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FOREWORD

It is customary in this Foreword to draw attention to meetings of particular interest to readers of FIRE RESEARCH ABSTRACTS AND REVIEWS. At the forthcoming Tenth Symposium (International) on Combustion, to be held in Cambridge, England, August 17–21, 1964, a full day of an invited Discussion on "Aerodynamics in Combustion" will be devoted to Fire problems, supplemented by an additional half-day of Contributed Papers on related topics. (Details are listed on the next page.) To make the Discussion as fruitful as possible, all active fire research workers are urged to attend this Symposium, to familiarize themselves with the contents of the preprinted papers and to contribute appropriate technical comments. Further details can be obtained from the Executive Secretary, The Combustion Institute, Union Trust Building, Pittsburgh, Pennsylvania. The Committee on Fire Research of the National Academy of Sciences—National Research Council was instrumental in planning and organizing this part of the Combustion Symposium.

In the October 1963 NFPA Quarterly (p. 201) a table of statistics was published nmarizing fire losses in fifteen countries during 1962. By reducing the figures to a -capita basis it is possible to make a rough comparison among nations. In terms deaths, property loss, and number of fires, the fire record of the United States is e poorest, lagging behind Switzerland by factors of 30, 3, and 17, respectively. ıe statistics for France and Japan, two countries quite different in population nsity, geography, climate, etc., are nearly the same as those for Switzerland. ven Canada, with the second worst reported record, has only half as many deaths ıd one-third as many fires on a per-capita basis.

This unfavorable showing should be of concern. Are the fire-prevention and re-fighting techniques in need of a major overhaul in the United States? Are the vailable tools up-to-date? Are the standards of training and of combat readiness dequate? Are basic fire problems well enough understood and applied in the ational development of better methods? Simple solutions can hardly be expected. It is disquieting, however, that none of the conclusions and recommendations in NAS Publication 949 "A Study of Fire Problems" [as summarized in FIRE RESEARCH ABSTRACTS AND REVIEWS *4*, 1 (1962)], have been implemented or refined by further analysis. If the fire incidence and loss record were one of excellence this neglect could be forgiven. However, the figures cited above make it appear that the United States is not served as well as it should be, and that a number of recognized areas of weakness are in need of improvement.

W. G. BERL
Editor

PRELIMINARY PROGRAM (FIRE RESEARCH TOPICS)

TENTH SYMPOSIUM (INTERNATIONAL) ON COMBUSTION

Cambridge, England, August 17–21, 1964

DISCUSSION ON "AERODYNAMICS IN COMBUSTION"

Free-Burning Fires

1. Fundamental Problems of the Free-Burning Fire
   H. W. EMMONS, Harvard University (US)
2. The Fire Plume Above a Free-Burning Fire
   H. J. NIELSEN AND L. N. TAO, Illinois Institute of Technology (US)
3. On Modeling Pool Fires
   B. MORTON, University of Manchester (UK)
4. Buoyant Diffusion Flames: Measurements of Air Entrainment and Conditions for Flame Merging,
   P. H. THOMAS, R. BALDWIN, AND A. J. M. HESELDEN, Joint Fire Research Organization, Boreham Wood (UK)
5. The Modeling of Fire Spread Through a Horizontal Fuel Bed
   H. C. HOTTEL, G. C. WILLIAMS, AND F. STEWARD, Massachusetts Institute of Technology (US)
6. Influence of Moisture and Wind Upon the Characteristics of Free-Burning Fires
   H. E. ANDERSON AND R. C. ROTHERMEL, U.S. Forest Service (US)
7. On the Flight Paths and Lifetimes of Burning Particles of Wood
   C. S. TARIFA, P. PEREZ DEL NOTARIO, AND F. GARCIA MORENO, Madrid (Spain)
8. A Model Study of Wind Effects on Free-Burning Fires
   A. A. PUTNAM, Battelle Memorial Institute (US)

CONTRIBUTED PAPERS

Fire Research

1. Diffusion-Controlled Ignition of Organic Solids by Intense Radiant Energy
   S. MARTIN, U.S. Naval Radiological Defense Laboratory (US)
2. Basic Studies of the Mechanism of Ignition of Cellulosic Materials
   W. D. WEATHERFORD AND D. M. SHEPPARD, Southwest Research Institute (US)
3. Heat Transfer and Rates of Pool Burning of Liquid Methanol
   K. AKITA AND T. YUMOTO, Fire Research Institute (Japan)
4. The Combustion of Wooden Dowels in Heated Air
   E. R. TINNEY, Washington State University (US)
5. Studies of Burning in Model Enclosures
   R. GROSS AND A. F. ROBERTSON, National Bureau of Standards (US)
6. Heat and Mass Transfer to, from, and within Cellulosic Solids Burning in Air,
   P. L. BLACKSHEAR AND K. A. MURTY, University of Minnesota (US)

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XII. Instrumentation

XIII. Fire-Fighting Techniques, Equipment

XIV. Miscellaneous

REVIEWS

Current Fire Research Problems

W. G. BERL

Applied Physics Laboratory—The Johns Hopkins University

[This paper is based on a lecture to the Division of Forest Fires, Society of American Foresters, Boston, Massachusetts, October 24, 1963.]

Introduction

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

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

The first estimate has to do with the relative magnitude of heat generation from forest fires as compared to the heat generation from the combustion of fossil fuels. Using the currently relatively stable statistics relating to acreage burned per year in the U.S. (4×10^6 acres/year), multiplying by 10 (ratio of world forest area/U.S. forests), utilizing a tree count made by Professor Emmons[3] as a "reasonable" fuel/acre figure (500 tons/acre), one arrives at the rather startling heat release of $400{,}000\times10^{12}$ Btu/year, which is roughly 10 times the world energy consumption/year from fossil fuels. However, a more realistic fuel consumption (per acre burned) is 5 tons/acre, which reduces the heat-release figure to one-tenth of the energy release—still a respectable number (equivalent to the energy release of ten 1-megaton bombs).

