potassium iodide was about 2.5 times as effective as sodium bicarbonate in the two larger models on surface-area basis. All four alkali metal salts were more effective than the inert glass beads.

Figure 5 shows that, for a given powder, an optimum range of particle sizes exists for which the minimum powder application rate in terms of its surface area, is effective for control of the 1⅛-inch fire model. This range is between 15 and 20 microns for many of the powders tested. In this 1⅛-inch model, powder particles approach the flame at or below the terminal velocity of free fall. Hence the extinguishing behavior of the powders in this model may be more sensitive to particle size, shape, and density than in the other models where powder was propelled into the fire. In this connection, the improved effectiveness of potassium iodide in the 1⅛-inch model as compared to the two other models (Table 2) may be attributed to the higher density of this ma-

TABLE 2. Minimum Effective Rates of Powder Application and Fuel Consumption for Various Fire Sizes and Powder Types in Size Range of 6–12 microns

Diameter of Fire	Application Rates				Ratios of Application Rates			Fuel Consumption Rate	Ratio of $NaHCO_3$ Application Rate to Fuel Consumption Rate
	cm²/sec								
inches	$NaHCO_3$	$KHCO_3$	KI	$K_2C_2O_4 \cdot H_2O$	$\frac{NaHCO_3}{KHCO_3}$	$\frac{NaHCO_3}{KI}$	$\frac{NaHCO_3}{K_2C_2O_4 \cdot H_2O}$	ml/sec	cm²/ml
1.12	68*	32*	15*	14*	2.1	4.5	4.9	0.0078	8.7×10^3
	90	42	18	17	2.1	5.0	5.3		11.5×10^3
6.0	2,100	800	900	500	2.6	2.3	4.2	0.23	9.1×10^3
22.8	25,500	9,500	9,500	5,500	2.7	2.7	4.6	6.0	4.2×10^3
40.6	100,000**							32	6.2×10^3

* Data shown are for 20 micron particle size powders.

** Data from reference 12.

terial. The other salts for which data are reported in the Table had a density of about two-thirds that of potassium iodide.

It was found that, within a limited range of particle sizes, extinction effectiveness was a function of specific surface of the powder. The data for sodium bicarbonate shown in Figure 8 illustrates this fact. Here, minimum powder application rates are shown to be closely the same for both 10 and 16 micron powder sizes when such rates are expressed in terms of surface area. For particles of smaller or greater sizes than those studied, buoyant or gravitational forces may limit introduction and retention in the flame zone. Consequently, the extinction effectiveness would not be a simple function of specific surface. Although sufficient data were not obtained to confirm the existence of this behavior in the larger fires, a somewhat similar, but less pronounced effect as that shown by Figure 5, should be assumed.

One method of overcoming the poor physical behavior of fine powders is to employ a carrier to introduce a very finely divided yet chemically effective material into the flame zone. Reference to Figures 4 and 6 shows that a mixture consisting of glass beads and only 8 per cent 8 micron potassium oxalate could be considered equivalent to the 22 micron "dry chemical." Besides increasing effectiveness, proper use of a carrier may reduce toxicity hazards.

Figures 7 and 8 provide a good illustration of the need for use of minimum application rates in measuring relative effectiveness of different agents. Thus, it would be difficult to distinguish between effectiveness of different powders in the field if high application rates were used which resulted in extinguishment times being close to the minimum shown in these figures.

Individual points on Figures 7 and 8 and vertical lines on Figures 4 and 6 indicate the magnitude of the error. Since the methods developed are primarily for comparative evaluation, no analysis of error was made. However, the discharge reproducibility of the rotor dispenser, as measured at the nozzle, was within 3 per cent for all free-flowing powders used.

Table 2 presents the ratio of $NaHCO_3$ application rate to fuel consumption rate for each fire size. Similar results for the other powders could have been presented. The variation of the ratio is not considered large in view of the very wide range of fire sizes and powder application rates which were used. Although not conclusive, the limited range over which this ratio varied seems to indicate that there was no drastic change in the character of the fire or the mechanism of extinguishment for any given powder. It seems that the minimum powder application rate required for extinguishment is very roughly proportional to the rate of fuel consumption. This latter fact may perhaps be more clearly illustrated by the data shown in Figure 9. Here the extent to which the burning rate curve is parallel to the minimum application rate data serves to indicate the degree of proportionality.

In considering these results, it should be remembered that different techniques were used for powder application. For the 1⅛-inch model, powder was applied to the flame under a condition of free fall. For the 6-inch and 22¾-inch models, powder particles were carried by a propelling air stream and discharged from a fixed nozzle. For the 3-foot square pan indoor, and the 10-foot square outdoor gasoline fire, Neill[10] used an especially adapted commercial extinguisher and attacked the fire manually by spraying from side to side. Hird and Gregsten[12] used a fixed nozzle to cover the fire area together with a modified commercial extinguisher. Their fire was supplied by a 1½-inch layer of gasoline in a 3 foot square pan involving 2½-inch freeboard.

Neill's results on extinguishment of gasoline fires shown in Figure 9 seem to present a reasonable extrapolation of the results obtained by the authors. In plotting these data, it was assumed that they could be shown as applicable to fires on circular pans having an equivalent surface area. Neill[10] did not mention specific surface in his paper, but found later,[15] that the $NaHCO_3$ powder had a specific surface of 1750 cm^2/gm. Specific surface for the $KHCO_3$ used by Neill was assumed to be the same on the basis of his results of sieve analysis. The extent of agreement between the two sets of results is encouraging especially when consideration is given to the differences in powder application techniques and the many other variables involved.

The higher application rates apparently required for Hird and Gregsten's experiments may have resulted from the need to cool the 2½-inch rim of the fuel container below the flash temperature of the fuel air vapors.

The methods described have been shown to be effective in evaluation of different powder extinguishing agents when applied to flammable liquid fires. It is not known to what extent these

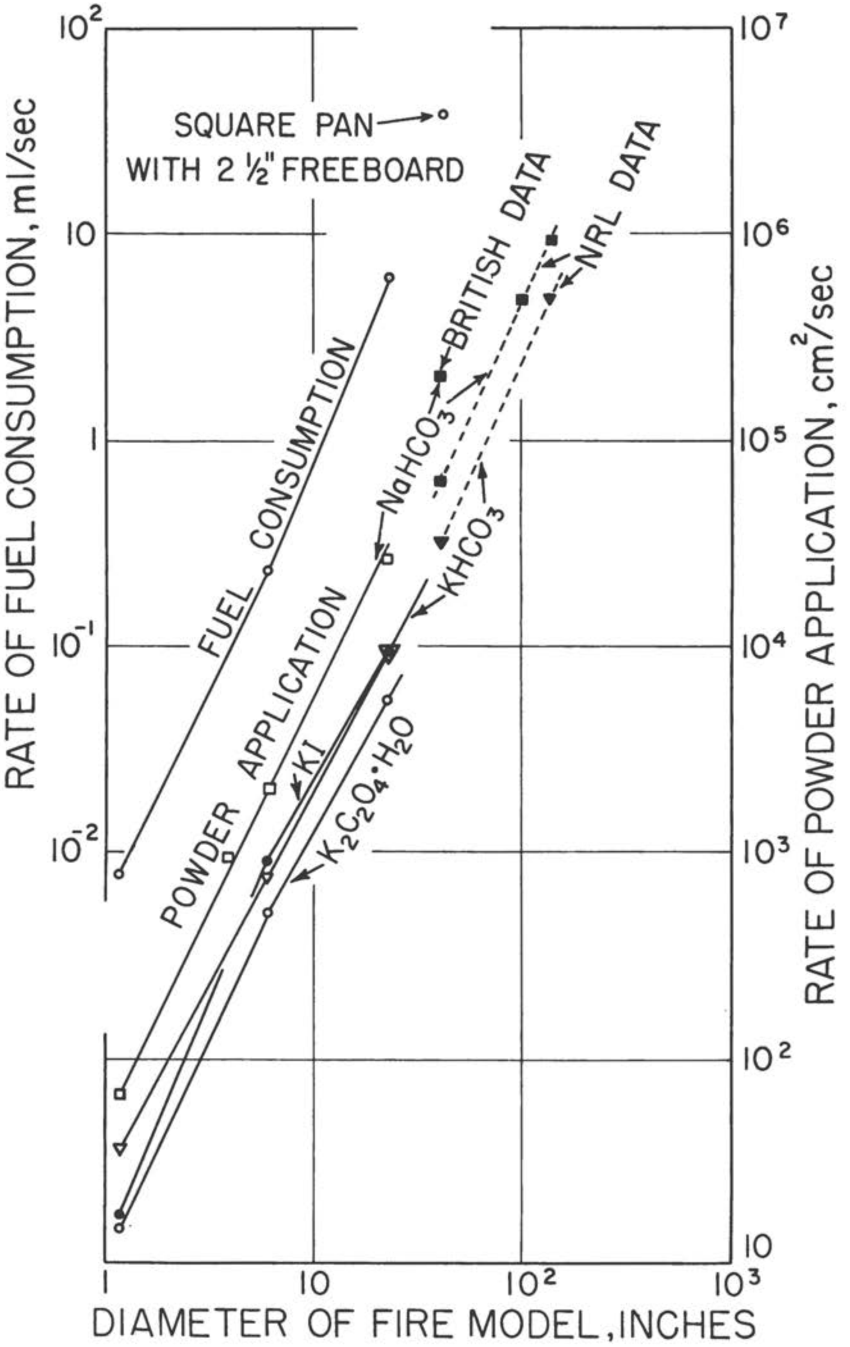

Figure 9. Rate of fuel consumption and minimum effective rate of powder application for extinguishment of fires of different diameters

measurement techniques will be applicable to very large fires although the work of Neill seems to indicate the possibility of such use. For study of second order effects, variables such as air velocity, powder concentration, and particle size distribution must be more closely controlled than was possible in the work described.

Summary

Laboratory methods have been developed to evaluate the fire extinguishment effectiveness of powdered materials. These methods employed 1⅛-, 6-, and 22¾-inch fire models of the free burning of a liquid hydrocarbon. Dispensers which permitted controlled application of powders to the fires were designed and used for the evaluation.

The extinguishment effectiveness of various powders, in the mean particle diameter range of 6 to 40 microns, was determined by measuring the minimum effective rate of application in terms of powder surface area required for extinction. The effectiveness of the powder was found to depend on (1) chemical nature, (2) specific surface, and (3) particle size of the powder.

The most effective material studied was potassium oxalate monohydrate. It was about four times more effective than sodium bicarbonate of optimum particle size, the commonly used extinguishing agent. On a surface-area basis, when using the 1⅛-inch fire model, particle sizes between 15 and 20 microns were generally most efficient.

The experiments show that for sodium bicarbonate the ratio of rates of powder application required for extinguishment to fuel consumption varied from 4.2×10^3 to 11.5×10^3 cm^2/ml. Considering the variation in application techniques and the wide range of fire sizes used, it seems reasonable, in the absence of more complete data, to consider that powder application rate required for extinction was very roughly proportional to fuel consumption rate. Limited extinguishment data on large-scale fires of other workers seem to confirm the usefulness of the model method for evaluating powder effectiveness.

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Discussion

Mr. Malcolm: I have a question on the fuel consumption rate. I did not understand how the fuel consumption rate fits into the picture.

Mr. Lee: A correlation was found between the fuel consumption and the minimum powder application rate for extinguishment, for the fire models used.

Commentaries

Dr. Avery: I have asked four persons to comment and bring out significant points in the comparison of these papers—Dr. Lewis, Mr. Grumer, Dr. Wolfhard, and Mr. Tuve.

Dr. Lewis: I should like to make my first remarks a common discussion growing out of the first three papers by Emmons, Burgess, and Magnus. These papers are concerned with aspects of the scaling laws that are operative in the burning of liquid fuels in pools, in an attempt to discover the experimental variables that play a role in the description of fire intensity.

Even a casual inspection of the general problems must convince one that the variables are complex, some of them interdependent, so that the attainment of this goal will not, I would think, be an easy matter. Although these authors have developed useful data, the work has not gone far enough to break down the complexities sufficient for a full treatment by dimensionless analysis.

The general approach has been to study the rate of burning of a pool of fuel, that is the rate of regression of the liquid surface as a function of the area of the pool. The geometries in the three studies were not quite the same so that certain differences in the results are to be expected. Nevertheless, enough has been learned to reveal the complexities that exist, and perhaps to reveal what further measurements need to be considered. As Magnus so correctly points out, the extinction of tank fires becomes more difficult with growing diameter and this cannot be explained simply by the growth of the burning surface. Other complex phenomena are superimposed that render a simple solution elusive.

I think we can all agree that the over-all mechanism of pool burning is that the fuel is volatilized by heat feedback from the burning fuel above the liquid surface, and that air is furnished by entrainment at the periphery. There is need to define more closely the relative importance of the heat transfer mechanisms of conduction, convection, and radiation as the scale increases, but it can be said that for small fires (under 4 to 6 inches in diameter) conduction and convection predominate, whereas for large-scale fires (12 to 40 inches and more in diameter) heat feedback by radiation predominates. It is clear that this must be so because for larger scale fires air entrainment from a chemical standpoint is not very efficient, resulting in formation of carbon, upon which depends an important part of the radiation.

The next element of importance is the state of flow of the fuel vapor from the liquid surface to the flame surfaces. Here the experiments of the Russians, Blinov and Khudiakov, as well as the present work by Burgess and possibly also that of Emmons, appear to indicate strongly that this flow is laminar in character for small-scale fires, and that it passes through a transitional phase to the turbulent regime for larger scale fires. Since for small-diameter fires the air entrainment requirements are better met, it is not surprising that the predominent heat feedback mechanism here is conduction, with the contribution from convection becoming important in the transitional range of fuel vapor flow. At least, the small-scale part of the Blinov and Burgess curve of burning rate versus pool diameter in which burning rate decreases with increasing diameter, can be ascribed to a growing deficiency in the specific air entrainment, that is the air entrained per unit pool area. However, the burning rate soon passes through a minimum with the onset of turbulence and from here on one must consider the important role played by turbulence in the fuel vapor approach flow.

It is well known from combustion studies of flammable mixtures in turbulent flow that turbulence generates flame surface. It is also known from studies of flame in high velocity turbulence streams that there exist critical velocity gradients across which flames cannot propagate, and that a dimensionless number, K, which is given by the velocity gradient in the stream divided by the velocity at the same point times a characteristic dimension which is related to the flame width, viz.,

$$K = \frac{du}{dyu} \times \beta$$

The experiments show that when this K number reaches a value of about unity, flame extinction takes place. Another way of looking at this is that when the rate of increase of flame surface over a distance of propagation corresponding to the flame width exceeds a critical value, the flame is extinguished. It is not clear to what degree the destruction of flame surface by turbulence plays a role in large-scale burning of pools, but certainly the turbulent regeneration of flame surface is an important aspect.

The flame surface plays a dual role. First, the rate of consumption of fuel vapor is directly proportional to flame surface, and secondly, radiation intensity is proportional to flame surface as well as being dependent upon the temperature.

As though this were not complicated enough, we need only remind ourselves of the burning of liquid monopropellants, like hydrazine, in tubes, which, when passing into the turbulent burning regime, undergoes an abrupt rise in the burning rate, with the physical ejection of liquid mass from the surface into the space above. In large-scale pool burning, the turbulence intensity must be of such magnitude as to similarly eject islands of liquid fuel.

The importance of air entrainment is one that would be recognizable a priori, but it is particularly brought out in the results of Magnus. His experiments provide consistent and reproducible data on the distribution of temperature above the burning liquid. These data, together with the simultaneously observed burning rates, provide an insight into the feedback mechanism which determines the intensity of the flame. Qualitatively, the data show trends about as one might expect. Above the liquid surface, the temperature rises sharply to a maximum, and then decreases gradually with increasing height. The value of the maximum temperature and its position above the liquid level are dependent on factors which appear principally to be associated with the penetration of air into the flame. The measurements are made possible by eliminating the factor of external air currents, which is acknowledged to be important but which is very difficult to control. The burning rate is found to be dependent upon the value of the maximum temperature and its position above the liquid level which are determined largely by air entrainment.

It is possible that the more or less constancy of the burning rate as the scale increases for large-scale burning (above 40 inches of pool diameter) is due to a balance between generation of flame surface and air penetration. If the aspect of generation of flame surface by turbulent motion possesses any merit in connection with pool burning, I would mention that Karlowitz, in the *Seventh Symposium (International) on Combustion* (1958 p. 604) has shown how to calculate the concentration of flame surface per unit volume for given turbulence intensity and scale.

Quantitative data of the kind presented in Magnus's paper together with certain other data presented in the work of Blinov and in the papers by Emmons and Burgess, hold promise of arriving at practical scaling laws based on a physical understanding of the process, which permits correlation of the various factors involved in combustion processes of this type.

About the last paper, I would like to commend authors Lee and Robertson for what appears to be a well planned and executed study which has yielded significant data. Concerning the effect of particle size, the authors suggest that the relatively poor performance of very fine powders is due to the lesser penetration of such particles in the combustion zone under the conditions of application. This is in accord with Dolan and Dempster's investigation of premixed gases in tubes [see *Sixth Symposium (International) on Combustion* (1956 p. 787)] and with Laffitte and Bouchet's investigation in tubes [*Seventh Symposium (International) on Combustion* (1958 p. 504)] where the experimental configuration, that is, the uptake of the powder by the flow ahead of the combustion wave, insured efficient penetration regardless of the particle size, and no adverse effect of fineness was noticed in these experiments.

The relatively greater efficiency of potassium bicarbonate over sodium bicarbonate is perhaps associated with the fact that the potassium bicarbonate decomposes at lower temperatures (between 100 and 200°C) than sodium bicarbonate (about 270°C). Similarly, potassium oxalate, which is even more efficient, decomposes somewhat above 100°C. With these powders flame quenching is possibly largely a thermal and diluent effect. In contrast, salts like potassium iodide and cesium iodide are thermally quite stable and their high efficiency suggest a chemical effect such as the removal of OH radicals by the reaction, KI plus OH to give KOH and I.

Particularly noteworthy is the observed approximate proportionality between the rate of fuel consumption and the critical rate of application of a powder to effect extinction. This is evidently a very reasonable and a priori relationship, and its experimental verification serves to confirm the validity of the experimental procedure and to establish confidence in the basic significance of the data.

Mr. Grumer: We have had this afternoon the benefit of hearing four stimulating and informative papers. Three of these were addressed to the problem of liquid burning, the rate at which the liquid disappears through combustion, and the fourth to problems involved in extinguishing fires. There may be a difference between the two problems. Whereas the burning mechanism of two fuels may be identical, the problem of bringing an extinguishing agent to each may be entirely different.

Two of the papers, which dealt with liquid burning, are related by having taken direction from the Russian work of Blinov and Khudiakov, which mapped out burning rates in pans of varying diameter as a function of the mode of heat transfer. Dr. Emmons looked over the multitude of areas for fruitful investigation and picked the small pool for careful examination. Dr. Burgess concentrated his attention on larger pools. There has been some healthy overlap of data, and I find it reassuring that about the same numbers have been gotten.

I would like to comment on Dr. Emmons's experiments where a difference was noted between the rate of liquid burning in pans completely enveloped in the table top and the rate with pans on top of the table. A four-step mechanism was proposed in which the flame radiated heat back to the table top; this in turn heated the air that was coming into the flame and this in turn heated the pan and the pan heated the liquid. These were very rich flames on burners of small diameter. Let me suggest for Dr. Emmons's comment that perhaps the direction in which air gets to the base of the flame is important when the tray is small (less than 1 inch in diameter). With the pan flush with the table top, air gets into the base, flowing nearly perpendicular to the rising fuel vapors. More mixing, concurrent with burning, occurs than when the pan is atop the table. In the case of the pan on the table, the flow lines of entering air could be bent by the sides of the pan, so that the air flow enters the flame column more parallel to the fuel flow. The better mixing and more confining flow of air in the case of the flush mounted pans could keep the flame further from the rim and reduce heat transfer from flame to rim and from rim to fuel. We are dealing with rich flames and these overhang burner rims generally—more so on small burner ports than on large ones. Anything which would reduce this overhang could be significant. I suggest that putting the burner rim flush with the table top would reduce overhang and licking of rim by flame. Such reduction would reduce heat transfer via the tray walls, from flame to liquid and correspondingly reduce the burning rate.

I am not going to comment on my colleague's paper from the Bureau of Mines, except to say that I know he has more material available and also to add a word about ethylene diffusion flames. Like the benzene flames Dr. Burgess discussed, these too have soot beneath the flame envelope, temperatures are high, oxidized combustion products are present—even at the plane of the port. So it appears that convection under diffusion flames is common to flames of liquid and gaseous fuels.

Dr. Magnus's observation that wind is highly important is intriguing. In the experiments which we did at the Bureau of Mines, we have been led to think that, insofar as the liquid burning rate in large pools is concerned, the wind is of minor importance. That is to say, we do not observe an effect which doubles or triples the burning rate. This change may be 10, 20, 30 per cent, something of that order. I wonder whether we have an area of agreement with Dr. Magnus.

Dr. Magnus: We do agree.

Mr. Grumer: In the fourth paper, we have considerable information with respect to the extinguishment of liquid fires and how to rate the effectiveness of any powder extinguishers. This paper shows the importance of knowledge of burning rate of liquids in that the specific minimum rate of application of powder for extinguishment is nearly proportional to the liquid burning rate. The powders considered were potassium oxalate monohydrate, potassium iodide, potassium bicarbonate, and sodium bicarbonate. All three potassium salts are better than sodium bicarbonate and their effectiveness is in the order mentioned. There is a lot of important practical information in this paper, such as the idea of using heavy powders covered with active finely divided extinguishing agents to get the agent across updrafts above the burning fuels. There is the intriguing point that chemical effects are no doubt important in the effectiveness of dry chemical extinguishers, potassium salts being better than sodium salts. I have heard it said that we can attribute this to the differences in the flame spectra of potassium and sodium– a thought I feel worthy of further consideration. Why is the oxalate so much more effective than the others? Do the absorption spectra of the products of decomposition of the oxalate have a role here too?

Dr. Emmons: In answer to Mr. Grumer's remarks about my paper, we have observed no difference whatsoever in the size of the base of the flame, whether the dish was submerged in the table or on top of the table. The flame seemed to fit just a trifle inside of the cup.

Dr. Wolfhard: The question of radiation from flames has been discussed in the preceding papers. Dr. Magnus, for example, measures this radiation by observing the temperature rise in a water-filled drum next to the drum containing the burning fuel. The heat absorbed by the water is then presumably taken as a measure for the heat that would be absorbed by the burning surface itself. This, of course, presupposes that the radiation emitted from the flame into space surrounding the flame is the same as the radiation within the flame. Let us investigate this question for a moment and consider a laminar diffusion flame of a hydrocarbon fuel vapor burning with air. The flame consists of a yellow carbon zone on the fuel side and a bluish zone where the temperature is highest, over on the air side. The carbon zone itself is not homogeneous but its luminosity is low on the fuel side and increases towards the air side where the temperature is higher. In other words, the radiation of a diffusion flame depends on the direction of the radiation.

This effect is especially noticeable for benzene flames. Looking from the fuel side the flame looks dark and black, whereas from the air side the flame is bright yellow. In benzene flames burning from large trays carbon is seen floating between flame and burning surface, shielding the surface from the heat radiation of the flame. In order to assess the effect of flame radiation on the burning rate of a liquid pool it is necessary to measure the radiation at the surface underneath the flame and the heat flux may well be very different from the intensity of radiation outside the flame. In turbulent flames, conditions may be more difficult to assess, but basically the same considerations apply. A further important point to consider is that the fuel vapor rising from the vaporizing surface might also absorb radiation from the flame and further shield the surface.

Dr. Burgess mentioned the influence of tray diameter on the rate of recession of the burning fuel surface. Beyond about one meter diameter the burning rate becomes independent of tray size. The implication is therefore that experiments on relatively small liquid fuel fires are representative of large-scale fires. This still remained to be experimentally verified. It is, however, useful to try and understand the underlying physical principles. The rate of surface recession of a burning liquid can be due to two causes: heat transfer by radiation and heat transfer by conduction. As we increase the size of the liquid surface the flame becomes larger not only in over-all size, but also in depth. Unless the emissivity of the flame is already unity for rather small fires, the emissivity is bound to become larger for larger trays. The intensity of radiation seen by an element of liquid surface will therefore depend on flame temperature, emissivity, and the effective solid angle of flame seen by the surface element. The flame temperature can be assumed to be independent of tray size. It is feasible that the effective solid angle is also independent of tray size if we assume that in larger flames the main body of radiating gases is at a greater distance from the surface. If flame radiation is mainly responsible for the vaporization of the fuel, then in the plateau region both emissivity and solid angle must have reached a limiting value. Heat transfer by conduction cannot be excluded from considerations. It is clear that no heat will be transmitted from a flame zone high above the surface through the ascending fuel vapor to the surface. However, flames burning from large trays are no longer strictly laminar. Flame elements sweep over the surface at irregular and for some flames even in regular intervals, and come in close contact with the surface in contrast to undisturbed flames where no such contact exists except at the perimeter of the tray. Thus, conceivably the plateau could be characterized by the existence of a flame where the sweeping action has become predominant and supplies the major part of the necessary heat of vaporization.

Dr. Lewis was considering the effect of turbulence on the detailed flame structure of a fuel fire. I feel that such considerations are important for the understanding of the local mechanism of fuel vapor consumption in the flame but will influence the rate of recession of the liquid surface only in a minor way.

Mr. Tuve: The question of emphasis of fire research is a flexible one, and we have had expressions of various ways in which this research can be done.

This is all good research. It will lead us to areas which are important, but I think a little realigning is in order. We must be worried more about *halting* combustion than combustion improvement, and we are getting too far away from the surface of the fire, the point at which extinguishment begins.

For instance, in the foregoing papers, there was no mention made of a phenomenon known as "heat wave." This is the downward travel of temperature and heat into the surface of the material. Some of the experimenters in this field show that a heat wave is set up, even in burning gasoline. (This originates principally in England.) There is a definite picture of a heat wave in other hydrocarbon mixtures, but we have dealt so far only with pure substances, and with shallow pools. Granted that we must deal with shallow materials before we can deal with deep ones, let us not forget to deal with the depths of these flammable materials, and let us study the reactions which occur *downward* as well as those which occur upward.

Incidentally, I think that any ideas as to the mechanism of flame suppression by potassium as against sodium are premature. I do not think we know enough of the entire picture of this situation between potassium and sodium. This is a complicated phenomenon and, to postulate the mechanism, we must learn more about it. It is an extinguishment phenomenon, not a combustion phenomenon.

Discussion

Dr. Emmons: With regard to the radiation questions raised by Dr. Wolfhard in some small flame measurements, 4-inch diameter pans, we have measured radiation from a flame. We then put a second flame behind the first one, directly behind, and measured the radiation and we got almost precisely the sum of the two as measured individually. This means that the flame, although it appears not to be transparent, is in large part transparent for the wave lengths effective in energy transport in the experiments we made.

Unidentified Questioner: What sort of a flame was that?

Dr. Emmons: It was an acetone flame, a small one. I think it might be worth saying a word or two in connection with the conductive, convective, and radiative effects; the laminar, transition, and turbulent effects. We have these two sets of three words each, which are passed around without very precise application to the burning process, and I thought I would make a few remarks with respect to my current understanding of them.

Let me sketch first the appearance of various flames (on blackboard); A is a small one, up to about three quarters of an inch. This one is a very small flame; sits quite still just like a candle flame. Let us make one a little bit larger as B for a 1- or 2-inch pan. The flame is, of course, larger and its tip may periodically break off or oscillate. These are, of course, well-known phenomena. As we go to still larger flames, C, larger pans of 3 to 12 inches, one obtains a flame which is closely fitted to the pan edge in the same fashion as the small ones, forming a very nice cone; perhaps luminous, perhaps not, depending upon the nature of the fuel. The cone is quite steady but above this the flame becomes highly turbulent. One visualizes, therefore—although I have not personally experimented with them—that for large fires, several feet and more, one would have turbulence beginning essentially at the pan edge. This may be because of the fact that the velocities have gotten high enough so that the oncoming stream or the inducted air is already turbulent, or perhaps a small laminar region still exists. But after all, a couple of inches out of ten feet does not make any difference to the heat transfer to the pool and hence the burning rate.

Undoubtedly in large fires, one obtains a highly turbulent combustion, and over a large portion of the surface, with, therefore, (as I believe Dr. Wolfhard noted) the flames actually sweeping down across the fuel surface part of the time. In this connection I would visualize a burning rate versus diameter for small pan diameters such as Blinov and Khudiakov have found. My experiments indicate that the small-diameter burning rates are the result of high conduction. For pan diameters from about 8 inches up, the conduction is no longer of any significance.

However, is this properly looked at as a transition, a transition of the flame from laminar form of combustion to turbulent? In the case of pan burning, transition does not mean this. Laminar pan burning merely means that turbulent burning is sufficiently removed from the fuel surface compared to the diameter, that the convective effects are not effective in transporting much heat to the fluid. But in both laminar and turbulent flames we have significant heat transport by radiation. Large fires are perhaps essentially black bodies. Small fires undoubtedly are not black. I would like to propose that the major difference between large and small fires is one of convection. In the large fire the turbulence has approached so close to the edge of the pan and has become so violent that the flames actually sweep over the full surface part of the time.

Mr. Royer: Has Dr. Emmons made any air flow measurements on the table tests on the entrained air? He mentioned hot air or air heated as it was brought into the area. We had a situation where we had a large mass of solid combustibles, which covered quite a large area; it was 493 tons of material and the phenomena which has just been described by Dr. Emmons were observed. However, at a level up to approximately 12 feet, there seemed to be no air movement. It was thought that this lack of air movement was due to radiated heat; some steam due to weather conditions had been produced and this steam blanket up to a level of approximately 12 feet remained completely still, where ordinarily one would expect it to be drawn into an entrainment process. This was one of the things which produced a very erratic air flow curve which we gathered from this large mass of burning material, and I am wondering if there have been any measurements on the effect of this heated air. What was produced by it? Dr. Emmons mentioned that it produced its own little agitation.

Dr. Emmons: I can hardly be expected to extrapolate from 10 inches to 493 tons, but I do not understand your explanation as to what happened. If you had a steam blanket, you must have vaporized significant water, and thus produced a gas of much lower density than the normal atmospheric air.

I had produced a thin layer of warm air of only slightly less density than normal. If you produced steam, you should have had a lot of gas with a lot less density. Your gas should have risen very rapidly in many places. The steam should have failed to stay down near the ground, so I do not understand it at all.

With respect to our measurements, we did not make any detailed quantitative measurements of the gas flow. We did a certain amount of investigation with smoke generators by following the smoke from small jets. This we thought was going to show us something about the rate at which air moved at various levels so that we might then use this information in the better design of the enclosures by which we attempted to control drafts.

This work was done incidentally in attempting to design the enclosures. It was quite clear that something of great complexity was going on but it did not appear worthwhile to expend any additional time studying until after we made some progress in the main part of the problem.

One must keep one's eye on what one has decided is the ball or else one soon spends all one's efforts wandering down miscellaneous blind alleys. The experiment which finally convinced us not to go into further investigations was the fact that we placed four symmetrically located smoke generators on the table to watch the smoke slowly moving toward the fire. Three of them moved in, one went in about two inches, turned around, went out and fell off the edge of the table.

Professor Hottel: I would like to ask Sir Geoffrey if he could help us with an explanation of the phenomenon that he discussed this morning in relation to those we are talking about this afternoon. As we try to get at the modeling of fires that do not have a valve on the fuel line—in contrast to fires such as described this morning, characterized by my "q" or his "H" which fixes the burning rate—but instead have a burning rate that depends on the interaction between radiation and the fuel, can we get a measure of q or H for these "uncontrolled" fires? In the morning discussion, velocity was a dependent variable in setting up the study of flow around a fire, and q was an independent variable. If the total magnitude of flow above the kinds of fires that have been talked about this afternoon is comparable to that above the fires of this morning and if the air flow can be expressed as a ratio to the burning rate, then maybe we have a condition to feed in that allows us to start modeling on the kinds of fires we have discussed this afternoon.

Do you visualize, Sir Geoffrey, whether the air drawn toward these pans might be comparable to the air that was drawn in in the natural convection situation? In other words, is the air flow very sensitive to the shape of the device used to liberate the heat? I am suggesting that the burning rate is quantitatively proportional to the amount of air that gets stirred into the fire, and the stirring operation has no force to make use of or to produce it other than buoyancy. Am I making sense?

* *Professor Taylor:* I think that this is like the question which Priestley and his colleagues in Australia have discussed, namely, how the air which has no vertical component of velocity near heated ground assembles itself into a column of rising air. It is true that the kind of analysis which Schmidt used in discussing the relationship between a localised source of heat and the convection current above it can only be strictly applied at a height which is several times the linear dimensions of the heat source. On the other hand it will probably give a fairly good approximation at heights comparable with the linear dimensions of the source. It is therefore worthwhile to calculate the total inflow of air into the convection column up to height z_o above a point source emitting H heat units per second.

For this purpose it seems unnecessary to use Schmidt's complete calculation. A simplified model in which the temperature rise, θ, above atmospheric temperature T, is assumed to be uniform at level z and the breadth of the convection currents taken as $z \tan \alpha$ may be used. This simple model is described in a paper by Morton, Taylor, and Turner.† If the semi-vertical angle of the core containing the convection column is α, the vertical velocity is

$$w = \left(\frac{3gH}{4\pi T\rho\sigma \tan^2 \alpha}\right)^{1/3} z^{-1/3}$$

where H is the rate of discharge of heat. The total amount of air which flows into the jet up to height z_o is $w\pi z_o^2 \tan^2 \alpha$ or

$$\left(\frac{3\pi^2}{4}\right)^{1/3} \tan^{4/3} \alpha \left(\frac{gH}{T\rho\sigma}\right)^{1/3} z_o^{5/3}$$

Here ρ is the air density and σ the specific heat at constant pressure.

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* These comments by Professor Taylor and those by Professor Hottel immediately following were prepared in correspondence subsequent to the meeting.

† MORTON, B. R., TAYLOR, SIR GEOFFREY, AND TURNER, J. S. "Turbulent Gravitational Convection from Maintained and Instantaneous Sources," *Proceedings of the Royal Society* (London) *A234*, 1–23 (1956).

If all this air is used in a combustion which gives n units of heat per unit volume of air,

$$H = n\left(\frac{3\pi^2}{4}\right)^{1/3}(\tan\alpha)^{4/3}\left(\frac{gH}{T\rho\sigma}\right)^{1/3} z_o^{5/3}$$

The value of z_o must be related to the size of the fire. If z_o is taken as proportional to the linear dimensions L of a fire the above equation shows that fires in which all the air that enters the burning structure is used up in combustion should be modeled on the principle that $H^{2/3}$ is proportional to $L^{5/3}$, i.e. the rate of burning proportional to (linear dimensions)$^{5/2}$. The velocity of the air pulled into the fire by suction of the rising column above it which is proportional to $H^{1/3}z_o^{-1/3}$ is therefore proportional to (linear scale)$^{5/6-1/3}$, i.e. it is directly proportional to the square root of the linear scale. I do not know whether this theoretical conclusion is verified in experiments with model fires.

Professor Hottel: This development of the quantitative consequence of the suggested assumption that heat liberation rate might be proportional to the buoyancy induced air flow rate is interesting. As I think about the problem, however, I suspect that the assumption grossly over-simplifies the problem. Mass and convective heat transport at the fuel surface and radiation from the flame onto the fuel to vaporize or decompose it must, as well as the general air flow, affect the burning rate; and failure to model these additional phenomena must result in failure to maintain similarity between model and prototype.

Professor Taylor: There is another thing I might comment on, and that is Dr. Burgess's paper. By far the most satisfying result to the ordinary physicist was the beautiful line that he got as between the ratio of the heat and the ratio of the chemical energy produced to the latent heat. Is that right? I suppose that really indicates what Emmons was saying, that when you get to the stage where radiation is the only thing that is producing the vaporization of the fuel, then it does not matter much what the shape of the flame is. If it is anything like black-body radiation, then of course, no matter what the shape of the burning surface is, you get the same amount of radiation. Is that really what you intended to show? It seems to me that is a very natural and simple result.

Mr. Fahnestock: With regard to Dr. Emmons's theory about the entire flame area becoming turbulent when the receptacle or the burning surface is large enough, in the case of beds of finely divided solid fuel which are ignited in the center, we observed some years ago that the flame was rather consistently conical, but with a breaking up into turbulence in the upper portion, until it had consumed enough of the fuel toward the center and the center apparently had cooled down. Then the entire flaming area appeared to be turbulent. This can be observed in some movies of these experiments which will be shown tonight.

AERODYNAMICS OF FIRES

HOWARD W. EMMONS, *Presiding*

Study of Convection Currents Created by Fires of Large Area

J. FAURE
National Hydraulics Laboratory, France

The Problem

Introduction

We know that the greatest fire hazard for a city is the fire storm.[1] In Hamburg, for example, on the 24th and 25th of July 1943, twenty minutes after the first wave of bombers had passed, two out of three buildings were on fire with a zone of 11 km^2 area. In the absence of a strong ground wind, indrafts engendered by individual fires, and augmented by thermal radiation, formed a vertical column of burning gases approximately 3 km high and 2½ km in diameter. The influx of cool air at the base of the column was such that at 2½ km from the fire zone, the velocity of the wind rose in a short period from 17 km/hr to 53 km/hr, and at the periphery of this zone, trees 0.90 meters in diameter were uprooted.

In Tokyo, on the 9th and 10th of March 1945, fire developed over an area of 40 km^2, and the velocity of the wind created by the indraft, measured at 1½ km from the periphery of the fire zone, rose from 45 to 88 km/hr. The updraft velocity was of such magnitude that some aircraft flying at 1,800 meters altitude over the fire zone were overturned.

Objective of the Study

Investigations carried out in Germany and in Japan have made it possible to set down the conditions for the formation of the fire storm. It seems that all of the following conditions may be required: a high density of construction (at least 40 per cent), a high heat loading (fuel), a high density of initial fires within a wide area (2 to 3 km^2), and an absence of wind and humidity.

The French National Service for Civil Protection, which is responsible for fire extinguishment measures in the case of generalized conflagrations, requested the National Hydraulics Laboratory at Chatou, France to study the conflagration problem from the point of view of fluid dynamics, in order to determine mechanisms involved and to devise effective means for combating the conflagrations.

Experimental Technique

The complexity of the phenomena concerned prompted the National Hydraulics Laboratory to undertake study of the simpler experimental systems and of those systems amenable to mathematical analysis.

The principal systems studied were based on the following points:

1) The steady state is established, or at least, the time for complete fire involvement following ignition is brief compared to the total time of burning. The rate of fire spread, a problem which exceeds the capability of this laboratory, was not considered.

2) The two principal causes for air movement are considered separately, that is, convection effects caused by simple heat sources, and convection effects caused by combustion systems.

In the first phase, the study is limited to convection currents due to point or two-dimensional heat sources and in the second phase, actual combustion systems are considered which include the added effects of indraft and its relation to the combustion process.

3) Problem analysis requires examination from two viewpoints, theoretical and experimental, in order to delineate the fundamental parameters characterizing the problem and develop the laws of similarity which may be verified experimentally on models of different sizes. Some large-scale tests have been made, and others are planned.

Convection from a Heat Source

Theoretical Study

Notation

p pressure
ρ density

T	temperature
u_i	velocity vector
x_i	space coordinates
t	time
X_i	vector of exterior forces
τ_{ij}	tensor of forces of viscosity
μ	first coefficient of viscosity
μ'	second coefficient of viscosity
h	enthalpy per unit of mass
e	internal energy per unit of mass
Q	heat increase per unit of time and mass
U	potential of exterior forces
q_i	vector of heat flow
κ	coefficient of heat transfer
$\frac{d}{dt}$	symbol of differentiation
$\frac{\partial}{\partial t}$	symbol of partial differentiation
$\frac{D}{Dt}$	symbol of differentiation for particles

For a problem in fluid dynamics, the unknown quantities are thermodynamic variables (p, ρ, T), velocity vector (u_i), heat flow vector (q_i), and tensor of viscous force (τ_{ij}). These unknown quantities are connected by four equations; the equation of continuity, the momentum equation, the energy equation, and the heat flow equation. The auxiliary variables, internal energy e and enthalpy h, are determined when the thermodynamic variables are specified. These equations are written in summation form:

continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

momentum equation which can be written in two forms

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = X_i + \frac{1}{\rho} \frac{\partial \pi_{ij}}{\partial x_j} \tag{2}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + X_i + \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial x_j} \tag{3}$$

where π_{ij} is the force tensor and τ_{ij} the tensor of viscous tension and related by

$$\tau_{ij} = \pi_{ij} + \delta_{ij}p \tag{4}$$

(δ_{ij} is Kronecker's delta)

τ_{ij} can be expressed as a function of the velocity gradients and the viscosity coefficients. It is known[2] that the tensor of viscous tension can be expressed as:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \left(\mu' - \frac{2}{3}\mu\right)\delta_{ij}\,\frac{\partial u_\kappa}{\partial x_\kappa} \tag{5}$$

μ and μ' depend primarily on temperature and less on pressure.

This representation of τ_{ij} is not valid if rapid changes occur in the time and the space of the functions for the probability distribution.[3] The energy equation treats the change of the sum of enthalpy, kinetic energy, and potential energy. It can be written:

$$\frac{D}{Dt}\left(h + \tfrac{1}{2}u_iu_i\right) = Q + \frac{1}{\rho}\frac{\partial p}{\partial t} + \frac{1}{\rho}\frac{\partial q_i}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_i}(\tau_{ij}u_j) + u_iX_i \tag{6}$$

where the enthalpy h is related to the internal energy of the unit mass of fluid by:

$$h = e + p/\rho. \tag{7}$$

If the external forces X_i depend on a potential $U\left(X_i = -\frac{\partial u}{\partial x_i}\right)$ eq. (6) can be written:

$$\frac{D}{Dt}\left(h + \tfrac{1}{2}u_iu_i + U\right) = Q + \frac{1}{\rho}\frac{\partial p}{\partial t} + \frac{\partial u}{\partial t} + \frac{1}{\rho}\frac{\partial q_i}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_i}(\tau_{ij}u_i) \tag{8}$$

The heat flow equation under normal conditions (without rapid changes in the functions for the probability distribution) is defined by:

$$q_i = -\kappa\,\frac{\partial T}{\partial x_i} \tag{9}$$

This relation (q) and equation (5) defining τ_{ij} permit writing the energy equation in the form

$$\frac{De}{Dt} = Q + \frac{1}{\rho}\frac{\partial}{\partial x_i}\left(\kappa\frac{\partial T}{\partial x_i}\right) - \frac{p}{\rho}\frac{\partial u_i}{\partial x_i} + \frac{\phi}{\rho} \qquad (10)$$

or

$$\frac{Dh}{Dt} = Q + \frac{1}{\rho}\frac{\partial}{\partial x_i}\left(\kappa\frac{\partial T}{\partial x_i}\right) + \frac{1}{\rho}\frac{Dp}{Dt} + \frac{\phi}{\rho} \qquad (11)$$

ϕ, the dissipation function, is defined as follows:

$$\phi = \tau_{ij}\frac{\partial u_j}{\partial x_j} = \frac{1}{2}\tau_{ij}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$= \frac{\mu}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2 + \left(\mu' - \frac{2}{3}\mu\right)\left(\frac{\partial u_i}{\partial x_i}\right)^2 \qquad (12)$$

The preceding system of partial differential equations consists of 10 equations, one for each unknown quantity. The problem will be defined when the boundary conditions are formulated, which requires information on the limits of:

the velocity vector	u_i
the temperature	T
the vector of heat flow	q_i.

Though the problem is complex, kinetic gas theory[4] allows us to assume for the velocity vector u_i that the velocity of a gas along a solid wall is equal to the velocity of the solid wall, a condition of no slip (relative velocity of the fluid at the wall being zero). Also, we may let the temperature of the liquid T at the wall equal the temperature of the wall (no temperature drop at the wall). These conditions are not attained at low densities; however, such a case does not apply to the problem at hand.