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

With regard to the physical phenomena of fires, it should be noted that the more

* References may be found on pages 13–14.

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

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

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

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

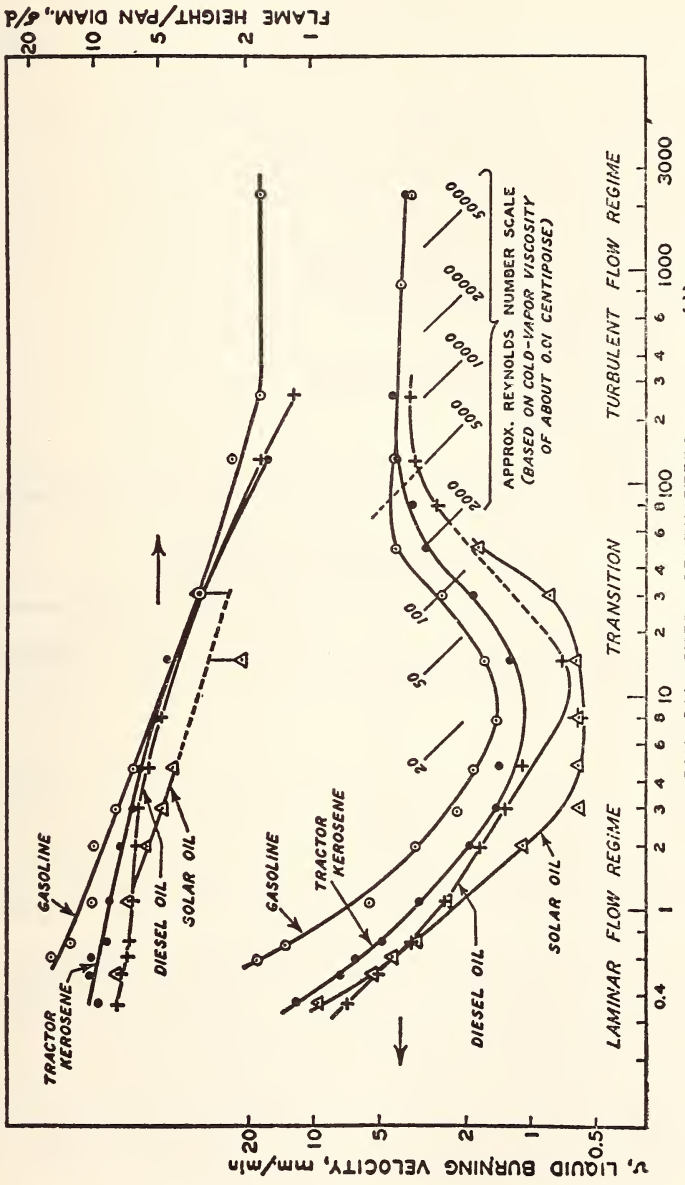

FIG. 1. Correlation of "two-dimensional" liquid pool burning rates versus pan diameter (Ref. 6).

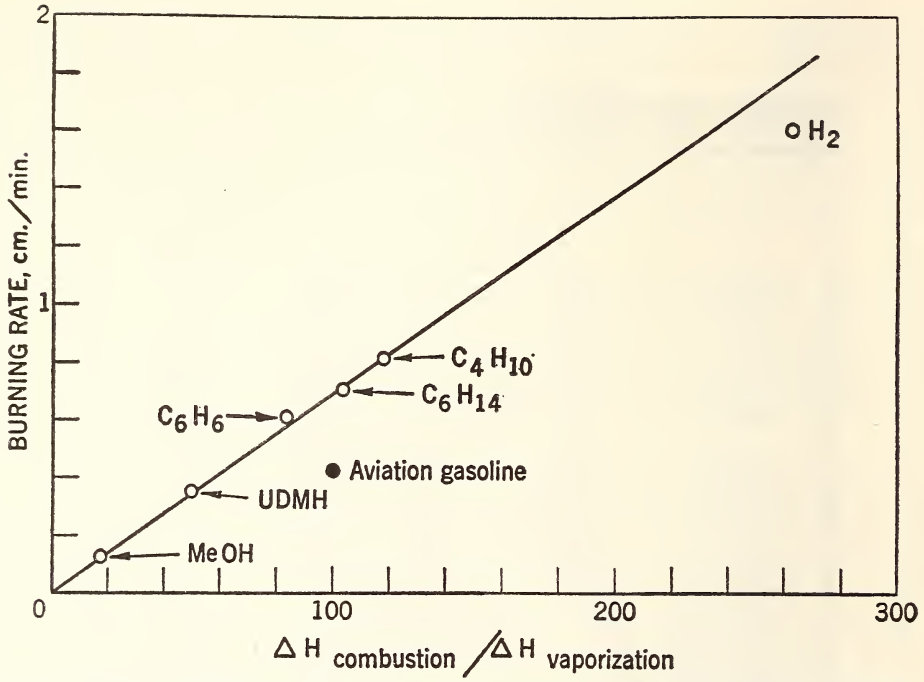

FIG. 2. "Ultimate" burning rates of various liquids as function of $\Delta H_{\text{combustion}}/\Delta H_{\text{vaporization}}$ (Ref. 7).

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

*Burning Rates**

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

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

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

* See "Two-Dimensional" and "Three-Dimensional" Fuel Bed Fires in the Bibliography.

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

ΔH_{vap} = heat of vaporization,

ΔH_{comb} = heat of combustion, and

Integral = heat content of liquid.

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

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

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

*Ignition**

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

Ignition by Pulses of Radiation.—The steps involved in the ignition of an organic material, heated by radiation in air, are too complex to permit their description in detail. Suffice it to say that the process includes the establishment of a heat wave moving into the solid, resulting in chemical (and other) generation of gases which escape into the surrounding atmosphere. After mixing with air and remaining in contact with oxygen for a sufficient time, an explosion may set in in the gas phase[10] or, in the presence of an already established high temperature ignition source,

* See "Ignition" in the Bibliography.

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

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

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

A model of a forest fire, in which propagation of flame is assumed to be by radiation only, has recently been proposed by Emmons.[3] It does not cover the more common flame propagation along a continuous line (in soil duff or tree crown, where convection and radiation effects are intimately intermixed), nor the setting of new ignition sources by brands. However, as an aerodynamic-ignition model it is unique and instructive, presenting a graphic picture of expected fire behavior as a function of fuel spacing (including "breaks" in fuel), energy flux, etc. Such modeling efforts uncover areas where experimental data are urgently needed for further progress.

*Suppression**

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

Here, too, the scientist is confronted by more questions than he can answer with confidence. Thanks largely to the impressive work of Fristrom and colleagues,[15] a

*See "Suppression" in the Bibliography.

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

How subtle the interacting threads by which inhibiting materials interfere with flame propagation are is shown by the ingenious experiments and explanations by Rosser *et al.*[16] concerning the effectiveness of inorganic powders in extinguishing diffusion flames. The superiority of $KHCO_3$ over other seemingly similar powders has been well established. The most consistent explanation of their action requires rapid evaporation and dissociation of the particles, formation of relatively stable compounds between metal atoms and flame radicals and subsequent reaction with another free radical to form a stable product. The metal atom acts as a catalyst to permit free-radical recombinations which, in its absence, would not be possible. To be effective, though, a particulate material must optimize several important requirements.

The action of water, the cheapest and generally most available extinguishing agent, has been under scrutiny under various situations.[17] Its effectiveness is clearly related to transporting it to the scene where it can be most useful, either as coolant of the gases (by reducing the emissivity of the flame), in reducing surface temperatures (by decreasing the rate of emission of combustible gases), as a radiation blanket to interfere with the radiation balance between fire and fuel, or as a means of raising the ignition energy requirements of the fuel. It has been established that water requirements are significantly less if the fuel surface is cooled in preference to the gas phase and that in the convection columns above fires the momentum of the water spray must be able to overcome the buoyancy of the convection plume. Quantitative deductions concerning minimum water requirements have shown that in large-scale operational fire extinguishments more than 100 times as much water is used than is necessary to successfully combat the fire! Such guidance, setting forth the achievable goals to the technologist, is one of the principal objectives of the research effort.

*Plumes**

Perhaps the best understood part of fires is the convection column by which the burned hot gases leave the combustion zone. Such wakes have been extensively analyzed for a variety of possible fluid dynamic conditions. The properties of the buoyant columns in a cross wind, in atmospheres of different lapse rates, the rate of rise and structure of the initial thermal, the effect of moisture condensation and of radiation have been reported, either as an exercise in fluid mechanics or in con-

* See "Plumes" in the Bibliography.

nection with air pollution problems where knowledge of the behavior of the buoyant column under a variety of atmospheric conditions is important.[18]

The simplifying assumptions in all these analyses are:

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

Applying the analysis to steady sources (fires or emissions from stacks), the strength of the source can be related to the height (under windless conditions) at which the buoyancy becomes zero and the plume ceases to rise.[19] The height of the plume (in meters) is

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

where $\mathcal{Q}$= rate of heat discharge at source in KW, and n= fraction of adiabatic lapse rate.

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

TABLE I. Computed heights of fire convection columns (H) as function of rate of heat discharge ($\mathcal{Q}$).

Source	Rate of consumption of fuel	$\mathcal{Q}$ (kw)	H (m)
Household chimney	4 lb/hr of coal ($\frac{1}{2}$ of heat in fuel)	8	80
Bonfire	400 lb wood/hr	450	200
Power station	Heat equivalent to $\frac{1}{2}$ Mkw	5×10^5	1200
Forest	1000 tons/hr (at 4000 cal/g)	5×10^6	2200
Burning town	250–500 houses/hr containing 10–20 tons combustibles (5000 tons/hr)	2.5×10^7	3200

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

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

One further example in which the fluid dynamic properties of the wake are predominant will be mentioned. Under conditions of cross wind, the transport and deposition of firebrands ahead of the reaction zone can be of crucial importance in setting the propagation rate of fires. This problem has been investigated more closely by Tarifa *et al.*[20] who has calculated the trajectories of burning particles of known drag and burning rate, from data obtained in a low speed wind tunnel. Flight paths, set by the vertical wake flow and horizontal winds, give the slant ranges which can be traversed by a still-burning brand. Despite somewhat artificial assumptions regarding the upward velocity in the wake and the interaction of the cross wind on wake and particle trajectory, the calculations are an instructive first step of predicting distances in which brands can be troublesome.