4) The case of several components: In the case where the fluid comprises several components and the possibility for disappearance or creation of one of these (sink or source) exists, for instance through chemical reaction, the development of equations becomes more complex. By the same token homogeneity is altered when large temperature changes occur, brought on by the effect of thermal diffusion, which may differ according to the diverse constituents of the mixture as discussed later in this

paper. In this case, for example, the continuity equation takes the form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho V_i) = - \Gamma \tag{13}$$

with $\rho V_i = \rho^1 u_i^1 + \rho^2 u_i^2 + \cdots + \rho^j u_i^j$ (14)

in the case of j constituents, and $\Gamma = \Gamma^1 + \cdots + \Gamma^j$, Γ^j representing the change per unit volume of the j^{th} constituent.

Conditions of Similarity

It is said that two problems in gas dynamics are similar when the equations which govern them are the same except for the constant coefficients.[5] This means that in expressing the values by dimensionless numbers, the equations of the two problems are identical.

Following the different scales, symbols with indices are thus dimensionless

θ	of time	$t = \theta t'$
T_∞	of temperature	$T = T_\infty T'$
χ	of exterior force	$x_i = \chi\, x'_i$
L	of length	$x_i = Lx'_i$
V	of velocity	$u_i = Vu'_i$
ρ_∞	of specific weight	$\rho = \rho_\infty \rho'$
e_∞	of internal energy	$e = e_\infty e'$
p_∞	of pressure	$p = p_\infty p'$
τ_∞	of internal tension	$\tau_{ij} = \tau_\infty \tau'_{ij}$
q_∞	of heat flow	$q_i = q_\infty q'$
Q_∞	of heat quantity	$Q = Q_\infty Q'$

The definitions of τ_{ij}, q_i, Q_∞ permit writing

$$\tau'_{ij} = \frac{\mu}{\mu_\infty} \left(\frac{\partial u'_i}{\partial x'_i} + \frac{\partial u'_j}{\partial x'_i} \right) + \left(\frac{\mu'}{\mu'_\infty} - \frac{2}{3} \frac{\mu}{\mu_\infty} \right) \delta_{ij} \frac{\partial u'_\kappa}{\partial x'_\kappa} \tag{15}$$

therefore,

$$\tau_{\infty ij} = \frac{\mu_\infty V}{L} \tag{16}$$

$$q'_{ij} = - \frac{\kappa}{\kappa_\infty} \cdot \frac{\partial T'}{\partial x'_i}$$

therefore,

$$q_\infty = \kappa_\infty T_\infty / L \tag{17}$$

$$Q_\infty = Ve_\infty/L. \tag{18}$$

Consequently the various equations become:
continuity equation

$$\left(\frac{L}{V\theta}\right)\frac{\partial\rho'}{\partial t'} + \frac{\partial\rho' u'_i}{\partial x'_i} = 0$$

momentum equation

$$\left(\frac{L}{V\theta}\right)\frac{\partial u'_i}{\partial t'} + u'_j\frac{\partial u'_i}{\partial x'_j} = -\left(\frac{p_\infty}{\rho_\infty V^2}\right)\frac{1}{\rho'}\frac{\partial p'}{\partial x'_i} + \left(\frac{g\chi}{V^2}\right)x'_i + \left(\frac{\mu_\infty}{\rho_\infty VL}\right)\frac{1}{\rho'}\frac{\partial\tau'_{ij}}{\partial x'_i}$$

energy equation

$$\left(\frac{L}{\theta V}\right)\frac{\partial e'}{\partial t'} + u'_i\frac{\partial e'}{\partial x'_i} = Q' - \left(\frac{\kappa_\infty}{c_{p\infty}\mu_\infty}\right)\left(\frac{\mu_\infty}{\rho_\infty VL}\right)\frac{1}{\rho'}\frac{\partial q'_i}{\partial x'_i} - \left(\frac{p_\infty}{\rho_\infty u^2}\right)\left(\frac{V^2}{a^2}\right)\frac{p'}{\rho'}\frac{\partial' u'_i}{\partial x'_i} + \left(\frac{\mu_\infty}{\rho_\infty VL}\right)\left(\frac{V^2}{a^2}\right)\frac{\tau'_{ij}}{\rho'}\frac{\partial u'_j}{\partial x'_i}$$

heat flow equation

$$q'_i = -\frac{L}{(\kappa_\infty T_\infty)}\kappa\frac{T_\infty}{L}\frac{\partial T'}{\partial x'_i} \equiv -\frac{\kappa}{\kappa_\infty}\frac{\partial T'}{\partial x'_i} \text{ by definition.}$$

The dimensionless numbers or coefficients of the various preceding equation terms are:

$\frac{L}{V\theta}$	the reduced time coefficient
$\frac{V^2}{Lg}$	Froude number (exterior forces derived from a potential)
$\frac{\rho_\infty VL}{\mu_\infty}$	Reynolds number
$\frac{p_\infty}{\rho_\infty V^2}$	the reciprocal of the Mach number squared
$\frac{V^2}{a^2}$	the square of Machs number

$\frac{\mu_\infty c_{p\infty}}{\kappa_\infty}$	Prandtl number (a measure of the relative importance of the influence of conductivity and viscosity)
$\frac{c_{p\infty}T_\omega}{e_\infty}$	in general of the order of 1, representing approximately the relation between enthalpy and internal energy

The making of a model, whose behavior may be representative of the natural phenomenon implies then equality, in the model and in nature, of the following dimensionless numbers:

$$\frac{L}{u\theta}, \frac{u^2}{gX}, \frac{\rho_\infty uD}{\mu_\infty}, \frac{p_\infty}{\rho_\infty U^2}, \frac{\mu_\infty c_{p\infty}}{\kappa_\infty}, \frac{c_{p\infty}T_\infty}{e_\infty}$$

which can be accomplished only by maintaining full-scale.

Depending on the problem under study, certain dimensionless numbers may become equal to 1 (the case of the number $\frac{c_{p\infty}T_\infty}{e_\infty}$ within the general case), and permit similarity. The equations lose some of their generality, but the problem may be studied on models.

Thus, when temperatures and pressures are not too far removed from natural conditions, the gas may act as a perfect gas satisfying the equation of state:

$$p/\rho = RT$$

The specific heats at constant pressure and volume are related thus:

$$c_p = c_v + R$$

and thus with γ:

$$\gamma = c_p/c_v$$

The velocity of sound a is given by

$$a^2 = \gamma p/\rho = \gamma RT$$

internal energy by

$$e = \int_0^T c_v dT$$

It is found after some calculations that two flows will be identical if the reduced time, the Mach, Reynolds, and Froude numbers are the same in the flows. Besides, the properties of the fluids must be such that the Prandtl number, the ratio of γ

be the same, and that the ratios $c_p/c_{p\infty}$, κ/κ_∞, μ/μ_∞, μ'/μ'_∞ be functions of temperature only and that Q be proportional to u_{e_∞}/L or uT_∞/L.

The two boundary conditions concern velocity and temperature. The condition of no slip at the wall (zero relative velocity) is a homogeneous condition which does not introduce a new parameter of similarity. The surface temperature condition imposes heat flow between the solid body and the fluid, and thereby introduces a new condition.

If $(q_i)_s$ is the flux at the surface, in dimensionless values, this relation is written:

$$(q'_i)_s = (q_i)_s \frac{L}{\kappa_\infty T_\infty} = F[(x'_i)_s, t']$$

$(x'_i)_s$ is a dimensionless length on the solid wall. F is dimensionless by definition. $T'_s = T/T_\infty$ is fixed and therefore the preceding equation is equivalent to

$$\frac{(q'_i)_s}{T'_s - 1} = (q_i)_s \frac{L}{\kappa_\infty T_\infty} \frac{1}{(T_s/T_\infty - 1)} = \frac{(q_i)_s L}{\kappa_\infty(T_s - T_\infty)} \qquad (19)$$

This ratio is called the Nusselt number of heat transfer

$$N_u = N_u[(x'_i)_s, t']$$

For example, for a viscous fluid such as a perfect gas in transient (non-steady state) conditions, with an increase of Q for each unit of mass and under the influence of gravity, the conditions of similarity require the equality of the following parameters.

Mach, Reynolds, Froude, and Prandtl numbers and reduced time,
ratios γ, $c_p/c_{p\infty}$, κ/κ_∞, μ/μ_∞, μ'/μ'_∞, function of T',
QL/UT_∞ function of $x'_i t'$
N_u function of $(x'_i)_s$, t'

In steady-state flow the reduced time parameter is of no importance.

When the influence of viscosity and heat conduction is small, the Reynolds, Prandtl, and Nusselt numbers and the ratios κ/κ_∞, μ/μ_∞, μ'/μ_∞ may be omitted.

When there is no field of exterior forces, F may be omitted.

Theoretical Results

The principal results pertaining to convection phenomena in liquids heated from below are mentioned in an article by S. Ostrach.[6] The primary theories are those by Lord Rayleigh, Jeffreys, Low, Pelley, and Southwell (see bibliography in reference 6) who studied the conditions at the initiation of convection, the stability of flow and the effect of turbulence. In particular, stability seems to depend only on *Ry*, the Rayleigh number, product of the Prandtl and Grashof numbers ($Ry = \beta g h^3 \Delta T / K V$) with

β volumetric coefficient ($1/T$ for gases)
h thickness of the layer
ΔT temperature difference
κ coefficient of heat transfer.

Most studies deal with convection between two plane surfaces at different temperatures which corresponds, for the problem which interests us, to the case of a stratified atmosphere with a cold front. They deal with the case of infinite surfaces with respect to the distance between the two layers of air of the Bénard cells while the flow which interests us is rather of the columnar type.

A very important study by Yih[7] concerns convection currents produced in an infinite medium by a point source of heat, a linear heat source, a source composed of two linear heat sources. This study provides, for the cases of laminar and turbulent flow, a picture of the velocity and density gradients, therefore, also the temperature.

Experiments with Models

Numerous model studies have been conducted, particularly on problems of heat transfer in nucleonics,[8] meteorology, and oceanography. A general characteristic of these studies is that they have been concerned with small-scale models of only several millimeters or centimeters in dimensions, so that their extrapolation to the actual phenomena which are of interest to us cannot be undertaken without some degree of reservation.[6, 7]

This latter consideration has led the National Hydraulics Laboratory to undertake new tests using larger scale models.

These are heated plates of 50 cm. and 100 cm. diameter.[9] The principal findings have not been subjected to theoretical interpretation.

The experimental setup had the following characteristics: the plate of 50 cm. diameter was made of aluminum 1 cm. thick, heated from below by electrical resistances, the combination of which made it possible to obtain heating loads of 3.10 KW, 5.30 KW, or 7.63 KW. Only the two lower values were used, because beyond them the aluminum plate suffered significant deformation. The plate was surrounded by sand, leveled to the same height as the plate to form a continuous plane between plate and sand. Thus perturbations due to the sharp edge of the plate were avoided, as well as drafts of warm air from underneath the plate, where the heaters were located.

The plate of 100 cm. diameter was made of steel 1 cm. thick, heated from below by electrical resistances which could be so combined to allow heating loads of 9.43 KW, 18.50 KW, 27.21 KW. For the reasons noted above, this plate was also surrounded by sand.

The measuring devices comprised a micromanometer set up and calibrated by the Laboratory for the measurement of pressure changes within 1/100 mm. of water. This apparatus provided a continuous record. For high temperatures (near the plate) and very low velocities, the measure of ascending velocities was accomplished by means of photography, where the convection currents were made visible by feathers. Temperatures were measured with a calibrated thermocouple.

The findings have been published in a report[8] and within the accuracy of the measurements, the temperature variations were similar to those indicated by the work of Yih.

Convection Resulting From Combustion

The problem which interests us deals with gas dynamics in connection with combustion. We will neglect particularly the questions on the rate of fire spread and on combustion stability which are more readily related to chemical kinetics. The question of detonations will not be included. In order to simplify calculations, the problem considered is unidimensional.

Calculations are made in two stages. The characteristics T, p, u of the flame are calculated, in particular at its limits. The convection currents created in the infinite fluid represented by air are calculated knowing the values for p, T, u at a boundary constituted by the flame.

Theoretical Study.[10–15]

With notations similar to those used in discussing convection resulting from a heat source, the three equations of the conservation of mass, momentum, and of energy, are written as for steady state in a flame.[15]

continuity equation

$$\rho u = m \tag{20}$$

momentum equation

$$p + \rho u^2 - \frac{4}{3}\mu\frac{du}{dx} = i \tag{21}$$

energy equation

$$m\left(c_pT + \frac{1}{2}u^2\right) - \frac{4}{3}\mu u\frac{du}{dx} - \kappa\frac{dT}{dx} - mq = E \tag{22}$$

A first experimental configuration consists of a system in which the solid fuels of the reaction are replaced by a combustible gas having the same combustion characteristics and whose output would depend on the chemical heat content per unit weight of the solid fuel.

A second experimental configuration is made up, in view of the various chemical compounds present, by giving the following definition to the equation parameters: the coefficients κ and μ are functions of temperature and of the composition of the mixture; the specific heat c_p is an average value for the mixture and varies with temperature and with the composition of the mixture; the average velocity u is the average velocity of mass and if u_{jd} is the velocity of diffusion of the j^{th} constituent in the mixture, we can write: $u_j = u + u_{jd}$ and since $\Sigma_j\rho_ju_{jd} = 0$, the product $\rho_iu_j = \rho_ju + \rho_ju_{jd}$ is called the mass flow of the j^{th} constituent.

Besides the above equations it is equally necessary to know the equation of state of the mixture, the laws of diffusion between the components, the laws of species production and disappearance by chemical reactions, and the amount of heat released by chemical reactions.

These equations are the general equations of flames in a steady state. The system of three equations contains three unknown quantities u, p, T and can therefore be solved. $u(x)$, $p(x)$, $T(x)$ are then determined. A system of more complicated equations could take account of the behavior of the axial symmetry of the flame and give $u(x, r)$, $p(x, r)$, $T(x, r)$ (r being the radial coordinate).

The convection currents from this flame will be found by solving the systems of equations written in pairs and having as conditions for the boundaries: on the surface $S(x, r)$, boundary of the flame, the calculated values $u(x, r)$, $p(x, r)$, $T(x, r)$; on the ground, the assumption of no slip between gas and solid.

The first hypothesis shown assumes the admission of a certain flow of air entering at the base of the flame. It is proper to verify whether the flow rate as obtained from the solution of the equations above is equal to the actual flow rate. If it is not, the flow rate is obtained through successive approximations.

Conditions of Similarity

Besides the conditions indicated in convection resulting from a heat source and pertaining to the flow outside of the flame, it is understood that for two models to be similar, the equality of 9 dimensionless parameters must be preserved for the central part of the flame. These parameters are:

1	Reynolds number	$R_e = \rho_\infty VL/\mu_\infty$
2	Schmidt number	$S_c = \mu_\infty/\rho D_\infty$
3	Prandtl number	$P_r = \mu_\infty c_{p\infty}/\kappa_\infty$
4	Mach number	$M = \sqrt{\rho_\infty V^2/\gamma_\infty p_\infty}$
5	Froude number	$F = V^2/gL$
6	Damköhler first number	$D_I = LU_{i\infty}/V_\infty$
7	Damköhler third number	$D_{III} = \Delta h U_{i\infty} L/V_\infty c_{p\infty} T_\infty$
8		$\varphi = \frac{1}{2} V^2/(c_{p\infty}/\gamma_\infty) T_\infty$
9		$\gamma_\infty = c_{p\infty}/c_{v\infty}$

with

D coefficient of diffusion

U_i reaction characteristic of the chemical species i

($U_i = \Gamma_i/\rho Y_i \quad Y_i$ mass of species i)

D_I represents the ratio of changes of i resulting from chemical reaction and from convection

D_{III} represents the ratio of temperature contributions by chemical reaction and by flow of enthalpy associated with convection.

In problems of low velocity where the chemical reagents are fixed, and in the absence of external forces, only parameters 1, 2, 3, 6, 7 must remain invariable (5 with external forces) in order to uphold the thermal, dynamic, and chemical similarities. If the complete chemical similarity of the reaction kinetics is maintained, the conditions at the boundaries of heat transmission will be satisfied (condition of Nusselt), except when a boundary wall plays an important role (in case of a solid combustible).

Completed Experiments

The National Hydraulics Laboratory has carried out two tests of this type with liquid combustible placed in pans of 1 and 5 m. diameter. The main purpose was to study a means of extinguishment with a new device. In the matter at hand, only measurements of pressure at the center of the pans were taken. A slightly reduced pressure was noted during the tests at the center of the second pan.[9]

Two tests were undertaken.[19] The first, conducted on April 13, 1955, had as a main purpose the incineration of 325 hectares (803 acres) of the waste land of Trensacq, 40 km. north of Mont-de-Marsan in the Landes Department in southwest France. This wasteland was covered with small bushes and gorse (thorn broom) of about 1 m. height. The temperature was 25°C and the wind was 5 to 8 m/sec. The fire was started by flamethrowers. The flames reached a height of 10 to 12 m. and the vertical smoke mushroom was little affected by the wind up to a height of 500 to 600 m.

The vegetation represented a weight of 1.7 kg/m² (0.34 lb/sq ft) and combustion time was about 35 minutes, corresponding to 2.63 M. T. (2.90 s. t.) of combustible per second, for the 5,500 M. T. (6,063 s. t.) of vegetation (3,250,000 x 1.7/1000). Assuming for combustion of vegetation the same air requirements as for combustion of wood [3.3 m³/kg (53 cu ft/lb)], this represents

$3 \times 2{,}630 = 8000$ m^3 (10,500 cu. yds.) of air per second. The air velocity has been estimated at 10 to 15 m/s about 100 meters from the fire.

Aerial observations supplied the following data. The height of the flames was 10 m.; the smoke column reached up to 2300 m. and became horizontal, the upper part being light (⅓ of the height) and the lower part being dark (⅔ of the height). The presence of a cold front in the upper reaches gave the smoke column a mushroom appearance and the smoke on the outside was brought down to the ground because of a convection current of cellular nature.

A second experiment on November 16, 1955, failed because complete ignition was not possible.

Studies Planned By The Laboratory

The Program

Proposed studies are oriented in the following directions:

1) To state precisely and to expand the known theoretical facts in the problem:

through development of theoretical calculations for the case of a distributed heat source and for the case of combustion, bringing into play the air flow necessary for combustion;

through experimental study of similarity of heat transfer and of similarity in the phenomena generated by a heated plate and by burning fuel surfaces in pans, so that eventually studies may be limited to heated plates thereby rendering experimentation more convenient;

through precise determination of the laws governing changes in velocity, temperature, and pressure above the heated plates and burning pans of fuel, such that the equations describing the phenomena concerned may be verified experimentally, and, as a consequence, we may limit our physical measurements to those of pressure and temperature. The equations describing the phenomena may then permit us to calculate the variations in velocity directly;

through study with an apparatus capable of functioning at a high temperature.

2) To study with one or more of the experimental devices, the influence upon the space distribution of velocity, pressure,

and temperature by the following parameters—geometric dimensions of the fire source, nature of the fire source (heating rate), state of the atmosphere (the case of a cold front, characteristics of the atmosphere), and the number of fires per unit surface.

3) To determine the composition of combustion products (from pan fires).

4) To study the efficacy of various means of extinguishment (on pan fires).

5) To carry out full-scale tests in the Landes Department in southwest France.

The similarity of the phenomena being known, the results will permit the establishment of tables which will give as a function of the parameters which characterize the fires, the relationships governing distribution of velocity, temperature, and pressure.

Experimental Setup

1) The tests with heated plates will be carried out with plates 50 cm. and 100 cm. diameter, arranged in such a way that all disturbing drafts will be avoided. The maximum electrical power for heating these plates will be 10 and 30 KW, which will make it possible to attain a temperature of 600°C. For each plate and for each heating rate the gradients of temperature, pressure, and velocity will be determined.

2) Tests with liquid fuels (kerosene or alcohol) will be burned in two cylindrical vessels of small depth, whose diameters will be 1 m. and 5 m. The 1 m. pan fire will be burned inside a building to avoid disturbances from drafts, because of the small quantity of fuel involved. The 5 m. tank fire will be burned in the open air when atmospheric conditions are especially favorable. So far as suitable instrumentation permits, measurements will be made of temperature, pressure, and velocity gradient for this series of experiments.

Necessary Apparatus

1) Temperatures will be measured by means of a series of Iron-Constantan thermocouples, shielded to protect them from direct thermal radiation emanating from the heated plates. They will be located in various radial positions and heights which will

enable the integral and systematic investigation of the thermal field above the plate. In the case of pan fires, special thermocouples will be used because of the high temperatures to be measured. The thermoelectric potential generated within the couples will be determined from readings on a highly sensitive galvanometer or recorded on a Philips potentiometer. The temperature of the plates will be checked with thermocouples.

2) A battery of 4 micromanometers calibrated at the Laboratory will permit the exploration of the pressure field above the plates. These micromanometers are of the vibrating needle type, their sensitivity being better than 5/1000 mm. of water level. The recording of the measurements by the apparatus will be accomplished on Rapidgraph SEFRAM with two pens (two coupled recording galvanometers). The pressure variations above the electrically heated plates are extremely slight; on the other hand, they reach considerable magnitude and are easily measured above the burning fuels in pans. The pressure readings about a horizontal area would be made at various heights.

3) Measurement of velocities is difficult because of their small magnitude and because of the high temperature in which the measurements must be made. Gas velocities can be measured above the plates through movement of dispersed particles. Eider down can be used. Soap bubbles are useful for measurement of approach velocities. Anemometers of the hot wire type are being studied, as well as techniques for adapting them to the tests under consideration.

4) Visual tracing, through photographic processes, will be undertaken above the plates in order to determine the appearance of convection currents. These visual traces will be obtained by means of particles of very small density as compared to air (eider down, soap bubbles). Motion pictures (in color so as to get an image free from grain) and photographs taken at regular intervals (say every 15 seconds) will make possible the dynamic study of stages of combustion over a body of liquid fuel.

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Discussion

Mr. Martin: Was the area of ignition of the three kilometers square at once or was it spreading, that is, on the area three kilometers square, was the fire ignited essentially simultaneously?

Mr. Faure: Yes.

Mr. Martin: Could you give us a brief idea of how this was accomplished?

Mr. Faure: The fire was started with a series of flame throwers in different sections of the surface that was ignited.

Combustion lasted for about an hour and the complete ignition was accomplished in a quarter of an hour.

Mr. Weske: It was mentioned that in the center of this flame of the upsurging smoke, there was a depression. Was that caused simply by lack of oxygen, or was there any other reason? And I would like to ask another question. Was any spinning motion, any vortex motion, observed in this quantum that rises?

Dr. Emmons: Perhaps we had better have one at a time because we have some translation problems.

Mr. Faure: On both small- and large-scale models we have observed an increasing depression, a depression that increased proportionately to the magnitude to the scale models. This was due to lack of oxygen for the big fires, but for small fires we have observed a slight depression in any case. The depression grew according to the size of the fire.

Mr. Weske: The second question is connected with the first one. Meteorologists know that in the center region of a vortex in the atmosphere steady updrafts as well as downdrafts may occur. Therefore, it may be of interest to know whether a vortex developed in the plume. Corresponding motions have been analyzed theoretically by J. M. Burgers* and recently by R. D. Sullivan.†

Mr. Faure: In the center of the flame, only ascending currents were noticed and they looked the same as those shown on the slides yesterday.

Professor Taylor: I should like to ask whether the temperature of the air above the place where the fire was to be started was known before they started.

Mr. Faure: We have made a series of tests and I have mentioned only one. The combustion was made on the ground when the temperature reached 20 to 25 degrees. A little later when the ground temperature was of 5°C, we did not succeed in igniting the experimental zone.

Professor Taylor: What I really was asking was whether the temperature gradient was known.

Mr. Faure: The gradients of temperature were known only

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* BURGERS, J. M., "The Effect of Stretching of a Vortex Core," AFOSR T.N. 56–376, AD-95812 (1956).

† SULLIVAN, R. D., "A Two-Cell Solution of the Navier-Stokes Equation," *Journal Aero-Space Sciences* 26, 767–768 (1959).

at three points; on the ground, at 100 meters, and at 300 meters altitude, and they were made from an airplane.

Mr. Labes: I do not recall that the type of fuel used in the full-scale fire was mentioned.

Mr. Faure: On one hand we used shrubs, trees, with pine trees mixed in, pine trees which had been partially destroyed in the previous fire, the nonvoluntary fire.

Mr. Grumer: What was the fuel in the five meter pans?

Mr. Faure: Various fuels were used. Gasoline, petroleum ignited through gasoline; we had to lay five centimeters of petroleum over which we poured about one centimeter of gasoline. Kerosene being not able to be ignited directly, all the gasoline was first burned down until the petroleum started burning.

Mr. Grumer: I would like to ask whether depressions were observed in liquid tank fires as well as in fires of solid fuel.

Mr. Faure: In liquid fuels the depression started when all the liquid was ignited and it lasted to the end.

Professor Hottel: Have the data been published?

Mr. Faure: All the results have not been published.

Some Studies of Building Fires Using Models

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SUMMARY

This paper reviews the results of experiments to study the ignition, growth, duration, and temperatures of fires in single compartments. Two types of fires are distinguished; one with relatively low ventilation burning at a rate proportional to the air flow and the other with a relatively large window area burning at a rate which increases with the exposed surface area of the fuel. A tentative explanation of the different types of behavior is offered.

Some measurements of radiation from fires with large openings in the wall are quoted and an outline is given of a means of correlating the heights of flames from fires in enclosures.

Introduction

Many of the building regulations in the United Kingdom relate to fire prevention. Some are based on a sound appraisal of what happens in a fire while others are more speculative. Economic pressure demands that fire regulations be not too onerous and in the past it has sometimes been possible to meet fire prevention requirements in the course of satisfying other requirements such as those relating to the strength of the structure. But now, for example, the use of new lightweight materials makes this less likely, and satisfying the fire requirements becomes relatively more difficult. For these reasons, it is necessary to know more exactly than in the past what factors influence the behavior of building fires so that building regulations may be based on scientific information. To meet this need the factors affecting the severity and duration of fires are studied in various laboratories in the United Kingdom and in other countries.

To study fires experimentally one has to study mainly small fires (any other approach is costly in time, money, and staff); and, to obtain accurate information about a phenomenon as variable as fire, experiments must be performed and repeated under controlled conditions. Some of the results of laboratory experiments, particularly those related to the study of building fires by means of small-scale models, follow.

Ignition

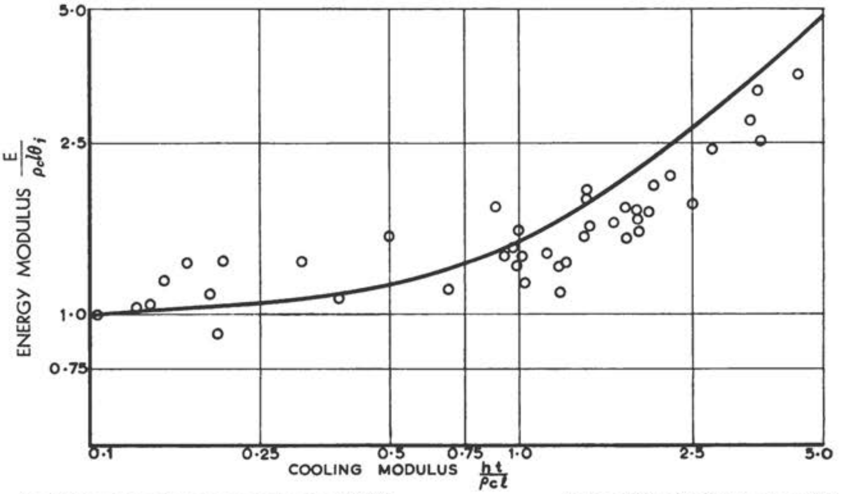
To reduce the risk of ignition, the conditions required for the ignition of various materials must be known. Ignition cannot always easily be prevented and measures must be taken to restrict the spread of fire to other materials. Since the spread of flame may be regarded as essentially a continuous ignition of material, the understanding of ignition, particularly of wood and other cellullosic materials, has an important place in fire research. Later in this paper ignition is used to illustrate some of the ideas involved in the use of small-scale experiments.

Ignition is a complex process depending on many other more fundamental processes, particularly heat exchange and reaction kinetics. For a wide range of conditions one can regard ignition as occurring when the material involved is raised to a certain temperature, called the "ignition temperature." Lawson and Simms[1] showed that the concept of a constant ignition temperature could be applied to the ignition by radiation of wood if the surface was heated to about 500°C in 1 to 20 seconds.

Recently Simms,[2] Martin and Lai,[3] and Sauer,[4,5] have been able to correlate the length of time for cellulosic materials of differing thermal properties and thickness to ignite spontaneously. Figure 1 shows Simms's results compared with a curve calculated from elementary heat transfer theory.

Very High or Very Low Rates of Heating

There are two regimes for cellulosic materials where the ignition temperature cannot be regarded as a constant for a material and where the chemical factors as well as the physical properties have to be considered.



θ—Ignition temperature above ambient = 525°C
E—Energy absorbed by material
t—Time of exposure
ρ—Density
c—Specific heat
l—Thickness of material
h—Surface cooling coefficient

Range of intensities 1–14 cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Range of thicknesses 0.02–0.065 cm
Range of times 1–20s

Figure 1. Ignition by radiation (thin cellulosic materials)

The first regime is the very rapid heating of materials. The external heating rapidly raises the surface to a high temperature but the penetration of heat is too small to produce sufficient decomposition products to cause ignition. This regime, in which the "ignition temperature" depends on the rate of heating, has little relevance to ordinary fires, but may be important in ignition by atomic explosions or by lightning.

The second regime is the very slow heating where in the limit no external heat is supplied once the material is above a relatively low "ignition temperature" and the material is self-heating by exothermic reaction to the point of ignition. Again the ignition temperature is not constant; it is related to the size of the material as well as to its chemical and physical properties. This type of ignition is in its essential features a thermal explosion and the well established theory of thermal explosion[6,7] can be applied.

The theory leads to the defining of a parameter

$$\delta = \frac{\rho Q f w_0^{\,n-1} r^2 E e^{-E/\mathbf{R}T_0}}{\mathbf{R} k T_0^2}$$

where E is the activation energy
Q is the heat of reaction per gram of total substance
f is the frequency factor
w_0 is the volumetric concentration of reactant causing ignition
T_0 is the absolute temperature
$\mathbf{R}$ is the universal gas constant
n is the order of reaction
r is the linear size of the material
k is the thermal conductivity
and ρ is the density.

The parameter δ is essentially a dimensionless heating rate and the critical condition for ignition or explosion to occur is that δ has a certain numerical value δ_c for a particular shape of material and boundary condition.

Contributions to the application of this thermal explosion theory have been made by several workers.[8-10] Although much of the interest in this field concerns the prediction of maximum sizes for safe storage, the study of self-heating enables one to obtain values of some of the rate constants for use in the study of the combustion of cellulosic materials.

One of the major differences between the two processes of slow self-heating and thermal explosion is that the heat of reaction in an explosion is very high and explosion occurs with only a little loss of reactant. This is not necessarily so for the slow self-ignition of cellulosic and similar materials and the effect is to increase the critical numerical value of the explosion (or ignition) parameter δ_c.

It can be shown[11] that for symmetrical heating the effect of reactant loss on δ_c is given approximately by

$$\delta_c(B) = \delta_c(\infty)\,[1 + 2.85\,(n/B)^{2/3}]$$

where

$$B = (\mathrm{E}/\mathbf{R}T_0^2)\,(Q/c)$$

and c is the specific heat.

The general formula is in good agreement with the theoretical numerical data obtained by Rice, Allen, and Campbell[12] for a first order reaction and gives twice the value for the correction to the value of δ_c that was given by Frank-Kamenetskii[13]. For wood fibre insulating board with an activation energy of 23 to 25,000 cal/g,[8–10] $c = 0.34$ and $Q \doteqdot 100$ cal/g,[10] and δ_c is about 40 per cent higher than if reactant loss is neglected. In these three theoretical analyses allowance is made indirectly for the spatial variation of temperature within the solid by an approximation in the differential equation but one expects the result to be satisfactory to a first approximation.

Ignition Experiments and The Effect of Scale

Clearly from the definition of δ and the fact that ignition just occurs when δ has a fixed numerical value, one can see that scale influences the self-heating behavior; the larger the value of r, the lower the "ignition temperature" T_0. The use of a theoretical analysis enables considerable progress to be made in the study of the self-heating problem by means of small-scale experiments. Since the derivation of this theory assumes certain simplifications in the reaction kinetics, the use of small-scale experiments to predict large-scale phenomena must be made with caution. Likewise, in the ignition of materials by radiation there are certain secondary effects associated with scale.[2] These are thought to arise from changes in the distribution of temperature and concentration in the plume of volatiles as the size of irradiated area changes and mainly affects the threshold conditions for ignition with very small specimens. If ignition occurs readily the time taken to ignite is not greatly affected.

Fires In Single Compartments

In a fire in a compartment, the relative importance of the physical and chemical processes which occur is less well established. This is especially true of the early growth when a fire is increasing in size from that of the initial outbreak to the involvement of the whole compartment. The behavior of the fire once it has filled the compartment is easier to study because it is less transient.

A description of some of the work undertaken by the Joint Fire Research Organization to study the behavior of fires in rooms follows. Experiments have been made over a range of scale so that an attempt can be made to correlate the behavior on different scales. As it becomes possible to define the main rate-controlling processes (these may well differ for different aspects of the behaviour) so it is hoped it will become possible to design models from basic principles to simulate actual building fires.

Growth to "Flash-Over" in a Room

A small fire in a room behaves as if it were in the open but generally spreads and becomes larger and, except in the case of rooms having relatively large windows and then only if these are open, its further growth will be affected by its being in an enclosure. This is because the enclosure tends to conserve heat and to restrict air supply.

The fire eventually involves the whole compartment—a process which may become very rapid towards the climax. This has been called the "flash-over". The amount of fuel consumed in the growth is generally a relatively small part of the total fuel content and in this period there is not much damage (except by smoke) to neighboring compartments. This period of the fire is very important from two points of view. Firstly, there is the risk to life because at "flash-over" the atmosphere in neighboring compartments becomes lethal and secondly, the quicker the growth of fire, the larger the fire is when the fire brigade arrives.

Large and small-scale experiments have been made to study this growth, particularly the effect of different types of wall linings. Hird and Fischl[14] showed that the course of development of a fire, in a furnished room with a wooden floor, with either flammable or incombustible wall linings, could be reproduced in model rooms of about one-tenth the linear size of the original.

Figure 2 shows the temperature-time curves obtained in two pairs of experiments on different scales. Despite some considerable variations in temperature between the model and the original, the patterns of growth in relation to time are very similar. These results are encouraging for future work in this field but a fire which is both increasing in intensity and spreading is a complex problem owing to the effects of the disposition of furniture and the physical processes involved. This work is still in its early stages.

Nevertheless, these experiments have already shown that the "surface spread of flame" test[15] leads to results where undue weight may be given to certain differences between the more flammable linings and insufficient weight to differences between the better wall linings. Because of this, a new test has been developed by Hird and Karas[16] and Bigmore [17] to assess the contribution of linings to the growth of fire to "flash-over".

Clearly, one of the important elements in a study of fire spread, be it inside an enclosure or on an external surface, is the height reached by the flames, because this determines the rate of preheating ahead of the flame and therefore the rate of flame spread. It also determines the radiation transfer to nearby materials. Some experiments are being made to discover how flame height varies for different conditions. These are described later.

Behavior after "Flash-Over"

About the time of "flash-over" flames emerge from the windows showing that not enough air is reaching the fire to burn all the gaseous fuel produced by decomposition. The fire then burns at an approximately steady rate until the production of volatiles falls and flames no longer emerge from the windows. A typical temperature-time record of a small-scale fire obtained by Hird and Wraight[18] is shown in Figure 3. Point (A) is the "flash-over". After "flash-over" the temperature continues to rise to a maximum at (B). In the final period, after (B), when the temperature falls because the production of gaseous fuel ceases, some of the residual charcoal may burn to ash.

Construction should be such that it is able to contain the fire and so prevent spread of fire to other compartments. It is necessary to predict the duration and temperature of fires for a wide range of conditions to determine the requirements for various structures and under what conditions they should be tested.

Immediate considerations are the rate of burning and temperature and what affects these quantities. There are many variables involved. Two of the more important, if not the most important, are the ventilation (air flow) and the total quantity and disposition of combustible material (fire load).

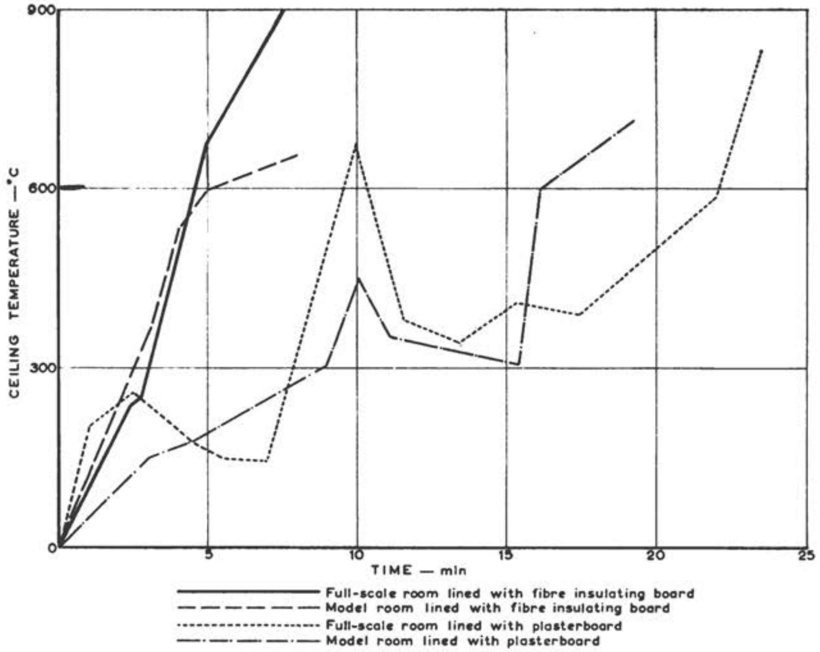


Figure 2. Comparative temperature records of full-scale and model rooms

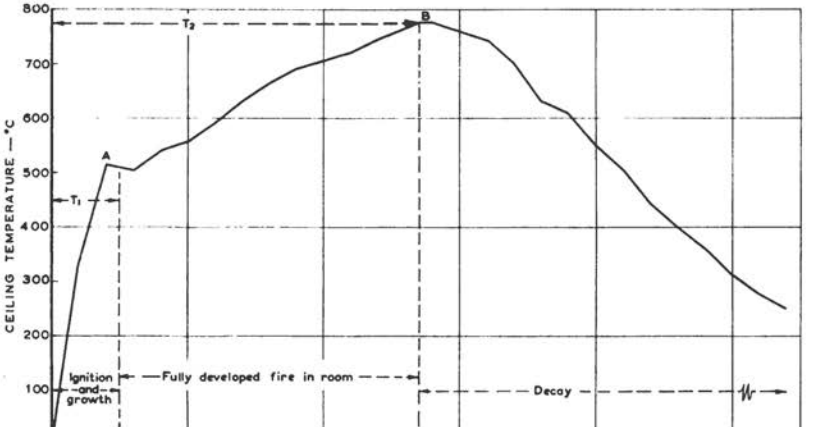


Figure 3. Temperature-time record for a typical fire (small scale)

Effects of Ventilation

The amount of air which enters an enclosure with one opening (the enclosure considered to be at a uniform temperature) has been shown by Fujita[19] to be approximately proportional to $A\sqrt{H}$ where A is the area and H the height of the opening. This proportionality is not very sensitive to variations in temperature if the temperature is over 600°C. The air flow depends in principle on the ratio of inlet flow of air to the rate of discharge of products of combustion but, since the rate of loss in weight of the fire, i.e. the mass flow of fuel, is of the order five times less (see below) than the mass air flow, the effect of small variations in this ratio may be disregarded.

Where there is considerable gaseous motion within the enclosure, the pressure differences tend to disappear because the accelerations in the flow occur within the enclosure rather than across the window opening, and as the window opening becomes larger and one obtains a rapidly moving flame zone which only partly fills the enclosure, the air flow may be expected to be determined by turbulent entrainment.

Simms and Hinkley have recently measured the rate of loss of weight of cribs of wood in small-scale enclosures having an opening at low level and sometimes also an opening in the roof. The total air flow was calculated from measured values of the inlet air velocity. The rate of burning was relatively constant over a long period and this value is shown plotted against the total air flow in Figure 4. It can be seen that the rate of burning depends markedly on the air flow at low air flows but at high air flows it reaches an almost constant value.

Fires with Low Ventilation—Rate of Burning and Duration

In compartments with low ventilation such as are common in traditional buildings, the duration of the middle period $T_2 - T_1$ (Figure 3) is generally long compared with the time to "flash-over". Figure 5 shows the relationship found by Simms, Hird, and Wraight[18] in small-scale experiments, between the time T_2 and the fire load. The time T_1 was approximately constant and was small compared with T_2 so that for a given degree of ventilation there was a mean rate of burning which was largely independent of the fire load.

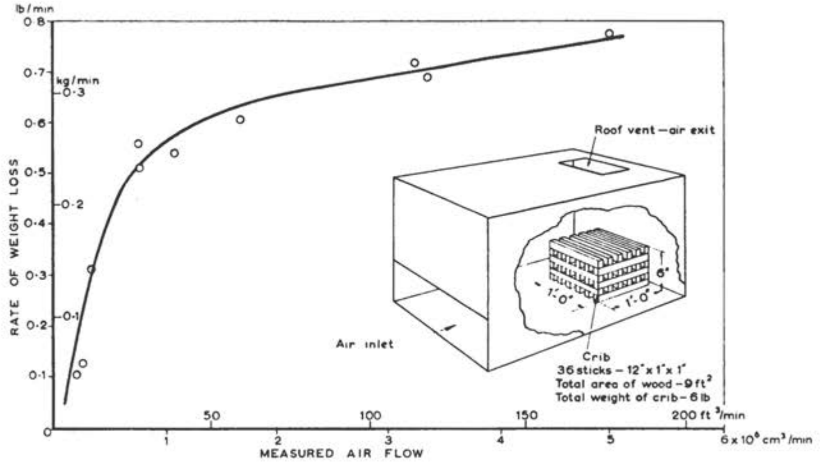


Figure 4. The Effect of air flow on burning rate

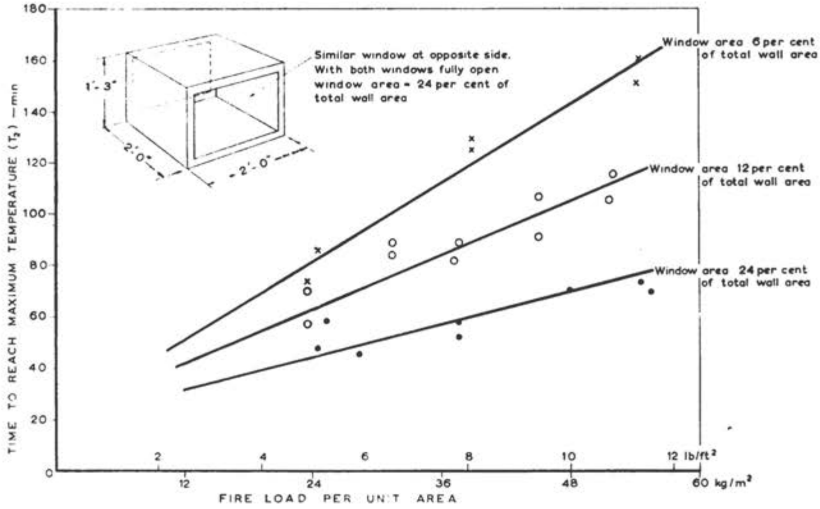
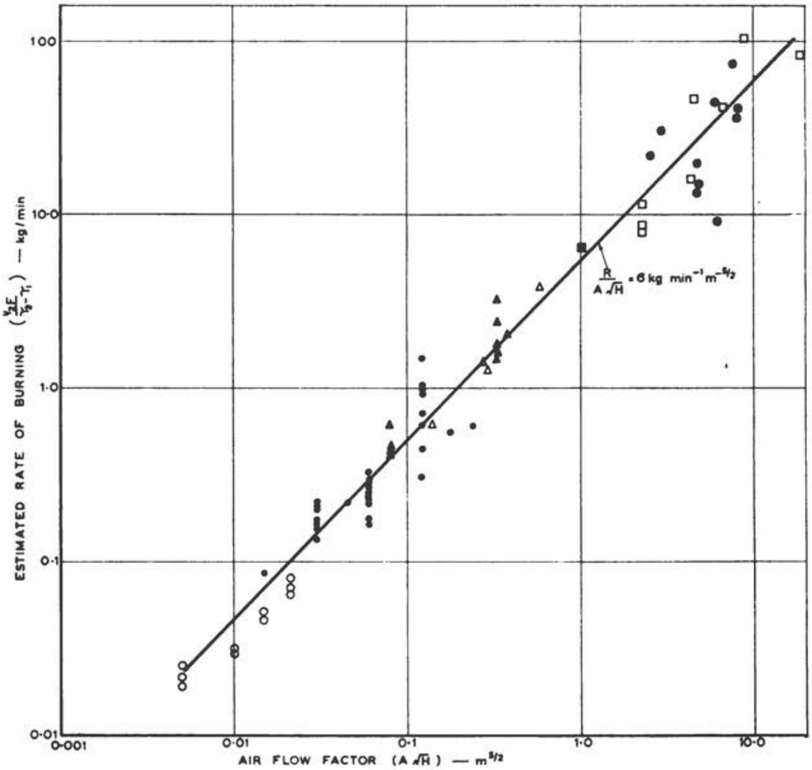


Figure 5. The Duration of small-scale fires (restricted air flow)

Ptchelintzev[20] has also reported experiments showing the effects of ventilation and fire load on rate of burning. Figure 6 shows the rate of burning as a function of $A\sqrt{H}$ for Kawagoe's experiments[21] over a range of scale together with those of Hird



KEY	FLOOR AREA ft²	m²	SYMBOL
Hird and Wraight	1 4 9	0·093 0·37 0·83	○ • ▲
Hird and Fischl	34	3·2	■
Kawagoe	11 100approx	1·0 9approx	△ □
Ashton & Malhotra	100	9	●

Figure 6. Burning rate and air flow

and Wraight.[18] Some recent experimental results obtained by Ashton and Malhotra[22] for full-scale rooms were also plotted on the same figure.