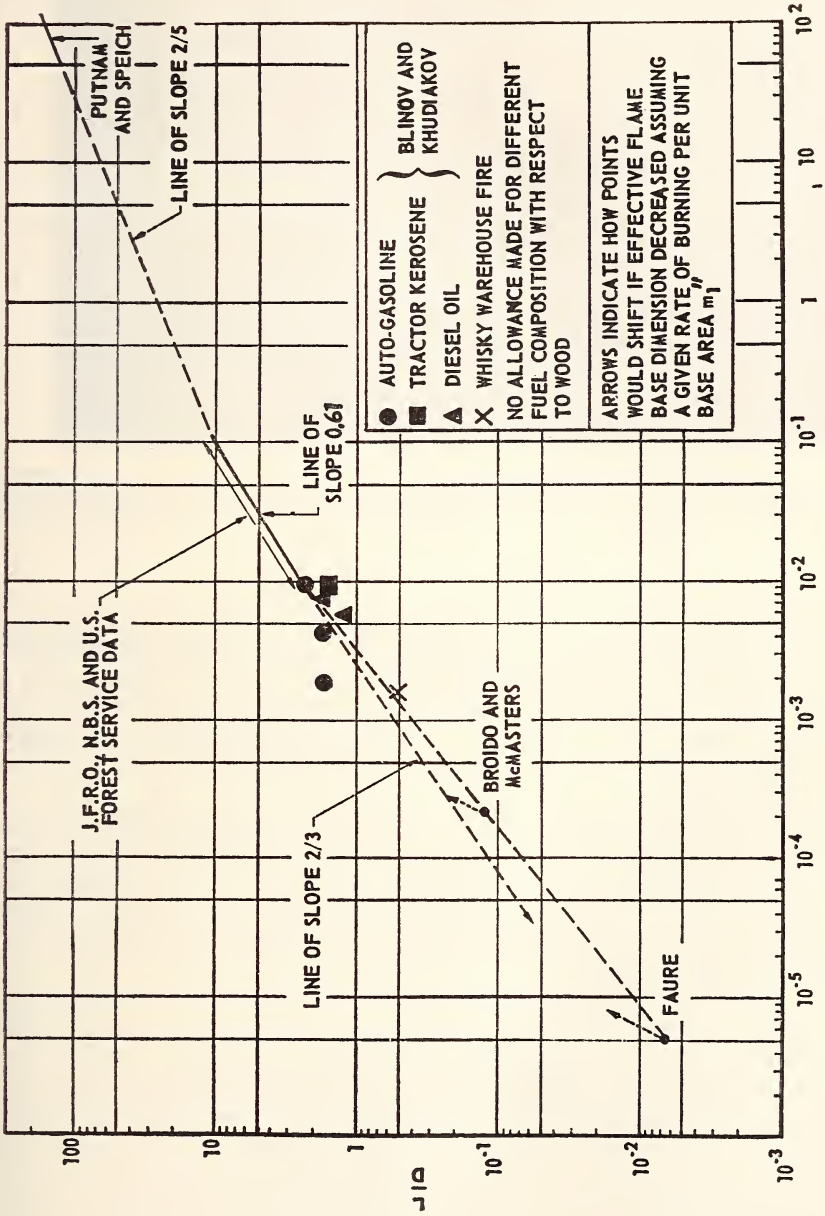

FIG. 3. Correlation of flame height, burning rates and dimensions for "three-dimensional" crib fires (Ref. 22).

FIG. 4. Vortex column in the lee of a fire plume generated by 100 burners regularly spaced over an area 125 by 125 meters, burning one ton of fuel per minute. The smoke tube is about 10 miles in diameter, 200 inches long and about 525 miles from the fire. Horizontal wind speed: 100 miles per minute (Ref. 24).

*Scaling**

None of the cases described previously have given any evidence that scaling-up of the area of a fire should bring with it an unusual behavior. The only semiquantitative and frequently quoted "large-scale" measurement (from the Trensacq Fire as reported by Faure[21]) has given flame heights and burning rates below what would be expected from correction of smaller crib burns (Fig. 3). Similarly in "two-dimensional" burns up to a diameter of 30 meters, no unusual behavior at the largest dimensions was noted.

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

Based on conservative estimates of burning rates and air requirements, it is difficult to account for the high surface winds unless the mechanism of air induction is basically different from that of the conventional line or area fires, namely that a large-scale vortex flow is established. This introduces flow problems previously recognized in dust whirls, dust devils, tornadoes, and hurricanes possessing rotating columns in which the angular momentum is several orders greater than in the surroundings. It is by no means clear under what conditions such large-scale fire whirls form and by what mode air is introduced into this rotating vortex near the ground. Similarly, little evidence is available from which to judge whether, if such a cyclonic flow is established, a substantial effect on the burning rate of the fuel bed should be expected. (Byram and Martin have observed a burning rate increase

* See "Fire Whirls" in the Bibliography.

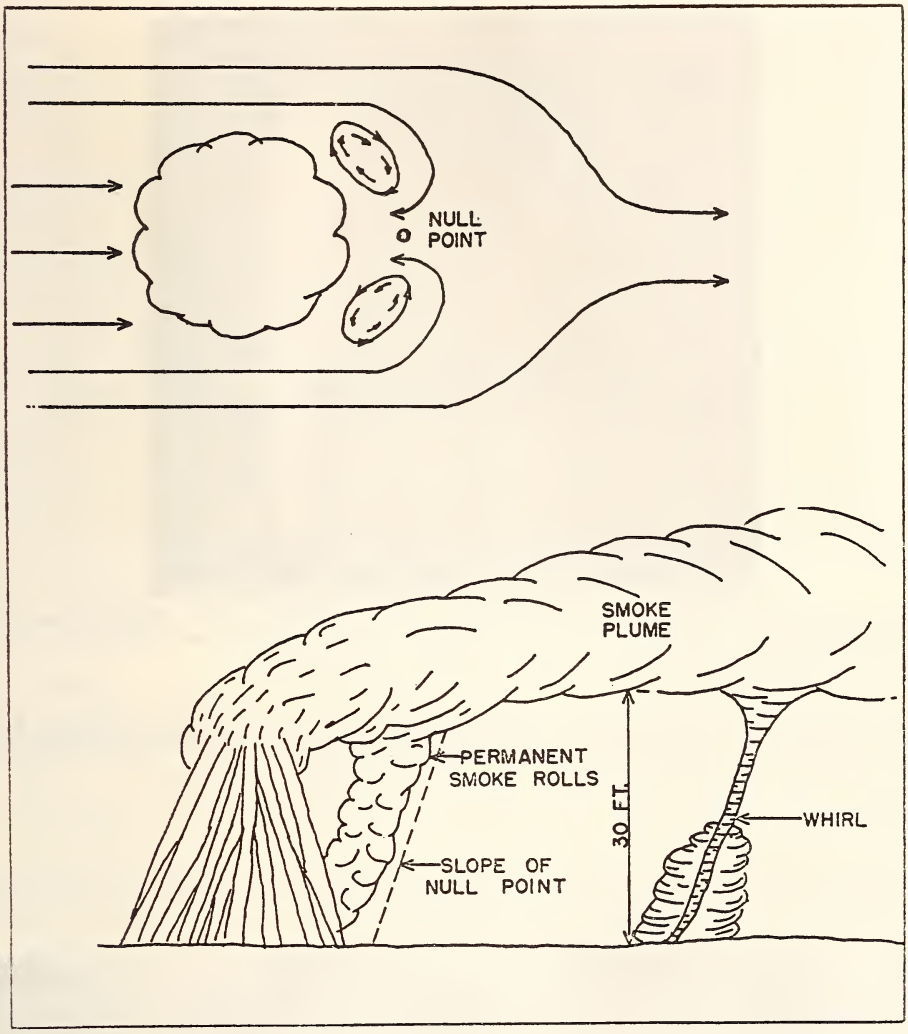

FIG. 5. Schematic diagram of fire-whirl development behind a bonfire. The whirls are reported to be formed when one of the "smoke rolls" breaks off from near a null-point in back of the wood structure (Ref. 25).

of 3 in model experiments.[23]) Only qualitative bits of evidence for circulation have been obtained, more or less by accident, in photographing air flow patterns near large fires, frequently not within the main heat release zone but in regions behind the convection column in the direction of the prevailing wind (Fig. 4). These secondary "tornadoes" appear related to the flow of wind around the fire column or the wood crib (Figs. 5 and 6).

Since the field observations of whirls occur at a scale which is difficult to reproduce on an experimental basis, their study has become, perhaps, the most challenging problem in the fire research field. The recent model experiments of Morton[26] on the behavior of low density liquids injected into a rotating tank (Fig. 7) are probably

FIG. 6. Sand devil near the well fire of Gassi-Touil, Sahara, November 1961. Height of flame: 150 meters. (Photograph supplied by J. Dessens, University of Toulouse. Presented at Third Conference on Severe Local Storms. University of Illinois, November 12–14, 1963.)

the first clear-cut indications that buoyant columns in a vortex field, while showing behavior which is not at variance with general expectations of vorticity, will produce effects which cannot as yet be predicted with any degree of assurance.

Conclusions

Fires pose questions to the physical scientist that will be answered only after the expenditure of much thought and ingenuity. Despite a few bold and successful

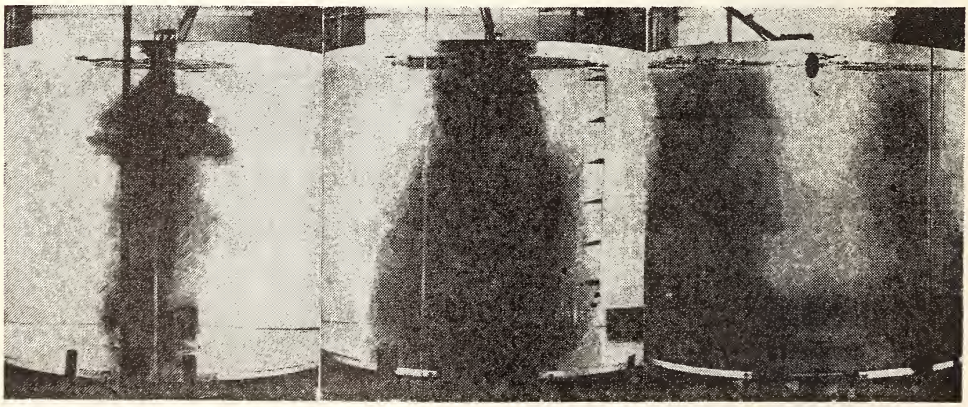

FIG. 7. Development of a positively buoyant downward jet of salt solution in a rotating tank (1.23 radians/sec). The jet ran for 15.2 seconds. The pictures were taken at 5.2 seconds, 20.8 seconds, and 40.2 seconds, respectively, after the start of the jet. In the final picture, the jet has separated into two rotating columns with almost vertical edges (Ref. 26).

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

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

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Fire Research at the U. S. Forest Products Laboratory

H. W. EICKNER

Forest Products Laboratory, Forest Service, U.S. Department of Agriculture*

[The Forest Service has, by public law, three primary missions: management and protection of the 186 million acres of National Forests and National Grasslands; cooperation with the States in the protection of non-federal forest lands and in improving forest practices in general on private lands; and Forestry Research. It operates as a decentralized agency through delegation of authority and responsibility to Regional Foresters for the first two missions and to Regional Directors for Research.

Fire Research within the scope of the Research mission is in two parts. One is aimed at evaluating the performance of wood products and wood product finished under exposure to fire and at enhancing their resistance to fire. It is carried out at the Forest Service's Forest Products Laboratory at Madison, Wisconsin. The other is a broad program of forest-fire research aimed at reducing the costs and losses due to forest fires and at developing techniques for using fire beneficially for various land-management purposes. It is conducted at ten regional Forest Experiment Stations.

At each of the Forest Experiment Stations the Forest Fire Research Unit has responsibility for carrying out applied research to solve high-priority regional fire problems. Special forest-fire laboratories are attached to three of these Stations. These laboratories at Macon, Georgia, at Missoula, Montana, and at Riverside, California are equipped to undertake basic research and comprehensive applied research projects of broader national scope. Regional Directors, through their project leaders in each subject matter field, consult with user agencies and assume responsibility for problem analyses on which to base selection and priority of the research projects they undertake.

Forest Fire Research does not include equipment development. That work is carried out at Equipment Development Centers maintained separately to serve all Forest Service equipment development needs.