Because in the experiments of Hird and Wraight and of Ashton and Malhotra no direct measurements were made of the loss of weight, a mean burning rate has been calculated from $\frac{\frac{1}{2}F}{T_2 - T_1}$ where F is the total weight of combustible and the fraction ½ has been assumed for the fraction of wood, producing a charred residue, burning largely as charcoal. However, for the purpose of comparing data over a wide range of scale this assumption is not critical.

Some of the scatter in the central part of the graph is due to the inclusion of results for fires in which the windows were large in relation to the wall area, where the behavior of the fire is dependent on the amount and surface area of fire load rather than on the value of $A\sqrt{H}$.

The results given in Figure 6 show that for compartments of approximately similar shape but varying in volume from about 0.2 to 300 m^3 the rate of burning R for small traditional windows, in relation to the value of $A\sqrt{H}$ does not show any marked scale effect. The mean value of the ratio between R and $A\sqrt{H}$ is about 6 kg min^{-1} $m^{-5/2}$ corresponding to an over-all air/fuel ratio of about 5.

The data in Figure 6 include some results for wood ½ inch as well as 1 inch thick. The greater surface area appears to give some, though not a proportional, increase in burning rates but, generally speaking, the rate of burning is largely independent of the fire load. These results show that for fixed low ventilation conditions the duration of the fire is proportional to the total fire load, not the fire load per unit area. The large-scale tests included in the data shown in Figure 6 are only full-scale in terms of a domestic room, but there is no obvious reason why the same relationship between the rate of burning and air flow should not apply for much larger fires, i.e. a single-story factory.

It is interesting to consider the relationship between the duration of a fire and area for such a building. For a given type of occupancy one may assume that the total fire load is approximately proportional to the total floor area A_{fl} and that the air flow for a given distribution of windows in the walls will be proportional to the perimeter, i.e. to $\sqrt{A_{fl}}$, for similarly shaped buildings. The duration of the fire will therefore be proportional to the ratio of these, i.e. to $\sqrt{A_{fl}}$, for a given shape. It is interesting to note that the time taken to control large fires by the fire brigade tends to follow the same law though there are other reasons in addition to the above why this should be so.[23]

Fires with Low Ventilation—Temperature

As the absolute value of $A\sqrt{H}$ is increased, the rate of burning increases and even when this is relatively the same in terms of floor area for fires of different scale, higher temperatures are obtained on the larger scale. Hird and Wraight's[18] results are shown in Figure 7. Results showing the same trend have been attained in several full-scale tests made by Kawagoe.[21] There is, however, a systematic difference between the two sets of data, possibly due to different positions for the thermocouples.

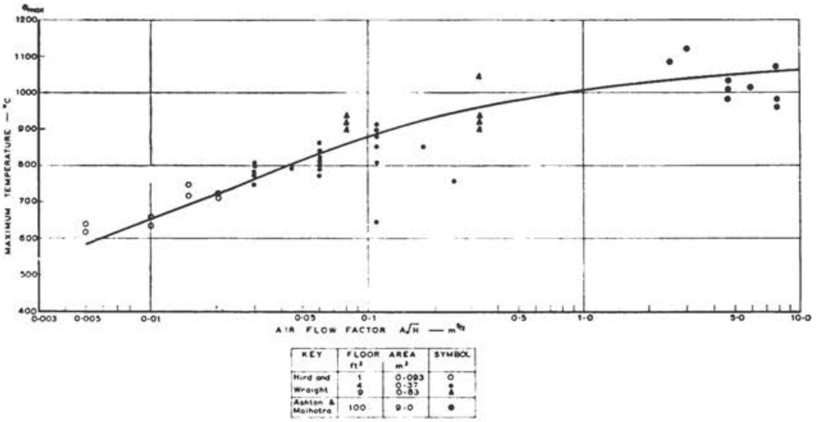


Figure 7. Maximum ceiling temperatures in room fires

The temperatures referred to are mean values during the period of rapid burning. The temperature is not constant but rises during the period AB—i.e. from T_1 to T_2 (Figure 3) in a way which depends mainly on the cooling effect of the walls. As the walls become hotter, less heat is lost to the walls and the mean gas temperature also rises. It is possible to calculate the mean gas temperature and its variation with time from the rate of burning if known.[24]

Well-Ventilated Fires—Rate of Burning

It has been shown above that, when the window opening becomes large in relation to the size of the room, the rate of burning no longer increases in proportion to $A\sqrt{H}$ but tends to a constant value for a given fire load. This limiting rate is approximately that typical for a fire in the open. The rate of burning for well-ventilated fires increases in proportion to the fire load, or more correctly, its surface area. Figure 8 gives some results obtained by Webster and Raftery[25] showing this relationship for cribs made of various numbers of 1-in. wood sticks spaced 3 in. apart, burning in cubical enclosures with one side open.

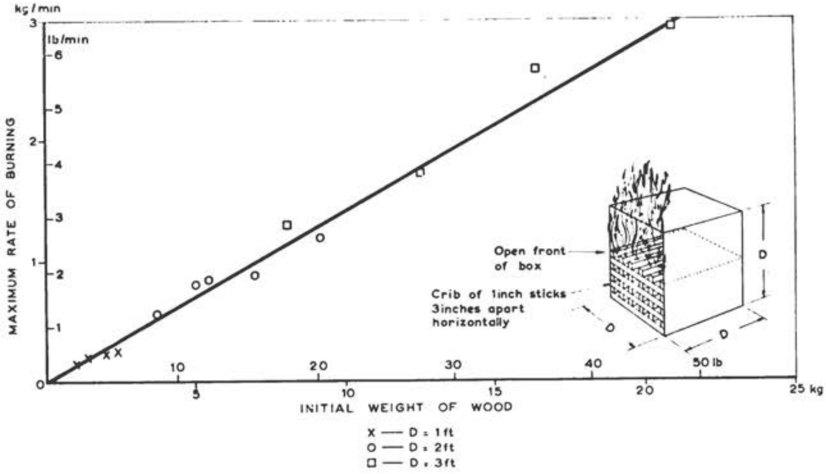


Figure 8. Rate of burning of well ventilated fire

Figure 8 gives data for tests in 1-, 2-, and 3-ft cubes and it is especially interesting to note that the same relationship holds between the rate of burning and fire load for all three sizes and hence there is no scale effect in this range. For wood of 1-in. section the rate of burning is relatively constant for a long period, which is partly due to the effect of the increasing temperature of the enclosure opposing the effect of the increased depth of char in reducing the rate of burning. With 2- and 3-in. wood, the rate of burning tends to decrease more markedly with time after an initial maximum rate has been reached. However, for this range of thickness and the relatively large spacing between the sticks that has been used in this work, the maximum burning rate is nearly proportional to the area of wood exposed.

Well-Ventilated Fires—Radiating Temperature

For the fires in cubes, Webster and Raftery[25] measured the radiation from the open side. The results are shown in Figure 9 where it can be seen that all the data have been correlated by reference to the rate of burning per unit area in the range of experiments so far made. Since the floor and window areas were the same and since the burning rate per unit area is almost proportional to the fire load per unit area, it is necessary to perform experiments with differently shaped enclosures before discussing their interpretation.

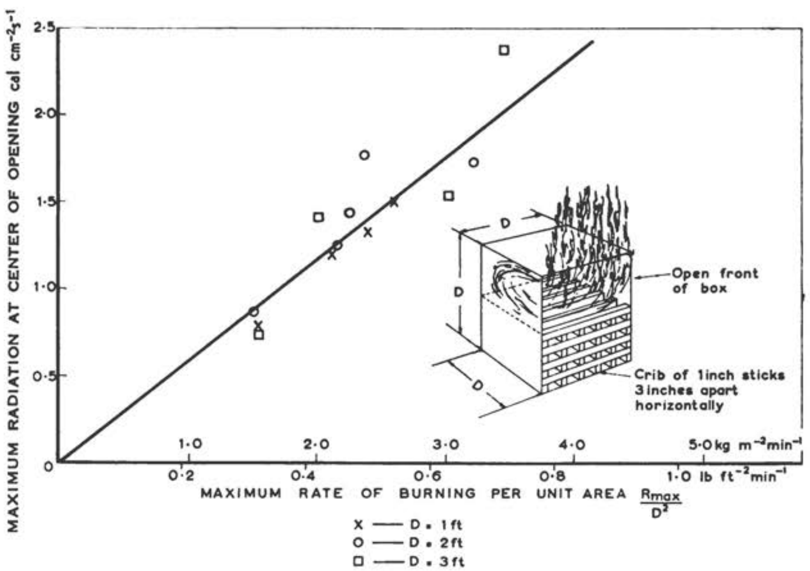


Figure 9. Radiation from opening

Application of Experimental Results

Fire Regulations for Fire Resistance

It has been found that for fires with low ventilation, the rate of burning is independent of the fire load and, for a given degree of ventilation, the duration is proportional to the total fire load, not the fire load per unit area. This has an important bearing on the present British fire grading of buildings[26]* where at present the fire resistance required of structural elements is based on an estimated fire load per unit area. However, if one fire lasts longer than another because of a smaller window, the temperature attained will be lower and this tends to make the severity of the exposure less than the increase in duration would lead one to expect at first sight. If the window openings are large, the rate of burning for a given thickness of fuel is proportional to the amount of fuel, and the duration tends to become independent of the amount of fuel. The radiation within the enclosure is dependent on the burning rate of the fuel. In both regimes the fire resistance required of a structure must be assessed in a way different from that assumed in present regulations.

Venting of Fires in Large Single-Story Buildings

Several fires in large undivided buildings in the United States and in the United Kingdom have raised interest in the practicability of venting the roofs of such buildings when fire breaks out. In the study of roof venting it is generally possible to make a model of the air flow, provided it is turbulent. The induced velocity of the air u is proportional to $\left(\frac{\theta L}{T_A + \theta}\right)^{1/2}$ where θ is the temperature above ambient in the enclosure, T_A the absolute ambient temperature and L the linear scale of the model.

There is also a relationship between velocity, temperature, and heat production Q which, neglecting heat loss to the walls, may be represented as:

$$u\theta L^2 \propto Q$$

so that to obtain equal temperatures Q must vary as $L^{5/2}$. Experiments on this basis are being made by the Joint Fire Research Organization.

In the special case of a fully developed fire it is possible to calculate the vent and curtain sizes required to ensure that all

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* In the report referred to by reference 26 the term fire load is defined as the amount of combustible material per unit area expressed in heat units. It is desirable to have a term for the total quantity of fuel or its calorific value and in this paper the term fire load is used for this total quantity and fire load per unit area for the other term.

low level openings in the buildings are inlets for cold air. Yokoi[27] and Diakov[28] have published methods of calculating these conditions. In the case of a small fire vented at an early stage in its growth it is possible to use the theory of plumes to arrive at the quantities and temperature of hot gases which reach the ceiling.

In addition to the flow problems one must take into account the effect of the changed ventilation conditions on the rate of heat production and a relationship of the kind shown in Figure 4 may be used.

Allowance must be made for the different geometry of the openings, because the air flow is a function of inlet and outlet areas in a way which cannot be described by the one parameter $A\sqrt{H}$. Because of the very different pattern of air flow in relation to fire load there may be a different constant of proportionality between air flow and burning rate at low air flow rates. Provided a localized fire is small enough not to be starved in any way, venting would not have a significant effect on the rate of burning.

The effect of venting on the rate of spread of flame over combustible surfaces is also of great importance and work on this aspect of the problem is now being started.

Relationship Between Burning Rate and Air Flow

Although it is not a constant, the amount of air required to burn unit mass of fuel must fall within certain limits if combustion is to take place at all, so that over a large range of fuel burning rates one would expect that the burning rate and air flow would increase almost, if not exactly, in proportion. For a fire in an enclosure, some of the burning takes place within the enclosure itself, utilizing air that enters the window and other openings while the remainder of the burning takes place outside the windows in flames which entrain additional air.

The fact that the burning rate and the air entering enclosures with small windows are found experimentally to be almost in direct proportion calls for further discussion. In general terms, the more air entering the enclosure, the higher the heat release within the enclosure and the higher the mean temperature of the gases, and the higher the heat transfer to the fuel. One would expect the gross burning rate to rise with increased air flow.

A heat balance is not sufficient to predict both the temperature and the rate of burning for a range of fuel and air flow conditions since this can only predict temperatures once the rate of burning is known. Similarly, Fujita's formula[19] for burning rate contains experimentally determined or assumed quantities, viz. the degree of incomplete combustion and the excess air factor. A theory should be able to predict these quantities and be able to predict when flaming combustion prevails as opposed to destructive distillation, a process which does occur when the air flow is very small and which may culminate in either self extinction or "flash-over". The theory should be able to predict the relationship between burning rate and air flow over the whole range of air flow conditions.

To derive such a theory one must discuss in addition to a heat balance,

1) the factors (mainly temperature) affecting the decomposition rate of the fuel.

2) the chemical kinetics of the reaction. A simplified equation such as is often used in engineering combustion problems may probably be employed for these.

3) the mixing pattern of the gaseous flow so that the effect of changes in the position of the reaction zone on the heat transfer to the fuel can be discussed.

At present insufficient quantitative data are available to discuss these questions in necessary detail and what follows must be regarded as somewhat speculative. However, in discussing, even in general terms, the construction of a theory it may be possible to focus attention on weak and strong points and thereby more profitably direct future efforts.

In view of the complexity of the processes and the diverse nature of the heat losses—loss by radiation from the window, loss of heat by hot gases through the window, loss due to the heating of the interior of the wood and the walls—considerable approximations will have to be introduced and the heat balance written in a simple general form assuming that the fuel is in excess so that the flow of oxygen governs the heat output. For any fire where flames emerge from the openings this is a satisfactory assumption. Also it can be assumed that a mean temperature $\overline{T}_f$ and a mean heat transfer coefficient $\overline{h}$ can be defined for the enclosure so that

$$[(R + M)\overline{c} + \overline{h}A_w](\overline{T}_f - T_0) = 0.23MQ_0 \qquad (1)$$

where R is the rate of loss in weight of fuel
M is the rate of air flow
$\overline{c}$ is the mean specific heat of hot gases leaving the enclosure
T_0 is the ambient temperature
Q_0 is the heat produced per unit mass of oxygen
$\overline{h}$ is the mean heat transfer coefficient from the flames to the interior of the fuel and to outside the enclosure through the walls
and A_w is the effective surface area of walls, ceiling, and fuel.

Equation (1) can now be drawn as curves in Figure 10 for various values of $\frac{\overline{h}A_w}{\overline{c}M}$ and a fixed value of Q_0. For $R \ll M$, these curves approximate to straight lines. Because $\overline{h}$ depends on the thermal capacity of the walls it changes with time, becoming gradually less. The value of M for fires with small windows is determined mainly by the geometry of the window. For high temperatures it is insensitive to changes in temperature.

The effect of heat on the decomposition rate of wood may be represented by

$$R = A_f m'' \qquad (2)$$

where m'' is the mass rate of decomposition per unit area of wood and A_f is the effective surface area of wood.

It is assumed that the formation of volatiles from the solid material is thermally determined,[29] the reactions occurring in the gaseous phase being determined by the gaseous composition within the enclosure. m'' is therefore assumed to be a function of the heat transfer rate at a particular time and, for a given mean heat transfer coefficient, it will depend on the temperature $\overline{T}_f$ in the way shown in Figure 11. At high temperatures this curve might be expected to approximate to the fourth-power radiation law. m'' is of course dependent on time so the curve in Figure 11 also depends on the temperature-time history of the fire. For a given time of heating the curve in Figure 11 will typify the relationship between m'' and $\overline{T}_f$.

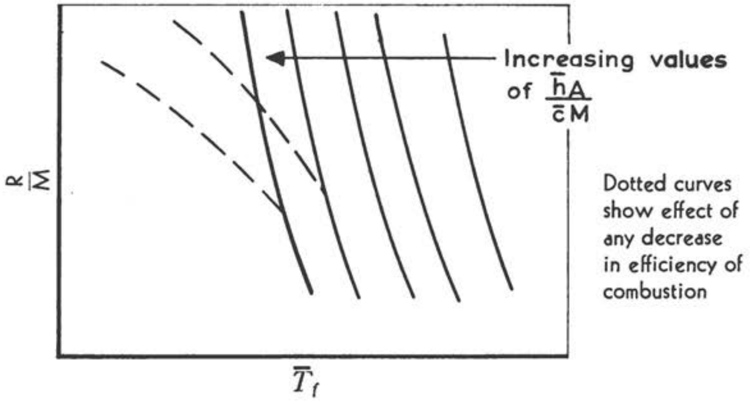

Figure 10. Diagrammatic Sketch of Heat Balance (α Curves)

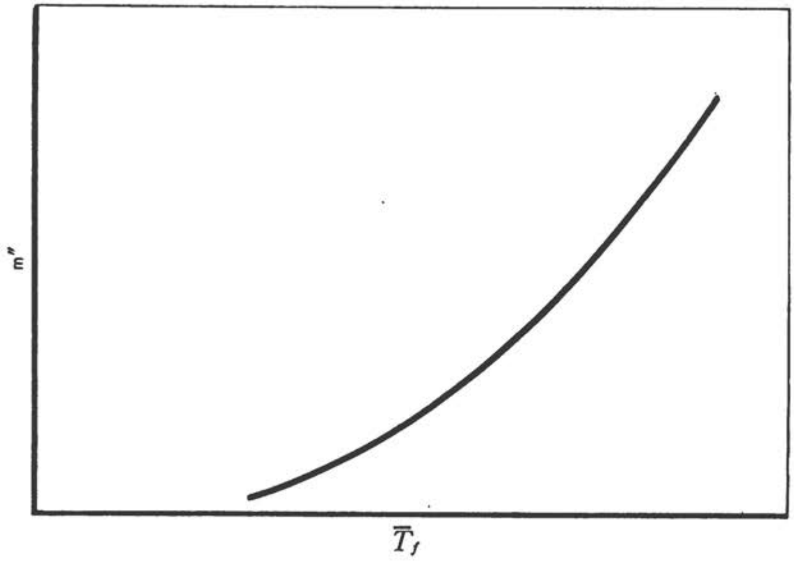

Figure 11. Diagrammatic Sketch of Decomposition Rate as Function of Temperature (β Curves)

The two relationships in equations (1) and (2) are superimposed in Figure 12 where the decomposition ordinate is proportional to A_f/M. Thus for any one value of $\frac{\bar{h}A_w}{\bar{c}M}$ there is a heat balance curve α and a decomposition curve β.

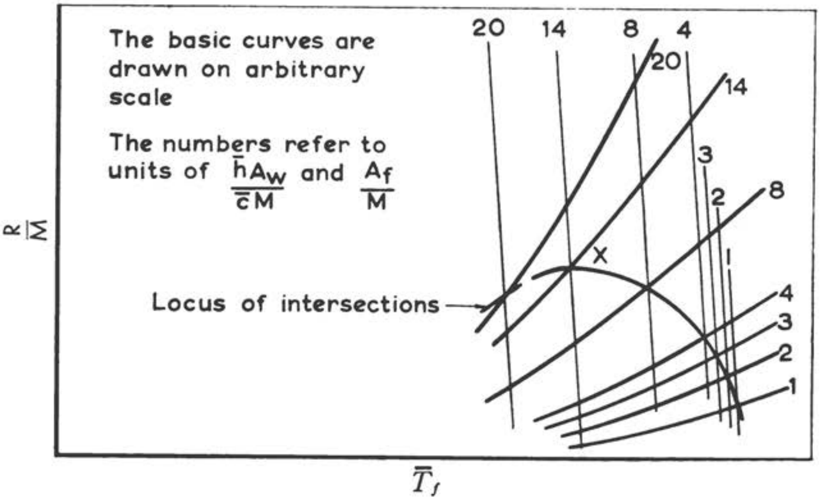

Figure 12. Determination of R and $\bar{T}_f$ (Diagrammatic)

The intersection X defines both $\bar{T}_f$ and R/M for given values of A_w, A_f, and M and in principle is the solution of the problem.

For large values of M, the ordinates of β are small and $\frac{\bar{h}A_w}{\bar{c}M}$ is small so the value of R/M at the intersection X is approximately proportional to A_f/M and R depends directly on A_f. This is the direct relationship between rate of burning and surface area of the fuel observed for large ventilation, which is not dependent on the air flow, and the heat transfer to the fuel is presumably the controlling factor.

As M decreases, the value of $\frac{\bar{h}A_w}{\bar{c}M}$ increases, i.e. wall loss becomes relatively more important in relation to the rate of heat production. The α curve moves to the left and the β curve moves upwards so that the equilibrium position moves upwards and towards the left in Figure 12, i.e. towards the lower temperatures. This is in accordance with the trend shown in Figure 7 for temperatures to decrease with a decrease in the amount of ventilation. The locus of the equilibria X is thus of the form shown in Figure 12.

The extent of the flattening of the curve would be determined by quantitative relationships between the various factors concerned but clearly the ratio R/M can only become relatively constant if there is a relatively large heat loss to the walls. It is of interest here that in the calculations of the heat loss for the one fire for which he has reported details, Sekine[24] found a 50 per cent loss.

There are minimum temperature conditions and oxygen/fuel concentrations at which flames can persist and, therefore, a minimum value of air flow for flaming. To discuss air flows lower than this value, requires the consideration of chemical kinetics because at very low air flows an equilibrium can be established in which a process of destructive distillation allows the fuel to be consumed at a very low rate and at a relatively low temperature. Any reduction in the efficiency of combustion decreases Q_0. This would tend to reduce the temperature for given values of R, M, and $\bar{h}A_w$ in equation (1) and so flatten the heat balance curves and make R/M even less variable with changes in air flow (Figure 10).

It has been shown how the ratio of heat loss to the wall to heat generated increases as the air flow decreases and how consequently the ratio R/M, at first inversely proportional to M so that R itself is independent of M, gradually becomes less dependent on M in accordance with the observed behaviour.

From the above arguments, increasing the fire load at fixed values of M and A_w would raise the β curve without affecting the α curve. The rate of burning would thus increase almost proportionally even at low air flows because the heat balance curves are only slightly inclined to the vertical unless combustion becomes increasingly inefficient at lower temperatures. The experimental data[18, 21] do not in general show the burning rate to depend on fire load, though there is some evidence in Hird and Wraight's experiments[18] that an increase in surface area produced some, though not a proportional, increase in burning rate. There is in general an apparent discrepancy between the experimental data and the simplified theory given above, but there are some possible reasons for this:

1) In both Hird and Wraight's and Kawagoe's experiments the density of packing for the various elements (sticks, planks, etc.) might have been too high for the effective exposed surface

area of fuel to increase much with the increases in the amount of fuel, so that there is doubt whether the experiments covered a large enough range of fuel surface area at any one level of ventilation to be conclusive.

2) A_w, the area determining the heat loss will, to some extent, increase with an increase in the surface area of fuel A_f inasmuch as some heat is lost from the gaseous phase to the solid fuel. Increasing the fire load surface tends to increase the term $\bar{h}A_w/\bar{c}M$. It has already been shown that the effect of increasing $\bar{h}A_w/\bar{c}M$ tends to offset the increase in R/M due to increasing the ordinate of the β curve.

3) Any inefficient combustion would tend to flatten the heat balance curve and restrict the upward movement of the equilibrium position X, i.e. would tend to make R/M less variable for different values of A_f.

4) The pattern of flow depends on the ratio of forced to free convection flow, i.e. on the ratio R/M. Increasing R/M would tend to move the reaction zone away from the fuel surface towards the window thereby reducing the total heat transfer to the fuel and lowering m'' for a given value of $\overline{T}_f$. This tends to counteract the effect of increasing the total surface area of fuel A_f.

Clearly, in view of the above discussion, more information is required on the effect of heat on the decomposition of wood at high temperatures, and further experiments in which the effective exposed area of fuel is varied systematically, are necessary. Nevertheless, the theory outlined above could be used as a basis for discussing the observed features of fires in compartments and provides a basis for a quantitative theory or a correlation in terms of dimensionless variables.

Hazards to Nearby Buildings

Radiation

Studies of the size of flames and the radiation from them and the radiation from the openings in the elevation of burning buildings are of great importance in assessing the hazard of a fire to a nearby building.

The radiation from the opening in a building has been mentioned earlier in connection with the levels of radiation within the cube, but the same intensity of radiation through the window opening can endanger neighbouring buildings if these are too near. In addition to this hazard, the flames themselves radiate heat onto other buildings and also onto the wall above the opening in the burning building itself.

Figure 13 shows the radiation intensity measured close to the flames and for this range of experimental conditions there is a correlation between the radiation intensity, and the rates of burning per unit floor (or window) area for the three sizes of cubes. Because the data refer only to cubes open on one side one cannot be specific as to floor, or window area. Because the radiometers were close to the flames, the changes in radiation intensity were mainly due to changes in emissivity, i.e. in flame thickness. Although no complete explanation is given of the reasons for this correlation, one must anticipate its possible breakdown for higher burning rates and large cubes because of the change in the relationship between emissivity and absolute flame thickness, i.e., for small flames these are proportional, for large flames emissivity is constant.

Size of Flame

In the experiments with wood fires in a cube[25] it was found that with an increase in the amount of fuel and a consequent increase in the total burning rate, the height z of the flames above the top of the opening also increased.

As a first attempt in correlating the results the ratio of the height z to the cube dimension D was plotted against the burning rate per unit area R/D^2. This is shown in Figure 14 where it can be seen that there is a slight but systematic trend for the flames from the small cubes to be relatively larger than from the large cubes. In explanation, the turbulent fuel jet discussed by Hawthorne, Weddel, and Hottel[30] may first be considered. They showed that the height of such jets is proportional to a linear dimension, namely the orifice size, and independent of the fuel flow velocity at the orifice. This was shown to be consistent with the view that air is entrained at a rate M' across the fuel-air interface proportional to the jet velocity and can be illustrated as follows:

$$M' \propto \epsilon \frac{1}{d} A$$

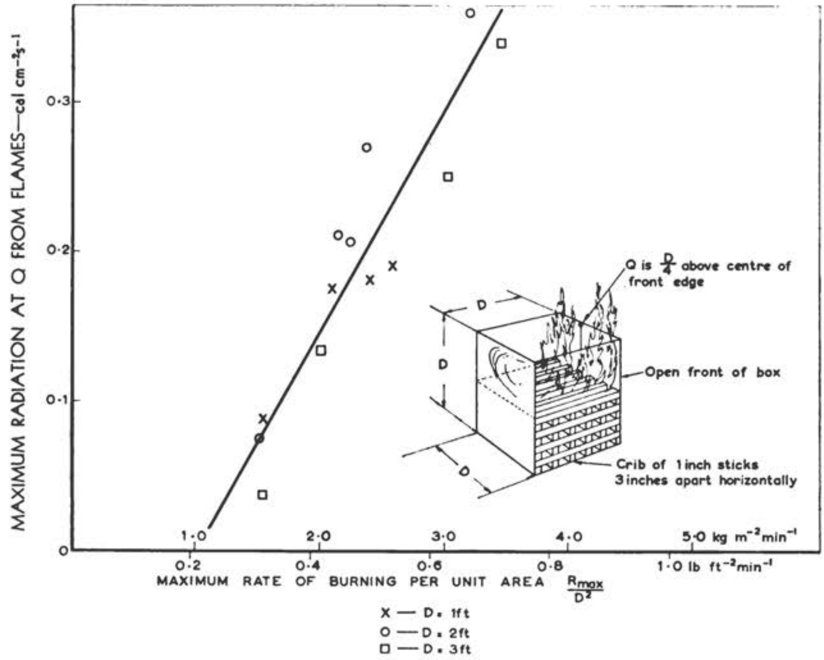

Figure 13. Flame radiation

where M' is the rate of air flow
A is area of interface
ϵ is the eddy diffusivity
and d is a characteristic length determining the concentration gradient.

Since for the turbulent flow ϵ may be written as $\epsilon \propto ud$ where u is the local velocity in the stream, it follows that the flow of air per unit area of interface is proportional to u. This relationship has been used by Morton, Taylor, and Turner[31] in their analysis of buoyant plumes without any other assumption about characteristic length. Now in a fuel jet the momentum at the orifice is large compared with the buoyancy forces, i.e. the Froude number $\frac{u^2}{2gz'}$, is large compared with 1, z' being the total flame height. The velocity at the orifice therefore determines the velocity u at all points along the jet. In flames from burning fuel this is not always so. The burning rate from these cribs was of

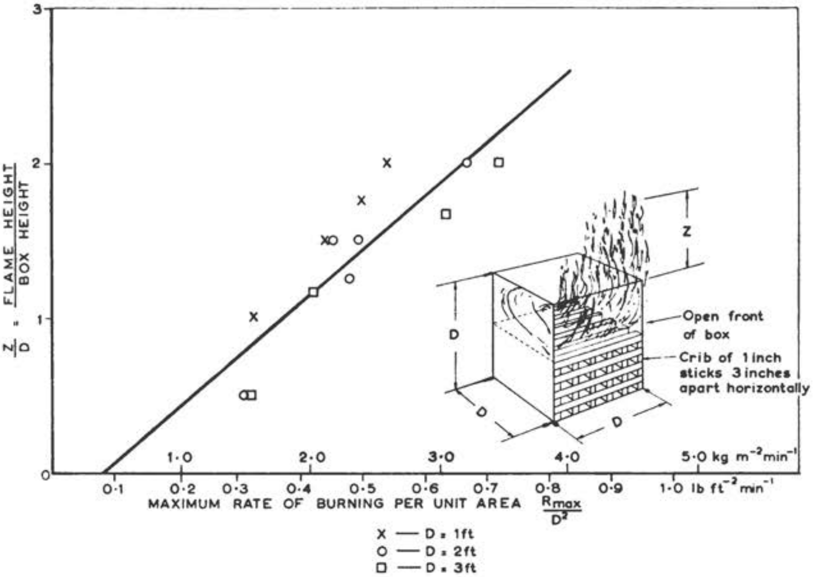

Figure 14. Correlation of flame height for fires in cubes with one open side

the order $\frac{1}{40}$ g cm^{-2} s^{-1}; so, for a gas density of 2g/l at room temperature and 0.4g/l at the flame temperature, the initial velocity is

$$u_0 \approx \frac{1}{40} \times \frac{1000}{0.4} \approx 60 \text{ cm/s}$$

which for flames of a height of the order 1 *m* gives a Froude number of $\frac{3600}{10^3 \times 10^2} \ll 1$.

The velocity determining the air entrainment is thus the velocity determined by buoyancy and it follows that

$$M' \propto \sqrt{z'} \times \text{area of fuel-air interface.}$$

This has the same form as the relationship between M and $A\sqrt{H}$ for an enclosure at uniform temperature but the constant of proportionality would not be the same.

In the case of a fire in an enclosure some combustion occurs within the enclosure and the remainder outside. The surface area of the external flame is equivalent to $2z(D + t)$ provided z

is not excessively large compared with D so that the surface may be considered rectilinear.

The mean velocity of the gases in the flame zone outside the enclosure is assumed therefore to be proportional to the mean value of $\sqrt{x}$ between $D < x < z + D$.

$$\text{Hence } \frac{1}{z}\ ((z + D)^{3/2} - D^{3/2})\ \ 2z(D + t) \propto M' \propto (R - R_0)$$

where R is the total rate of burning of fuel
R_0 is the part of fuel burning in the box
and t is the thickness of the flames as they emerge.

Since t is small compared with D the following simple correction suffices.

For the highest rates of burning when z is of order $2D$ visual observation shows $t \sim \frac{1}{3}\ D$ and it is reasonable to take $t \propto R$, i.e. approximately $t = \frac{z}{6}$.

Therefore

$$D^{1/2}\left(1 + \frac{z}{6D}\right)\left((1 + \frac{z}{D})^{3/2} - 1\right) \propto \frac{R}{D^2} - \frac{R_0}{D^2} \tag{3}$$

The data in Figure 14 have been replotted in Figure 15 in terms of the two sides of equation (3) and it can be seen that a straight line is obtained with no apparent systematic scatter. The intercept $\frac{R_0}{D^2}$ appears to be constant but there is no obvious reason for this. The highest value of the Reynolds number based on the cold gas velocity is of the order 2000 so that part of the flow within the box may be assumed to be laminar. On the other hand the velocities induced by buoyancy are of an order larger than those of the fuel leaving the crib so that turbulence will set in at some point in the box. In view of the extrapolation necessary to obtain $\frac{R_0}{D^2}$, the error in measuring visually, and the uncertainty about entrainment under the ceiling, it is not possible to explore the variation in R_0 for these results.

The flame lengths of fuel jets were shown by Hawthorne, Weddel, and Hottel[30] to depend markedly on the composition of the fuel. For the volatiles emitted from wood this is somewhat

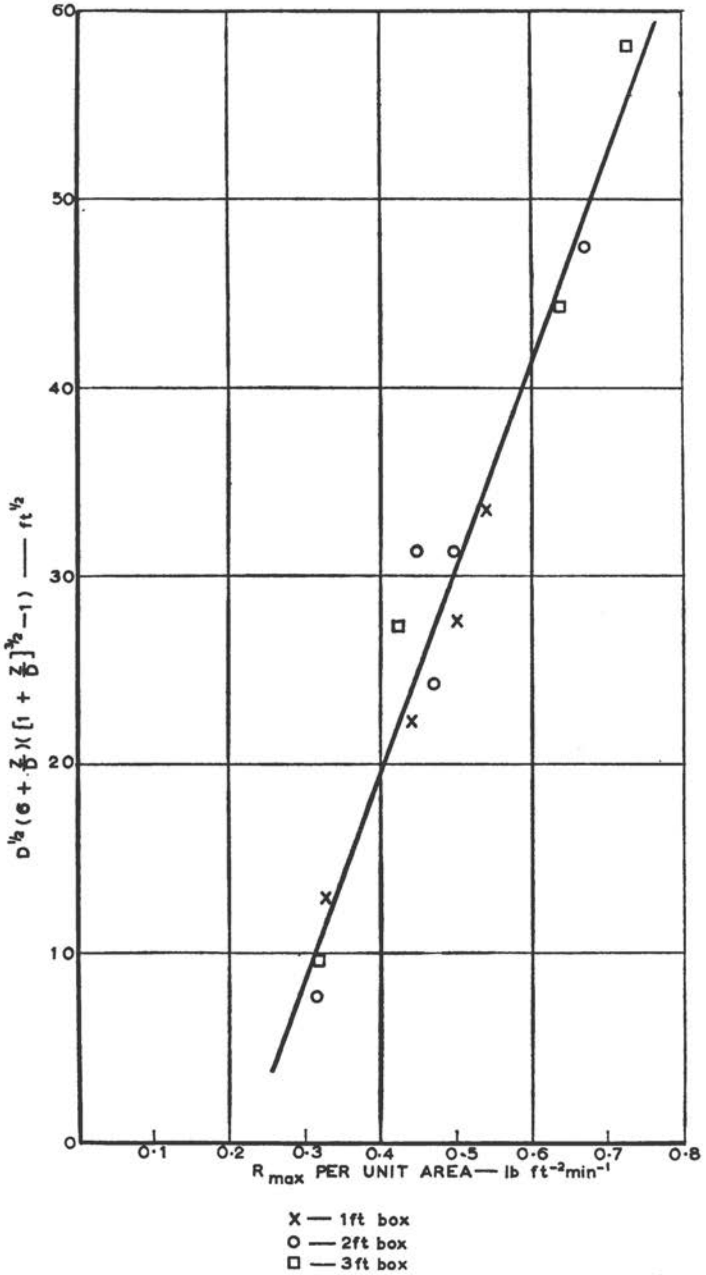

Figure 15. Improved correlation of flame height (same data as in fig. 14)

uncertain and consequently a quantitative theory has not been discussed here.

Discussion and Conclusion

Although the work on radiation and temperature from fires is incomplete so that it is not yet possible to relate actual fire behaviour to fire resistance requirements over the whole range of possible circumstances, it has been shown that the present basis of fire resistance requirements is deficient in some respects.

Experiments on the behaviour of fire in rooms both in the United Kingdom and in Japan have shown that, over a wide range of scale, fires in single compartments with relatively small windows burn at a rate proportional to the total air flow that is induced by the fire.

An outline of a tentative explanation for this behaviour has been given but as has already been pointed out further experimental work is required before this formulation can be regarded as a satisfactory approach. With large windows the air flow is not restricted by the window and the fires burn at a rate which does not depend on window size. The flames from these fires increase in size as the burning rate increases with increased fire load and a qualitative explanation of the observed scale effect has been given in terms of the entrainment of air by turbulence.

So far the main approach to building fires has been experimental and models have at all times had to be justified by comparison with large-scale tests. Even this use of models, limited though it is, has provided information which would have been very much more costly if obtained from full-scale tests alone. It is hoped that future progress will be hastened by the development of an understanding of the basic mechanisms involved in room fires. A start has been made and, though tentative, it explains some of the observed experimental features and justifies one's hopes that modeling can be used as a technique in the examination of building fires.

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Discussion

Mr. Barrows: Your experiments have rather a remarkable similarity to some of those used where forest fire fuels are involved. Did you determine the moisture content of the smaller sized wood materials?

Dr. Thomas: Yes, they were at a standard moisture condition but we have not investigated the effect of different moisture levels.

Professor Hottel: Where was this radiation measured? I am not clear in the case of the open box. You used the term "maximum radiation." Was that hard up against the front of the openings, so that the radiometer "saw" throughout 2π steradians?

Dr. Thomas: No, we measured a little distance away from the opening.

Professor Hottel: Then how is it a maximum?

Dr. Thomas: I am sorry, maximum in time. Then we made a correction for the configuration and quoted the value that one would get if the radiation were a black body of equal intensity all over a rectangle.

Professor Hottel: And then you spoke of a radiometer facing away from the flame. I do not visualize that set-up at all.

Dr. Thomas: If you envisage a cube facing you, flames would rise above the top of it. You would see the inside of the cube and you would also see flames rising above the roof or the top of the box, and the radiometer is placed above the cube so that it could "see" only the flames.

Professor Hottel: I am still not clear.

Dr. Thomas: The radiometer was facing toward the flames, but it would be facing toward you so that it would not "see" anything of the fire inside the enclosure at all.

Dr. Emmons: The radiometer was over the top of the box facing the open end?

Dr. Thomas: Yes.

Mr. Bond: Have Dr. Thomas's colleagues in England who are interested in building codes expressed any observations as to how they might use or apply some of this data, or what factors of building codes his work will throw light on?

Dr. Thomas: I have not discussed these recent ideas with them yet.

Mr. Bond: I think this does have some important value in building codes because there is a good deal of argument going on as to how large window openings in buildings ought to be. A number of sessions have been held under the auspices of the Building Research Advisory Board of the National Academy of Sciences—National Research Council. The first of these sessions dealt with the question of spandrel walls, because how much money you put into the wall surface is an economic matter.

These experiments in Britain and Japan and other places are valuable in emphasizing the importance of window openings and their relationship to the spread of fire between floors. Dr. Thomas mentioned the size of windows in homes. We are faced with a serious situation in this country with small windows located at heights from which no one can escape.

Dr. Thomas: This window opening affects the problem in two ways. The smaller the window, the longer the fire lasts and the lower is its temperature, but the smaller is the flame. We are looking at large windows because of the trend in modern design for large windows and for curtain walling, which may or may not stay in place for the duration of the fire. With large openings one may get flames which reach the floor above but, on the other hand, the duration of the fire is less than with small windows and one is faced with deciding whether the one factor or the other is the more important. We hope to discuss these questions in relation to building codes very shortly.

Mr. McGuire: Do I understand that the radiometer on the left-hand side of the drawing on the blackboard was quite close to the orifice so that it was looking only at the orifice and not at the whole assembly including the flames around the orifice?

Dr. Thomas: It did "see" some of the flame and we have not corrected it, but the configuration factor with respect to the flame is very much smaller than it is for the opening. The levels of radiation that were measured from the flame are something of the order of a tenth of those from the opening, so that while there should be a correction, we anticipate it to be relatively small.

Dr. Huff: I would appreciate information on the determination of the composition of the gases emitted when the air was severely restricted.

Dr. Thomas: We have not measured this, but these measurements have been made in Japan by Mr. Kawagoe and I think I am right in saying that they measured the ratio of carbon monoxide to carbon dioxide, but did not measure the unburned hydrocarbons. The measurements were made at a point fairly near where the flame emerges from under the window.

Dr. Avery: As I understand it, your slides showed that the maximum burning rate was proportional to the mass of material in the cribs. It would appear that the rate should be proportional to the surface area of the wood. Did you make any examination of that relationship?

Dr. Thomas: Yes, these cribs were almost exclusively of one thickness, and the area and weight are proportional, both being proportioned to the number of sticks in the crib. We have started to look at the difference with different thicknesses of wood and therefore with different areas for a given weight of wood. We have done a few experiments, and these show that the area is a factor.

There is a complication in a wood fire. One gets a period of growth so that the temperature and the heat transfer are increasing over a period of time in the early stages of the fire and to some extent, one might anticipate that these will act in an opposite direction to the reduction of burning rate due to the increase in char thickness which tends to insulate the wood. With one inch wood, we find a more or less constant rate of burning over approximately three quarters of the duration of the fire but with the thicker woods, the burning rates are less constant in time owing to the fact that these two effects are separated in time. However, the maximum rates of loss in weight are approximately proportional to the surface areas of wood.

Dr. Emmons: I have here an abstract of a paper "Duration of a Room Fire" by Mr. Kawagoe of the Building Research Institute, Ministry of Construction of Japan, which appears to discuss the problems raised by Dr. Thomas's paper.

Abstract—Duration of a Room Fire by K. Kawagoe

When the temperature of a room is uniform and higher than that of the outdoors, a neutral zone is found somewhere in the middle of the opening and the profile of pressure-height is shown in the inclined straight line. The inflowing velocity v' of air from a window into the room at the point h' below the neutral zone has been expressed by Bernoulli's theorem as follows:

$$v' = \sqrt{2gh' \frac{\rho_0 - \rho_1}{\rho_0}}$$

The outflow velocity v'' at the point h'' above the neutral zone has been:

$$v'' = \sqrt{2gh'' \frac{\rho_0 - \rho_1}{\rho_1}}$$

where ρ_0 is the density of open air, ρ_1 is that of the air inside the room.

If we denote the actual volume of air necessary for burning of 1 Kg of wood by $L\ m^3$, the volume of discharging gas which is produced by combustion of 1 Kg of wood by $G\ m^3$, the width of the opening by $B\ m$, the height from the top of the opening to neutral zone by $H''\ m$ and the height from the zone to the bottom of the opening by $H'\ m$, the following equation is obtained by continuity of fluid.

$$\frac{H''\ B\ V''_{\mathrm{mean}}}{H'\ B\ V'_{\mathrm{mean}}} = \frac{G}{L}\ i.e.\ \frac{H''}{H'} = \left\{\left(\frac{\rho_1}{\rho_0}\right)^{1/2}\frac{G}{L}\right\}^{2/3}$$

From this equation the height of neutral zone is calculated.

Denoting the coefficient of vena contracta of the opening by a, the volume air flow into the room per unit time is

$$a V'_{\mathrm{mean}} H'B$$

and the mass rate w of burning wood is

$$w = \frac{a V'_{\mathrm{mean}} H'B}{L}$$

From this, the fire duration, i.e. the period from when the temperature begins to rise to when it reaches its maximum is obtained, provided the total weight of fuels within the room is given.

From model room and full-scale fires, the following conclusions have been derived:

1) The temperature in a room is approximately considered to be uniform when combustion is active.

2) The profile of pressure-height in a room is regarded as a straight line.

3) The excess air factor is considered to be from 0.8 to 1.2.

4) The rate of burning is regarded constant when the window is small and there are a lot of fuels in the room.

The fire duration obtained by experiments agrees approximately with that computed from the theoretical rate of burning.

Dr. Emmons: Dr. Thomas, do you care to comment?

Dr. Thomas: I am rather embarrassed at commenting on Mr. Kawagoe's paper in his absence. I have seen this calculation before and I think it was first put forward by Dr. Fujita some time in the forties. The problem, as I see it, is not in the air flow calculation with which I agree, but in how one can make the assumptions that follow. I think they are probably true as regards small windows but experiments with large windows show that the assumptions break down; for large windows the flame zone is not necessarily uniform within the enclosure and the assumption of a uniform temperature is not satisfactory. One can only get a proportionality between burning rate and air flow into the window if there is no significant flame outside the window but the flame outside the room may be appreciable in size and some of the air for combustion is entrained into this flame and does not enter the room at all, so that one is faced with the problem of finding out why one can assume, for small windows, a proportionality between the rate of burning and the amount of air entering the window, or, in other words, why there is no significant flame outside the window for those conditions.

Upward Convection Current From A Burning Wooden House

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Introduction

The purpose of this study is, first, to find the approximate similarity law of temperature distribution along the central axis of upward currents from a circular and a rectangular heat source and, secondly, to calculate the temperature above a burning wooden house in a calm condition, based on this similarity law.

Temperature Distribution of Upward Current from a Circular Heat Source

Dimensional Analysis

Let us take the origin of coordinates at the center of the heat source, the z axis in the upward vertical direction and the r axis in the radial direction. Equations of momentum and heat balance are represented as follows:

$$\frac{d}{dz}\int_0^\infty \rho w^2 2\pi r dr = g \int_0^\infty \rho \frac{\Delta\theta}{\theta_0} 2\pi r dr \tag{1}$$

$$\int_0^\infty C_p \rho w (\Delta\theta) 2\pi r dr = Q \tag{2}$$

where w is the upward velocity, $\Delta\theta$ is the excess temperature at any point in the current, θ_0 is the absolute temperature of the surrounding air, C_p and ρ are the specific heat and density of the gas in the current, g is the acceleration due to gravity, and Q is a heat quantity conveyed by the current per unit time.

Although it is impossible to solve these equations directly, it is possible to know in what dimentional relation, the temperature $\Delta\theta$ and the upward velocity w at an arbitrary point (r, z) are related with the heat quantity Q. Suppose that the radius of heat source is r_0, and replace the coordinates r and z with the non-dimensional ones r/r_0 and z/r_0, then equations (1) and (2) are changed to equations (3) and (4).

$$\frac{d}{d(z/r_0)}\int_0^\infty\left(\frac{w}{r_0^{1/3}}\right)^2\left(\frac{r}{r_0}\right)d\left(\frac{r}{r_0}\right)=\int_0^\infty\left(\frac{\Delta\theta g\;{}^{1/3}}{\theta_0}\right)\left(\frac{r}{r_0}\right)d\left(\frac{r}{r_0}\right) \quad (3)$$

$$\int_0^\infty\left(\frac{w}{r_0^{1/3}}\right)\left(\frac{\Delta\theta g r_0^{1/3}}{\theta_0}\right)2\pi\left(\frac{r}{r_0}\right)d\left(\frac{r}{r_0}\right)=\frac{Qg}{C_p\rho\theta_0 r_0^2} \quad (4)$$

The solutions of the above equations have the following forms:

$$\frac{w}{r_0^{1/3}} = A^x f_1(r/r_0,\ z/r_0) \quad (5')$$

$$\frac{\Delta\theta g r_0^{1/3}}{\theta_0} = A^y f_2(r/r_0,\ z/r_0) \quad (6')$$

where f_1 and f_2 are certain functions which represent the velocity and temperature distributions of the current and A is

$$A = \frac{Qg}{C_p\rho\theta_0 r_0^2} \quad (7)$$

x and y are exponents to be determined later. If equations (5′) and (6′) are substituted in equations (3) and (4) and the exponents of A in both sides of equations are compared, then the following equations are derived:

$$\begin{cases} 2x = y, \\ x + y = 1 \end{cases}$$

In other words, $x = 1/3$ and $y = 2/3$. Therefore, equations (5′) and (6′) become:

$$\frac{w}{r_0^{1/3}} = A^{1/3} f_1\left(\frac{r}{r_0},\ \frac{z}{r_0}\right) \quad (5)$$

$$\frac{\Delta\theta g r_0^{1/3}}{\theta_0} = A^{2/3} f_2\left(\frac{r}{r_0},\ \frac{z}{r_0}\right) \quad (6)$$

In order to change the above equations to non-dimensional ones, let us use the following substitutions:

$$\overline{W} = \frac{w r_0^{1/3}}{\sqrt[3]{\dfrac{Qg}{C_p \rho \theta_0}}} \tag{8}$$

$$\Theta = \frac{\Delta\theta r_0^{5/3}}{\sqrt[3]{\dfrac{Q^2 \theta_0}{C_p^2 \rho^2 g}}} \tag{9}$$

Let us call these, the non-dimensional upward velocity and non-dimensional excess temperature and use them hereafter in expressing the results of experiment. We obtain

$$\overline{W} = f_1(r/r_0,\ z/r_0) \tag{10}$$

$$\Theta = f_2(r/r_0,\ z/r_0) \tag{11}$$

The forms of the functions f_1 and f_2 should be determined according to the results of experiments.

Experiment and Results

Two types of heat sources were employed. In the case of the first type, alcohol was burnt in seven circular vessels with radii of 3.3, 6, 9.9, 14.3, 18.75, 23.75, and 37.5 cm. A communicating tube connecting the vessel and the alcohol tank was employed so as to keep the surface of alcohol at a definite height. The type of heat source in this case is provisionally called "continuous heat source." In the second type, a great many little wicks of alcohol lamps were placed within a circle of a certain radius. This is provisionally called "discontinuous heat source." The method of using a solid heat source such as an electric heater was considered. However, this method was not employed because, according to this method, the greater part of the heat produced is lost by radiation and only a small amount of heat is given to the ascending current, so that the ascending current is weak and is liable to be disturbed by a faint accidental breeze in the room. Also, the thermocouple, under direct influence of the radiation of the heat source, may indicate a temperature considerably different from that of the ascending air. We took the gas temperature with bare chromel-alumel or copper-constantan thermocouples connected to a slow-moving oscillograph. The average value for about 10 minutes was obtained by observing the record on the oscillograph with the eye, and it was considered the temperature of that point. Figure 1 indicates the horizontal distributions of temperature of the upward current from a continuous heat source of 9.9 cm. in radius and a discontinuous heat source of 20 cm. in radius. They are expressed in a non-dimensional coordinate system. From this figure, we can recognize the following two facts:

1) The horizontal temperature distributions at any height in the upward currents from the circular heat sources of various radii can be represented by one curve in these non-dimensional coordinates.

2) There are two kinds of domains as to the horizontal temperature distribution. In the domain nearer to the heat source, ($z/r_0 < 2.5$) the horizontal distribution of the temperature takes the shape of a plateau and the hot current does not spread as widely in a horizontal direction as it rises, whereas in

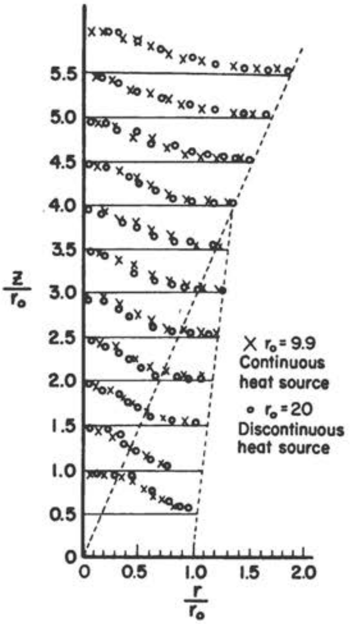

Figure 1. Horizontal distributions of temperature above circular heat source

the domain farther from the heat source ($z/r_o > 2.5$), the horizontal temperature distribution is like the one of the upward current from a point heat source and the hot current spreads widely as if it started from a point heat source placed at the center of the circular one.

Figure 2 indicates the vertical distributions of temperature of the upward current from the circular heat sources of various radii. In this figure, coordinates are represented by non-dimensional ones; instead of height z from the origin and excess temperature $\Delta\theta$, the non-dimensional height z/r_o and temperature Θ, represented in equation (9), are used. We can divide the regions into two domains as to the vertical temperature distribution. In this figure, all the vertical temperature distributions in the current from the sources of various radii can be represented by one curve although there are some exceptions in the cases of sources whose radii are $r_0 = 3.3$ cm. and 6 cm. This shows that there also exists a similarity law as to the vertical temperature distributions of the currents from circular heat sources.

Figure 3 shows the diagrammatical temperature distribution near a heat source. Near the heat source, hot gas and surrounding air mix at the boundary with drop in temperature. The higher the gas rises upwards, the deeper the air penetrates from the surroundings into the hot gas and at last the boundary between the mixed and unmixed gases disappears at A in Figure 3. In the domain BAB, the temperature of the gas is nearly constant, but above A, the central temperature decreases with height because the mixing is performed even on the central axis. This is why there are two different parts in this upward current.

In the case of a rectangular heat source, we can imagine two kinds of boundary lines A_1B_1 and A_2B_2 which represent the boundaries due to the shorter side of the rectangle and to that of the longer one respectively. Figure 4 shows the diagrammatical picture of these boundaries. At point A_1 the boundary due to the shorter side disappears, while the one due to the longer side still remains. So in the domain between A_1 and A_2, the temperature remains constant in the direction of B_2B_2 and the temperature distribution is similar to the one produced by a line heat source.

In the domain above a point A_2, hot gas and surrounding air are mixed in all directions, and so the temperature distribu-

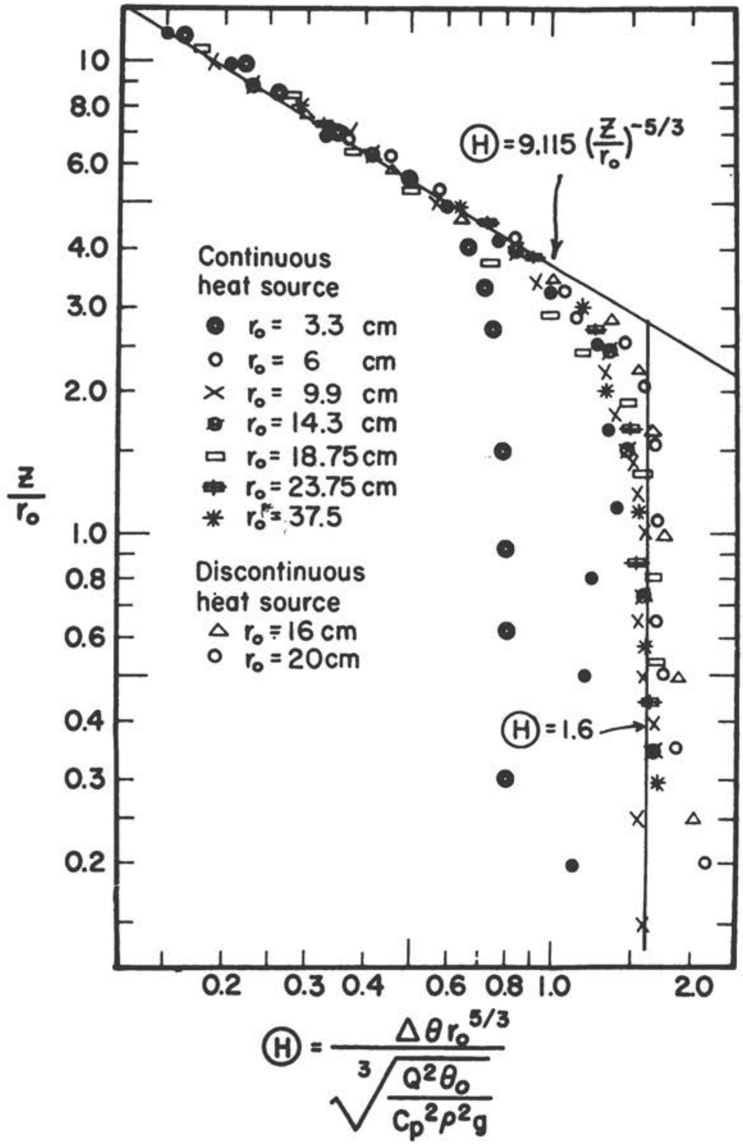

Figure 2. Temperature distributions along the central axes of upward currents from circular heat sources, expressed on the non-dimensional coordinate system

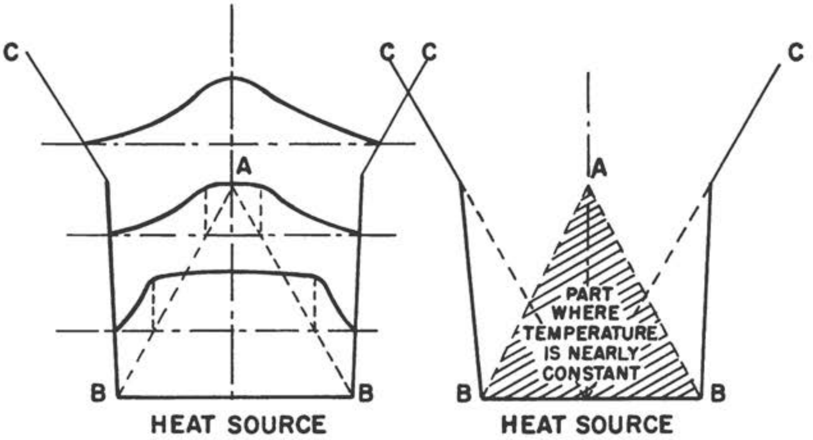

Figure 3. Diagrammatical temperature distributions near a circular heat source

tion must show a similar distribution to the one when a point heat source exists at the center of the rectangle.

Temperature Distribution in the Domain Far From the Heat Source

In the case of the point heat source, the domain of the air current spreads in the shape of an inverted cone with its vertex at the heat source. Thus, if instead of the horizontal distance r, measured from the central axis in the radial direction, the non-dimensional quantity r/z is employed as the axis of the abscissa, and the non-dimensional quantity obtained by dividing the temperature $\Delta\theta$ at an arbitrary horizontal distance r by the temperature $\Delta\theta_m$ at the central axis in the same level, is employed as the axis of the ordinate, the law of similarity states that the horizontal distribution of temperature at any height may be expressed by a single curve. In a preceding paper,[1] the expression was generalized even further, and instead of r/z, the quotient $r/zc^{2/3}$ was employed, where c was a parameter expressing the strength of turbulence in the current.

Judging from the result of experiment, it can be presumed that the temperature distribution of the upward current from a circular heat source, in the domain far from the heat source, is the same as that of the upward current from a point heat source.

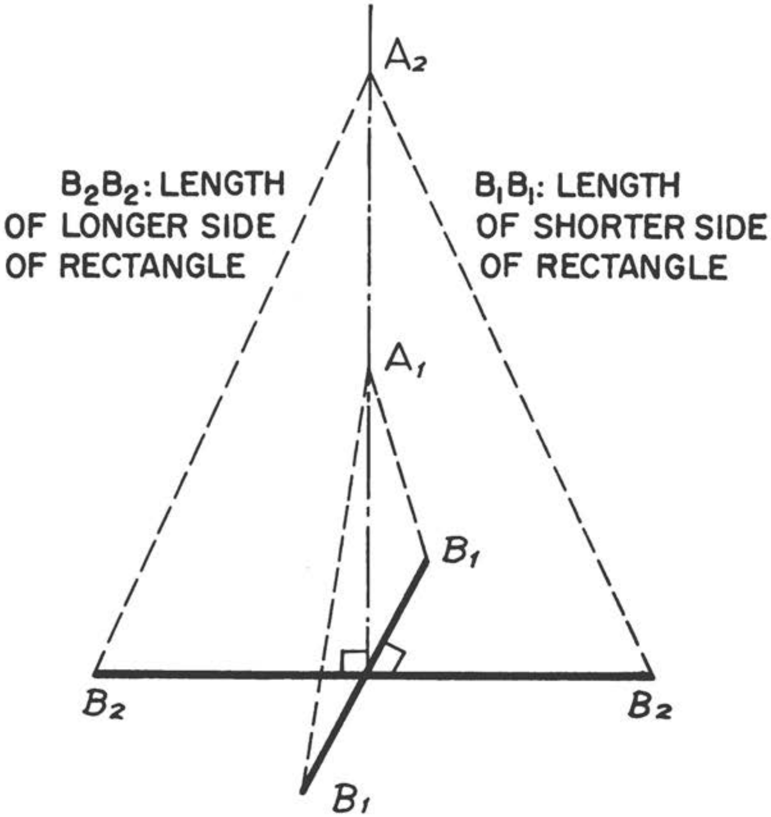

Figure 4. Front lines in the case of a rectangular heat source

In Figure 5, results of the experiments as to the horizontal temperature distribution of various circular sources and at various height, are plotted and the temperature distribution curve corresponding to a point heat source is also drawn. We can see that this curve passes near the center of the plotted points. This shows that the horizontal temperature distribution of the upward current from a circular heat source, in the domain far from the heat source, is similar to that of the current from a point heat source.

Next, let us proceed to the temperature distribution along the central axis. Figure 2 shows the result of experiment and is expressed in both non-dimensional and logarithmic coordinates. The inclination of the temperature-distribution line is nearly

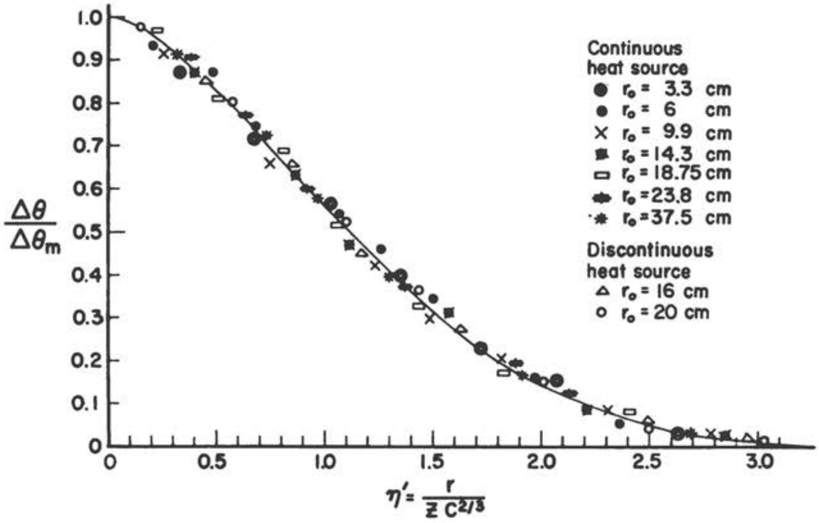

Figure 5. Horizontal temperature distribution of the upward currents from circular heat sources, in the domain farther from the sources

$\pi - \tan^{-1}(3/5)$. The vertical temperature distribution in this domain is the same as that of the current from a point heat source. The vertical temperature distribution in the case of a point heat source can be expressed:[1]

$$\Delta\theta_m = 0.423 \sqrt[3]{\frac{\theta_0 Q^2}{c_p^2 \rho^2 g}}\, c^{-8/9} z^{-5/3} \tag{12}$$

where c is a parameter relating to the strength of turbulence of the stream. From equations (9) and (11) the temperature distribution along the axis of the upward current can be expressed in non-dimensional form:

$$\Theta = \frac{\Delta\theta_m r_0^{5/3}}{\sqrt[3]{\dfrac{\theta_0 Q^2}{c_p^2 \rho^2 g}}} \tag{13}$$

Eliminating $\Delta\Theta_m$ from both equations, we obtain

$$\Theta = \frac{0.423}{c^{8/9}} \left(\frac{z}{r_0}\right)^{-5/3} \tag{14}$$

If we use the numerical value of $c^{2/3} = 0.1$, derived from the laboratory experiment, we obtain

$$\Theta = 9.115 \left(\frac{z}{r_0}\right)^{-5/3} \tag{14'}$$

This is the non-dimensional equation for the vertical temperature distribution of the upward current from a circular heat source in the domain far from the source.

Temperature Distribution in the Domain Near to the Heat Source

In Figure 2 the temperature distribution along the axis of upward currents is plotted in a non-dimensional coordinate system. We find that in the domain nearer to the heat source ($z/r_o < 2.5$), the experimental points, except in the cases of the small continuous heat sources of $r_o = 3.3$ cm and $r_o = 6.0$ cm, cluster along a line roughly expressed by

$$\Theta \sim 1.6 \tag{15}$$

In other words, we find that in this domain, the similarity law expressed by equation (15) holds concerning the vertical distribution of temperature.

In the cases of the heat sources of $r_0 = 3.3$ cm and 6.0 cm, no similarity law holds, as is shown in Figure 2. This may be due to the following facts: the flames rising from heat sources of $r_o = 9.9$ cm and larger are turbulent flames and alcohol burns on nearly the entire surface whereas the flames from heat sources of $r_o = 3.3$ cm and 6.0 cm may be roughly considered as laminar flames in which alcohol burns chiefly on the boundaries of the containers. We exclude these laminar flames here.

Temperature Distribution of Upward Current from a Rectangular Heat Source

In the preceding paragraph, the temperature distribution of the upward current from a circular heat source was discussed, but the plan of a house is generally a rectangle and not a circle. Therefore, the conclusion in the preceding paragraph cannot be applied directly to the actual fire. In this section, the temperature distribution in the upward current from a rectangular heat source will be obtained based on the conclusion of the preceding paragraph.

Experiment and Its Results

For the rectangular heat source, a square (29 × 29 cm.) and rectangles (33 × 23 cm., 47.5 × 17.5 cm. and 66.5 × 12 cm.) in which alcohol-lamp wicks were made to stand close together and burn, were used (discontinuous heat source). Also, in order to confirm the similarity law, a continuous heat source was used consisting of a rectangular vessel (27 × 10 cm.) in which alcohol was burned. The method of measuring the temperature was the same as in the case of the circular heat source.

Following the arguments for a circular heat source, the distribution of temperature of the upward current from a rectangular heat source will be as follows: with regard to the temperature distribution along the central axis of the current, there must be three domains—the first domain directly above the heat source where the temperature varies little with the height; above this, the second domain where the vertical distribution of temperature is similar to the case of the upward current from a line heat source; and at the top, the third domain where the distribution of temperature is similar to the case of the upward current from a point heat source. The results were anticipated.

If the temperature distribution of the upward current ultimately becomes similar to the case of a circular heat source in the third domain, there must exist for the various forms of rectangular heat source a circular heat source which gives a similar temperature distribution to the rectangular one in the third domain. The radius of this corresponding circular heat source r_o will be called the "equivalent radius" of the original rectangular heat source. It was expected and confirmed by the results of experiments that the value of the equivalent radius r_o is equal to the value of the radius of a circle having the same area as the original rectangle. That is to say, if we suppose the lengths of the adjoining sides of the rectangular heat source, a and na respectively ($n \geqq 1$), the equivalent radius r_0 of this heat source satisfies the following equation:

$$\pi r_0^2 = na^2 \tag{16}$$

If we plot the results of the experiments on the temperature distribution of the upward current from a rectangular heat source, by using this r_o on the same non-dimensional coordinates as in the case of the circular heat source, the results are as shown in Figure 6.

In this case, vertical temperature-distribution curves do not reduce to one curve, but become different according to the value of the ratio n (n is the ratio of the length of adjacent sides of rectangles). But we can suppose that the curve is determined only by the value of n and is independent of the dimension of the rectangle as in the case of the circular heat source. To make sure of this fact, we burnt alcohol in a rectangular vessel (27 × 10 cm.), making it a continuous heat source ($r_o = 9.3$ cm, $n = 2.7$) and measured the vertical distribution of the temperature. We plotted the results on the non-dimensional coordinate system such as Figure 6 and it was confirmed that they agreed well with the vertical distributions of temperature of the rectangular discontinuous heat source (47.5 × 17.5 cm, $r_0 = 16.3$ cm, $n = 2.7$) used in the previous experiment. This is only one example, but we think it is sufficient to confirm the validity of the above mentioned similarity law.

Temperature Distribution in the First Domain

This is the domain where the temperature of the upward current does not change very much with height along the central axis of the current. The results of the experiment show that the temperature drops somewhat as the current goes up, especially in the case of slender sources. The reason for this may be as follows: (1) Since the temperature is high in this domain, even in the case of alcohol flames, there is gas radiation through the fuel vapor and carbon dioxide contained in the flame. This quantity becomes larger as the shape of the source becomes slenderer, because the length of the circumference of the square is the minimum of all the equal-area tetragons. (2) The transition from the first domain to the second takes place slowly over a wider range as the shape of the source becomes slenderer, and the greater part of what was thought to be the first domain in the slender-shaped source is really a range of transition to the second domain.

As in the case of the circular heat source, non-dimensional equation of the temperature distribution in the first domain may be determined by the following equation:

$$\Theta = 1.6 \tag{17}$$

In Figure 6, if we define the height at which the line of vertical distribution of temperature seems to change from the first domain to the second, the height of that boundary should comply with the following rule: in the case of the circular heat source with a radius r_0, the height of the boundary was about 2.5 r_0. If this is applied to the rectangular heat source, the height where the first domain ends should be $z = a/2 \times 2.5$ where a is the length of the shorter side of the rectangle. If this height is represented by the non-dimensional quantity z/r_0, using equation (16), it reduces to

$$\frac{z}{r_0} = \frac{2.5}{2}\sqrt{\frac{\pi}{n}} \sim \frac{2.215}{\sqrt{n}} \tag{18}$$

If we apply this to the three kinds of rectangular heat sources used in the experiment, the upper limit of the first domain will be as follows:

for heat source of 39 × 23 cm $(n = 1.4): z/r_0 = 1.85$
47.5 × 17.5 cm $(n = 2.7): z/r_0 = 1.35$
66.5 × 12 cm $(n = 5.5): z/r_0 = 0.94$

According to the results of the experiments, since the transition from the first domain to the second takes place slowly, it is not possible to indicate the boundary point distinctly, but roughly speaking, the above points can be said to be boundary points.

Temperature Distribution in the Second Domain

Here, the vertical distribution of temperature of the upward current is the same as in the case of the line heat source or

$$\Delta\theta \propto z^{-1}$$

That is to say, on the double-logarithmic coordinate system the vertical temperature distribution line inclines 135 degrees to the horizontal axis.

The definition of Θ which expresses the temperature in terms of non-dimensional quantity is in accordance with the equation (13). This time, however, instead of using the heat quantity Q

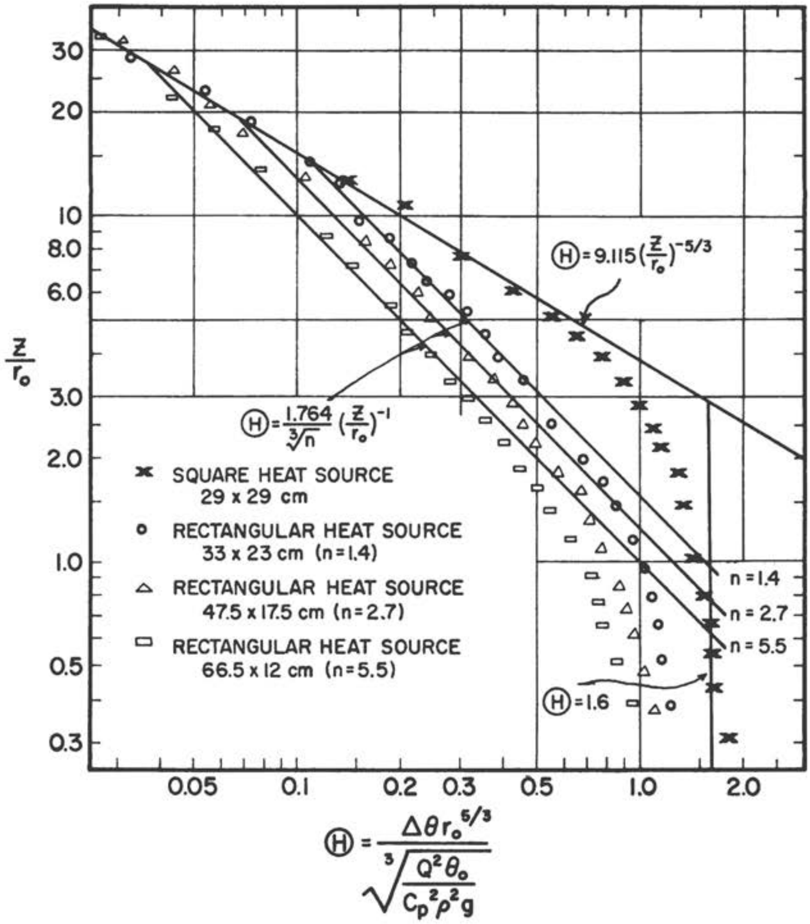

Figure 6. Temperature distributions along the central axes of the upward currents from rectangular heat sources

given to the air in unit time from the entire heat source, we use the quantity Q_0 which, as in the case of the line heat source, is given to the air in unit time from the part constituting a unit length in the direction of the longer side of the rectangular heat source. That is,

$$Q = anQ_0 \tag{19}$$

where a and n were defined in the equation (16). Since the distribution of the temperature $\Delta\theta_m$ along the central axis of the upward current from a line heat source was represented as follows:[1]

$$\Delta\theta_m = 0.663c'^{-4/9}z^{-1}\sqrt[3]{\frac{\theta_0 Q_0^2}{c_p^2\rho^2 g}} \tag{20}$$

If we eliminate $\Delta\theta_m$, Q_0 and Q from (13), (19), and (20), we obtain

$$\Theta = \frac{0.663}{c'^{4/9}}(n\pi)^{-1/3}\left(\frac{z}{r_0}\right)^{-1} \tag{21}$$

This is the equation for the line which expresses the vertical distribution of temperature in this domain in non-dimensional form.

Since the right side of equation (21) includes n which expresses the ratio of the lengths of the two adjacent sides of rectangular heat source, the position of the temperature distribution line varies on the graph according to the shape of the rectangle. Even if the strength of the heat source is the same, the slenderer the heat source, the lower is the temperature at the same height from the source. When the numerical value of π and parameter $c'(c'^{2/3} = 0.13)$ (the value obtained in the laboratory experiment) is substituted

$$\Theta = \frac{1.764}{\sqrt[3]{n}}\left(\frac{z}{r_0}\right)^{-1} \tag{21'}$$

The three straight lines inclined 135 degrees to the horizontal axis in Figure 6 represent the three equations derived by giving n the equivalent numerical values of rectangles used in the experiment. We can see that the points obtained by experiments cluster around the lines corresponding to the respective heat sources.

The height of the boundary point between the second and third domain can be obtained on Figure 6 as the point of intersection of the two straight lines of the equations (14) and (21). The reason is that in the third domain, regardless of the slenderness of the heat source, the temperature distribution along the central axis of the upward current can be given by the equation (14). If we calculate and express the height of this boundary point non-dimensionally, we obtain

$$\frac{z}{r_0} = 0.510\frac{c'^{2/3}}{c^{4/3}}\sqrt{n\pi} \tag{22}$$

Substituting in the above equation the values of $c'^{2/3} = 0.13$ and $c^{2/3} = 0.10$ obtained by the laboratory experiments and the numerical value of π, we obtain

$$z/r_0 = 11.75\sqrt{n} \tag{22'}$$

Temperature Distribution in the Third Domain

In this last domain, the temperature distribution is the same as that in the case of a point heat source of the same strength placed at the intersecting point of the diagonals of the rectangle. Also, it accords with the temperature distribution in the upper domain of the circular heat source with a radius equal to the equivalent radius of the rectangle. In other words, the temperature along the central axis of the upward current decreases in inverse proportion to the 5/3 power of the height from the heat source. We can express this vertical distribution of temperature in non-dimensional form as follows:

$$\Theta = \frac{0.423}{c^{8/9}}\left(\frac{z}{r_0}\right)^{-5/3} \tag{23}$$

which is the same as the equation (14), the formula for the distribution of temperature along the central axis in the domain farther from the circular heat source. If we substitute the numerical value of $c^{2/3} = 0.10$ obtained in the laboratory experiment in the above equation, we obtain

$$\Theta = 9.115\left(\frac{z}{r_0}\right)^{-5/3} \tag{23'}$$

which is the same as equation (14′). Regardless of the slenderness and size of the rectangle, the vertical temperature distribution in this domain can be represented by one line. In Figure 6, we can see that the points derived by the laboratory experiment using the rectangular heat sources of 29 × 29 cm., 33 × 23 cm., 47.5 × 17.5 cm., and 66.5 × 12 cm. fall near the line of the equation (23′) in their third domain.

The Distribution of Temperature Near a Burning Wooden House

The above mentioned similarity-law of temperature distribution can be applied to a wooden house fire, if we eliminate heat radiation. We will calculate temperature distribution above a rectangular burning wooden house during the period of its maximum intensity, giving the scale of the house and amount of combustion materials contained in it.

Rate of Heat Generation in a Burning Wooden House During the Period of its Maximum Intensity

We will first obtain the quantity of heat produced from a burning wooden house during 10 minutes of its maximum intensity. Assuming the plan of the house to be a rectangle, we make the lengths of two sides of the house a meters and b meters respectively, and the height of the ridge and eaves of the house, h_1 meters and h_2 meters respectively, as shown in Figure 7. Let us make the quantity of combustibles contained in the house w kg/m². Generally, the value of w is considered to be 165 kg/m² for a dwelling and 135 kg/m² for other houses. The total quantity of combustibles in this house is wab kg. Assuming that the house burns completely, and that the amount of the generated heat per kg of lumber is 3560 kcal, the total of quantity heat generated from the house during the period of fire is 3560 wab kcal. In order to find the approximate ratio of the generated heat quantity during the above-mentioned 10 minutes, to the total heat quantity, we take the standard time-temperature curve for a wooden house, which was obtained by averaging the results of a large number of fire tests of full-size wooden houses. In this, the indoor temperature θ corresponding to time t (unit:hour) is approximately expressed by the following equation:

$$\theta = 6200(e^{-10t} - e^{-15t}) + 200 \tag{24}$$

Here, $t = 0$ does not refer to the time of the start of the fire, but indicates the time when indoor temperature reaches 200°C. It is not until about four minutes after the start of fire that the above formula holds good. The percentage of heat generated during the period from six to sixteen minutes after the fire starts (we regard this period as the one of maximum intensity of fire) to the total heat quantity is calculated by use of this equation. For this purpose, the calculation is made on the assumption that the amount of heat generated is approximately proportional to the temperature; that is to say, we neglect the decrease of gas

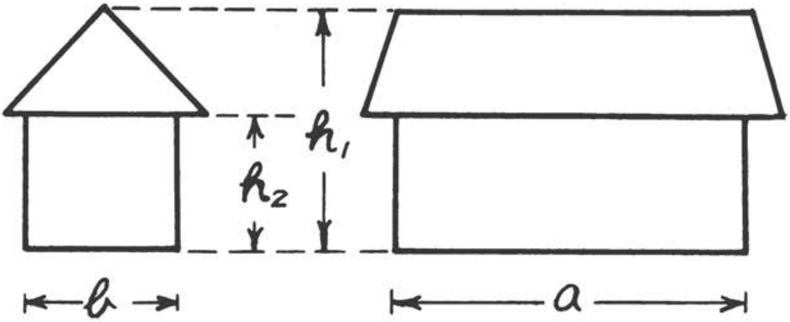

Figure 7. Dimensions of a wooden house on fire

density caused by the rise of temperature. This is not strictly correct, but it will do for the approximate calculation. As the sixth minute after the start of the fire approximately corresponds to $t = 1/10$ hr. and the sixteenth minute to $t = 1/5$ hr. let us integrate the equation (24) from $t = 1/10$ to $t = 1/5$. The temperature rise thus obtained is 170°C. Correspondingly, the temperature rise for a fire of one hour duration is 407°C. Accordingly, we may conclude that during the 10 minutes of maximum fire intensity, about 170/407 or 42 per cent of the amount of heat, produced in the course of one hour of fire, is liberated. Now, as it is known by experience that about 80 per cent of the total amount of heat is produced in the course of one hour of the fire, the amount of heat during the 10 minutes is 33.6 per cent of the total heat quantity in a wooden house fire. The absolute value of that heat quantity is $0.336 \times 3560\, wab \sim 1196.2\, wab$. Accordingly the amount of heat Q produced per second is

$$Q_1 = 1993.6\, wab \text{ cal/sec} \tag{25}$$

Calculation of Temperature Distribution Above a Wooden House Fire

The flames in an actual fire, unlike the flames from alcohol in the laboratory, contain a large amount of heated carbon particles and the amount of radiation from these is considerably large. Thus, we cannot regard the value of Q in equation (13) as being independent of the height from the heat source but assume instead that it decreases with the height. According to

Dr. Kinichiro Fujita's paper,[2] the area of the flame is approximately equal to the side area of the house and the emissivity of the flame is approximately 114 × 10^3 kcal/m^2hr. If we use the same house as was introduced in the last paragraph, the heat quantity Q_2, emitted by radiation in a fire is

$$\begin{aligned} Q_2 &= 114 \times 10^3 \times 2(a+b)h, \text{ kcal/hr} \\ &= 63330(a+b)h, \text{ cal/sec} \qquad (25') \end{aligned}$$

As the radiation from the flame occurs mainly when the flame temperature is higher than 500°C, we suppose that the radiation is practically nil when the temperature drops lower than 500°C. Therefore, at this height we can change the value of $Q_1 - Q_2$ to Q in equation (13).

$$Q = Q_1 - Q_2 \qquad (26)$$

At the height where the temperature on the central axis of the upward current is 500°C, we put into equation (13) $\Delta\theta = 500°\text{C}$, $c_p = 0.24$ cal/g. deg, $g = 980$ cm/sec^2, $\rho = 0.000456$ g/cm^3 and we obtain

$$\Theta_{500} = \frac{1.717 r_0^{5/3}}{Q^{2/3}} \qquad (27)$$

If we substitute the value of Q, calculated by equation (26) and the value of r_0 (the equivalent radius of the burning house) into the above equation, we obtain the numerical value of the non-dimensional temperature Θ_{500} corresponding to 500°C. If we further calculate the value of n of the house ($n = a/b$), and use the corresponding curve in Figure 6, we can find the height z_{500} where the temperature on the central axis of the upward current drops to 500°C. Temperatures at height z lower than z_{500} can be obtained in the following ways: supposing that the amount of radiation decreases inversely proportional to the height from the top of the burning house, we substitute the value of

$$Q_1 - \frac{Q_2 z}{z_{500}}$$

for Q into equation (13). Using the curve corresponding to the value of the burning house, we obtain the value of Θ, and from this we can calculate the value of $\Delta\theta$.

As a numerical example, let us take four wooden houses, all having a ridge height of $h_1 = 4$ meters, and eaves height $h_2 = 3$ meters, whose cross sections are 12 × 12 m., 24 × 6 m., 48 × 3 m., and 12 × 3 m., respectively. We suppose that each contains combustibles of $w = 165$ kg/m². We will calculate the temperature of the upward current of each of them at the height of 0 m., 5 m., 10 m., and 25 m. above the top of the house. The result of this calculation is as follows:

	House Number	1	2	3	4
	a	12 m	24 m	48 m	12 m
	b	12 m	6 m	3 m	3 m
	r_0	677 cm	677 cm	677 cm	338 cm
	$n = a/b$	1	4	16	4
	Q_2	6080×10^3 cal/sec	7600×10^3 cal/sec	12919×10^3 cal/sec	3800×10^3 cal/sec
	wab	23760 kg	23760 kg	23760 kg	5940 kg
	Q_1	47368×10^3 cal/sec	47368×10^3 cal/sec	47368×10^3 cal/sec	11842×10^3 cal/sec
	$Q = Q_1 - Q_2$	41288×10^3 cal/sec	39768×10^3 cal/sec	34449×10^3 cal/sec	8042×10^3 cal/sec
	$r_0^{5/3}/Q^{2/3}$	0.4369	0.4480	0.4930	0.4086
	Θ_{500}	0.750	0.769	0.846	0.700
	z_{500}	2681 cm	575 cm	190 cm	372 cm
$z = 0$m	Q(cal/sec $\times 10^{-3}$)	47368	47368	47368	11842
	$r_0^{5/3}/Q^{2/3}$	0.399	0.399	0.399	0.316
	Θ	1.70	1.20	1.03	1.20
	$\Delta\theta$	1354° C	1354° C	1354° C	1207° C
$z = 5$m	Q(cal/sec $\times 10^{-3}$)	46152	40759	34449	8042
	$r_0^{5/3}/Q^{2/3}$	0.406	0.438	0.493	0.409
	Θ	1.52	0.80	0.57	0.59
	$\Delta\theta$	1327° C	570° C	265° C	373° C
$z = 10$m	Q(cal/sec $\times 10^{-3}$)	44936	39768	34449	8042
	$r_0^{5/3}/Q^{2/3}$	0.413	0.448	0.493	0.409
	Θ	1.33	0.59	0.41	0.36
	$\Delta\theta$	1284° C	324° C	141° C	180° C
$z = 25$m	Q(cal/sec $\times 10^{-3}$)	41698	39768	34449	8042
	$r_0^{5/3}/Q^{2/3}$	0.434	0.448	0.493	0.409
	Θ	0.79	0.29	0.195	0.154
	$\Delta\theta$	555° C	118° C	67° C	63° C

With regard to houses 1, 2, and 3, whose floor areas are equal to one another, the decrease of temperature with the height is most pronounced in the case of the narrowest house (No. 3). Conspicuous differences are seen between this and the square house (No. 1) at the same height.

Conclusion

We found the approximate similarity law for the temperature distribution of the upward current from a rectangular heat source, based on dimensional analysis and the results of experiments in the laboratory. Then we tried to calculate the temperatures above a burning wooden house, making corrections for the influence of radiation.

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2. FUJITA, K. *Transactions Architectural Institute of Japan No. 4* (1941).

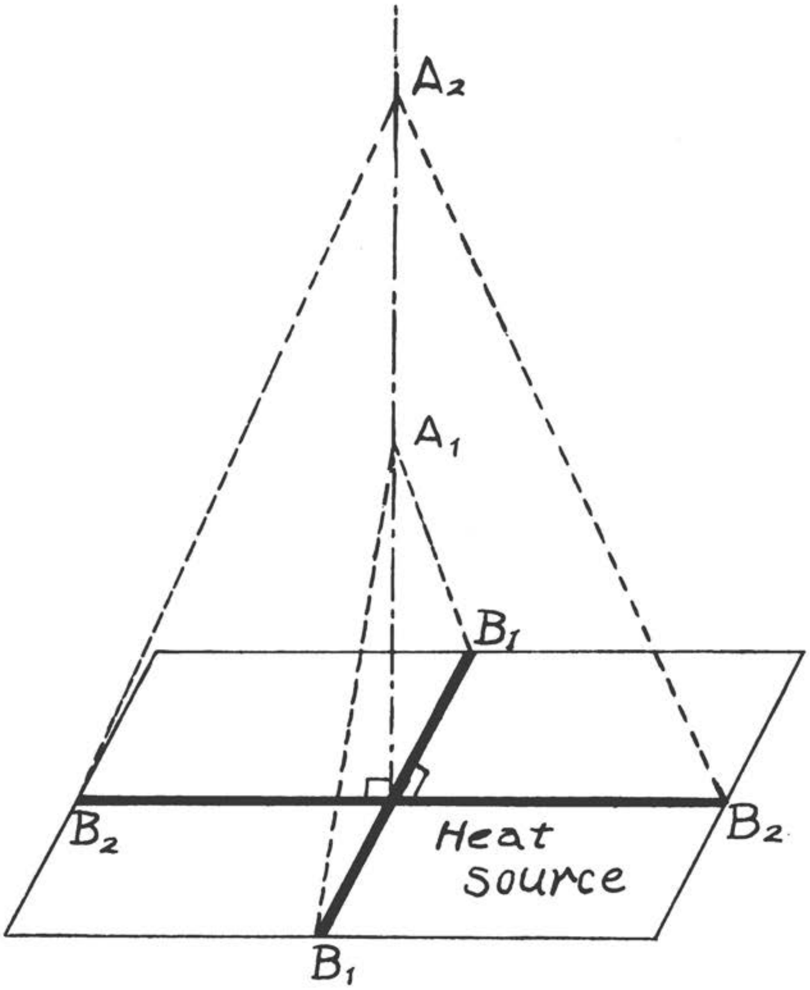
Discussion

Professor Hottel: I am not clear on the details of the distributed source; are the alcohol wicks separated? Where does the air come from; is it from below?