In carrying out its three missions the Forest Service operates with a line-staff organization. Within Forestry Research, research workers report through a project leader to the Director of a Regional Forest Experiment Station or in the case of Forest Products Fire Research to the Director of the Forest Products Laboratory. The Director, in turn, is responsible to the Chief of the Forest Service through the Deputy Chief for Forestry Research. The Deputy Chief is advised by a technical staff of subject matter specialists. Under his direction they formulate national research programs within their respective fields, serve as technical subject matter advisors and consultants to other programs of the Forest Service, to the Department of Agriculture, and to other federal agencies. Members of the staff inspect progress and performance of subject matter research at the Experiment Stations and advise the Deputy Chief on needed changes and adjustments.

The accompanying article describes the fire research work of the Forest Products Laboratory. A later article will describe the Forest Fire Research Program being carried on in laboratories and in the field through the ten Forest Experiment Stations throughout the United States.—A. A. Brown, Director, Forest Fire Research, U.S. Forest Service.]

Throughout more than 50 years, the U.S. Forest Products Laboratory in Madison, Wisconsin, has earned a world-wide reputation for its research on efficient utilization of wood and wood products. The Laboratory was established in 1910 by the Forest Service, U.S. Department of Agriculture, on the University of Wisconsin campus. In 1932, when enlarged facilities were needed, it moved to its present location.

Besides research on the fire performance of wood, many other types of research studies have been conducted at the Forest Products Laboratory: basic studies of the structure of wood; chemical composition of wood and the production of many chemical compounds from wood; use of wood fibers in the fabrication of paper and allied products; changes in the chemical and physical properties of wood with heat, moisture, and pressure; and the strength, durability, drying, machining, chemical

* Maintained at Madison, Wisconsin, in cooperation with the University of Wisconsin.

and resin treatment, gluing, and finishing characteristics of wood. Many applied research studies have also been conducted to improve the dimensional stability and durability characteristics of wood products, to utilize lower grades and wood residue, and to develop laminated, plywood, stressed skin, and sandwich-type wood constructions for improved structural applications.

Early FPL Fire Research Studies

Research on the fire performance of wood was started at the Forest Products laboratory in 1912, when R. E. Prince developed a furnace apparatus and started a series of "flammability" (ignition) studies on various wood species, and investigated the effect of fire-retardant chemical treatments on the ignition characteristics. Next, a second flammability apparatus was developed and used for a study of various chemical and paint treatments for reducing the fire hazards of wood shingles. Of the treating systems that had been evaluated for use on the shingles, the double-impregnation treatment with zinc chloride and sodium borate appeared to be the most promising. The results of these studies were published in the National Fire Protection Association Proceedings for 1915.[1]

In 1917–18, a "fireproof" room was installed at the Laboratory and a small series of "full-scale" tests were run to determine the conditions that must exist within a room to cause wood to ignite and burn. Work on fire research was discontinued until 1927. M. E. Dunlap then started the development of the fire-tube apparatus, which is now American Society for Testing and Materials Standard E–69.[2]

During the next 6 or 7 years, the development of the fire-tube method was completed, and it was used by T. R. Truax and C. A. Harrison to study fire-performance properties of different wood species, and about 130 chemicals or combinations of chemicals for the treatment of wood. Seventeen of these chemicals were further studied in relation to the minimum quantity that would be effective. Monoammonium phosphate appeared to be the most effective chemical treatment, but combinations of salts were used to obtain neutral mixtures that reduce corrosion to metals, improve resistance to leaching, improve gluing and finishing characteristics, and reduce cost. Some data were obtained on the apparent moisture content of the salt-treated wood and on the gluing characteristics. The results of these studies were included in the American Wood Preservers' Association Proceedings for 1930 to 1933[3] with a summary report in 1935.[4]

In 1935, a 30 by 44 foot fire test house was constructed on the grounds of the Laboratory, and a large 10 by 10 foot vertical furnace was installed within this structure. This furnace was subsequently used by G. C. McNaughton and C. A. Harrison[5] to determine the effect of type of adhesive, plywood thickness, and insulation on the fire endurance of prefabricated plywood walls. Under proper construction conditions with mineral-wool-type insulation, these plywood-stud panels would withstand the 1-hour endurance exposure. McNaughton also used this furnace to study the temperature distribution and char penetration rate for 8 inch thick wood walls that had been exposed on the one surface to standard fire exposure conditions. This furnace has also been used for the study of the construction details for providing 1 hour fire endurance from wood core and wood-composite fire doors.

For a short period, during 1937 to 1940, the Laboratory undertook studies[6,7] of chemical solutions and wetting agents for the extinguishment of wood crib, grass, and brush fires, and eventually carried these on to field tests in Washington and

California on slash and log fires. These initial tests indicated good performance from monoammonium phosphate solutions both for pretreatment and extinguishment. This type of study has since been carried on by the Forest Fire Research Division of the Forest Service.

A. Van Kleeck in 1941 developed a technique using metal test coupons for comparing the corrosion characteristics of fire-retardant chemical solutions, and evaluated many combinations of these chemicals.[8] Many of these chemical solutions were corrosive to either brass, steel, or aluminum, but by the addition of 0.25 to 0.50 per cent by weight of sodium chromate to the solution, corrosion became negligible.

With the advent of the war, considerable emphasis was given to the study of thick coatings that might be applied in attics to reduce hazards from incendiary-type bombs. The results of this study are discussed in the National Fire Protection Association Quarterly.[9]

Shortly after the war, H. D. Bruce and others of the staff, also conducted studies in cooperation with the Armed Services Special Weapons Project on the critical radiation energies for the ignition of combustible materials and the attenuation of the radiation effects by intervening materials.

Starting about 1945, increased emphasis was given to fire endurance and surface flammability properties of walls with low-density cores and blanket insulation. The surface flammability and heat contributed by wood fiber boards that were used as interior lining materials were also investigated. For one of these series of tests, Bruce, Van Kleeck, and Martin[10] built an 8 by 12 foot test room of concrete block and wood joists with an 8 foot ceiling. They included within the room "mock-up" furniture at a fire load of about 4 pounds per cubic foot. A standard wood crib fire was then started in the center of the room, and the times to reach the "critical" and "flashover" conditions and other temperature, gas, and pressure measurements were taken. It was found, when the fire was started in the center of the room, that the nature of the walls, whether plaster, fiber insulation board, or plywood, had little or no effect on the time when the wall surfaces would have a rapid temperature rise, and only small effect on the time to flashover. The flashover occurred in all cases at wall temperatures too high for human life.

Flame-spread tests[11] were also performed on fiber insulation board, including small-scale tests and tests in the corner and ceiling of the 8 by 12 foot room. Starting in 1951, work was started on an 8 foot tunnel flame-spread method that would provide good correlation to full-scale tests, such as the corner-wall test, but yet would give well-defined values for surface flammability without the need for large samples of the test material. This test method[12,13] was subsequently developed by T. R. Truax, H. D. Bruce, and V. P. Miniutti, and was used for determining the surface flammability[14] of 29 species of wood and 50 commercially-produced wood panel products.

Since the start of the fire research program, several studies have also been conducted on the effectiveness and durability of various fire-retardant coating materials as applied to wood, and the effects of various fire-retardant chemical formulations on the moisture sorption, strength, and gluing properties of wood.

Current FPL Fire Research Program

The current fire research program at the Forest Products Laboratory involves both basic and applied types of studies which can be divided into four general

study areas: (1) pyrolysis and combustion reactions for untreated and treated wood to determine effect of chemical treatments on reaction rates, activation energies, endothermic–exothermic transition temperatures, heats of pyrolysis and combustion, and reaction products; (2) evaluation and formulation of improved fire-retardant chemical treatments and paint coatings, including empirical evaluation of fire-retardant properties and determining related properties such as durability, hygroscopicity, corrosiveness, strength retention, machining, painting, and gluing characteristics; (3) surface flammability of untreated and treated wood products, including the improvement of methods to measure this property and correlation to ignition characteristics; and (4) fire endurance of wood structures, including basic charring and heat penetration rates of wood, the development of mathematical relationships between fire exposure of such structures.

Basic Study of Pyrolysis and Combustion of Wood

Much of the past research on fire-retardant chemical treatment of wood to reduce its flammability and improve its performance in fire has been of the empirical nature, without a good knowledge of how the chemicals react with wood to reduce its flammability. In 1958, Dr. F. L. Browne made an extensive survey[15] of the available information on the pyrolysis and combustion of wood and how the reaction processes are changed by chemical treatment. This survey indicated the need for better basic information on how fire-retardant chemical treatments change the pyrolysis and combustion reactions for wood, and such information might be the basis for the more systematic selection of efficient fire-retardant chemicals.

Therefore, work was initiated in 1960 by Dr. Browne, W. Tang, F. Baird, and J. Brenden, to study these reactions. These studies, which are currently being continued by W. Tang and J. Brenden, involve the following methods of analysis to determine the basic thermal, kinetic, and chemical data for these reactions.

Static Thermogravimetric Analysis.—The first analytic method being used is static thermogravimetric analysis where the loss in sample weight is recorded as a function of time at a constant temperature. Assuming pseudo first-order reaction, the reaction rate constant can be computed from these data as the slope of the plot of the log of the residual sample weight versus exposure time. The activation energy or thermal stability for the samples can also be obtained by performing the static thermogravimetric analysis at a series of constant temperatures. By applying the Arrhenius equation, activation energy can be computed from the slope of a plot of the log of the reaction rate constants at a series of temperature versus the reciprocal of the absolute temperature.

Dynamic Thermogravimetric Analysis.—In a second method of analysis, dynamic thermogravimetric analysis, the wood sample is continuously weighed while it is being heated steadily at a linear rate under controlled atmospheric conditions and the results plotted versus the sample temperature. Such analysis discloses the threshold temperature for active pyrolysis, the range of temperature within which most of the pyrolysis occurs, and the yield of charcoal or the extent of volatilization when the pyrolysis is practically completed.

Differential Thermal Analysis.—A third general method of analysis being used in the studies of the effect of the chemical treatment on the thermal decomposition of wood is differential thermal analysis. In this analysis method, finely ground wood samples and thermally inert reference samples are heated under the same conditions

at a constant heating rate. The difference in temperature between the sample and reference is plotted versus the reference temperature. Such analysis reveals occurrence of endothermic and exothermic reactions at various levels of temperature and an estimate of the amount of heat evolved or absorbed in the reaction.

These analyses can also be performed under static gas conditions, with either nitrogen to determine the heat of pyrolysis reaction or with oxygen to determine the heat of combustion reaction, and under dynamic gas-flow conditions with either nitrogen or oxygen to determine the separate endothermic and exothermic peak.

Heat of Combustion Analysis.—A fourth method of analysis being used involves the determination of the potential heat of combustion of the volatile products that are released when wood samples are pyrolyzed to different degrees of volatilization. In this method the heat of the combustion of the residue, after volatilization of the sample to different degrees, is determined by standard oxygen bomb calorimeter techniques. The potential heat of the combustion of the volatiles previously released is then computed as the difference between the heat of combustion of the residue and a similar wood sample before pyrolysis.

Char–Tar–Water–Gas Ratio Analysis.—The fifth analysis involves the pyrolysis of untreated and treated wood samples under controlled conditions, with the immediate collection of the products into the char, tar, water, and gas fractions, and possible further analyses of the tar and gaseous fractions.