Mr. Yokoi: Alcohol wicks were separated one from another. I put the heat sources on the floor so the air came from sideways.

Dr. Blackshear: Concerning the two temperature distributions near the source for the rectangular flame, you had two sets of triangles meeting and the temperature distribution above the place where the smaller triangles met; I did not understand how you got the temperature distribution from the top of the small triangle to the top of the large triangle.

Mr. Yokoi: I will write on the blackboard.



$A_1 B_1$ means the boundary between the unmixed hot gas and cooled gas mixed with surrounding air in the direction parallel to the shorter side of the rectangular heat source. $A_2 B_2$ means the boundary parallel to the longer side of the heat source.

In the domain $A_1B_1B_1$, the gas temperature must be constant if we neglect the heat loss by radiation. Near the axis A_1A_2

there is a temperature gradient in the direction parallel to B_1B_1 but no temperature gradient in the direction parallel to B_2B_2, because hot gas is not yet mixed with the outer air in that direction. So, on the axis A_1A_2, the temperature distribution pattern is the same as in the case of the upward current from a line heat source.

Dr. Emmons: I gather that the combustion is rather conveniently simple in this case; it is moderately complex right at the fire. It is two-dimensional for a while and then becomes three-dimensional, going rather rapidly from one to the other. It looks like a rather convenient way to behave rather than some of the other ways combustion sometimes behaves.

In constructing this program, various requests to present material were sent out. Some did not get into the program because the material was not received in time. Dr. Zabetakis of the Bureau of Mines has some information to present on hydrogen burning.

Dr. Zabetakis: The work on which I would like to report briefly is part of a larger program, a portion about which you heard yesterday when Dr. Burgess spoke. Unfortunately, we did not feel there would be sufficient time to complete this work and present a formal report on it at this session; as a result, we thought it best to give a short informal presentation.

In this program we have looked at the explosive vaporization and burning of liquid hydrogen. When hydrogen burns above a well insulated pool of the liquid, it burns rather slowly. Those who are familiar with the burning rates of volatile liquids might find this a little surprising. However, it turns out that when the liquid is spilled onto the ground, one obtains the expected results. That is, the hydrogen vaporizes quickly and if ignited, burns very rapidly.

We have attempted to make several types of measurements to date. In one, we spilled the liquid hydrogen onto various surfaces (steel plate, gravel, and macadam) and measured the hydrogen concentration above the spill area. We thought we would get some sort of continuous rising cloud but were surprised to find that this was not the case. By sampling at a very large number of points above the spill area at various times following spillage, we were able to construct plots of the hydrogen concentration as a function of time following a spill. These showed that the rapid vaporization and mixing produced bursts or pulses of flammable hydrogen-air mixtures above the spill area. In some cases, these were entirely detached. However, we found later that a flame could propagate from one region into the other under certain conditions.

We were also interested in knowing what happens to the energy liberated during the visible burning period, so we measured the radiation in a horizontal plane, the blast pressure, and the flame volume. We then made plots of each of these as a function of the quantity of liquid that was spilled, and as a function of the time from the instant of spillage to the instant of ignition.

Vapor clouds were found to rise at the rate of three to five feet per second depending on the surface on which it was spilled. Flame balls that resulted upon ignition of the first pulse of hydrogen rose at something of the order of 20 feet per second. Initially flames traveled at speeds varying anywhere from just a few feet to several hundred feet per second, depending on the amount of premixing prior to ignition. When the liquid was spilled and permitted to mix for a short period of time, the resultant flames were usually plume- or mushroom-shaped.

Flame volumes were found to vary from essentially 0 to roughly 25 times the gas volume produced. They were, of course, not as big as the total volumes to be expected under confined conditions.

The most bothersome part of the above flames was the amount of radiation that was produced. Assuming complete combustion and spherical distribution of the radiant energy, measured values of the radiant energy were as high as thirty per cent of the total available energy.

Finally, we were also bothered somewhat by what appeared to be loud blasts (neighbor complaints were obtained from homes three miles away). However, the actual pressures that were produced were relatively small.

Studies with liquid hydrogen present additional interesting problems. For example, when the liquid is spilled, we start with a source of approximately the same density as air, but with a temperature of 20.4°K. As the surrounding air cools it becomes a little more dense than the hydrogen. Also, as the hydrogen picks up heat, it becomes roughly $^1/_{15}$ as dense and then rises quite rapidly. If we ignite the resultant mixtures, the product gases are very much more buoyant, so that we have a sudden rapid rise which gives results that are quite similar to those that are found (at least on a very small scale) in the atom bomb explosions, i.e. mushroom-shaped flames.

Dr. Huff: Without claiming any knowledge of this particular phenomenon, the statement that a large amount of energy was radiated in an incidental fashion is interesting. The general conception is that symmetrical gases are not very good radiators. Symmetrical gases form almost two-thirds of the theoretical combustion products, and the percentage can be very much higher with excess air. I would like discussion on this point and I expand my question to ask if this radiation phenomenon had been examined in other environments. My personal experience has indicated that contaminants may have some influence in this in a secondary effect, one of the pitfalls when we move from theory to practice.

Dr. Zabetakis: The total amount of radiation observed was at first glance surprising. The flames were extremely nonluminous; one could see through them. This made it necessary to do our work after dark in order to get satisfactory photographs for use in estimating flame volumes. The first surge burned contaminants because initially there was a bright pulse but the subsequent large volume of flame is fairly nonluminous. We used 12-junction bismuth-silver thermopiles to measure the radiant energy that was received at various distances from the flame.

Professor Hottel: On the matter of radiation, I do not see why you suggest that it comes from a symmetrical molecule. It almost certainly comes from the hot water vapor that is produced in the combustion. The amount of radiation that comes from the chemiluminescense associated with the act of union of the hydrogen and oxygen is almost certainly minute compared to thermal radiation from the water vapor.

If this is the case—and I am almost certain it is—then the expression of the radiation as a fraction of the heat of combustion can be very misleading. I spent the first years of my technical career converting an M.I.T. associate, making measurements of flame radiation, from this viewpoint that there was some meaning to the expressing of radiation emitted during combustion as a fraction of the heat of combustion over to the concept that it was a function of time and temperature and shape and concentration of the radiating mass.

If one were able to prevent dilution of the water vapor from the combustion of hydrogen with air, and if one waited long enough, the temperature would ultimately drop to the ambient temperature. That is the definition of temperature; it does not matter whether transfer is by radiation or any other mechanism. And so, if one waited long enough, the radiation from the combustion products would be equal to the enthalpy of combustion. Consequently, I am always distressed when radiation is expressed as a fraction of the heat of combustion.

Dr. Wolfhard: There are two ways of looking at the radiation from flames. If one wants to study the mechanism of radiation, then the proper way of doing this, as Professor Hottel suggests, is to find the emitters such as CO_2 and H_2O measure the temperature, and find the emissivity at any wave length. This procedure is bound to be cumbersome for fuel fires where the temperature is not uniform and the distribution of the emitters in space varies with time. A more empirical consideration is therefore acceptable as long as it is based on solid physical principles. A column of hot CO_2 will lose heat by radiation and heat transfer to the surroundings. As long as the diameter of the column is small, i.e. the emissivity is small, radiation is emitted from the whole volume, whereas heat transfer is a surface effect. As we increase the size of the column the energy lost by radiation will increase relative to the energy lost by conduction. Beyond a certain size radiation itself may originate from the surface rather than the whole volume when the emissivity has reached unity and the radiation from the center of the column is reabsorbed and cannot leave the flame. The ratio of radiated energy to the total enthalpy of the column may thus become a constant for large flames. The column just considered is a poor approximation for a large fuel fire; however, experiments at the Bureau of Mines have confirmed that the ratio of radiated energy of a fuel fire to the heat of combustion approaches a constant value for large trays. Thus, if we know the size of a liquid pool, we know the rate of recession of the liquid from experimental evidence. The total heat of combustion is thus known and, therefore, the total radiated energy. We have, therefore, a practical modeling law which is what we try to achieve at this conference.

The ratio of radiated energy to total heat of combustion depends, of course, on the type of emitters available in a flame. Thus, hydrogen flames have practically only one emitter, i.e. H_2O, whereas alcohol flames have H_2O and CO_2. This does not mean that a hydrogen flame will emit less than an alcohol flame as the flame temperature has to be considered too. Benzene flames radiate up to 60 per cent of the heat of combustion and this is due to the wide wave length range in which the flame emits as carbon particles emit as black bodies.

Thus, there is ample theoretical background to justify the expression of radiated energy as part of the total available energy, at least for large flames where this ratio has become a constant. This constant depends only on fuel type and flame temperature. Measurements taken at the Bureau of Mines have borne out these considerations.

Dr. Zabetakis: The usual practice is to do as Professor Hottel has indicated. However, from the standpoint of safety, we felt that to give an expression in terms of an apparent ambient temperature would be rather useless in this particular application, because we were specifically interested in knowing how close we could place storage tanks to other tanks, to inhabited buildings, and to personnel. If I find that my clothing catches on fire when I am a certain distance from a burning pool, this I feel is quite significant. Since I know that it takes something of the order of two or three calories per square centimeter delivered in something of the order of two or three seconds to ignite fabric or to cause serious burns to flesh (in this study we had explosions that occurred in the order of five to ten seconds), then it is quite important that I know how much of the total energy I can expect to receive if ignition occurs under optimum conditions.

Dr. Lamb: Were the wavy variations of the concentration of hydrogen with height measured experimentally, or were they based upon conclusions drawn from flame photography?

Dr. Zabetakis: These were experimental measurements. We made hundreds of samplings and analyses and were able to construct the concentrations up to something like fourteen feet from two to six seconds after the liquid was spilled.

Dr. Lamb: Have you an explanation as to why the wavy curve is obtained? I would have thought that the usual diffusion transport equations would indicate a smooth curve of hydrogen concentration with height.

Dr. Zabetakis: I should let someone better versed in that sort of thing answer this. My crude explanation is that you get flash vaporization. This causes a very rapid updraft which pulls air into the base, diluting the subsequent material. At the same time the surface temperature is falling, so that although the vaporized gas has a certain amount of momentum initially and pulls in a certain amount of air at ground level, the rate of production of gas falls off as the temperature of the ground falls and rate at which air is pulled in slows down. This permits another little burst of hydrogen to be produced which then accelerates and pulls in more air, etc. We have gotten as many as six distinct pulses in this way; that is, pulses of hydrogen, and pulses of flame.

Professor Hottel: I do not want to imply that there is so much an argument here as a question of definition. If you would say, because you want to use the number practically, that for balls of fire of a certain size a certain fraction of the heat of combustion is radiated (counting radiation down to where its intensity is one hundredth or one thousandth, or whatever you want to say, of the maximum intensity reached), then I would quite agree that there is a number. I do not like the unqualified statement that the fraction of the heat of combustion able to be radiated by the hydrogen combustion process is thirty per cent. I do not object to your number. I would like to have a little qualification of its meaning.

Professor Taylor: I would like to ask whether any measurements were made of the rate at which this ball of fire rose. The point is that in the atomic bomb, there was quite a calculable rate of rise of the ball of fire at different stages, and you might get an idea of the amount of heat contained in it at any time since the heat radiated out does not contribute to the gravitational buoyancy.

Dr. Zabetakis: I do not know if I heard the first part of your question correctly, but if I did, the answer is that the ball itself (when we had a detached ball, which we did in many cases) rose at the rate of approximately twenty feet per second and then gradually disintegrated as it reached about fifty or sixty feet, depending on the quantity spilled.

Professor Taylor: Roughly one would expect the ball of hot gas to rise at speed $\frac{2}{3}\sqrt{ga\left(\frac{\rho_a - \rho_b}{\rho_a}\right)}$ where a is the radius of the ball, ρ_a the density of the atmosphere and ρ_b the density of the gas in the ball. Measurement of the speed of rise and dimensions of the ball might therefore give an idea of $\frac{\rho_a - \rho_b}{\rho_a}$ which is approximately equal to $\frac{T_b - T_a}{T_b}$ where T_b and T_a are the temperatures of the ball and atmosphere, respectively.

Professor Hottel: According to Mr. Sauer, Dr. Wise has something significant to say about yesterday's discussion on pool burning. In the absence of Dr. Wise, Mr. Sauer will present these ideas.

Mr. Sauer: This is in relation to the constancy of the mass burning rate at large diameters. Experiments were performed at Stanford Research Institute on the burning of liquid droplets* and we inquired as to the scaling at very low pressures, because there was a question of whether convective action was taking place. A correlation was performed with standard groupings used in heat transfer and mass transfer.

The Nusselt number, prime, contains the mass burning rate, $\dot{m}$. The convective action was expressed as a function of the Grashof number shown on the board by Professor Hottel. The curve of the Nusselt number *vs.* the Grashof number for the burning drops was similar to that for heat transfer.
When the burning became turbulent we got a one third slope. The mass burning rate, which is the mass of fuel consumed per second, divided by the radius is like Nusselt's prime. The Grashof prime contains the third power of the radius so that for turbulent burning

$$\frac{\dot{m}}{r} \propto (r^3)^{1/3}$$

and

$$\frac{\dot{m}}{r^2} \alpha \frac{m}{A} = \text{const.}$$

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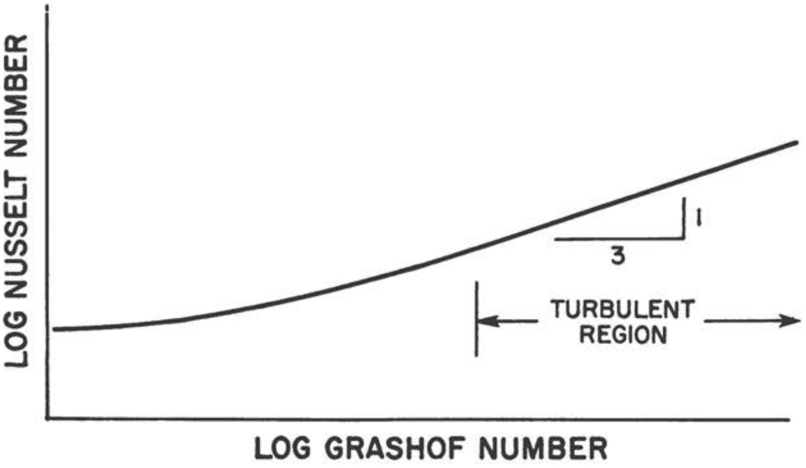
* Agoston, G. A., Wood, B. J., and Wise, H. "Influence of Pressure on the Combustion of Liquid Spheres," *Jet Propulsion* 28, 181–188 (1958).

So this comes out to be that the mass burning rate per unit area is a constant if you have the one-third slope associated with the turbulent convection. This is a well-known fact in heat transfer and mass transfer.

It seems that this constant burning rate with the larger diameter is completely consistent with past history and there is no reason to believe, in view of our similarity concepts, that this one-third slope would deviate. Essentially we got an independence of diameter effect. About three years ago I discovered the British had reported this phenomenon in *Fuel.*



Dr. Emmons: It is clear that experimentally with the meager data we have for large sizes, the rate of burning per unit area is a constant. Since it is quite clear that there are convective and radiative mechanisms both operating, either both of them vary significantly but add to a constant or they both are constant. The latter seems to be the best guess at the moment.

Dr. Burgess: My comment on this is that I do not believe that a plateau value in the burning rate is a typical behavior. That was the argument I made yesterday, that in the absence of atmospheric disturbances, the burning rate curve is typically exponential. With regard to droplet burning, it is my impression that radiation is completely immaterial. Is that correct?

Mr. Sauer: Yes, the radiation factors would have to be unimportant in this treatment, since the breakdown on this relationship is probably due to radiation.

Dr. Burgess: I agree that if convection were the dominating mode at large diameters, one should have a plateau.

Dr. Agoston: Following his presentation this morning, Mr. Faure elaborated on the appearance of test fires he had observed. He stated that after the occurrence of a fire covering a large area, there is often appreciable unburned material in the central region. This indicates that the burning rate per unit area or, the heat flux to the bed of combustibles at the center is not equal to that out toward the periphery. Gaseous combustion products and smoke may prevent a significant amount of radiant energy from reaching the central regions. Hence, owing to this shielding action, the over-all burning rate per unit area can be expected to decrease with increase in diameter. This decrease in over-all burning rate may be mitigated by convective heat transfer since, on the basis of the afore-mentioned studies on burning spheres, the over-all convective heat flux is probably independent of diameter when the diameter is large.

EXPERIMENTAL TECHNIQUES

WALTER T. OLSON, *Presiding*

A Steady-State Technique for Studying Properties of Free-Burning Wood Fires—*W. L. Fons*

Experiments with Model Mine Fires—*J. G. Dawes*

On the Self-Ignition of Wood Materials—*T. Kinbara*

Dr. Olson: We will present three papers, each concerned with a different experimental technique. These three techniques typify some of the methods presently used in fire research laboratories. As you listen to them and anticipate discussion, keep certain questions in mind. In the long run, model studies are intended to help predict fire behavior on a large scale. The experiments performed in the laboratories are to verify modeling concepts or to reveal important relations related to modeling concepts. Experiments seldom suffer from lack of proper instruments, although the use of instruments may be difficult. Experiments do not suffer from the inability to achieve reproducible phenomena, although sometimes this taxes ingenuity. We must ask ourselves the following questions. Is the model good? Have we designed the correct experiment? Are we observing the right things? Are the results amenable to analysis in terms of understandable physical phenomena? Does the work teach us something that is generally applicable? If the work does not teach us something that is generally applicable, does it at least give us a correctly scaled and studied answer on the physics of some particular phenomenon in which we are interested? These are the kind of questions I think we should keep in mind, because there is always the potential liability of patiently learning, at a cost of time and toil, the details of some man-made system which really gives little or no insight into the problems with which we are concerned. As we listen to these discussions and papers, we should keep in mind that we seek not just improved techniques to use in laboratories, but better experiments than we are performing.

Following the presentation of the papers, the authors will sit on the platform as a panel, briefly discussing their work with each other. They then will receive comments and answer questions from some prepared interlocutors, and finally they will participate with the audience in answering questions and in discussing both their particular work and experimental techniques in general.

A Steady-State Technique For Studying The Properties of Free-Burning Wood Fires

W. L. FONS, H. D. BRUCE, AND W. Y. PONG

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Forest Service—U. S. Department of Agriculture

ABSTRACT

A laboratory study was set up by the U. S. Forest Service with the ultimate objective of determining model laws for properties of wood fires, including rate of spread. This is a report of the first phase of the work, the development of a suitable bed of solid fuel and the technique of study. The bed chosen for initial study is in the form of long cribs of wood sticks. The technique is to start the crib burning at one end and to move the crib so as to keep the flame in a fixed position in space. Thermocouples in the convection column, radiometers, Pitot tubes, gas sampling tubes, and other equipment are stationary. After an initial period of growth, the fire reaches a steady state. The effect of such variables as species of wood, density of wood, moisture content, size of fuel particle, spacing, dimensions of crib, wind, and slope, on the rate of the fire and the partition of energy can be measured.

Introduction

Much has been written concerning the process of combustion, mostly on controlled combustion. Relatively little has been written on uncontrolled fire. The reported work on models of uncontrolled fires [1–3] consists of studies of laboratory fires under transient conditions, which includes the build-up time in the determination of the rate of burning. Some workers have made contributions to convection column theory[4, 5] and others have stressed the need to design an appropriate model representing an uncontrolled fire for development of model laws of fire behavior.[6, 7]

To the authors' knowledge, a technique for studying uncontrolled fires under steady-state conditions for wood fuels has not been reported. Such a technique could make it possible to study all phases of solid fuel fires, both theoretically and experimentally, investigating individually all parameters that affect the fire, and inquiring into the effect of each independent variable on each aspect of the fire behavior.

The U. S. Forest Service has conducted research for many years on free-burning forest fires under realistic or simulated natural conditions. A recent study at the Pacific Southwest Forest and Range Experiment Station was made on free-surface burning of liquid hydrocarbon fuels. From data on 148 experimental fires, a dimensionless correlation based on heat transfer-mass transfer analogy was established for rate of combustion for liquid fuel fires of limited size. The free liquid surfaces differed radically from those of solid fuels, and the liquid-fuel fires never reached a steady state. There was a clear need to develop a steady-state technique in wood fuels for basic studies of fire.

Following the recommendations of the Committee on Fire Research of the National Academy of Sciences—National Research Council for an expanded research program on fire, the Office of Civil and Defense Mobilization made funds available to augment fire model research work of the Forest Service. The objective of the first phase of Project Fire Model has been to develop a steady-state aerothermodynamic system, burning solid fuels, in which the parameters that govern the combustion may be examined over an extended period of time.

It is planned to use this system in a program of "diagnostic modeling" of a free-burning fire with the following objectives:

1) To study this type of system with experimental fire models in which fuel, fuel bed, fire base, and atmospheric conditions are controlled; to evaluate quantitatively the effects of each variable on the fire; and to determine the model laws for fire properties including rate of fire spread;

2) To obtain information about the effects of the properties of the air, fuel, and fire base on the following:

a) Total rate of energy release
b) Distribution of the released energy

c) Temperature, pressure, convection, and radiation pattern in and around the fire;

3) To achieve a heat balance on a free-burning wood fire.

Method

Essential elements for the fire model are a wood fuel bed, a combustion table equipped to transport the fuel bed at a controlled rate, a base of slabs on which the fuel rests, and instruments to measure specified variables.

The fuel bed is a crib of wood sticks of square cross section (Figure 1). The physical features of such a crib can be controlled —for example, the species of wood, the density of the wood, the dimensions of the sticks, the moisture content, the spacing, and the width and height of the crib.

The crib is formed by placing the sticks in tiers with a particular spacing between sticks. A small drop of thermo-setting resin glue is placed on each junction to bond the crib into a rigid assembly. Before testing, the cribs are conditioned to moisture equilibrium in an atmosphere of constant relative humidity and temperature. The moisture content of the conditioned wood is determined by xylene distillation.

The ignition device (Figure 2) is a shallow trough containing 10 to 20 cc of n-hexane and an asbestos wick. One end is set afire by lighting the asbestos wick. The fire gradually spreads to the other end of the crib, reducing the wood to a residue of charcoal.

A chain-belt mechanism in the combustion table is used to move the crib (Figure 3). The crib and its base rest on the chain belt which is moved manually by a worm-gear drive to hold the column of flame stationary (Figure 4). The mechanism also draws two heavy asbestos sheets (Figure 3), one on each side of the fire, in synchronism with the flame spread to simulate the relative movement of ground and fire front.

Several separate slabs make up the base for the test cribs. Any practical material may be used for the slabs, such as earth, concrete, or prepared flooring. Thus far, preformed concrete slabs with a density of about 90 pounds per cubic foot have been used.

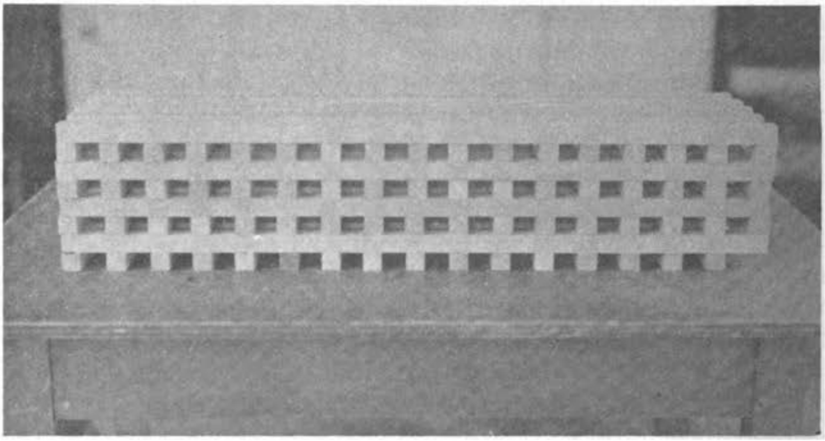

Figure 1. Wood crib assembled for a test fire. A trough of hexane will be ignited under the left-hand edge, and the flame will travel through the crib from left to right.

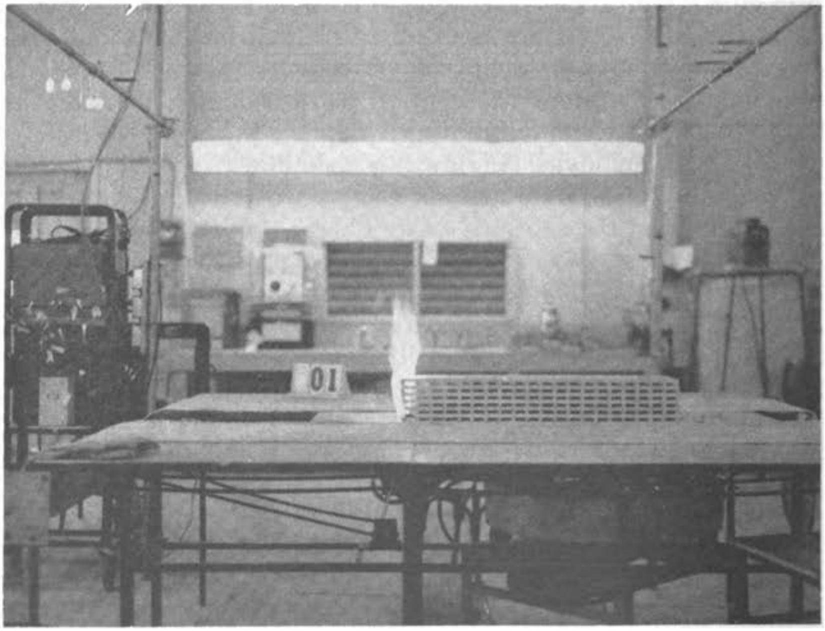

Figure 2. Ignition of a test crib. The flame is from burning hexane in a shallow trough beneath one end of the crib. The hexane soon burns away leaving the wood afire.

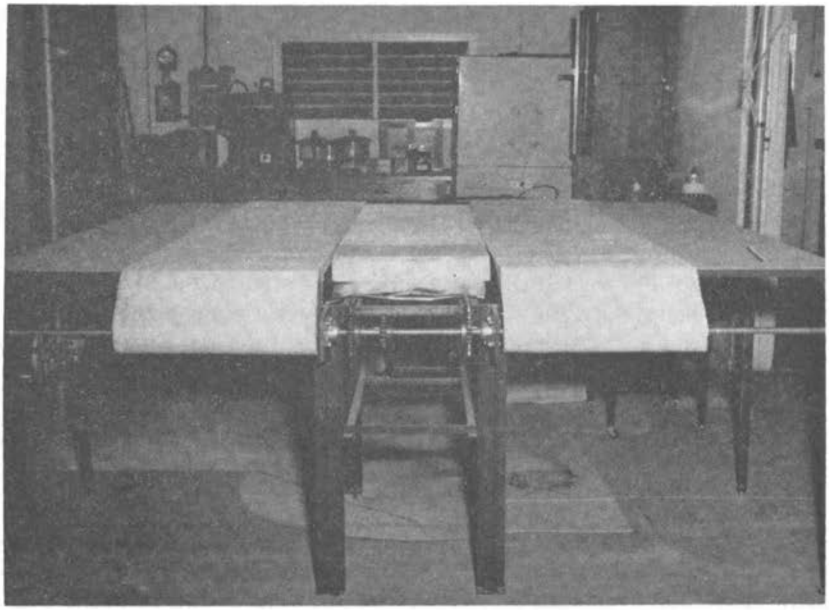

Figure 3. Combustion table with chain belt manually driven by the hand wheel seen under the table at the far left. On the chain belt are concrete slabs on which the test crib will be placed. At each side of the concrete slabs are asbestos belts which move with the slabs.

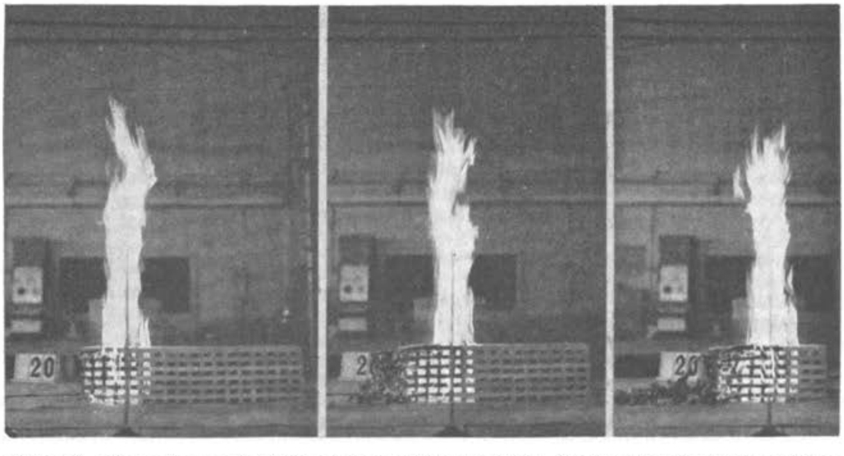

Figure 4. Flame from a test fire at three different times, illustrating the fixed position of the flame as the crib moves.

To measure temperatures of the convection column, a grid of 36 chromel-alumel thermocouples is placed above the combustion table, crosswise and lengthwise of the crib, from 1 inch above the top of the crib to 10 feet above the level of the table (Figure 5). The thermocouples are connected to multipoint recording potentiometers.

The smoke from the fire flows up into an 11-foot square hood and is vented through a stack 13 inches in diameter. Near the top of the stack is a motor-driven blower to force the exhaust. A thermocouple in the stack measures the temperature of the combustion gas. A Pitot tube connected to an ionization-type pressure transducer measures the velocity of the stack gas.

Radiation from the crib fires is measured by a thermopile radiometer (Figure 6) mounted so that it can be pointed toward the fire at various angular elevations from the horizontal, the radiometer being always at a radial distance of 14 feet from a selected point in the fire. The stand is movable so that the radiometer can be pointed at the fire from front, back, or either side.

To measure the heat transmitted from the fire to the base, the center slab of the base is removed soon after each fire and immersed in water in a sealed and insulated calorimeter box (Figure 7). The temperatures of slab and water gradually come to equilibrium, and the heat content of the hot slab is calculated from the rise in temperature of the water.

The burning wood leaves a residue of charcoal consisting of ash, carbon, and partially carbonized wood. The residue from each fire is collected, weighed, and pulverized. Samples of the charcoal powder are burned to ash in a muffle furnace to determine their carbon content, and other samples are tested for their heat value in a bomb calorimeter.

A technique of collecting samples of combustion gas in glass sampling bottles has been developed for analysis either in Orsat apparatus or by gas chromatography.

A series of thermocouples, suspended from ceiling to floor in the laboratory and connected to a multiple-point recording potentiometer, gives a continuous record of the lapse rate inside the room during each experimental fire. Also, thermopile heat-flow meter plates, fastened to the walls and ceiling of the room,

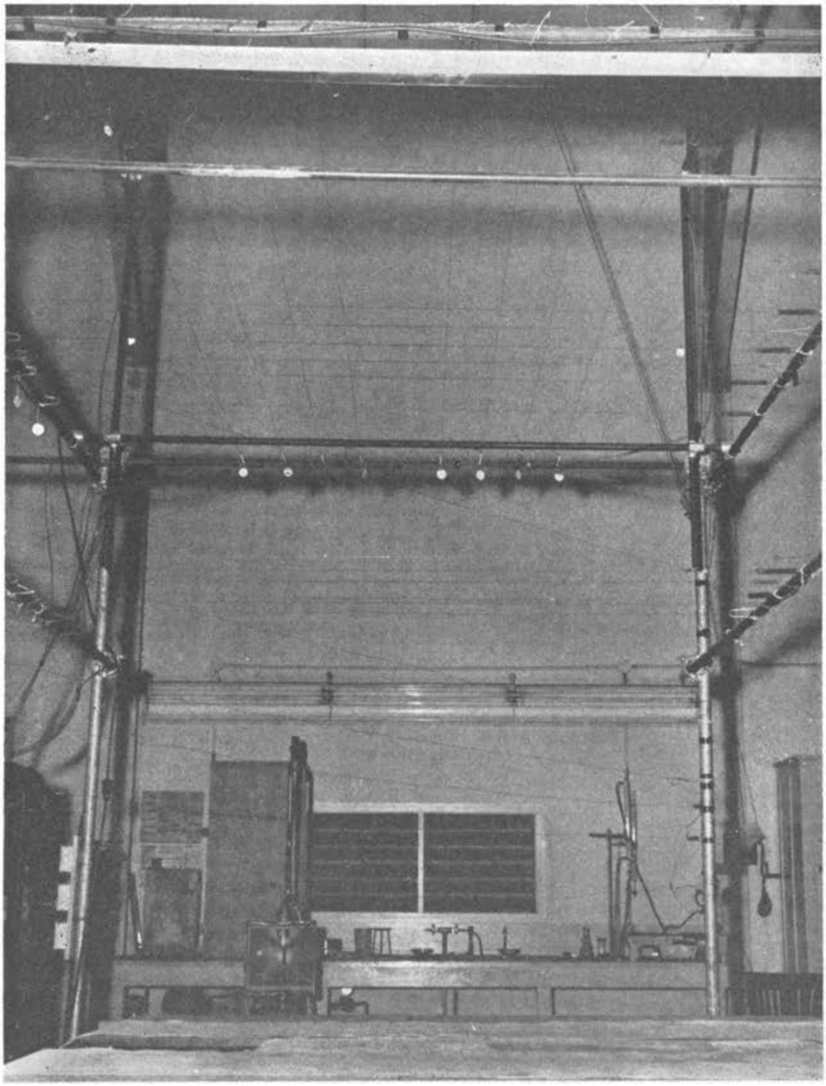

Figure 5. Grid of thermocouple wires above the combustion table

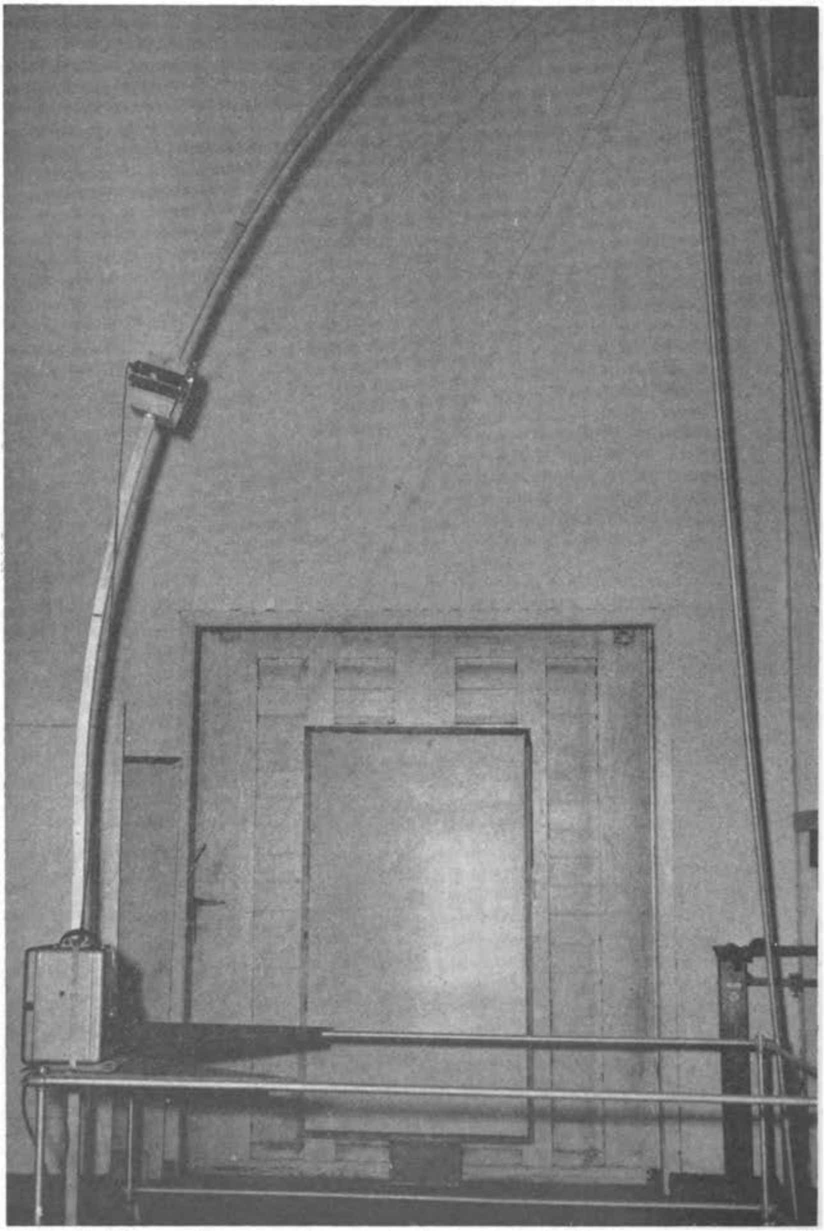

Figure 6. Thermopile radiometer mounted on a long circular-arc arm on which the radiometer can be slid up or down to various altitudes, always pointing at a selected point in the fire.

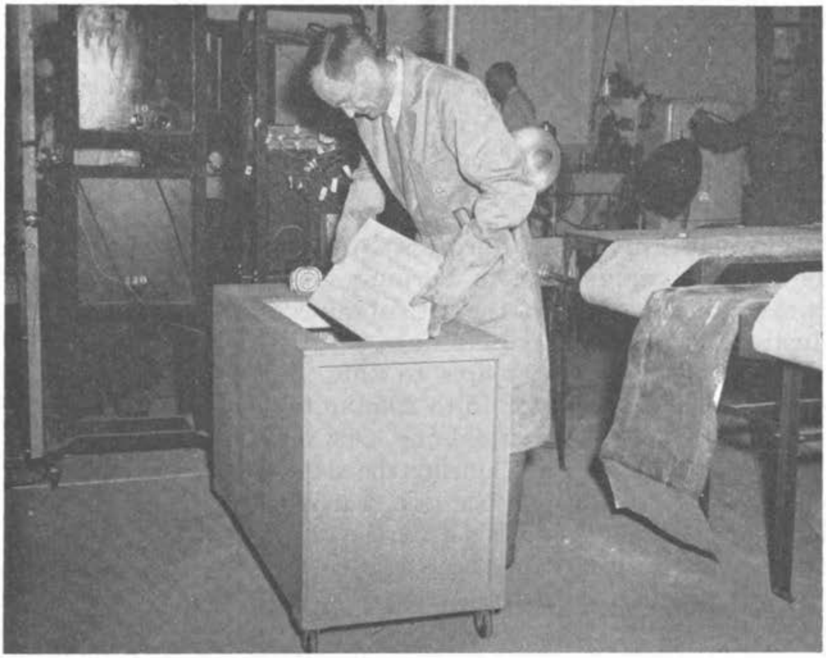

Figure 7. Hot concrete block being put into a water calorimeter to measure its heat content.

provide data on the rate of transfer of heat out from or into the room through the ceiling and walls during the tests.

Two motion-picture cameras take time-lapse movies of the fires from the side and rear. From these photographs the width and height of the flame can be measured and any unusual behavior can be detected. A carbon arc casts shadowgraphs of the flame and convection column onto a screen, and the images are photographed.

Two important features of the procedure are: (1) The crib is made relatively long, and a zone or band of fire travels the length of the crib. After an initial period of buildup, the crib fires reach a steady state which they hold until near the end. Thus is overcome the difficulty of investigating a fire that starts small, grows to a maximum, then declines. It is the behavior of the fire in the steady state that is currently being investigated. (2) The position of the flame is held fixed in space by moving the fuel into the fire. This technique permits thermocouples, radiometers, and other instruments to be stationary. The rate of fire spread is the rate the fuel has to be moved to maintain the flame in fixed position.

Results

Project Fire Model during its first year has developed an aerothermodynamic system burning solid fuels under steady-state conditions. Some of the data obtained are presented here to illustrate its diagnostic usefulness.

In the experimental fires to date steady-state conditions have been maintained for 15 to 30 minutes, but the duration of the steady state is limited only by such practical considerations as the length of the crib. During the steady-state burning, rate of spread of fire through the crib was linear (Figure 8). The linearity of the rate of spread after the critical build-up indicates how well a steady state has been achieved.

The effect of density of the wood on the rate of spread of the fire was investigated early because the information was essential to the selection of wood for the cribs. An increase in specific gravity decreased the rate of spread of the fire through the crib (Figure 9). The rate of combustion expressed in Btu. per second plotted against specific gravity of the wood in the crib was linear (Figure 10).

The horizontal distribution of temperature in a convection column at several heights is shown in Figure 11, and the change in temperature up the central axis of a convection column in Figure 12. Thermocouples in the flame just above the crib registered a lower temperature than those a short distance higher in the flame, where maximum temperatures were recorded up to 1650°F.

The part of the heat of combustion that went into the concrete slabs on which the cribs rested, varied from 2.3 per cent for the largest crib tested to 7.1 per cent for the smallest. In Figure 13 the rate of penetration into the concrete is plotted against the fire intensity, both expressed in terms of Btu. per second per foot of fire front. The points plotted in Figure 13 are rather scattered inasmuch as the rate of penetration depends also on the width and height of the crib and the density of the

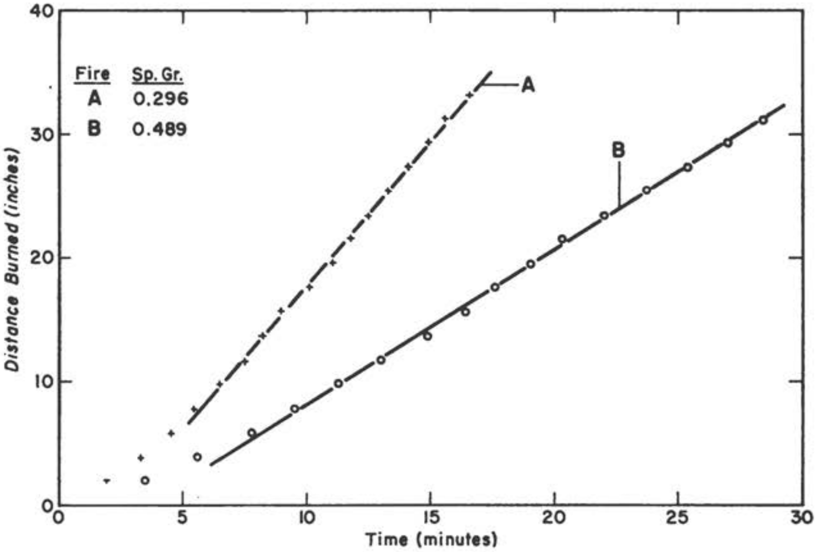

Figure 8. Spread of fire through cribs of white fir wood of two different specific gravities.

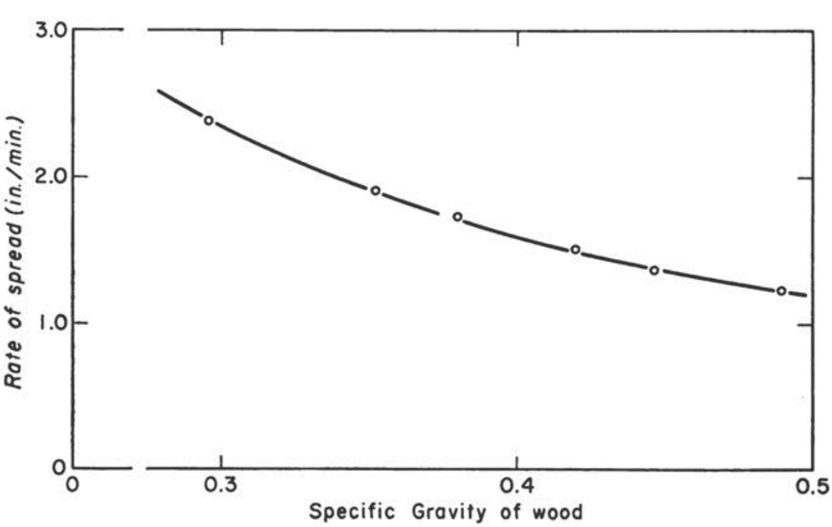

Figure 9. Rate of fire spread through cribs of white fir of different specific gravity.

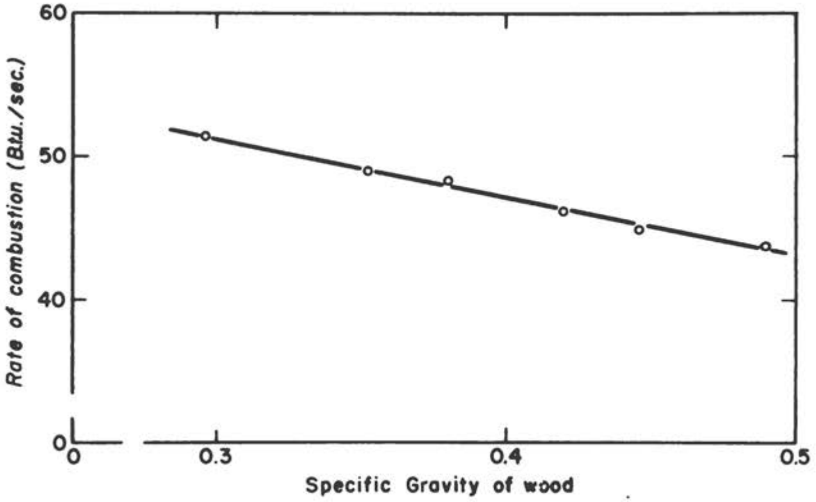

Figure 10. Rate of combustion through cribs of white fir of different specific gravity.

wood, and the data are insufficient to allow segregation of these four parameters.

Some of the heat value of the fuel is always left in the form of unburned charcoal. Figure 14 shows the amount of charcoal left as a residue from cribs of different weights. The heat remaining in the charcoal averaged 1.21 per cent of the total heat of the fuel.

Figure 15 plots irradiance to the side of the fire at an angle of 20° from the horizontal against rate of combustion. With irradiation measured from the sides, front, and rear of the burning crib at several angular altitudes, it should be possible to get a close estimate of the radiation energy from these model fires.

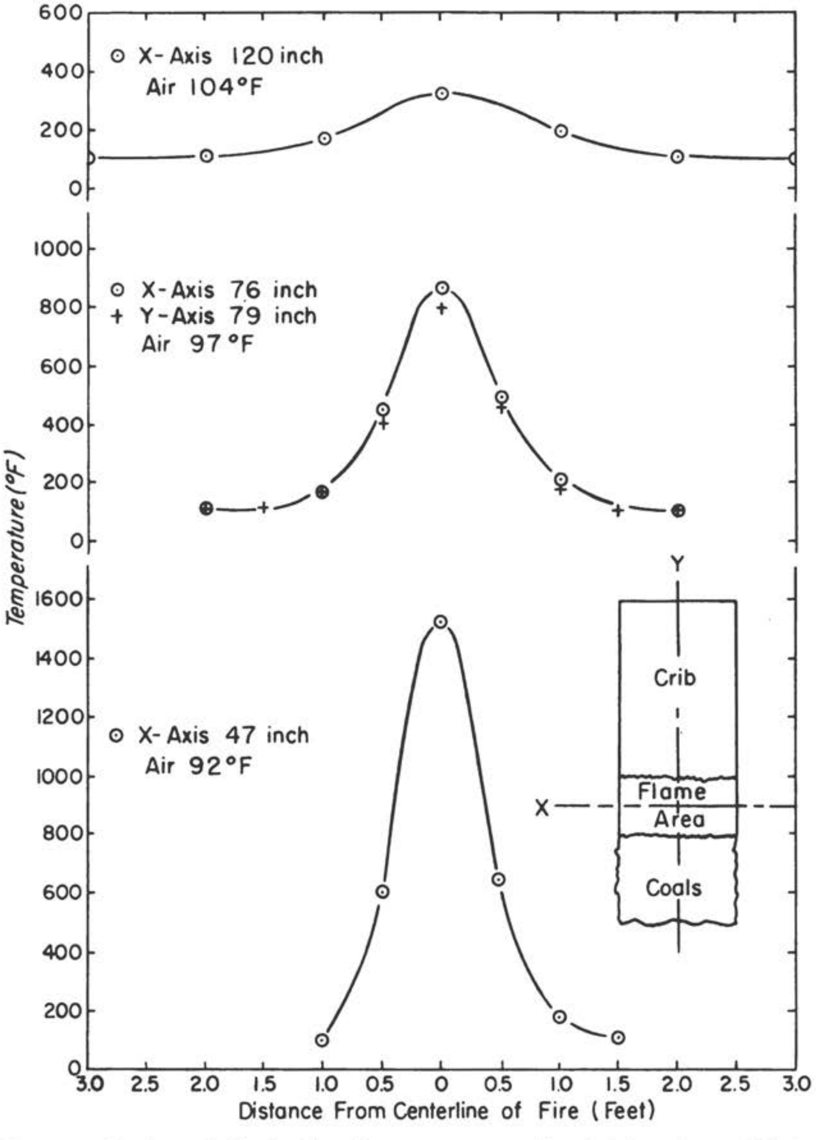

Figure 11. Horizontal distribution of temperatures at four heights above table top measured by thermocouples along X and Y axes.

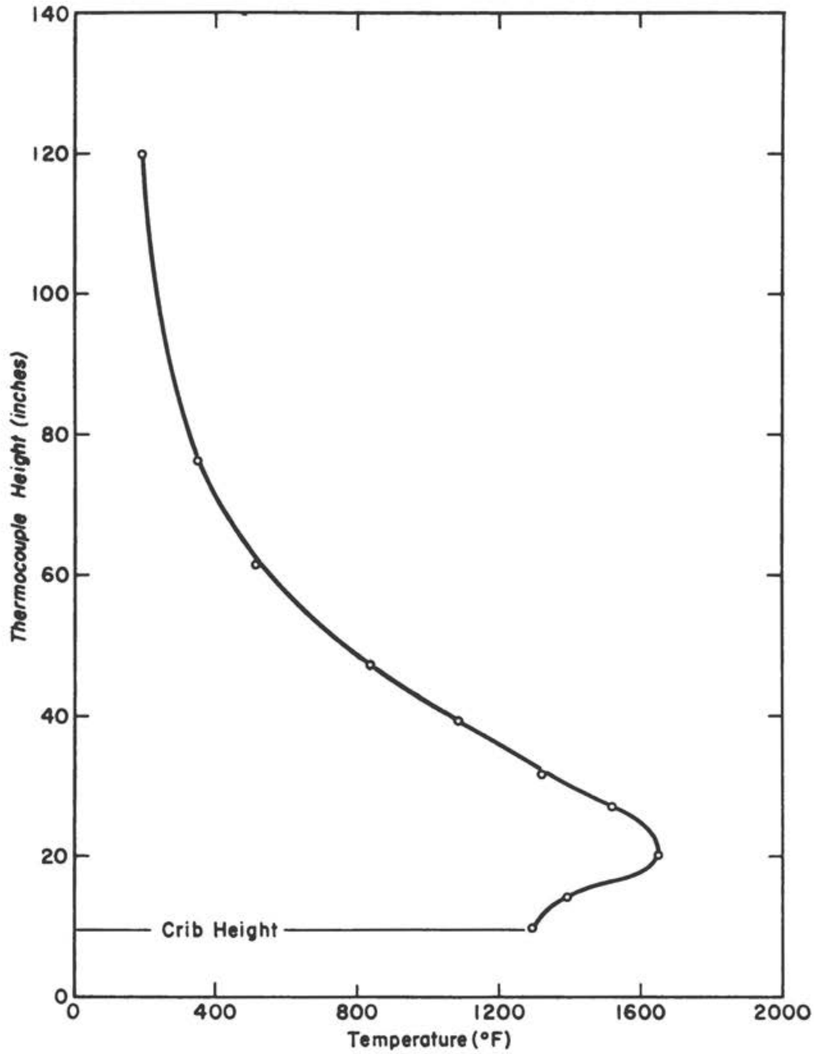

Figure 12. Vertical temperature distribution along central axis of flame and convection column.

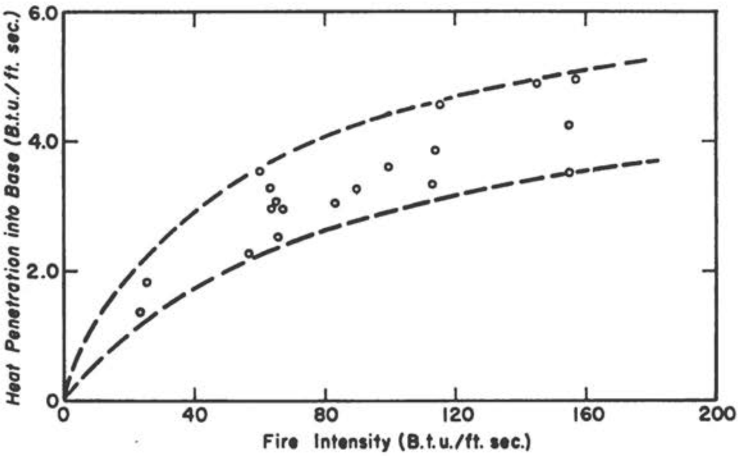

Figure 13. Relation between fire intensity and penetration of heat into the concrete base.

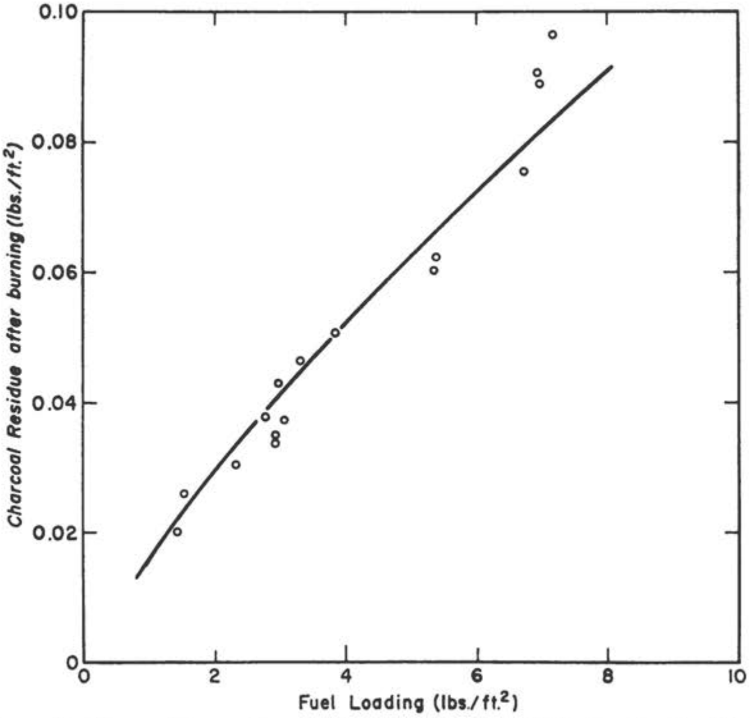

Figure 14. Charcoal from cribs of different fuel loading (½-inch white fir sticks).

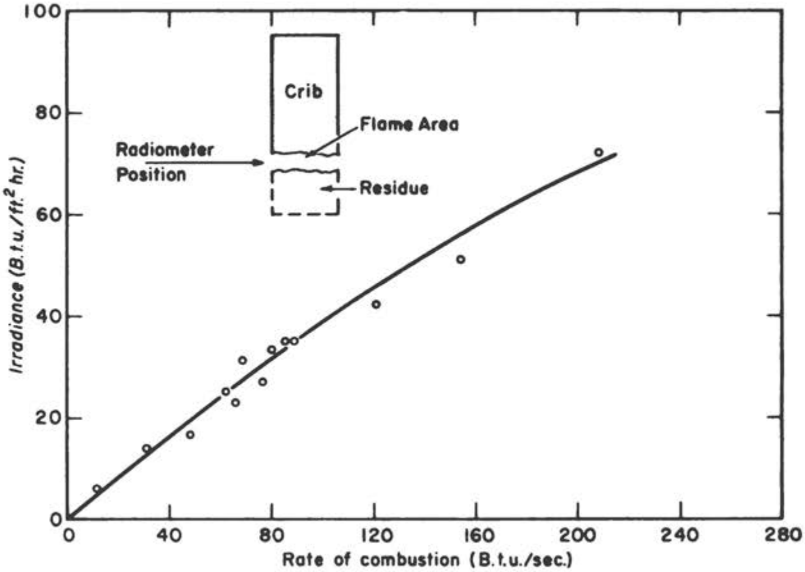

Figure 15. Irradiance from wood cribs at various rates of combustion. Radiometer at a radius of 14 feet, 20° above the horizontal.

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Experiments With Model Mine Fires

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SUMMARY

This report describes some experiments on the burning of wood in a ventilated duct. The wood was arranged to represent that normally present in a wood-lagged mine roadway. Preliminary experiments were made to decide the choice of suitable fuels and appropriate fuel density. In a second series of tests the effect of varying the air speed on the temperatures developed and on the production of oxides of carbon was studied. Differing modes of fire propagation in different air speed ranges were revealed and relationships were obtained between air speed and the length of fire in the duct and between air speed and the rate of penetration of the wood by the fire.

Introduction

The documentation of large fires in coal mines is seldom satisfactory because, when danger to life or of serious economic loss is involved, extinction of the fire is more important than recording its progress. Some large-scale experimental fires have been studied in detail and the results are extremely valuable. Experiments of this kind are time-absorbing and expensive and the use of small-scale models seems to offer a way of obtaining useful knowledge quickly. As a first step towards determining the applicability of model techniques, a simple model of a mine gallery was constructed and exploratory experiments on the propagation of a fire along the model gallery (or duct) were conducted. Because one factor of great importance in the development of mine fires is the supply of oxygen (which in practice depends on the air velocity along the duct), the effect of varying this on the propagation of a fire in the model was studied in some detail.

Apparatus

The Ventilated Duct

The duct was 48 feet long, composed of eight sections of equal length, and made of sheet steel; the bottom and sides were formed as a trough and lined with fire brick 1 inch thick. On top, each section had a removable lid lined with asbestos ½ inch thick. The internal dimensions were 6.5 by 4.75 inches and the cross-sectional area was 0.214 square feet. This represents a typical mine roadway of 8 by 6 feet to a linear scale of 1:15.

Ports were formed as tubes 4 inches long and 2 inches diameter, set into the side wall of the duct, having both inner and outer ends covered with transparent mica discs. The discs were easily replaceable and the inner ones were not tightly sealed to the ports, which were kept free of smoke by a slow stream of air fed to each port from a central supply. The quantity reaching the fire through the ports was quite negligible compared with the main flow.

The main air supply for the duct was provided by blowers of the forge type with a maximum capacity of 115 cu ft/min. The air flow was measured by the pressure difference across a standard orifice plate in the supply pipe, and was controlled by a gate valve.

Instrumentation

Temperatures were measured by 18 unshielded chromel-alumel couples, situated centrally in the duct section, one opposite each viewing port. They were switched in turn to a recording milliammeter by a thyratron switching circuit through a D.C. amplifier and a reference unit.

Gas analysis for carbon monoxide and carbon dioxide was by infrared analysers. The sampling point was 3 feet beyond the end of the fire zone and the samples were drawn by a suction pump through a narrow bore tube and appropriate drying and absorption vessels. The instantaneous values recorded by the analysers were corrected for the delay in sampling. The total gas flow for analysis was about 9 l/min.

Experimental

Some preliminary experiments showed that a suitable means of starting the fires was to use an electrically heated wire to ignite a small quantity of wood wool. Tests were then made to decide the choice of a suitable fuel.

Tests with Hardwood

The results of experiments with various types of hardwood are summarized in Table 1. The method of arranging the fuel was varied and it was found that only when the wood lagging covered both sides and roof of the duct did the fire progress along the whole of the fire zone. The importance of supporting radiation to the continuance of a full-scale fire is well known and it was satisfactory to note that a similar criterion applied in a small-scale model. In these first experiments, visual observation of the fire was unsatisfactory as arrangements for purging the ports of smoke had not been made and no reliable measurements of fire length could be made.

Gas analyses showed that at maximum burning rate all the available oxygen was used. In experimental fires of limited length in an underground roadway at Buxton, the oxygen concentration seldom fell below 15 per cent. This difference must be remembered when the results are being compared.

Tests with Softwood

Strips of red deal 0.25 inch thick were arranged on the floor, larger pieces being supported at one end by smaller ones. The arrangement was similar to that used in experiment 9 with hardwood. Results are given in Table 2. Continued propagation was obtained in three of the tests. The results are consistent with the idea that regular propagation is obtained with fuel densities of about 1 lb/cu ft of duct volume, which is almost exactly the same as that in an arched roadway of the typical dimensions, 8 by 8 feet, lined on sides and roof with boards one inch thick. When the density exceeded this figure, fires in the duct had alternating periods of greater and lesser activity and the time of burning increased. Below this figure fires did not propagate.

TABLE 1. Tests with Hardwood

Expt. No.	Placing of fuel	Moisture Content %	Density lb/cu ft of duct	Airflow cu ft/min	Duration of fire min	Products of Combustion Max. CO_2%	Products of Combustion Max. CO%	Remarks
4	Roof and Sides	14	8	61	82	21	5.7	Extended full 37 ft
5	" " "	16	8	61	87	22	5.7	" " " "
6	" " "	15	8	50	89	15	5.7	" " " "
7	" " "	15	8	66/120	67	20	10.0	" " " "
23	" " "	10	8	35/66	89	20	5.0	" " " "
24	2 Sides	10	4	42/61	14	—	—	Went out at 21 ft
8	1 Side	15	2	50	—	—	—	" " " 2 ft
22	Roof	10	4	30/70	—	—	—	" " " 1 ft
18	Random on floor	10	2	50	10	15.7	5.0	" " " 6 ft
19	" " "	10	1	39/66	—	—	—	" " " 7 ft
9	Echelon on floor	15	1	55	—	—	—	" " " 6 ft

TABLE 2. Tests with Softwood

Fire No.	Moisture Content %	Density lb/cu ft	Airflow cu ft/min	Duration of fire min	Remarks	Maximum Waste Gases CO_2%	Maximum Waste Gases CO%
11	10	0.5	33/47	—	Went out at 14 ft	6	0.15
12	10	0.5	35	11	" " " 7 ft	—	—
10	10	1	45/50	13	Extended full 37 ft	10	0.6
13	10	1	41/53	20	" " " "	13.5	5.9
14	10	1	35	21½	" " " "	13.5	5.5
17	10	3	30/50	42	Spasmodic propagation	13	5

Tests with Fibreboard

Attempts to establish a self-propagating fire with fibreboard strips were unsuccessful. The fuel only smouldered for a short time after ignition.

Discussion

These experiments showed the importance of fuel type, method of arrangement and fuel density, and it was decided that, for the next phase of the work (the effect of ventilation), hardwood disposed on the sides and roof of the duct would be adopted as standard.

Although in the early work the control of variables was to some extent unsatisfactory, temperatures of about 850°C were recorded by the thermocouples. This figure corresponds with that recorded for full-scale fires.

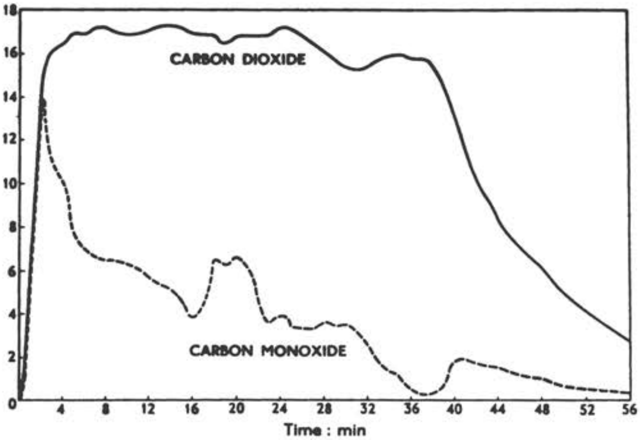
Later, this experience resulted in improved control and improved methods of temperature recording were adopted.

Effect of Variations in Air Speed

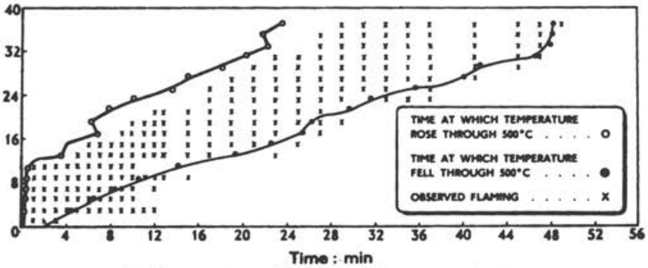
These experiments were made with pieces of hardwood conditioned to a moisture content of 10 per cent. The sides of the duct were lined with pieces 4.5 by 4.5 by 0.5 inches and the roof with strips 8.5 by 4.5 by 0.5 inches for the whole 37 feet available as fire zone. The fuel density was about 8.0 $\mathrm{lb/ft^3}$ of duct volume. The air speed was constant throughout each experiment, but air flow was not started until the igniting source (wood wool) was well alight. The delay was 10 to 20 seconds. Analysis for carbon monoxide and dioxide was, as before, by infrared analysers, readings being taken every half-minute. The instantaneous results were corrected to allow for the delay in sampling. A complete cycle of eighteen thermocouple readings was taken every minute. Visual observation through the air-purged ports was satisfactory.

Results for a Typical Fire

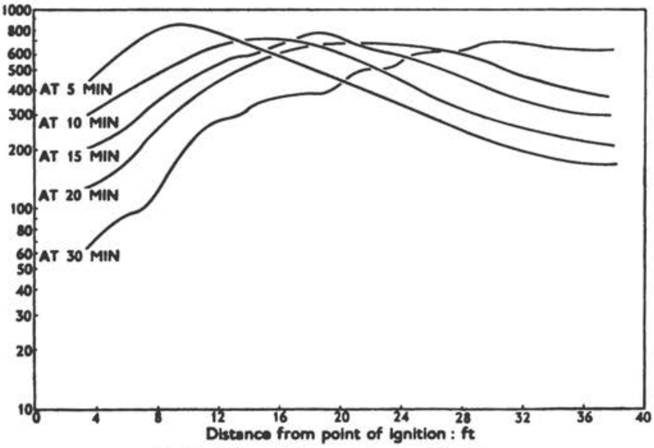
The way in which the proportion of the oxides of carbon in the waste gases varied with time is illustrated in Figure 1 (a).



(a) Variation of oxides of carbon with time



(b) Comparison of lengths of observed and derived zones of flaming combustion



(c) Variation of temperature with distance

Figure 1. Development of fire 33, Type III, continuous

In some fires there was a steady rise in the proportion of oxides of carbon from the moment of ignition; in others, the burning of the wood wool (used to ignite the main fuel) led to a rapid rise in the production of oxides of carbon followed by a fall as the wood wool burnt out.

The temperature attained by each of 18 thermocouples was recorded each minute; fire 33 lasted some 40 minutes and 720 temperatures were recorded. It is not possible to show these with clarity on a single graph. Figure 1 (c) shows selected results, namely the variations of temperature along the length of the duct at four times (10, 15, 20, and 30 minutes). The point of maximum temperature moved along the duct at the rate of about 0.6 ft/min. Once the conditions were approximately stable, at any one time the temperature fell exponentially with the distance along the duct.

The duration of a fire varies with the criterion adopted for defining it. The minimum temperature for the ignition of wood in an unvitiated atmosphere has been stated to be about 300°C and a fire may be considered no longer active when temperatures near the fire (but not actually in the fuel embers) fall below this figure. It must be noted that when the atmosphere reaching the fire is low in oxygen, the temperature at which active flaming ceases may be much higher than the 300°C at the start when the atmosphere had its normal proportion of oxygen. Many fires suggest 500°C as the appropriate figure. For fire 33, duration is recorded on four separate criteria:

Time during which temperature exceeded 300°C	59.3 min.
Time during which temperature exceeded 500°C	48 min.
Time until visible flaming ceased	49 min.
Time until all glowing ceased	61 min.

The differences between the first and last and between the second and third are unimportant. Because oxides of carbon continue to be produced as long as there is smouldering, there is possible correlation (which in practice was quite good) between the rates of fuel consumption measured directly, using the appropriate duration figure, and calculated from gas analysis figures. Arbitrarily, the durations listed in Table 3 are based on the first criterion.

The average rate of fuel consumption was estimated in two ways: (1) the known weight of fuel consumed divided by the

TABLE 3. The Effect of Air Speed Variation

Fire No.	Air Speed ft/min.	Fire Duration min.	Average % over the period of fire duration CO$_2$	CO	Average burning rate lb/min.	Maximum burning rate lb/min.	Maximum fire zone length ft	Maximum rate of penetration of burning in./min.
31	43	15.3	12.45	6.20	0.09	0.11	3	0.0086
37	100	25.3	—	—	—	—	7	—
26	133	36.0	10.20	5.70	0.23	0.37	9	0.0084
27	133	27.0	11.00	5.90	0.25	0.37	8	0.0105
35	154	152.0	8.50	2.85	0.20	0.43	9	0.0108
34	184	109.0	9.65	2.72	0.27	0.47	10	0.0106
38	186	121.0	—	—	—	—	12	—
28	206	136.8	9.85	4.76	0.33	0.57	11	0.0118
30	250	85.0	—	—	—	—	16	—
25	284	90.0	11.00	6.00	0.53	0.79	14	0.0128
33	350	59.3	12.52	3.48	0.66	1.00	21	0.0085
39	393	64.5	—	—	—	—	19	—
32	453	49.3	10.85	3.57	0.76	1.24	17	0.0166
36	482	50.7	—	—	—	—	17	—
40	490	52.0	11.40	4.00	0.87	1.28	21	0.0139
41	537	42.7	9.30	3.20	0.77	1.38	20	0.0157
29	615	41.7	9.90	3.48	0.94	1.70	21	0.0185

time of duration of fire 33 gives a figure of 0.70 lb/min, (2) the values for the proportions of oxides of carbon averaged over the whole period of burning, and a figure for the average rate of fuel consumption calculated as follows:

If the average $CO_2\%$ = X, and if the average $CO\%$ = Y,

$$\text{average rate } CO_2 \text{ production} = \frac{X}{100} \times V \text{ cu ft/min}$$

and

$$\text{average rate } CO \text{ production} = \frac{Y}{100} \times V \text{ cu ft/min}$$

where V = volume flow of air in cu ft/min.

Then, since $C + O_2 = CO_2$ and $2C + O_2 = 2CO$,

$$\text{average amount } O_2 \text{ used for } CO_2 \text{ production} = \frac{VX}{100} \text{ cu ft/min}$$

and

$$\text{average amount } O_2 \text{ used for } CO \text{ production} = \frac{1}{2}\frac{VY}{100} \text{ cu ft/min}$$

$$\text{Total } O_2 \text{ used} = \frac{V}{100}\left(X + \frac{Y}{2}\right) \text{ cu ft/min}$$

$$\text{Total air used} = \frac{100}{21}\,\frac{V}{100}\left(X + \frac{Y}{2}\right) \text{ cu ft/min}$$

The average amount of air required to consume one pound of hardwood is stated by Speirs[1] to be 67 cu. ft.

Hence, average rate of fuel consumption is given by

$$\frac{V}{21}\left(X + \frac{Y}{2}\right) \Big/ 67 \text{ lb/min}$$

For fire 33, application of this formula gives a value of 0.66 lb/min, which agrees well with that obtained by the first method.

If in this formula we substitute the maximum figures for the average ones, we obtain the figure of 1.0 lb/min for the maximum rate fuel consumption.

It may be noted that the sum of X and $\frac{Y}{2}$ as defined above equals the percentage of oxygen consumed by the fire. In many of the fires the sum approached 21 per cent which shows that the atmosphere was almost completely vitiated. In these conditions the zone of flaming combustion did not correspond with the zone over which the temperature exceeded 300°C.

Comparison of the observed fire zone length with the temperature records suggested that when the atmosphere was greatly vitiated a temperature of 500°C or above must be substituted for that of 300°C applicable when the atmosphere was fresh. Figure 1 (b) illustrated how the two criteria (observation and temperature in excess of 500°C) correspond for fire 33. The maximum observed fire zone length was about 21 feet and this occurred when the fire was 24 minutes old. At this time the fire front had reached the end of the duct and it is not possible to state whether the zone would have continued to increase had the duct been longer.

From the values for the maximum fire zone length and the maximum burning rate a value for the rate of penetration of the wood by burning can be derived.

If the maximum burning rate $= p$ lb/min, and the maximum fire zone length $= q$ ft, then, since the perimeter of the wood in the duct is 4.5 in + 4.5 in + 8.5 in $= \frac{17.5}{12}$ ft, the area of wood burning $= \frac{17.5q}{12}$ sq. ft.

Now a burning rate of p lb/min $= \frac{p}{36}$ cu ft/min since the measured density of the fuel used was 36 lb/cu ft.

The rate of penetration of burning into the wood

$$= \frac{p}{36}\,\frac{17.5q}{12} \times 12 \text{ in./min} = 0.222\frac{p}{q} \text{ in/min.}$$

In the case of fire 33, the rate was found to be 0.0085 in/min.

Results for All Fires

Fires may conveniently be described and compared by statement of a limited number of parameters. These may be, for instance, duration, proportion of oxides of carbon in the waste gases, average and maximum rates of fuel consumption, fire zone length and rate of penetration of the solid fuel by burning. Table

3 compares fires of 17 experiments on the basis of these headings. The gaps in the table are due to faults in sampling of the waste gases, to blockage by soot and tar, or to leakage of air into the sampling train.

Three types of fires are described in Table 3.

1) Fires which did not propagate at low air speeds (Nos. 26, 27, 31, 37). When the oxygen vitiation was almost complete, active flaming ceased and production of the oxides of carbon decreased rapidly. Smouldering continued for some time after this, but was eventually extinguished when the fire had only travelled a short distance along the duct.

2) Fires which propagated at medium air speeds along the whole length of the duct, although not at a steady rate (Nos. 25, 28, 30, 34, 35, 38). In fire 25, a period of high activity was followed by one of slow smouldering which lasted as long as 25 minutes. Flaming combustion recommenced, died again and a second period of smouldering began. This cycle of lull and revival was repeated several times.

3) Fires which propagated at high air speeds through the whole fire zone without check (Nos. 29, 32, 33, 36, 39, 40, 41).

Figure 2 shows the duration of the fires plotted against air speed. There is a marked discontinuity at about 150 ft/min when there is a transition from a fire which does not propagate to one that propagates cyclically. This point may correspond with a transition from laminar to turbulent flow. Turbulent flow is generally associated with Reynolds numbers exceeding 3,000. A dimension of 14.2 cm. can be calculated as the equivalent diameter of the duct; taking the viscosity of air at 850°C as 450×10^{-6} poise, a value for the critical velocity of 142 fpm is obtained. This lies in the transition region between 133 and 154 fpm in which the discontinuity occurs in Figure 4.

A low degree of turbulence may be expected to lead to an accumulation of products of combustion on the fuel surface and may thus explain why type (1) fires are self-stifling. As turbulence increases with increasing air speeds, the transition zone is reached and, although some self-stifling occurs, it does not persist because as the temperature drops turbulence is increased. The fire then revives and the cyclic phenomena with fires ventilated at air speeds between 150 and 300 ft/min are observed.

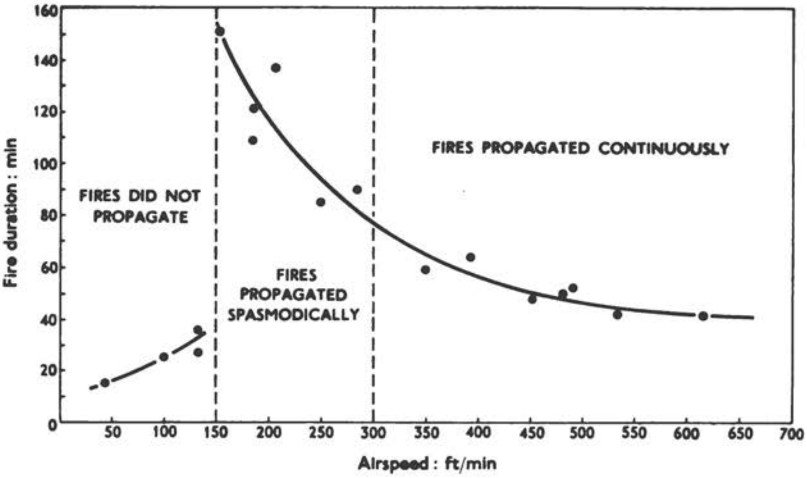


Figure 2. Variation of fire duration with air speed

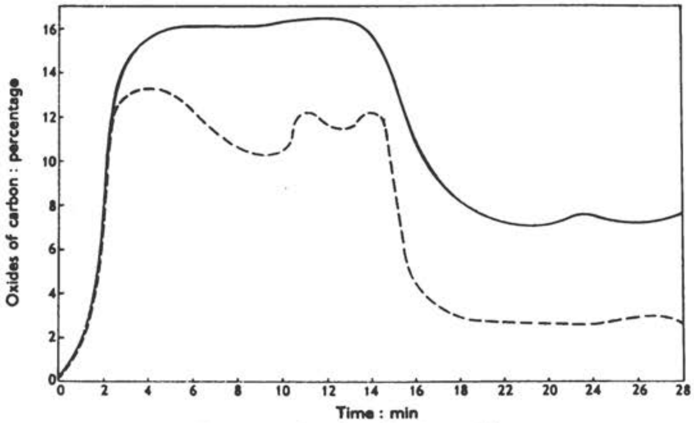
Above the latter figure, turbulence is complete, and the fires propagate continuously.

It is worthy of note that in none of the type (2) fires did the temperature fall below 325°C during the periods of quiescence, and that, when the oxygen supply was adequate, flaming combustion recommenced.

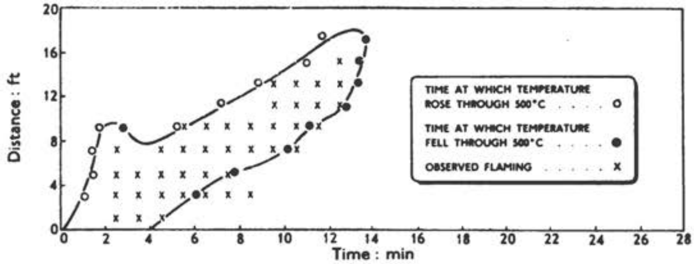
Figures 3, 4, and 5 show the variation of carbon monoxide and dioxide with time, comparisons of the observed and derived fire zone lengths, and the variation of temperature with distance from the ignition point at various times, for the three types of fire.

Figure 6 shows that the relationship between maximum burning rate derived from the analyses of oxides of carbon and air speed is nearly linear over the range considered. The graph of average burning rate against air speed shows a discontinuity at about 150 ft/min corresponding with the one already found in the duration of fires at the same air speed. The flattening of the curve at higher air speeds suggests that an average burning rate of about 1 lb/min is unlikely to be exceeded. The curve in Figure 7 (variation of maximum fire zone length with air speed) also flattens at high air speeds.

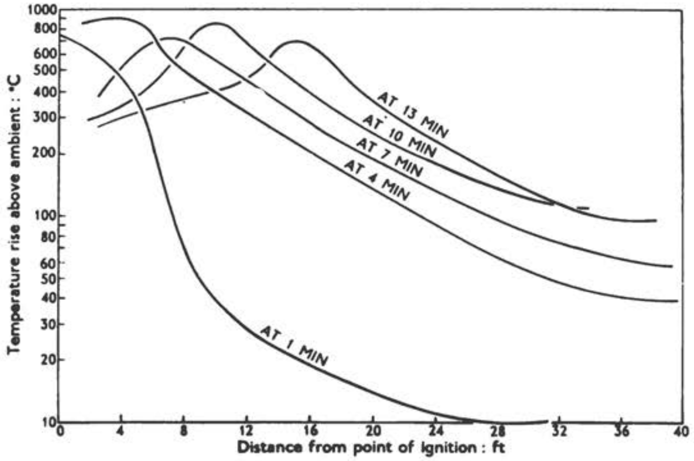
The observed fact that duration, average burning rate, and maximum length all tend to approach limiting values at high air



(a) Variation of oxides of carbon with time

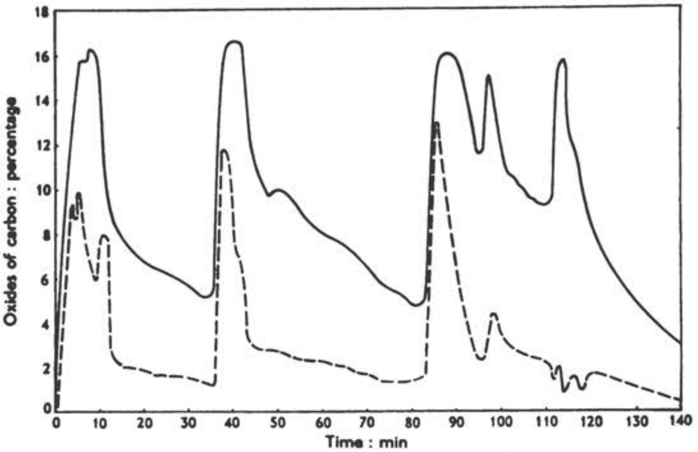


(b) Comparison of lengths of observed and derived zones of flaming combustion

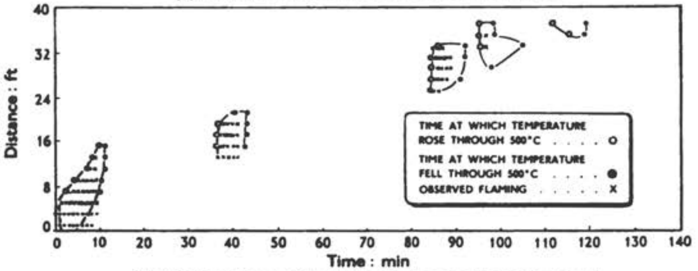


(c) Variation of temperature with distance

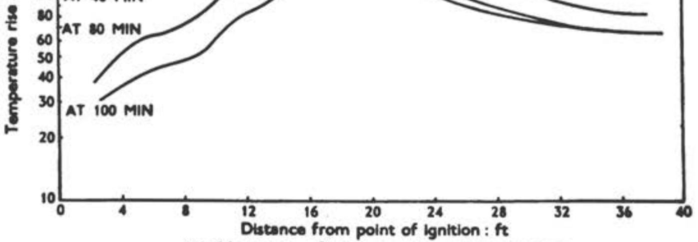
Figure 3. Development of fire 26, Type I, self-stifling



(a) Variation of oxides of carbon with time



(b) Comparison of lengths of observed and derived zones of flaming combustion



(c) Variation of temperature with distance

Figure 4. Development of fire 35, Type II, spasmodic

speeds may be because the duct is of limited length. There was no similar observed limit to the maximum burning rate. It is to be expected that, when all or nearly all the available oxygen is being consumed, the burning rate will depend only on the air speed.

Figure 8 shows that the variation of the maximum rate of penetration of the wood by burning with air speed is approximately linear, but the scatter of the results makes any rigid conclusions impossible. At the highest air speeds the maximum penetration rate approaches the figure of 0.025 in/min quoted by Lawson and others.[2]

Discussion of Results

The results obtained during the tests are useful chiefly in indicating the limits of a model duct as small as the one used. Calculation shows that of the heat developed during a fire in the model, between 50 and 65 per cent is lost by conduction through the walls. In a full-scale fire, conduction losses are quite small. Although accurate analyses of the waste gases of large fires are rarely available, it is believed that the oxygen content seldom falls below 15 per cent, whereas, in the model vitiation was almost complete. In a model considerably larger than the one described, heat losses could be minimised and it could be expected that atmospheric conditions would approach those of a large-scale fire. As a guide to future experimentation and the design of larger models, the results may be summarised as showing that, with the existing small duct and in the conditions described

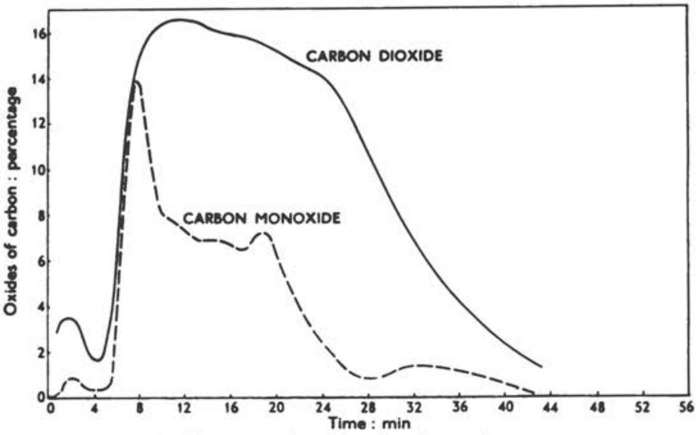
1) continued propagation of a fire with wood was only possible when roof and sides were lined with fuel, that is, when there was supporting radiation,

2) when the fuel was softwood,

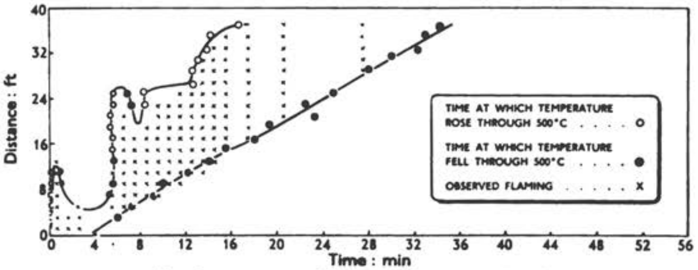
a) increasing fuel density increased the time of duration of the fire,

b) for continued propagation there was an optimum fuel density corresponding with that recorded for some large-scale fires,

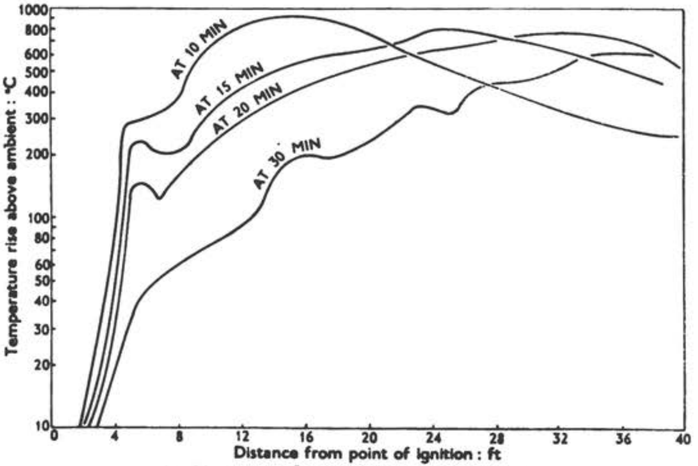
c) above this fuel density, fires propagated spasmodically,



(a) Variation of oxides of carbon with time



(b) Comparison of lengths of observed and derived zones of flaming combustion



(c) Variation of temperature with distance

Figure 5. Development of fire 29, Type III, continuous

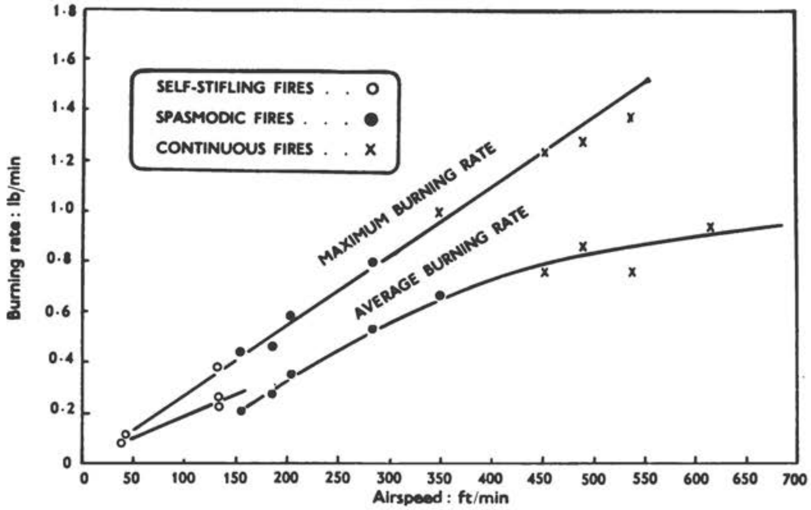


Figure 6. Variation of average and maximum burning rates with airspeed

3) maximum temperatures attained approached 1000°C as in full-scale fires,

4) there was a narrow range of air speeds (150 to 300 ft/min) below which fires did not propagate and above which they propagated continuously; at air speeds in this range propagation was spasmodic; there is some evidence that the range covers the transition from laminar to fully turbulent conditions,

5) when the atmosphere reaching the fire was greatly vitiated, a fall of temperature below 500°C might cause the extinction of active flames, but any criterion of the "duration" of a fire must be to some extent arbitrary,

6) when the fuel was hardwood the maximum burning rate bore an approximately linear relationship to the air speed.

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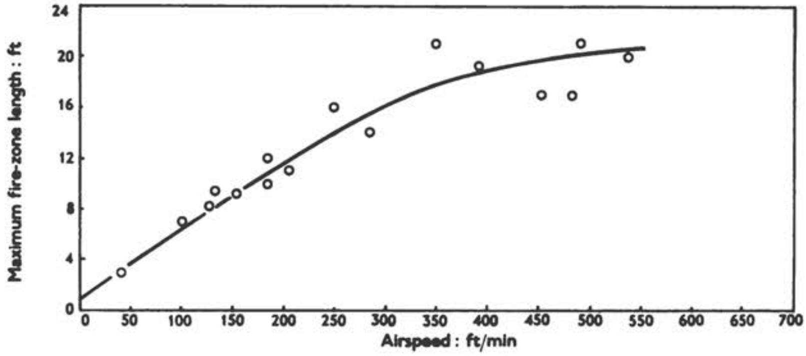

Figure 7. Variation of maximum fire zone length with airspeed

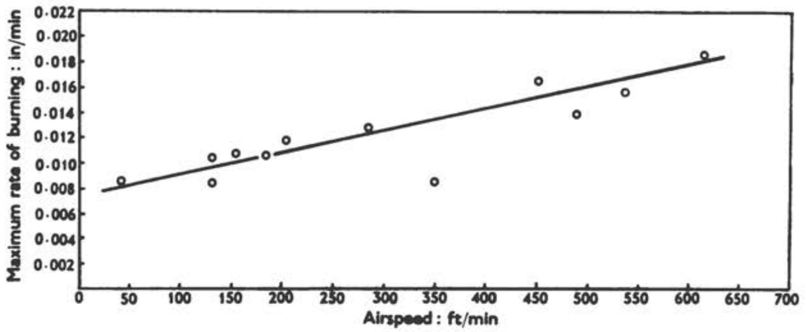

Figure 8. Variation of maximum rate of penetration of burning with airspeed

Discussion

Dr. Dawes: With the permission of the Chairman, I would like to tell you a little about two other types of work on models being carried out at the Safety in Mines Research Establishment (Great Britain). The first is connected with the forensic work that proceeds after there has been an ignition of methane-air in a coal mine. After the incident there may be doubt about the cause of the ignition, even about the site of the point of ignition. Often the only definite information the investigators have is that obtained by themselves on the geographical spread of the flame in the underground workings. The possibilities of models in helping to determine the point of ignition, the disposition of flammable gas mixtures and the progress of the flame have been explored at the Safety in Mines Research Establishment by Dr. H. Titman.*

A number of models of underground workings in which ignition of gas had occurred, where there were surviving witnesses and where there was little doubt about the point of ignition, were constructed. Flammable gas mixtures were created in different parts of the models and were ignited at different places. The progress of the flame and its spread were noted. (A film was then shown in which experiments on flame propagation in two transparent plastic models were demonstrated.) Titman has shown that so long as the model is aerodynamically matched to the rest of the ventilating circuit in the same way as in the actual incident, then the spread of flame and the relative duration of burning observed in different parts of the model is only matched if the point of ignition and the disposition of gas is the same in the model as in the real life incident. This leads to the possibility of using a model technique to locate a source of ignition.

The second sphere of work in which modeling techniques are being used concerns the behaviour of buoyant gas in an air stream. Since the work is likely to be of interest in the field of fire research, I take this opportunity of bringing it to your notice. So far we have published only one interim report.†

In coal mining we are faced with the ever present hazard of methane, which of course is a flammable buoyant gas and which seeps into the roadways and working places of a coal mine. The ventilation of a coal mine is largely designed to dilute this methane to below its flammable limit and thus to avoid the hazard due to explosion following an ignition that might follow adventitious mechanical or electrical sparking. But, it is not sufficient just to provide enough air to dilute the methane; it is, of course, essential that the air and the methane are mixed. This means that, in a given situation, with a given inflow of methane, there is a requirement for a minimum air velocity as well as a

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* TITMAN, H. "The Use of Models in the Investigation of Underground Methane Explosions," Safety in Mines Research Establishment (Sheffield, England) Research Report No. 163 (February 1959).

† BAKKE, P. "Some Interim Notes on Methane Roof Layers," Safety in Mines Research Establishment (Sheffield, England) Research Report No. 164 (February 1959).

minimum air quantity. In order to make recommendations on the operational criteria to aim for, it has been necessary to study, both theoretically and experimentally, the general problem of movement and turbulent diffusion in flows of mixed fluids. This problem is analogous in some ways to the buoyancy problems encountered in fires. The treatment of the problem, which has been developed by Bakke is based on the simultaneous solution of the equations of motion, continuity, and diffusion with an eddy diffusivity depending on the Richardson number. It incorporates a leading assumption regarding the expression of the Richardson number in terms of average properties of the flow. The theory therefrom developed enables predictions to be made of the rate of movement and turbulent diffusion of the buoyant layer in dependence on the velocity of the ventilating flow. A graph showing an example of the theoretical results was shown. This concerned the relation between the parameters $\bar{u}/\left(g\frac{\Delta\rho}{\rho}\frac{V}{D}\right)^{1/3}$ and $u_\delta/\left(g\frac{\Delta\rho}{\rho}\frac{V}{D}\right)^{1/3}$ where u_δ is the ventilating velocity at the edge of the buoyant layer, $\bar{u}$ is the mean velocity of the layer, g is gravitational acceleration, $\Delta\rho/\rho$ the relative density difference, and V the volume flux of the layer prior to mixing. D is the width of the channel.

The predictions of the theory have been verified in such experimental work as has been completed. Experiments are in part large-scale, but the bulk of experimental information is obtained from small-scale models.

Dr. Olson: In the model mine fire where you had the wood with a forced draft, as I understand it, this flame would build up with time over a reasonably long period, several minutes, and then die down; is that the time scale?

Dr. Dawes: It depends on the velocity range. At air speeds above about 300 ft/min in the model gallery the fires propagate continuously. They reach maximum intensity in about 5 minutes and burn evenly for about 50 minutes. At air speeds below about 150 ft/min the fires again take about 5 minutes to build up, but after about 15 minutes have stifled themselves and do not revive. In the intermediate range of 150 to 300 ft/min a type of spasmodic burning occurs. The fire will burn brightly for perhaps 5 or 10 minutes and then will be quiescent, perhaps for as much as 30 minutes before again reviving, and this type of cycle may be repeated a number of times. Dr. Roberts of Imperial College, London, has offered a quantitative explanation of the observed phenomena which will eventually be published as a Safety in Mines Research Establishment Research Report. Qualitatively, his picture is that when the flame has been started, heat is transferred from the flame to the wood and products are distilled off and inflame. If the heat transfer is adequate the fire will propagate continuously. If, however, there is insufficient heat transfer from the main air stream to the wood, the distillation is reduced and inflammation ceases. However, smouldering combustion continues and if the heat conducted from a smouldering region through the wood promotes sufficient distillation the products can be ignited by the smouldering area and again inflammation will occur. The periods of inflammation are, however, quite short in comparison to the over-all duration of the fire. Figure 4 (b) in the paper gives typical quantitative information.

Dr. Olson: Are they on the order of a minute or two?

Dr. Dawes: Inflammation continues for periods of a few minutes, the quiescent periods cover up to 40 or 45 minutes. During the quiescent periods the temperature, measured by thermocouples in the center of the cross section remains, over some region at least as high as 300°C, but did not, in the quiescent periods, exceed 500°C.

Dr. Shipman: Can you tell us what the capital V is?

Dr. Dawes: The parameter shown on the graph relating methane layer velocity with ventilating stream velocity, i.e. $u/\left(g\frac{\Delta\rho}{\rho}\frac{V}{D}\right)^{1/3}$ is not the Richardson number. It is a parameter which it is convenient to use in describing methane layering phenomena. At the Safety in Mines Research Establishment we call it the Bakke number, after the man who has developed the theory. In the case presented in the graph, V is the volume of methane entering the system in unit time and $\Delta\rho$ is the difference in density between the methane and the air. A discussion of the Richardson number is to be found in the paper by Bakke which has been referenced earlier.

Dr. Shipman: And the D is the dimension?

Dr. Dawes: D is the width of the roadway into which the volume V of methane is issuing in unit time.

On The Self-Ignition of Wood Materials

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Introduction

If combustible materials are piled on the ground they often ignite spontaneously. Whether they ignite by themselves or not depends not only upon the chemical and physical properties of the materials, but also upon their quantities and the ambient temperature.

If wood materials are piled in the open air, self-ignition takes place only if the materials are piled mountain-high. This is because the accumulation of heat from the chemical reaction inside the pile is very slow. It is, therefore, practically impossible to carry out experiments on self-ignition of this kind.

If the differential equation for self-ignition could be solved analytically, experimental investigations for this phenomenon would be of no use, but actually it is impossible to solve the equation completely. Thus, to study self-ignition of slow-heat-producing materials, it becomes necessary first to find an approximate solution which does not depend on the size of the sample, and second to ascertain whether this solution is consistent with the experimental results obtained using a sample of small size.

The authors have solved the differential equation approximately in the case of a spherical sample kept in a uniform temperature field, and have found how temperature rises with time.

These results were compared with those of experiments conducted using sawdust contained in a sphere of wire gauze. The theoretical and the experimental results showed close agreement with respect to the qualitative pattern of temperature rise with time; and, if the consumption of material during the process is suitably assumed, the agreement becomes quite satisfactory.

Thus the solution is considered to be applicable to the self-ignition of spherical samples of large size placed in a constant uniform temperature field.

Fundamental Equation for Self-Ignition

We considered the heat generation due to chemical reaction of the material to be of the Arrhenius type, as is commonly assumed. Then, if the thermal conductivity of the material is assumed constant, the fundamental equation for self-ignition is as follows:

$$c\rho \frac{\partial T}{\partial t} = k\nabla^2 T + Ae^{-E/RT} \tag{1}$$

where $Ae^{-E/RT}$ = Arrhenius heat generation term per unit volume
T = absolute temperature
c = specific heat of the material
k = thermal conductivity of the material
ρ = density of the material
E = activation energy of the material
R = gas constant.

We considered the case in which a specimen of uniform material in the form of a slab, cylinder, or sphere is placed in a region of temperature T_a. The above equation is transformed into the following well known equation of dimensionless quantities, assuming c and ρ constant.

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial \xi^2} + \frac{m}{\xi}\frac{\partial \theta}{\partial \xi} + \delta e^{\theta} \tag{2}$$

where δ = discriminant $= A\,\dfrac{r^2}{k}\,\dfrac{E}{RT_a^2}\,e^{-E/RT_a}$

θ = reduced temperature $= \dfrac{E}{RT_a^2}\,(T - T_a)$

ξ = reduced distance = $\frac{x}{r}$

τ = reduced time = $\frac{k}{c\rho r^2} t$

m = 0 for a slab, $m = 1$ for a cylinder and $m = 2$ for a sphere

r = radius for a cylinder and a sphere, half thickness for a slab

x = distance from the center (for $m = 2$), from the central line (for $m = 1$), or from the central plane (for $m = 0$).

Strictly speaking, A and accordingly δ cannot be constants but must change gradually due to the consumption of the material. However, we assumed first that their variation was very slow, and examined this assumption to determine whether it was reasonable in the light of experimental results.

Solution of the Fundamental Equation

Equation (2) for the case of a steady state, i.e. for $\frac{\partial \theta}{\partial \tau} = 0$, has been extensively studied and solved by several authors.[1] However, the equation in its complete form is unsolvable, and therefore we tried to arrive at an approximate solution for it.

Since the difficulty in solving (2) arises from the inclusion of the term e^θ, we assumed the approximation

$$e^\theta = 1 + \beta\theta \tag{3}$$

where β is a constant with respect to θ and ξ. If one assumes β to be a certain absolute constant, equation (3) will be too rough an approximation. Therefore, we assumed β a function of θ_0, i.e. the temperature in the center of the specimen and the highest among the temperatures at all points of the specimen at that time. Thus we put

$$\beta = 1 + a_1\theta_0 + a_2\theta_0^2 \tag{4}$$

If the temperature in the center at an instant t is θ_0, we consider that equation (4) holds throughout the time interval 0-t. The constants a_1 and a_2 depend on the shape of the specimen.

For the steady state, we obtain

$$\frac{d^2\theta}{d\xi^2} + \frac{m}{\xi}\frac{d\theta}{d\xi} + \delta(1 + \beta\theta) = 0$$

We can easily solve this approximate equation and its solution should concide with the one which has been already obtained by many authors. β should be chosen just to meet this requirement. Thus, for example, if the specimen is spherical[2]

$$\beta = 1 + 0.3691\theta_0 + 0.0908\theta_0^2 \tag{5}$$

This is the answer obtained for the stationary state. Nevertheless, if we assume that equation (5) can be extended to the non-steady state, the fundamental equation

$$\frac{\partial\theta}{\partial\tau} = \frac{\partial^2\theta}{\partial\xi^2} + \frac{2}{\xi}\frac{\partial\theta}{\partial\xi} + \delta(1 + \beta\theta)$$

is solved, and for the conditions

$$[\theta]_{\tau=0} = 0, \left[\frac{\partial\theta}{\partial\xi}\right]_{\xi=0} = 0, \left[\frac{k}{r}\frac{\partial\theta}{\partial\xi} + \alpha\theta\right]_{\xi=1} = 0 \tag{6}$$

where α means heat transmission coefficient, the solution is as follows:[2]

$$\begin{aligned}\theta = \frac{1}{\beta}\left(\frac{\mu \sin q_0\xi}{\xi(q_0 \cos q_0 + \overline{\mu - 1}\sin q_0)} - 1\right) \\ - \frac{4\mu q_0^2}{\beta}\sum_{n=1}^{\infty}\frac{e^{(q_0^2 - q_n^2)\tau}\sin q_n}{q_n(2q_n - \sin 2q_n)(q_n^2 - q_0^2)}\frac{\sin q_n\xi}{\xi}\end{aligned} \tag{7}$$

where

$$\mu = \frac{\alpha}{k}r \tag{8}$$

$$q_0 = \sqrt{\beta\delta} \tag{9}$$

$$\tan q_n = -\frac{q_n}{\mu - 1},\ n = 1, 2, 3 \tag{10}$$

Thus, for the center temperature θ_0, we obtain

$$\begin{aligned}\theta_0 = \frac{1}{\beta}\left(\frac{\mu q_0}{q_0 \cos q_0 + \overline{\mu - 1} \sin q_0} - 1\right) \\ - \frac{4\mu q_0^2}{\beta} \sum_{n=1}^{\infty} \frac{\sin q_n}{(2q_n - \sin 2q_n)(q_n^2 - q_0^2)} e^{(q_0^2 - q_n^2)\tau}\end{aligned} \qquad (11)$$

Now, when μ is not small, equation (10) shows that $q_n \simeq q_1 + (n - 1)\pi$, and the terms for $n > 2$ in the series (11) can be neglected except for the short period after the start. Then equation (11) transforms into

$$\begin{aligned}\tau = \frac{1}{q_1^2 - q_0^2} \log_e \left\{ \frac{1}{(2q_1 - \sin 2q_1)(q_1^2 - q_0^2)} \right. \\ \left. \times \frac{4q_0^2\mu \sin q_0}{\dfrac{\mu q_0}{q_0 \cos q_0 + \overline{\mu - 1} \sin q_0} - (1 + \beta\theta_0)} \right\}\end{aligned} \qquad (12)$$

This equation together with (9) and

$$q_1 = -(\mu - 1) \tan q_1, \ (q_1 < \pi)$$

gives τ corresponding to any θ_0. Figure 1 shows some examples of the relation between τ and θ_0. For some (δ, μ), θ becomes stationary after a long time, while for others (δ, μ), θ rises very rapidly after a certain time. This is to be considered the ignition time.

Comparison with Experimental Results

These theoretical results were compared with the experimental ones obtained by one of the authors.[3] In this experiment a spherical gauze (wire screen) basket containing sawdust was suspended in the center of a rectangular copper vessel which was heated uniformly from outside by a number of nichrome heating systems. Figure 2 shows the heating system as well as the spherical basket. The temperatures inside the sawdust were observed by thermocouples (copper-constantan, 0.18 mm. diameter) at six points along a horizontal radius. Various spherical baskets of different sizes were used and the temperature of the copper vessel was adjusted to several values.

Figures 3 and 4 are examples of these results, and the latter corresponds to the case of self-ignition. The time in these figures

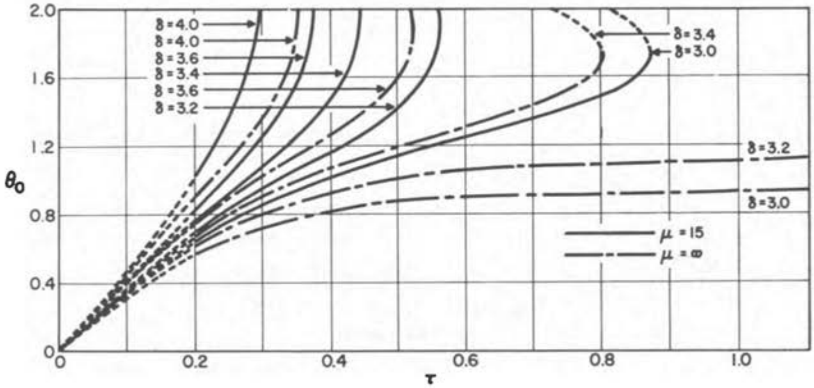

Figure 1. Relations between θ_0 and τ for several δ's and for $\mu = 15, \infty$.

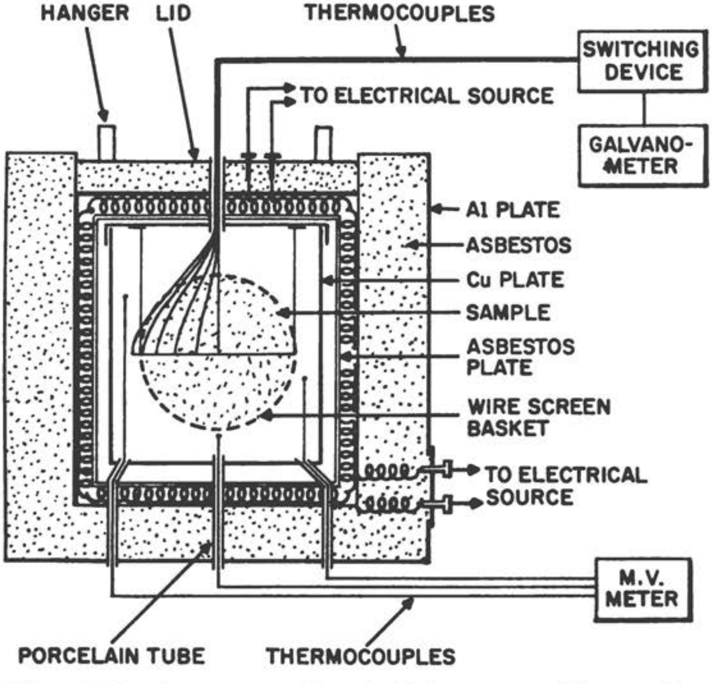

Figure 2. Heating system and a spherical gauze containing sawdust

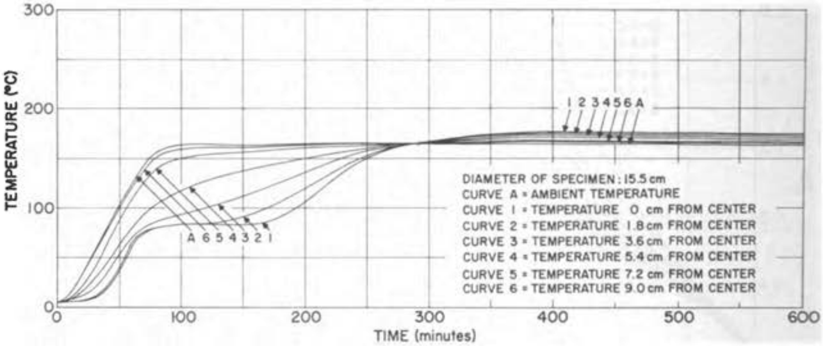

Figure 3. Variation of temperatures inside a sawdust (Japanese cedar) specimen. No self-ignition.
$\delta = 3.19, \mu = 24.3$

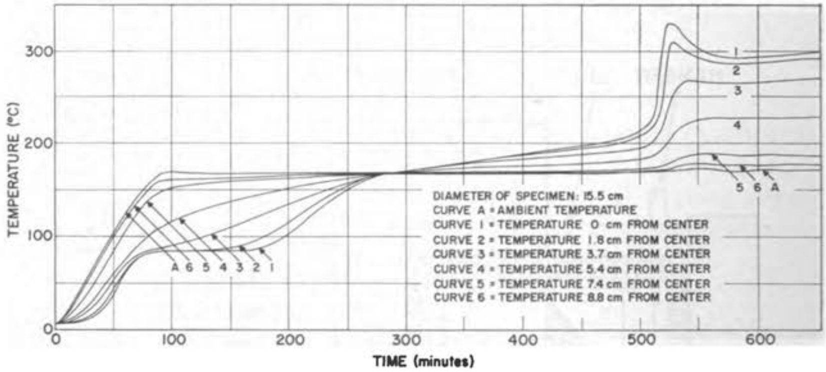

Figure 4. Variation of temperatures inside a sawdust (Japanese cedar) specimen. Self-ignition.
$\delta = 4.62, \mu = 24.3$

is measured from the instant the basket is put into the copper vessel.

It is interesting that, in both cases, the temperatures at all points of the sample attain the ambient temperature at the same time, that is to say, the temperature inside the sample is uniform and equal to the surroundings at this instant. We can choose this instant as the origin of τ, and thus the initial condition $[\theta]_{\tau=0} = 0$ is satisfied.

Figure 5 shows one of the experimental results expressed in terms of τ and θ. Small circles mean the experimental results and the dotted curve means the corresponding theoretical one calculated by equation (12), using the following data which have been obtained by the same author with several other experiments.

$$
\begin{aligned}
c &= 0.44 \text{ cal g}^{-1}\ {}^\circ\text{C}^{-1} \\
\rho &= 0.14 \text{ g cm}^{-3} \\
E &= 26.1 \text{ kcal mol}^{-1} \\
A &= 1.46 \times 10^{9} \text{ cal cm}^{-3} \text{ sec}^{-1} \\
k &= 1.4 \times 10^{-4} \text{ cal cm}^{-1}\ {}^\circ C^{-1} \text{ sec}^{-1} \\
\alpha &= 4.4 \times 10^{-4} \text{ cal cm}^{-2}\ {}^\circ\text{C}^{-1} \text{ sec}^{-1}
\end{aligned}
$$

δ and μ in this experiment are 4.15 and 24.3 respectively.

Consumption of Material

The experimental and the theoretical results show agreement with respect to the qualitative behavior of temperature rise with time, but from the quantitative point of view the agreement is far from perfect. This discrepancy may be due partly to the errors in the physical constants used, but it is impossible to make the theoretical curve coincide with the experimental results by assuming these constants suitably, because the theoretical curve is too steep and intersects the observed one.

Figure 4 and even Figure 3 show that the temperature has a tendency to decrease after a certain time. It means that the material is partly consumed and production of heat decreases as the chemical reaction proceeds. Figure 6 shows the carbonization which appeared in the sawdust in the experiment of Figure 5.

To take this consumption into account, A and accordingly δ in equation (2) should be considered to decrease with the reaction, and if our consideration is limited to the period before ignition, the amount consumed until a certain time may be considered as a function of the temperature at that moment. Thus, for the sake of simplicity we assumed,

$$
\begin{aligned}
A &= A_0 e^{-\lambda\theta} \\
\therefore\ \delta &= \delta_0 e^{-\lambda\theta} \qquad (13)
\end{aligned}
$$

where λ is a certain constant.

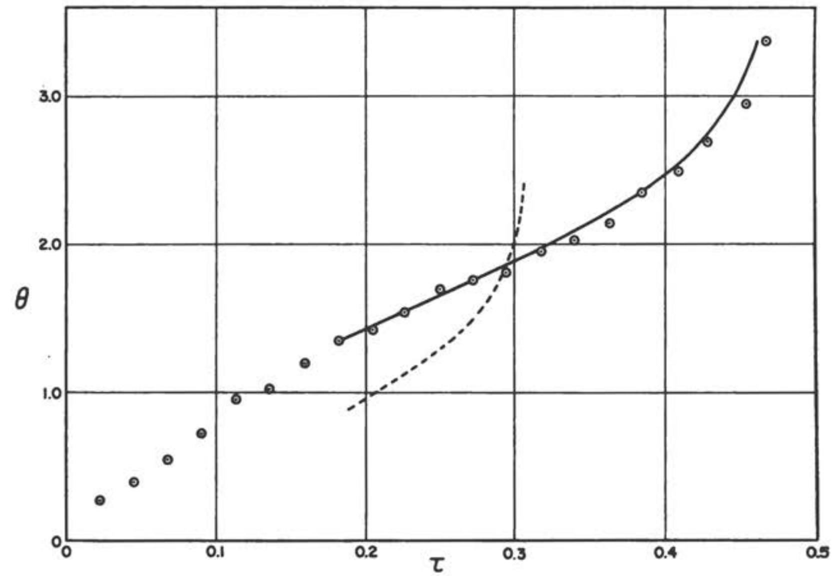

Figure 5. Comparison of experimental and theoretical results
$T_a = 167°\ C$, $r = 7.8$ cm, $\delta = 4.15$, $\mu = 24.3$, $\delta_0 = 6.1$, $\lambda = 0.43$.

Then the fundamental equation (2) transforms into

$$\frac{\partial\theta}{\partial\tau} = \frac{\partial^2\theta}{\partial\xi^2} + \frac{m}{\xi}\frac{\partial\theta}{\partial\xi} + \delta_0 e^{(1-\lambda)\theta}$$

This equation is again transformed into

$$\frac{\partial\theta'}{\partial\tau} = \frac{\partial^2\theta'}{\partial\xi^2} + \frac{m}{\xi}\frac{\partial\theta'}{\partial\xi} + \delta' e^{\theta'}$$

where

$$\theta' = (1 - \lambda)\theta$$
$$\delta' = (1 - \lambda)\delta_0$$

Now, suppose δ_0 and λ are given, then δ' is known and the relation $\theta' - \tau$ will be known from Figure 1. Accordingly the relation $\theta - \tau$ will also be obtained. The constants δ_0 and λ should be chosen so as to make this relation coincide with the observed $\theta - \tau$.

In the case of the example shown in Figure 5, δ_0 and λ were found, by the method of trial and error, to be 6.1 and 0.43 respec-

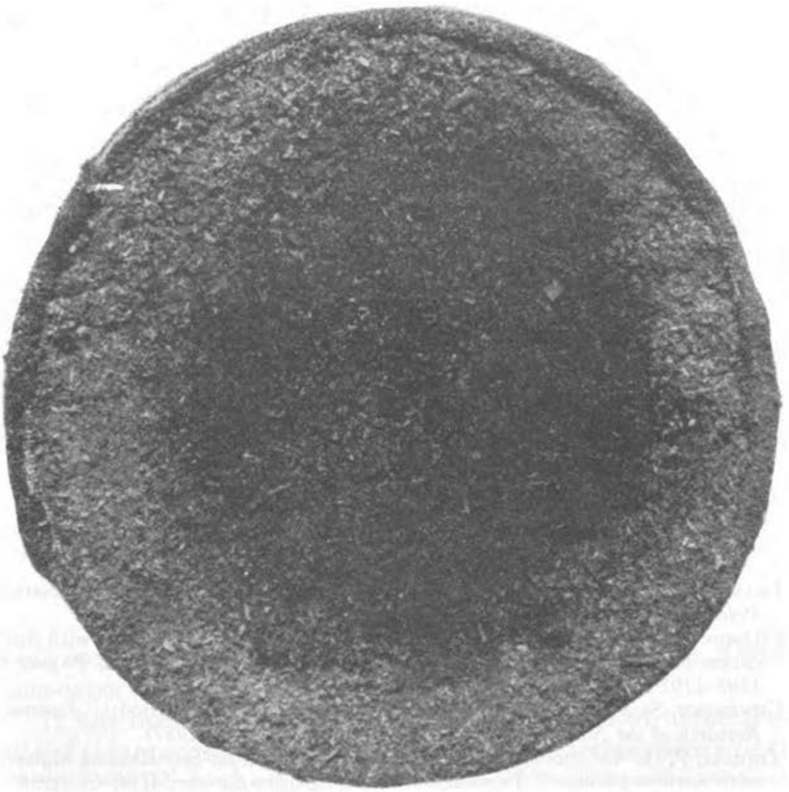

Figure 6. Carbonization of sawdust seen in the sample used in the experiment of Figure 5.

tively. The solid curve in Figure 5 shows $\theta - \tau$ obtained in this way.

The same method was applied to other experiments and the following are the examples of them.

(1) $T_a = 179$ °C, $r = 5.25$ cm, $\delta = 3.95$, $\mu = 16.5$, $\delta_0 = 5.6$, $\lambda = 0.39$.

τ	0.20	0.25	0.30	0.35	0.40	0.45
δ (Obs.)	1.25	1.48	1.70	1.95	2.30	3.07
δ (Cal.)	1.24	1.50	1.73	2.03	2.36	3.02

(2) $T_a = 173\ ^\circ\text{C}$, $r = 6.25$ cm, $\delta = 3.89$, $\mu = 19.6$, $\delta_0 = 5.3$, $\lambda = 0.40$.

τ	0.20	0.30	0.40	0.50	0.60	0.70
δ (Obs.)	1.08	1.31	1.54	1.80	2.16	2.75
δ (Cal.)	1.08	1.47	1.77	2.04	2.32	2.65

The agreement of the calculated and observed θ is always almost satisfactory, and it is interesting that λ has a common value approximately equal to 0.4 in all cases.

Thus, assuming the consumption of materials in the process, our theory seems to be applicable to the self-ignition of spherical samples of any size. However, further investigations should be required concerning this problem.

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Discussion

Mr. Fons: Dr. Dawes, in describing the first model, you did not mention the moisture content of the wood.

Dr. Dawes: The timber used in the experiment was controlled within 1 per cent of 10 per cent moisture, 10 per cent being the average.

Concerning Dr. Kinbara's paper, unfortunately I have not had time to follow through all the equations, but I would welcome Dr. Kinbara's comments on the following. In Figure 3, there is a set of temperature curves corresponding to different positions in the sphere, and the ambient temperature is also shown. The various curves coincide at a given point which is taken as the time zero. However, the center of the sphere rises above the ambient temperature. Does this mean that there is some form of self-heating? Secondly, have you of necessity to quantify the value of δ? Did you explore experimentally the region between the value of $\delta = 3.19$ in Figure 3 and the value of $\delta = 4.62$ in Figure 4? Is there any effect for values of $\delta > 3.19$ but for $\delta < 4.62$, if the time scale goes on far enough? One assumes that Figures 3 and 4 are two curves of a family; what criteria do you use to decide when you have self-ignition, and when you have not, if there is some form of self-heating going on?

Dr. Kinbara: It has not yet been manifested why temperatures at all points inside the sphere attain, at the same time, the same temperature which is equal to the ambient temperature T_a.

As for δ's in Figures 3 and 4, they were calculated by the formula already given:

$$\delta = A \frac{r^2}{k} \frac{E}{RT_a^2} e^{-E/RT_a}$$

where we used the data for A, k, and E obtained by one of us by other experiments.

It has been well known that there is a critical value for δ, and if δ is larger than the critical δ, i.e. δ_c, the temperature of the specimen will increase infinitely, while if it is smaller than δ_c, the temperature cannot increase indefinitely but arrives at a stationary state. The critical δ_c for spheres is 3.32.

Dr. Dawes: I am not sure of the use of terms. The temperature rises above the ambient at the centre. It seems therefore that there is a reaction, but this is not defined as a self-ignition.

Dr. Kinbara: It is a phenomenon which has been commonly called "spontaneous ignition." But we call it "self-ignition."

Dr. Olson: Is that due to a small amount of decomposition of the sawdust?

Dr. Kinbara: Yes. Theoretically speaking, the accumulation of heat inside any exothermic decomposable substances occurs at any temperature. At the early (low temperature) stage, the sphere is heated mainly by the heat conducted from outside. So the temperature is lowest at the center. At the late (high temperature) stage, however, it is heated by the heat of decomposition and this heat flows out of the sphere by radiation and conduction. So, the temperature is highest at the center. If the heat produced by decomposition and the heat dissipates just balance, the sphere will keep a stationary temperature.

Dr. Dawes: Is the definition of self-ignition independent of the time involved? Does a continuing reaction at a low activity level constitute a self-heating or a self-ignition? Does it matter when the activity dies down?

Dr. Kinbara: The definition of self-ignition or spontaneous ignition is independent of the time. Even though a reaction is at a low activity, it can constitute a self-ignition if, for instance, the radius is large and accordingly, δ is greater than δ_c. The material dies down with time and δ will decrease gradually. This is what I have discussed.

With regard to Mr. Fons's experiment, I think the difficulty in such experiments as Mr. Fons has described is that the experiment is not reproducible. When the same experiments are repeated, the results are not necessarily the same. This is because it is very difficult to have the same fuel and to keep it in the same condition. I tried, several years ago, to find the velocity of propagation of combustion along a rod, paper, and a group of them, and so I know the difficulty very well. In Mr. Fons's experiment, all the fuels and the equipments were carefully arranged and it is admirable that he got very systematic results as were shown in his many figures.

He got several very interesting results. I would like to comment on one of them. He said that the velocity of spread of burning along a crib, measured in inches per minute, decreases as the specific gravity of the material increases and there is a simple relation between them.

I have deduced a simple law from my experiment using paper as a fuel. It seemed that the rate of burning, i.e. the weight of the fuel burned in unit time, was the same for all the fuels, if the chemical properties and the shapes of the fuels were very similar. Thus, the velocity of propagation along one sheet of paper is twice the velocity along two sheets of the same paper.

It seems to me that the same holds in the case of Mr. Fons's experiment. This is because, I think, the factor which plays a most important role in spreading of burning is "how air is supplied."

This may be demonstrated clearly by the following experiment. Suppose we prepare two similar boxes, each of them being divided into two rooms by a sheet of paper *P* as shown in Figure A. Air and carbon dioxide are contained respectively in the lower and upper halves of the box *A*, while they are contained respectively in the upper and lower halves of the box *B*. We can kindle the paper in both cases, but the flame in box *B* dies down after a short time, while in box *A* it spreads in the same way as in the open air. This shows that the air necessary for the combustion is supplied mostly from under the paper.

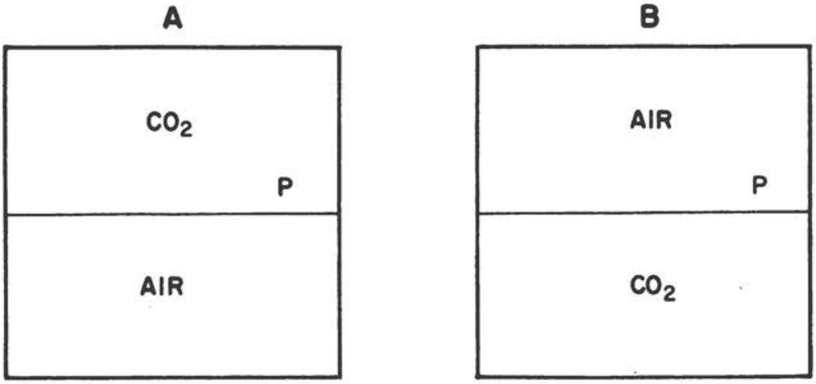

Figure A.

There is another interesting experiment which shows the effect of air supply to the mode of burning. As shown in Figure B, a sheet of paper *P*, cellophane being most favorable, is stretched along an inclined glass plate leaving a space of about 3 mm thickness between them. The most favorable angle of inclination of the glass plate is about 30 degrees. If the paper is kindled at a point *O*, the flame will spread, contrary to our expectation, only downward. The upper side of the flame front *F* automatically dies down and there remains a fan-shaped hole on the paper. This is because air cannot be supplied to the upper side of the front. Thus the mode of burning changes greatly according to the air supply from under the fuel. In Mr. Fons's experiment, the rate of burning would be very much changed if the cribs were suspended in the air.

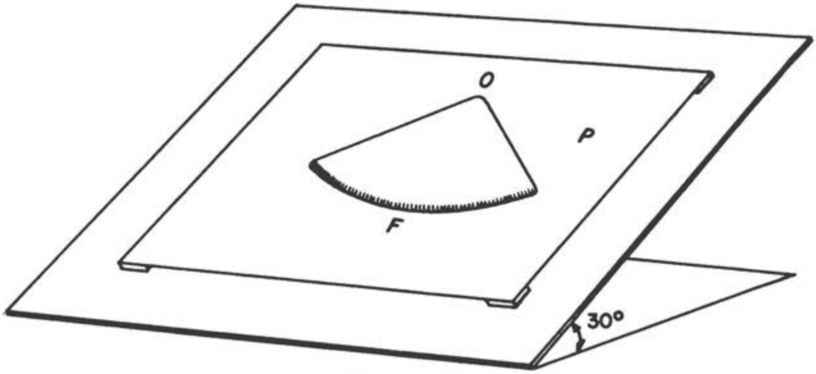

Figure B.

Mr. Fons: If we suspend a crib in the air, I would expect the fire to spread at a different rate, how differently I do not know for we have not carried out that experiment. If we change the spacing between the particles (the distance between the sticks) the rate of spread would be affected. We do not yet have data on the effect of spacing, but we changed the size of the sticks and found interesting results.

Perhaps eventually we can put numbers together to get some sort of composite quantity or dimensionless ratio that will describe the fuel bed. There must be an explanation of why two pieces of the same paper burn faster. It could depend on the volume of fuel. What happens when you increase the size to three or four sheets of paper?

Dr. Kinbara: If a fair wind is blowing along the surface, the velocity increases as the flame goes on, because the paper in the lee side is heated before ignition by the hot gas from burning parts, whereas the velocity is independent of the size of the paper if no wind is blowing. However, the velocity depends on the thickness of the paper. I pasted two sheets of paper on each other and got 2-sheet paper. In the same way, I made 3-sheet, 4-sheet, and so on up to 10-sheet paper, and observed the velocities of spreading of fire along their surfaces. The result showed that the velocity was just inversely proportional to the number of sheets. It means that the mass of paper consumed per unit time is the same, i.e. the air that can flow into the fuel is the same. I suppose this is because the shape and size of the fuel as well as the temperature of flame is the same for all cases.

Commentaries

Mr. Caldwell: In connection with Mr. Fons's paper, it seems to be a needed piece of experimental work but I am surprised at the reproducibility or precision that he and others get. We work with conditions beautifully set up, steady states, and we get all kinds of scatter, but Mr. Fons gets the good results. In connection with the dimensions of the crib, Mr. Fons, you mentioned that you had worked with several crib dimensions. Do you plan standardizing on this crib?

Mr. Fons: We think that this model could be adapted for some other kinds of work, such as testing fire-extinguishing chemicals. In that case, we would select and use one particular size crib only, but for data on burning rates, we will vary the crib by testing different sizes and arrangements and materials (different species of wood). We would like to take other wood fuels to extend the density range and learn whether the data for other species will fall on this same curve for white fir.

Mr. Caldwell: In connection with your crib, you can, as you say, use it for different materials, different kinds of woods, or chemicals, or anything you choose. How are you going to apply this in a larger scale, say to forest fires, where you have complicating conditions of terrain and underbrush and such things as that?

Mr. Fons: The system is designed to answer certain questions in burning and, once we get some numbers in answer to these questions, we can perhaps design a predictive model which will represent a complete natural free-burning fire.

I did not mention this, but we visualize this model as being a section of a moving front. We made tests on the effect of width of crib on rate of spread, and we found the cribs do not have to be very wide for the effect of additional width to be negligible. In this case the sides do not know what the middle is doing. The same was true with depth or loading; the spread was increased little by making the cribs higher than 13 inches. This kind of information may be useful in planning experiments.

Professor Hottel: On this same question, I am rather surprised by the comment that the middle does not know what the side is doing. Do you have data on cribs twice as wide as these, to see whether the combustion-front propagation velocity depends on air flow?

Mr. Fons: We have kept the height of the crib constant and increased the width from five inches to sixteen and a half inches, and we found the forward rate of spread levelled off when the crib was about ten inches wide; sixteen inches made no further difference. We do not have extensive data for different depths, but only data for two particular depths. We did the same, holding the width constant and increasing the height and again we reached a plateau.

Professor Hottel: The spread is into the interior, away from the fire front? And the air to burn that wood— does it come into the center and onto the back side of the fire? It must come in from the sides, and I suppose when you get very close to the other end the speed changes?

Mr. Fons: Just before the flame reaches the far end of the crib, its speed does slow down. It looks as if, after a certain width, the air coming in from the side meets enough resistance so that the spread does not change more. We measured the width of the fire, the burning area. With one particular size crib, for the ¼-inch material, the width of the burning area measured from the ignition front back to the embers where no flame could be seen was about four inches; for 1¼-inch material, the burning area measured about sixteen inches.

Dr. Robertson: I was under the impression that this was a one-dimensional fire, most of the air for combustion diffused in from the burning face. Is that not so?

Mr. Fons: The air comes in from all directions, probably primarily from the sides.

Mr. Grumer: The impressive films shown by Mr. Barrows in his discussion of "Natural Phenomena Exhibited by Forest Fires" (see Appendix) indicated the effect of loading on the rate of flame spread. In your experiments with crib fires, height was varied. I imagine this is comparable to varying the loading as shown on the films. Were the loading ratios about the same in these crib fires as in the fires shown in the film? Should we conclude that the loading has a tremendous effect on the rate of flame spread or does it have a minor effect as soon as the surface of the ground is fully covered?

Mr. Fons: This is where one gets into trouble in thinking from model to prototype. I think we can explain it this way: the difference in loading shown in the films probably was in the range of our model. Below five- or six-inch heights is where we found most change in rate of spread with change in height. I want to make one other point. Our tallest crib was 13½ inches high. Calculating pounds per square foot, this represents a loading of 180 tons per acre. Mr. Barrows was talking of fuel loadings of the order of 7 to 30 tons per acre.

Dr. Van Dolah: The paper by Smith and Rhodes presents some interesting and pertinent aspects of fire problems in mines but illustrates a general problem concerning the concept and meaning of modeling. To some, modeling is making something on a small scale, to others a model in some way attempts to reproduce a real life situation on a more tractable scale. In the Smith-Rhodes paper, there is some difficulty with respect to the latter concept of modeling. Thus one can be concerned that in reducing the mine roadway to a $^1/_{15}$-scale on a linear basis, there is a vast increase in the surface to volume relation, in fact by a factor of fifteen. With this change one can expect peculiar effects. For example, the authors report a complete loss of the oxygen from the air. In a real life situation, much of the air would flow through the center of the roadway, never becoming involved in a combustion process. This is well borne out by the rather discouraging results obtained in this country and in England with attempts at underground gasification of coal. Here the coal along a narrow channel is ignited and caused to burn with air pumped through the channel. In the beginning the process yields gas of a reasonably high Btu. content but it very quickly begins to deteriorate when, because of channeling, most of the air does not enter into the combustion process and thus dilutes the gasification products.

The authors report a relationship between air velocity and the spread of fire but I am not sure how to extrapolate the results to a real life mine roadway. The explanation offered is that perhaps the break in the propagation curve (actually it is a burning time versus air-flow curve) is the result of induced turbulence at some critical level. If this is the case, it is perhaps pertinent only to the small-scale experiment and not to the real life situation. I think there may be a more simple explanation, being merely that of oxygen depletion. If one looks at the data on the intermittant self-extinguishing flame, one finds that when the flame has used up most of the oxygen, it extinguishes, but the fire continues to smolder with a very low rate of combustion. The suggestion offered by Dr. Dawes involving thermal-conductivity and regeneration of volatiles sounds quite reasonable. The volatiles burst into flame, depleting the oxygen; then the flame extinguishes because of lack of oxygen. If, on the other hand, enough air is put through this channel, a constant flame of propagation can be sustained to burn to the end of the channel.

While I have been critical of this paper, I would like to extend my sincere congratulations to the colleagues of Dr. Dawes for the elegant approaches to the modeling of gas explosions in mine situations. Here I think they have given attention to the problems of scale and have attempted to seek a means of modeling the actual event. I have had an opportunity to witness these demonstrations in England and I found them convincing. I am equally impressed with the very excellent work done by Mr. Bakke at Safety in Mines Research Establishment on the problem of methane layering. This problem is important and has unfortunately been neglected.

Dr. Dawes: Of course we at the Safety in Mines Research Establishment recognise the limitations pointed out by Dr. Van Dolah in connection with the fire modeling work we have carried out. The scale was too small and the Reynolds numbers were much smaller than those obtained in practice. The mixing of air, distillation and combustion products in the model must be affected by the buoyance effects associated with temperature. These effects can be described in terms of the Richardson number. The effect of scale on the mixing of different fluids in situations appropriately identified by the Richardson number has been discussed by Bakke (1959 *loc.cit.*). It was not to be expected therefore that the work on this, the first pilot model, would reproduce the mixing conditions or the complete phenomena observed in a mine fire. What is important about the model work that has been done so far is that it has afforded staff the opportunity of studying a combustion process in controlled conditions and has provided data and phenomena demanding explanation. This has deepened the understanding of the combustion process in a situation somewhat similar to the practical situation. The work cannot be applied directly to the full-scale practical situation, but the results help to interpret phenomena observed on the larger scale.

It may be useful to say something about the background against which this model work has been done. When there is a fire in a coal-mine there are two things in connection with the ventilation that one needs to know, for it is on occasion possible to exercise some control over the ventilating air that reaches the fire. One needs to know the effect of the ventilation on the fire, and the effect of the fire on the ventilation. This latter is important for in many coal mines there are large volumes of free methane and any change in the general pressure distribution in the ventilation circuit may result in the migration of these bodies of methane into the fire zone. The subsequent ignition of the methane-air mixture can give rise to disastrous firedamp or coal-dust explosions. This side of the problem contributes a study in aerodynamics once an "equivalent" for a given fire is known and will not be considered now.

Study of the effect of the ventilation on the fire in particular situations is possible with certain facilities we have at the Safety in Mines Research Establishment. We have a full-scale roadway about 800 ft. long and cross section about 57 sq. ft. with a slope of 1 in 28 up (in the direction of the ventilation). In this roadway we can work with timber fuel bodies (representing the linings and supports of a coal-mine roadway) of up to about 100 ft. in length. This is a large-scale model of what we get in practice, but the roadway has only one slope and by some mining standards, it is not large enough. Nevertheless we hope to examine the correspondence, if any, between this large-scale model and smaller-scale models. If there are differences, we hope to win an understanding of them, particularly through work in controlled conditions on the small scale, and thereby enlarge our knowledge of what goes on on the full scale.

In the work we have done so far, we pretend to have done no more than make a start. We have discovered limitations in the first model and we now feel better able to design an improved version which we are sure will improve our knowledge of combustion processes in this type of geometry.

In addition to the above, however, and this is our reason for presenting this paper to you, we believe that we have produced information which will be of interest to those concerned with combustion and heat transfer in similar situations.

Dr. Fristrom: Have you considered the possibility of scaling by changing the pressure and/or composition of gas inside, or is this too dangerous?

Dr. Dawes: Control of the gas pressure inside the model is not, of course, possible with the facilities at our disposal at present. It would obviously provide a useful extra degree of freedom in our next model.

Professor Toong: I think the work of Drs. Kinbara and Akita is very interesting. By adjusting the values of a few parameters used in their analysis, they succeeded to bring the theoretical and the experimental results into fairly good quantitative agreement. One critical test of the model used by the authors can be obtained by comparing the theoretical and the experimental results at the various radial positions and for different sizes of the specimens by the use of only one set of values for the floating parameters. I wonder whether the authors have done that.

The authors observed in Figure 4 that the temperature rises to a peak and then drops. They explained that the temperature drop is due to the consumption of material and the decrease in the heat produced as the chemical reaction proceeds. But the authors apparently fail to comment on the steady-state temperature profiles which were attained after the temperature drop. It seems to me that this steady-state situation is very important and deserves detailed investigation. Also, I wonder whether these steady-state results check with their predictions using the assumed value of β.

Perhaps I should point out another physical phenomenon which has not been mentioned in this paper. This is the circulation of air and gaseous products of combustion inside the sawdust specimen. I think that the presence of these internal convective currents can probably explain the more gradual rise in the measured temperature at the center of the specimen, as shown in Figure 5.

Dr. Kinbara: The equation for the steady state of the self-heating of a sphere of decomposable material has been solved by Chambré using Chandrasekhar's table. We solved approximately the same equation using a parameter β which depends on the central temperature. Our paper about this is now in the press and will appear in *Combustion and Flame* 4, 173–180 (1960).

Our solution showed a very good agreement with Chambré's, and so far as the stationary state is concerned, I believe that there can be no question about our solution.

We tried to extend our method of parameter β to the case where the temperature changes with time. However, it is not granted that this method can be applied to the non-steady state. Thus the solution was tested comparing it with experimental results. The agreement with respect to the temperature rise with time was not satisfactory, and we tried to find an assumption with which an agreement can be arrived at.

It is not necessarily only one assumption, as Dr. Toong pointed out, that brings the experimental and the theoretical results together. However, our assumption that the quantity of material decays by decomposition is one of the most reasonable ones and made the agreement quite satisfactory not only in the central temperature, but in the temperatures at all points.

The fundamental equation (1) is applicable only when the temperature is not so high. At high temperatures, heat will be produced by the oxidation of the material and a convection current may flow inside it, as Dr. Toong pointed out. Our solution is applicable only to the early part of the self-ignition process, but it is useful for finding the time of self-ignition. Anyway, Dr. Toong's comments are very suggestive. We will make an effort to improve our theory.

Dr. Thomas: I would like to ask Dr. Kinbara about some numerical values in his calculations. I have seen a previous paper by his colleague, K. Akita, in which a heat of reaction of 30 cal/gm was used. Now it is possible quite independently to calculate a theoretical relationship between the heat of reaction and the loss of reactant during the induction period so that the empirical constant λ which Dr. Kinbara introduces is related to the heat of reaction. I find that if one uses a value of about 100 to 150 cal/gm for the heat of reaction, the order of value we have found experimentally for fiber insulating board, one gets a figure of about 40 per cent for the reactant loss which is the order magnitude that Dr. Kinbara finds necessary for correcting his theoretical relationship. According to calculations made in connection with thermal explosion theory, the figure of 30 cal/gm seems too low to account for the sharp distinction that is observed between a state of no ignition and ignition.

Dr. Kinbara: The data used here came from the results of experiments made independently by K. Akita. Some errors might be involved in them. Dr. Thomas's suggestion about the heat of reaction is very interesting. We will turn our steps to this point according to his suggestion.

ADJOURNMENT

H. C. HOTTEL

Chairman, Committee on Fire Research and Fire Research Conference

I WOULD like, on behalf of the Committee on Fire Research and the Fire Research Conference, to thank you all for your interest in fire as indicated by your coming to this Symposium. Especially, we would like to thank our foreign guests for taking so much time and trouble to come and tell us what they are doing. If you have gotten as many ideas about what you ought to be doing in the future in the fire research field as I have, you will feel that the meeting was well worth your while. I am full of thoughts about how to change some of my approaches to various problems, and I am sure many of you are. The Symposium is adjourned.

Appendix
Full-Scale Studies and Tests

Natural Phenomena Exhibited by Forest Fires—*J. S. Barrows*

The St. Lawrence Burns—*G. W. Shorter*

Operation School-Burning—*R. M. Hill*

Natural Phenomena Exhibited by Forest Fires

J. S. BARROWS
U. S. Forest Service

ABSTRACT

Forest fire phenomena are presented through a series of motion pictures and 35 mm slides. These films have been taken by the staffs of the Southeastern, Pacific Southwest, and Intermountain Forest and Range Experiment Stations of the U. S. Forest Service and by Dr. Vincent J. Schaefer during the course of fire research activities. Both regular speed and time-lapse motion picture photographic techniques are employed. During parts of the presentation two motion picture projectors and two screens are used simultaneously to facilitate comparisons of fire behavior under various fuel and weather conditions. The films illustrate certain behavior features of wild fires as well as small-scale experimental fires in forest fuels.

Examination of the natural phenomena of forest fires is related to the International Symposium topic of Fire Models. Analysis of the behavior of large-scale forest fires and smaller scale experimental fires in forest fuels permits critical examination of combustion theory for free-burning fires. Introduction of the atmospheric, topographic, and heterogeneous fuel factors associated with forest fires indicates the complexity of the many variables to be considered in the development of fire scaling theory. Many of the characteristics of forest fires have not yet been measured or analyzed in relation to existing theory. The viewing of forest fire phenomena through the medium of various photographic techniques presents an opportunity to consider some of the courses for future fire research.

Introduction

Forest fires are free-burning fires. Unless restricted by suppression measures the rate of spread, size, intensity, and life cycle of forest fires is governed by natural phenomena in the forest and in the atmosphere above the forest. Complex interrelationships of physical, chemical, and atmospheric factors influence forest fire behavior. In particular, forest fire behavior is influenced by fuels, weather, and topography.

In some parts of the world the vegetative cover forms one of the most massive fuel bodies for fire. When extensive areas of certain brush and forest types become critically dry, violent fires may result from almost any ignition source. Wind velocities of 13 to 18 miles per hour or more are often present during fires of the type viewed here, although wind is not an essential prerequisite for violent fire. Such fires display massive flames, an advancing flame front, frequent small and sometimes large flame whirls, a pulsing motion to flames, and extremely rapid destruction of all finely divided fuel particles.

Large forest fires produce great volumes of smoke which vary in character and color in accordance with variations in fuels and rates of combustion. The Dudley Lake Fire shows many distinct phenomena that are typical when a massive wind driven fire develops in a dense coniferous forest. The smoke column is carried forward in a long relatively narrow band perpendicular with the wind. Vertical development of the convection column is restricted by the wind. Relatively small vertical smoke columns develop over the site of more intense combustion. Occasional black puffs of smoke usually come from rapid combustion of coniferous tree crowns and limbs. The main smoke column exhibits an almost continuous cork screw motion.

Massive flames extending 100 feet or more vertically from the fuel body or nearly equal distances horizontally when driven by wind are characteristic of violent forest fires. Flames from burning gases appear sporadically in the convection columns. Topography influences heat transfer by radiation and convection processes. Heat transfer is so intense that fires jump from one side of a canyon to another. As shown in the Topango Canyon Fire, barriers such as roads are of little consequence in stopping the fire spread. Fire brands are lifted in the convection columns and fall out to start new fires. The phenomenon of vegetative cover on an entire mountain being on fire and then moving rapidly to the next mountain indicates the great amounts of energy being released.

The foregoing serve as a brief introduction to forest fire phenomena. Because of the complexity of the many factors involved, it is necessary to attempt to simplify forest fire behavior through separate examination of some of the major variables.

Fuel Factors

Forest fuels are heterogeneous in character. Part of the forest fuel body, commonly known as ground fuels, lies on the forest floor. This fuel complex includes duff, freshly fallen tree leaves, grass, low shrubs, dead tree branches, and down logs. Another part, known as aerial fuels, is suspended above the ground. This includes tree trunks, limbs, leaves, hanging moss, and dead standing snags. Such fuels involve a wide range of surface exposure to weight ratios.

The Dudley Lake Fire, Arizona, illustrates some of the features of rapid and large-scale combustion of heterogeneous fuels. In a 48 hour period some 20,000 acres of mature timber, fresh logging slash, and the normal fuels associated with this type were consumed. Estimates indicate that about 300,000 tons dry weight of forest fuels were consumed. During the peak burning periods fuels were being consumed at a rate of about 22,500 tons per hour.

Close-up views of the Dudley Lake Fire show some of the phenomena existing when both ground and aerial fuels are burning. The fire on the ground is intense and advances wherever fuels are continuous. Fuel concentrations cause heat to be transmitted vertically to ignite the tree crowns. Wind driven flames sporadically travel horizontally through the tree crowns. The flame front travels through the finer fuels. The heavier fuels continue to burn for many hours after the flame front has moved ahead.

The Topango Canyon Fire illustrates fire behavior when the fuel body is composed primarily of small size materials. In this case the fuel body is mainly brush. Green vegetation in brush fields may contain as little as 50 per cent moisture content. Dead vegetation will contain as little as 3 per cent moisture content and measurements of ½ per cent have been recorded. The fuel body on this fire contains about 15 to 20 tons dry weight per acre. Such fuels are extremely flammable and are a major factor in a violent fire such as the Topango Canyon Fire. A nearly solid flame front moves rapidly through the area.

The Intermountain Lumber Fire illustrates fire behavior features when the fuel body is composed primarily of large-size material. The fire is in a log deck containing some 6½ million feet of timber. The log deck contains about 130,000 tons dry weight of fuel. A fire of this type travels slowly, but develops very intense heat. Relatively little smoke is produced in comparison to fires burning in green vegetation. Pulsing flames are shown by the time-lapse photography. Rising currents in the convection column carry some of the chemicals dropped by low flying aircraft upward and away from the fire. Chemicals dropped at the outer edge of the convection column fall to the fuel body at the fire front. Small whirls occur in the flames and in areas adjacent to the fire at infrequent intervals.

Experimental burning of logging slash plots at the Priest River Experimental Forest in Idaho illustrates fire behavior characteristics in fuels containing a large amount of finely divided particles. Each plot contains a measured amount of slash.

Time-lapse photography shows the behavior characteristics of different weight concentrations of logging slash. Light slash plots contain 7.5 tons of fuel, dry weight per acre; medium slash 20 tons; and, heavy slash 32.5 tons. Rate of spread, flame heights, and fire intensity increase as the amount of fuel increases.

Simultaneous projection of time-lapse motion pictures of fires in two different weight concentrations of logging slash permits comparison of fire behavior characteristics. One of these fires is burning in heavy white pine slash (32.5 tons per acre). This fire has an average linear rate of spread of 18.3 seconds per foot. The other fire is burning in light white pine slash (7.5 tons per acre). This fire has an average linear rate of spread of 84.1 seconds per foot. The fire in the greater weight concentration of slash exhibits a well developed convection column and much greater flame heights.

Weather Factors

Weather factors have a major effect on fire behavior. Part of these effects may be expressed in terms of fire spread according to the dryness of the fuels, the amount of moisture in the air, and wind velocity. These three measurements of weather factors and their effects on fuels have been combined into a single numerical expression known as burning index. Great diurnal changes occur in burning index.

Time-lapse photography with an 84 degree sphere camera during three days of the Coal Creek Fire illustrates variations in fire behavior according to typical diurnal changes in weather factors and burning index. During the afternoon hours the fire produces a well developed convection column and fuel consumption reaches peak intensity. At night the fire dies down. In the early morning hours the valleys are filled with drift smoke and the combustion rate remains at a low level. As air temperature increases and air moisture decreases the fire increases in intensity. Drift smoke clears and the fire again develops a strong convection column. These diurnal changes illustrate the importance of fire environment and especially the importance of weather factors to combustion rates in forest fuels.

Wind is a vital element in fire behavior. The Dudley Lake Fire is a classic example of the violent combustion which takes place when high winds and low humidity occur in a fire area. Winds here range from 20 to 35 miles per hour. During the late afternoon the relative humidity fell to less than 5 per cent. As a result the fire was driven some ten miles and would have gone further had it not run out of the heavy fuels in the ponderosa pine type. The smoke column extends nearly 200 miles downwind from the fire. The smoke is so intense that the fire front is obscured. Measurements from an airplane showed that the maximum height of the smoke column was about 7000 feet above the fire. Without wind the smoke column would be much higher. Under these wind conditions a massive convection column becomes horizontal. Minor vertical convection columns appear for short periods over areas of intense combustion.

Changes in wind direction are of major importance in fire behavior. Upslope winds occurring in the afternoon hours because of thermal activity may become downslope winds in the evening when surface heating is reduced. These downslope winds are especially pronounced when the gradient wind corresponds to the slope direction. Flames which climb upward on steep slopes are bent back down the slope. Under these conditions flames assume erratic behavior. Upslope convection currents collide with the downslope winds. Pockets of unburned gases periodically burst into flame in the smoke column. The bases of the flames creep into th ewind. Firebrands are carried from the upper to the lower slopes.

Dryness of the atmosphere has a significant effect on combustion rates. Simultaneous viewing of two fires burning in identical fuels, but under different conditions of air temperature and relative humidity illustrate the differences in combustion rates. Each of these fires is burning in western hemlock slash, 32.5 tons per acre dry weight. One is burning when dew point temperature is 43, relative humidity, 26 per cent. The average linear rate of spread of this fire is 16.7 seconds per foot. The other fire is burning when dew point temperature is 48, relative humidity, 61 per cent. The average linear rate of spread of this fire is 55 seconds per foot.

Topographic Factors

Steepness of slope, altitude, aspect, position of fire on slope, and the shapes of mountains and canyons are all factors of topography which have an influence on fire behavior. Nearly all of these topographic factors are present in the Coal Creek Fire burning in the rugged mountain country of Glacier National Park, Montana. Wind direction changes at various points because of the shape of the mountains and the direction of canyons. The smoke column changes in both its vertical and horizontal configuration. A fire running up a steep slope changes to parallel the slope as it reaches a point where adjacent topography permits the gradient wind to have effect.

Fires on steep slopes burning during periods when upslope winds prevail have great capability to transfer heat up the slope. As displayed in the Refugio Fire in California, the result may be a massive fire which spreads rapidly and violently. As such fires near the ridgetops, the interplay of thermal and gradient winds causes erratic behavior.

Convection Columns

The convection columns of forest fires display many distinct phenomena. The strong vertical column indicates intense combustion and will extend to great heights (5 miles or more) unless altered by gradient winds. The nature of atmospheric lapse rates may either favor or retard convection column development. Other features of convection columns include whirling motions, rhythmic pulsing, and sudden vertical accelerations.

Time-lapse photography of the Merten Creek fire in Idaho shows strong vertical motion above the fire. The smoke column continues upward until winds aloft break the ascent. Cloud motion indicates the direction of the gradient wind aloft.

Time-lapse photography of the Pungo Fire in North Carolina shows a convection column strongly altered by wind at the surface. However, convective activity is strong enough to permit the smoke to continue vertically as it moves with the wind. Rapid bursts of smoke are visible as new fuel areas burn. A rolling motion continues in the smoke column for several thousand feet beyond the site of initial convective activity.

Photography of a Priest River slash fire shows some of the features of a convection column throughout its life cycle. As the fire grows in intensity a single, well developed convection column forms. While the fire is at its peak intensity, rhythmic, pulsing motion characterizes the flame action. This pulsing continues until the fire passes its period of peak intensity. At this point the main convection column subsides and several small columns appear at the edges of the fire. This sequence of events was observed repeatedly on fires in heavy slash, but was not evident in lighter amounts of fuel.

Occasionally large and violent whirls occur in convection columns. One of the largest whirls viewed to date was seen in the Poleline Fire in Southern California. Estimates indicate a whirling velocity in excess of 200 miles per hour. Both horizontal and vertical motions are evident. The flames extend more than 500 feet into the whirling convection column.

Conclusion

This review has presented a few of the phenomena exhibited by forest fires. Analyses of these phenomena indicate the need for specific measurements of many forest fire factors and for continued study of them in relation to fire theory. Experience with these fires suggests the need to carry forward some of the research outlined by the NAS-NRC Fire Research Committee. In particular the viewing of forest fire phenomena suggests the need to carry out three specific fire research projects: (1) analyses of existing forest fire data in relation to atmospheric variables, (2) measurements on forest fires, and (3) study of model fires in forest fuels in laboratories where some of the key atmospheric variables may be varied and controlled.

The St. Lawrence Burns

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SUMMARY

A field operation at Aultsville, Ontario, carried out by the Fire Section, Division of Building Research, National Research Council, Canada, early in 1958 is described. Eight buildings were burned under controlled conditions. Factors governing the scale of the operation are outlined. Measurements made were primarily associated with the survival times of the occupants and the radiation levels at various distances from the buildings. The results are discussed in terms of their immediate practical application and their relation to possible model studies.

When it became known that the international St. Lawrence Power Project would result in the flooding of large areas in Canada, including a number of small Ontario towns, it was realized that this would provide a unique opportunity for carrying out full-scale experiments on the buildings which could not be moved away. The first suggested objective was a study of the development of mass fires. A survey of the villages involved indicated that this suggestion was impractical. In the one instance where the building density, following the removal and demolition of a number of the buildings, might have been adequate for such a study, the proximity of one of the new townsites made the operation too dangerous. As the development of a fire in a single building is the subject on which information is most needed in peacetime, consideration was then given to studies involving individual buildings.

Many studies immediately suggested themselves but only two were finally selected. The first was to study the development of a fire in a dwelling with regard to the time of survival of the occupants and the second was to determine the effect of the development of a fire in a building with respect to the probability of its spread to adjacent buildings. The British Joint Fire Research Organization, which co-operated in the project, was particularly interested in studying a fire in a large compartment with reference to the initial growth of the heat content of the gases and to the ventilation rates.

The next question was to determine the number of buildings to be burned. The object of burning a large number of buildings would have been to increase the number of useful results. The independent variables would be such factors as the internal linings, exterior claddings, ventilation, size of building, geometry, etc. It was already known that at least some of these factors have interactions so that a factorial design of the experiment suggested itself. The available buildings did not, however, lend themselves to such a design. Further, this was the first time that a field experiment of this kind had been attempted in Canada and it was possible that the instrumentation to be developed or otherwise adapted for the tests might fail. It was desirable on these counts to limit the extent of the operation.

It was decided that the effect of combustible interior linings and of timber claddings would be two factors to be investigated carefully in dwellings. A search was therefore made for a group of residences that were similar in other respects. With this restriction the choice was reduced to six. There were only two large buildings available in the same location — a school and a community hall — so that no decision was necessary regarding the scale of the operation involving this type of building. Accordingly, arrangements were made with the Hydro-Electric Power Commission of Ontario to have six two-storied dwellings and the two larger buildings at Aultsville made available to the Division of Building Research, National Research Council of Canada, for experimental burns.

After minor modifications, three of the dwellings were lined with combustible material, at least on the ground floor, and three were lined with noncombustible material. One dwelling in each of these categories had timber exterior cladding; all dwellings had wood floors and subfloors. Uniform wood cribs were used as the igniting source. The two large buildings, two stories in height, were converted to single compartments by the demolition of the upper floors. Most of the resulting scrap lumber was left on the ground floor and the fire was started in this wood.

Measurements were made of carbon monoxide and oxygen concentration, smoke density, sound, temperature, black-body temperatures and radiation intensity at all the dwelling fires. In the case of the two larger buildings, no sampling of the atmosphere was carried out but measurements were taken of the ventilation rates.

For the interpretation of the gas analysis and smoke density results, survival criteria were required. For carbon monoxide concentration, it was assumed that life could not be sustained after a concentration of 1.28 per cent had been attained, or after a time when $\int_0^t K_{co}dt = 4.5$ where K_{co} = concentration (%) and the unit of time is the minute. This latter criterion is based on the relationship between the amount of carbon monoxide that the body retains and the conversion of blood haemoglobin to carboxy haemoglobin. The lower limit of oxygen was taken as 10 per cent. There is almost certainly an interaction between the effects of carbon monoxide and oxygen concentration. Survival time should be expressed in terms of one equation involving both parameters but unfortunately no such relationship is known to have been established.

The limiting temperature which was adopted was 300°F. The smoke criterion was a range of visibility of 4 feet. Visibility here indicates the distance at which the holder of a fireman's handlamp can perceive objects by the light it reflects. The critical times for the survival of occupants in the upstairs bedrooms are given in Table 1.

TABLE 1. Critical Times for Survival

Type of Wall lining	Closed Bedroom		Open Bedroom	
	Gas or Temp. Criterion	Visibility Criterion	Gas or Temp. Criterion	Visibility Criterion
Noncombustible	11.7 mins. (300°F)	6.4 mins.	2.5 mins. (300°F)	2.1 mins.
Combustible	5.6 mins. (1.28% CO)	3.4 mins.	1.8 mins. (300°F)	1.6 mins.

Only the times given by the smoke criterion and the shortest of those given by the other criteria have been included. The time at which visibility falls to a low level has been included in a separate column because interpretation of the significance of this criterion is difficult. The critical times given by the CO, O_2, or temperature criteria relate to death or loss of consciousness, but this is not the case with the visibility criterion.

Radiation levels were correlated in terms of the hypothetical levels at window openings which would have produced the measured values on the assumption that window openings were the only sources of radiation. The agreement between the hypothetical values relating to different radiation measurements on the same side of a building was good, indicating that this method of correlation was satisfactory. It was found that the maximum values of the hypothetical levels of radiation were 40 cals/sq cm/sec where the buildings were lined with combustible material and about half this value for those with incombustible material. The black-body temperatures never exceeded 1000°C which corresponds to a radiation level of 3.6 cals/sq cm. It is thus apparent that the greatest contribution to the measured levels of radiation remote from the buildings was from the volume of flame surrounding the window openings rather than from the window openings themselves. Wind conditions affected radiation levels; it appeared that both direction and velocity could have had an influence. The results obtained, however, were not adequate to allow an analysis of these effects.

The black-body temperature measurements were of interest in considering the validity of the furnace time-temperature curve specified in ASTM Standard E119-58 for the fire resistance testing of building constructions. The results answer the criticism that the rise in temperature of the ASTM Standard curve is greater than would be found in practice. For the combustible lined buildings, the black-body temperatures were in general about 150°C higher than those prescribed by ASTM. The maximum values of measured air velocity compared favorably with those predicted by an application of Bernoulli's equation on the assumption of equal inlet and outlet areas and a gas temperature of 1000°C.

Upon studying the results obtained from the St. Lawrence Burns operation, it became apparent that full-scale burns have a threefold purpose. Firstly, they can supply results which may have immediate application. Secondly, they direct attention to problems which require further investigation. Thirdly, they supply results which allow correlation between full-scale and small-scale work.

When considering radiation from burning buildings the St. Lawrence Burns fulfilled all three purposes. As an example of the first function, the results of the St. Lawrence radiation measurements have direct application in the formulation of building code requirements intended to govern the minimum spatial separation which should be established between buildings. The result of primary interest in this respect is that buildings lined with combustible materials can give rise to radiation levels about twice those that will be produced by incombustible lined buildings. In adopting precise values of the radiation levels to be anticipated, importance should be attached to the time at which peak values were attained during the St. Lawrence experiments and the probability of the development of effective fire fighting during this time.

The St. Lawrence radiation results showed that radiation levels differed appreciably where linings were combustible as compared with incombustible. The results thus fulfilled the second purpose, in suggesting that radiation levels might vary with the proportion of combustible linings in a room. The effect of combustible linings on walls or ceiling only was not investigated; hence, further work will be called for if this information is to be obtained. It is thought that smaller scale studies could achieve this object since no reliance need be placed on the absolute values resulting from such studies. The radiation levels will lie between those given by the two types of linings investigated on the full scale. It is therefore only necessary to infer from model studies the approximate nature of the law which should be used for interpolating between the two full-scale results. It follows that in the carrying out of such work, the St. Lawrence radiation results could achieve the third purpose by providing results which would permit of the correlation of full-scale and small-scale work.

The results of the survival time studies illustrate how the operation achieved the second purpose listed above. The pertinent results show that times were short for the conditions investigated and that simply closing a bedroom door gives no appreciable delay in the time taken for the room to become smoke logged. This indicates that the main effort towards ensuring that occupants escape from a building which is on fire should be directed towards containing the fire within one compartment and to maintaining a safe atmosphere in the areas not directly involved in the fire. It is hoped that an investigation will shortly be made into the orders of pressure which have to be established in an escape route in order to confine smoke to the compartment of origin of a fire. A preliminary experiment has indicated that, when a fire is vented to some small extent, the pressure required in an escape route would be quite low; it is probable that it could be achieved with a small conventional fan system. If this suggestion is verified, the concept will have application to the design of stairwells and corridors in, for example, hospitals and hotels.

At all stages of the St. Lawrence operation, consideration was given to the possibility of burning models of the eight buildings with a view to establishing simple scaling laws. If this were possible such scaling laws might conveniently be extended to allow the prediction, by the use of models, of the development of fire in other buildings. Theoretical considerations have suggested, however, that such an approach might not be rewarding. The variables involved in this development of fire include radiative, convective and conductive heat transfer, ventilation rates, gas evolution, and various chemical processes. While the mechanism of radiative transfer appears to be amenable to scaling, other processes such as convective heat transfer and ventilation follow laws which insofar as they are known, have conflicting scaling requirements. A limited program of model studies carried out by the Fire Section has confirmed this view. Full-scale and quarter-scale burns of a furnished room indicated that any relationship, if one exists, is extremely complicated. In one instance, the quarter-scale burned more rapidly than the full-scale while in another, the reverse obtained.

Consideration has also been given to the concept that the St. Lawrence burns might constitute a portion of a larger operation, involving various scales of model burn, aimed at acquiring a deeper fundamental knowledge of the phenomena associated with fires in buildings. The complication of the problem and the interactions involved suggest that the experiment should be of a factorial or statistical design. Even if many of the variables are eliminated, the number of experiments involved appears to be prodigious. It is not obvious that the outcome of such a program would be the derivation of results of general application.

In the immediate future, therefore, model experiments undertaken by the Fire Section will be confined to problems in which the number of independent variables is very restricted.

Operation School-Burning

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Introduction

As a result of the tragic fire at Our Lady of the Angels School, Chicago, Illinois, on December 1, 1958, in which 95 pupils and teachers died, intensive inspections of the Los Angeles schools were made. The Board of Education gave to the Los Angeles Fire Department a three-storied section of the Robert Louis Stevenson Junior High School which was scheduled for demolition. The Educational Facilities Laboratories, Inc., established by the Ford Foundation contributed $25,000 for the project.

Tests were designed to find ways to increase the safety of occupants under fire conditions in multi-storied, open stairway school buildings. It is recognized that the enclosure of stairways will minimize fire and smoke spread. Fire protection authorities often find stairway doors locked and administrators object to closed doors because they may interfere with safe and free passage of students.

Scope and Limitations of the Tests

Fires were built at the bottom of an open stairway, in classrooms, and in corridors. Individually and in combination, tests were made of the effectiveness of curtain boards, roof vents, and complete and partial automatic sprinkler systems. Tests were varied to simulate conditions existing in winter and summer. Data was tabulated on the operation of automatic fire and smoke detection equipment, fusible links and automatic door closers. Temperature, pressure, and smoke density were recorded as well as the functioning of the fire protection equipment during each test. Evaluations were made from these records and these were correlated with the judgment of observers.

The tests reported herein were conducted in a building involving a specific type of construction and with open stariways. The test fires, while believed to be representative of the type of fire which might occur in a school, involved ordinary combustible materials and were planned and built to produce conditions most desirable for these tests.

Participants

Among the organizations that participated were:

1) Sponsoring agencies
    - Los Angeles Board of Education
    - Educational Facilities Laboratories, Inc.
    - Office of the Fire Marshall, State of California
    - Los Angeles Fire Department
2) Major contributors
    - National Fire Protection Association
    - National Automatic Sprinkler and Fire Control Association
    - American District Telegraph Company
    - Minneapolis-Honeywell Regulator Company
3) More than 40 other organizations made contributions of material and labor.

The Building

The school used for testing was built in 1925. By using fire resistive partitions, a 90 foot section of the building was isolated. The exterior walls were brick; the floors of the corridors were reinforced concrete and the walls were plastered hollow clay tile; the rooms had double wood floors on wood joists with metal lath and plaster ceilings; partitions between rooms were metal lath and plaster on wood studs; stairways were of reinforced concrete with walls of brick or plastered hollow clay tile. The portion of the building used was 65 by 90 feet, three-storied, with partial basement, two open stairways, and an exterior metal stairway.

Instrumentation and Fire Protection Equipment

Temperatures were recorded at 23 places and included measurements 5 feet above the floors to simulate the average head height of school children. Two photoelectric cells to measure smoke density were used on each floor. Inclined manometers measured pressure and vacuum. Six firemen, two on each floor, stayed as long as the floors were tenable, to act as observers. They recorded their subjective reactions during the fire.

Fire protection equipment included: automatic sprinklers valved in such a manner as to simulate complete automatic sprinklers as well as various arrangements of partial automatic sprinklers; roof vents having a free open area of 63 square feet were installed above each of the open stairways; curtain boards (draft or fire curtains) were installed in corridors and stairway openings to retard the spread of heat and smoke and aid vent action; automatic fire detection systems including both heat sensitive and smoke sensitive systems; fusible link operated devices of various kinds; and a water aspirator for testing induced draft ventilation at the top of one stairway.

The Test Fire

All test fires were in wood pallets, each roughly 4 by 5 feet, constructed of well-seasoned boards nailed to 2 by 4 inch wood, generally with space between the boards. The majority of the fires involved 1,400 pounds of pallets.

This type of test fire was selected because it resulted in a moderately fast developing fire. It involved a fire load of about one-third of what might be expected in an average classroom of a school; however, the fire load in a classroom would be spread over a much larger area than the test fire. The test fire produced realistic quantities of smoke typical of the amount generated from fires in ordinary combustible materials.

On the basis of an average calorific value of the wood used in the test fires of 8,000 Btu/lb and complete combustion of the wood in 30 minutes, an average rate of heat release would be 374,000 Btu/min.

It was estimated that about 75 per cent of the wood pallets were burned in a twenty minute period. Of this, about 66 per cent (or 50 per cent of the total) were burned in the period between 5 and 15 minutes from the start of the fire. This would give a maximum average heat release of 560,000 Btu/min for this ten minute period.

Criteria of Untenability and Evacuation

As used throughout this report, smoke and temperature conditions are based on the following criteria.

Untenable smoke conditions were based on two combined factors (1) visibility and (2) the irritant effects of the products of combustion. Visibility was determined by placing an illuminated placard bearing a 12-inch letter, 5 feet from the floor 45 feet down the hallway from an observer. When the letter was no longer visible to the observer, the time was recorded as the point of untenable smoke conditions. The judgment of firemen and nonfire department personnel observers determined when the products of combustion were so irritating that evacuation would not be possible. These two determinations were correlated with smoke density readings of equipment installed by the American District Telegraph Company.

A maximum tenable temperature of 150°F was established. A human can stand temperatures considerably above 150° for very short periods of time in a relatively dry atmosphere, but children and teachers would not be likely to enter a corridor from a cool room when the temperature at the 5 foot level was more than 150°.

It has been estimated that an average three-storied school building with adequate exits can be evacuated in 2 to 3 minutes under practiced fire drill procedures. This estimated vacuation time is used throughout this report.

Summary of Results

The results of the tests indicate that most of the methods of protection did not provide satisfactory safeguards against smoke and heat conditions.

1) With the test fires with no fuel added to the fire (due to the construction of the building), lack of visibility and irritant effects of smoke were the principal hazards to life. Untenable smoke conditions preceded untenable temperature conditions in nearly every test.

This might be expected with smoldering fires; however, this was true even with free-burning fires. In the base series of fires (no protective features), untenable smoke conditions were reached in 2 to 7 minutes on at least one entire floor above the fire. This series included fires at the bottom of a stairway and in rooms. Conditions within the building were varied by having the doors, windows, and transoms in both the open and closed positions.

2) Natural draft vents of the sizes tested in this investigation and installed and opened as described in each test did not keep corridors and stairways tenable for exit use.

Untenable smoke conditions were reached in 4 to 5 minutes from the start of the fire, on at least one entire floor above the fire. When vents were opened by means of fusible links, untenable smoke conditions were reached several minutes before the vents opened. Even when vents were opened before the test fires were started, untenable smoke conditions followed in some cases. Opening of vents increased draft on the fire resulting in an increase in the rate of heat and smoke development that made smoke in the corridors and stairways more dense until vent action started. The action of vents eventually cleared smoke from the building but, by this time, untenable temperatures had been reached on all floors. The unsatisfactory results concerning the effectiveness of natural draft vents should not be considered as evidence of the unsuitableness of vents for all uses. Vents in industrial, warehouse, and similar occupancies are a proven desirable feature to minimize fire damage and to facilitate fire fighting under certain conditions. However, the tests reported herein on natural draft vents were conducted to investigate the life safety possibilities through their use in the multi-storied building used for test purposes.

3) The addition of curtain boards (draft or fire curtains) with roof vents did not significantly aid in decreasing smoke spread through the building and, in fact, had an adverse effect on the action of the vents in some tests.

Curtain boards, while not effective against smoke spread did "bank" heat as would be expected. The latter has been the primary purpose of curtain boards in industrial fire protection applications. Smoke "cutoff" is more important than heat "banking" where life safety is the objective.

4) Forced draft up to the capacity tested failed to produce more satisfactory venting action.

5) A complete system of automatic sprinklers will maintain low temperatures throughout the building and will reduce build-up of smoke and irritating gases.

With a complete automatic sprinklers system, untenable smoke conditions were not reached in any corridors except two local areas closest to the test fire. However, when the test fire was arranged so as to provide extensive shielding against sprinkler water distribution, untenable smoke conditions developed in the corridor of fire origin and those above. Under these conditions, the fire was held in check but not extinguished by the sprinklers. This points to the necessity of eliminating any arrangement of the building or its contents that could shield a fire from sprinkler discharge.

6) Partial automatic sprinklers (sprinklers installed in corridors and stairways but not over the test fire) did not prevent smoke spread throughout the building even when installed to provide a water curtain between the test fire and the corridors.

The purpose of placing sprinkler heads in exitways only in certain tests was to evaluate a type of installation that had been suggested as suitable to protect exitways so that occupants could escape safely. Operating sprinklers in the building kept temperatures in the corridors at or below the tenable level (150°F), but in many cases untenable smoke conditions existed in the building before sprinklers operated. Furthermore. in the cases when sprinklers opened, steam resulting from their operation drove observers from the immediate vicinity. Water discharge from a sprinkler head is not designed to provide a smoke barrier but rather to distribute water over a specific area at a rate capable of absorbing heat in quantities sufficient to cool the burning material below its kindling temperature. Sprinklers are usually installed to cover all areas and obstructions should be removed to facilitate good water distribution. These two conditions for satisfactory sprinkler performance were intentionally disregarded.

7) Roof vents and partial automatic sprinklers (installed in corridors and stairways but not over the test fire) were not an effective combination.

Sprinkler action was similar to that in tests without vents. Natural draft vent action was slowed down considerably due to the low temperatures existing within the building resulting from the operation of the sprinklers. Forced draft effectiveness with the water aspirator was similar to that in tests without sprinklers.

8) Combinations of roof vents, curtain boards (draft or fire curtains), and partial automatic sprinklers (installed in corridors and stairways but not over the test fire) did not prove to be satisfactory.

Untenable smoke conditions existed in all corridors before sprinklers operated. Sprinkler cooling action tended to nullify the thermosiphon effect of the roof vents in addition to producing steam. The curtain boards did not improve vent action.

9) Untenable smoke conditions, and in many cases untenable heat conditions, existed in the building before the operation of fusible link actuated devices.

This was true even with free-burning fires. Under the conditions of these tests, untenable smoke conditions existed before temperatures were reached at which fusible link actuated devices would operate.

10) Enclosed stairways will not provide protection against heat and smoke unless the doors are kept closed or are closed immediately after an outbreak of fire.

Tests employing temporary enclosure of stairs, except for the door opening, showed that if stairway doors are not closed when fire occurs or immediately thereafter, heat and smoke will make corridors and stairs untenable in about the same time as though they were not enclosed. Present day fusibly operated door closing devices will not operate rapidly enough to close doors before corridors are untenable. Automatic closing devices activated by the ordinary heat responsive fire alarm system would not be fast enough to guard against spread of smoke.

11) Automatic heat detection devices detected the presence of fire at about the same time that untenable smoke conditions were reached within the building.

Prompt notification of fire was experienced when detection equipment was located directly over the test fire. Fire detection devices when spaced at the maximum distance recommended will operate in two minutes or less when subjected to the standard fire test conditions used by testing laboratories. Under conditions of the tests discussed in this report, a fire signal in 2 minutes would not allow sufficient time for safe evacuation of the building.

12) Automatic smoke detection devices detected the presence of fire before untenable smoke conditions were reached, but not in sufficient time to allow complete evacuation of the building.

It appears that automatic smoke detection devices, if directly over the test fire, would provide an early notification of fire and could allow reasonable time for evacuation. However, it is questionable whether smoke detection devices would allow reasonable time for evacuation under all conditions.

13) Opening a hole to provide a vertical flue in the stairways did not significantly change any of the results.

This hole was opened in the stairways in order to provide a vertical flue in an attempt to overcome the circuitous route for smoke and heat. With the stairways open, smoke and heat circulated through the building somewhat faster but the effectiveness of roof vents, curtain boards, and automatic sprinklers was not improved.

14) Cellulose fiber acoustical tile (Classified Class C under U. S. Federal specification SS-A-118b and commonly known as "slow-burning") resulted in very rapid fire spread when ignited. This constituted a distinct hazard in that it was the means by which fire could be readily transmitted throughout the building endangering all portions and persons therein. The rapid flame spread characteristic of the tile can be reduced with the application of a fire retardant paint.

The cellulose fiber tile ignited at temperatures from 700°–800°F and the flame progressed with a "wave-like" action for a few minutes, then suddenly developed a deep (3 to 5 feet) flame front that spread with such rapidity (5 to 10 feet per second) that observers fled their posts. In one demonstration fire (not included in this report because it was not part of this series) the flame spread rapidly over the surface of the cellulose fiber acoustical tile even though the ceiling was broken into bays, 5 by 5 feet in size, separated by ceiling beams 2 feet in depth.

Future Investigations

The speed at which untenable smoke conditions were reached in these tests emphasizes the need for prompt notification of fire conditions and rapid evacuation from school buildings. A review of the time available for evacuation may prompt school administrators to re-evaluate their fire drill procedures.

Certain basic fundamentals and conclusions derived from these tests point to the need for re-evaluating some current provisions for life safety in existing codes and standards and for further tests to establish more information of a basic nature on which future recommendations may be based.

More tests of vents of larger sizes are needed, possibly up to the total area of the stairway enclosure, with corridor curtain boards. The vents should be operated so that they will be open before untenable smoke conditions prevail. Any favorable results obtained should be weighed against the economic and practical problems encountered in the use of large vents.

The relatively fast operation of the automatic smoke detection equipment in some of the tests indicates the need for further research on automatic detection equipment which is actuated by smoke in order to obtain reliable early notification of fire conditions.

There is a great need for a standard method of classifying the sensitivity of fire and smoke detection equipment as it relates to response time for the area protected. As previously pointed out, when detection equipment is spaced at the maximum distances recommended, it should give an alarm in two minutes or less when subjected to the standard test fire. There is no information available on response time when spaced at lesser distances.

These tests indicated that thermal devices on door closers were slow to operate. Further research should be done on other methods of opening and closing doors.

Tests should be conducted in buildings of other types of construction and with different arrangements and numbers of stairways to determine if there would be any variation from the results obtained in the tests reported herein.

The smoke conditions experienced in these tests indicate that smoke can be the critical factor in defining life safety in schools and, therefore, flame spread characteristics should not be the sole criterion for determining the life hazard of interior finish materials. A study should be made on tenable levels of smoke generation. Standards should be developed for classifying interior finish materials based on these predetermined tenable levels.

A minimum number of tests were run to simulate complete automatic sprinkler coverage because sprinkler performance has been tabulated for many years and has been shown as excellent for the protection of property. More tests should be run simulating complete coverage to obtain more data on operating times in relation to smoke conditions with various sizes of test fires. These tests should include the installation of sprinklers designed for fast operation.

It would be desirable to test some interior finish materials that have been listed by Underwriters' Laboratories, Inc., as having been subjected to the "tunnel test" (NFPA Standard, Fire Hazard Classification of Building Materials No. 255) to verify the classification of such materials for life safety purposes based on the flame spread rating determined by this Standard.

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