Special Thermal Equipment.—In order to make dynamic studies of the thermal degradation of wood, it was desirable that apparatus be obtained that could expose specimens under controlled atmospheres to precise temperature conditions (either constant temperature or constant rate of heating) and at the same time give a continuing record of the change in weight for the specimen during exposure. A thermogravimetric balance has been used very actively in pyrolysis and combustion research since 1960. With this furnace, wood samples can be subjected to constant temperatures up to 1000°C or at constant heating rates from 3° to 18°C per minute under vacuum or controlled atmospheres of air, oxygen, nitrogen, or helium. A continuous record of the sample versus sample temperature or time is then made.

The thermogravimetric balance has also been modified by W. Tang for use with several different thermal probes. The ground wood sample and reference material can be heated simultaneously in the balance furnace at a constant heating rate and under a controlled atmosphere, and the difference in the temperature between the two samples is recorded versus the reference sample temperature. Apparatus has also been developed whereby wood samples can be heated under precise pyrolysis conditions and the products of decomposition divided into char–tar–water–gas fractions.

The results of the initial studies on the pyrolysis and combustion of wood have been summarized in several articles[16,17,18] and others are in preparation. In particular, these studies show that many of the effective fire-retardant chemicals tend to lower the temperature at which pyrolysis decomposition starts, but this results in the more complete decomposition of the wood to charcoal and water instead of forming intermediate flammable tar products. Sodium tetraborate differs from many of the other fire-retardant chemicals in that it does not lower the temperature of the initial decomposition. Decomposition of the alpha-cellulose fraction of the wood has been found to be mainly responsible for the flaming reactions; and the lignin fraction contributes mainly to the glowing reactions at higher temperatures.

Evaluation and Formulation of Improved Fire-Retardant Chemcial Treatments and Paint Coatings

Empirical tests are being made on the fire performance in wood of many of the new organic–inorganic chemicals, originally developed as fire retardants for fabrics and plastics. Several of these recent formulations are also being evaluated for their effectiveness as fire retardants for wood shingles.

With the increased acceptance of fire-retardant-treated wood by code and insurance authorities, there is more demand for information on the related properties such as strength, hygroscopicity, corrosion, and gluing. While some studies have been conducted in the past on the related properties of fire-retardant-treated wood, the information is usually incomplete and involves antedated formulations and processes. More comprehensive studies are currently being undertaken in these areas both on the individual salts and processing variables, by the gluing and wood engineering project groups of the Laboratory. New techniques are also being used in some of these studies. For example, some recent preliminary work completed by C. Peters and H. Eickner on an electrical resistance method for quickly determining the corrosion characteristics of fire-retardant-treated wood appears to be more promising than the early type of coupon test developed by A. Van Kleeck[8] providing certain inconsistencies in the metal probe wires can be reduced.

Surface Flammability of Untreated and Treated Wood Products

The 8 foot tunnel furnace, which was developed at the Forest Products Laboratory, has been used by H. Eickner and C. Peters[19] for further studies of the effect of decorative and fire-retardant paint coatings on the fire performance of wood. This study shows that most of the decorative finishes, with the exception of shellac and lacquers, slightly reduce the surface flammability of wood. The commercial types of fire-retardant paints, when applied in relatively heavy coats as recommended by the manufacturers, can reduce the surface flammability of wood by as much as 75 per cent.

There has also been some work in the correlation of a "flame propagation temperature" for materials within the tunnel furnace with the 8 foot tunnel flame spread index values.[20] Increased acceptance is being given to the 8 foot tunnel furnace method as a standard flame spread test for research and development purposes. and six other research laboratories have installed this equipment. Considerable work is being devoted to the correlation of the index values between the different furnaces of this same type. It is also planned to determine the treatment levels with various individual fire-retardant salt and salt combinations to be effective in reducing the surface flammability of wood as measured by this method.

Fire Endurance of Wood Structures

Considerable additional work is necessary on the endurance of untreated wood structures under combined fire and load conditions. This work is currently being started on a small scale, by determining the basic charring and heat penetration rates for wood, including the effects of such parameters as species, density, moisture content, and grain orientation. Previous work by G. McNaughton on a limited number of samples indicated the charring rate for wood under fire exposure conditions is about $1\frac{1}{2}$ inches per hour. However, no valid information is known as to how the parameters mentioned above affect the char penetration rates.

At the same time that the experiments are being conducted on the char penetration rates, the mathematical theory for predicting the rate of char penetration for wood and wood construction is being developed. After the initial work on char penetration, it is planned to use the Laboratory's furnace equipment to determine the relationship between fire exposure, char penetration, and retention of strength for wood members. This information will then be combined with the theoretical design data to predict the performance of large wood assemblies under combined load and fire exposure. In the same general area of research, other studies are being conducted to determine the performance of various types of adhesive bonds and joint fasteners under the fire exposure conditions and relationship to the over-all fire endurance of wood structures.

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ABSTRACTS

I. Ignition Phenomena

Squire, W. (West Virginia University, Morgantown, West Virginia) "A Mathematical Analysis of Self-Ignition," *Combustion and Flame* **7**, 1–8 (1963)

An exact numerical method and an approximate analytical treatment are applied to the effect of reactant consumption in nonsteady explosion theory. The results for the critical conditions of self-ignition are compared with expressions given by Thomas[1] and Frank-Kamenetskii[2] who also considered reactant consumption. The approximate analysis of Thomas is seen to give more accurate results than the present method of analytical approximation.

Squire also presents ignition delays for the unstable supercritical condition, and compares the delays with the analysis of Thomas. Squire also compares them with the numerical integrations of Rice, Allen, and Campbell[3] who do not take reactant consumption into account vigorously. The results of the two methods of Squire are seen to be in agreement themselves, but not precisely with the ignition delays of the other investigators.

Squire also computes temperature and time histories of the combustion of wood by the exact numerical method, and compares the values with the experimental results reported by Akita[4] and by Kinbara and Akita.[5] Experimental and theoretical results are in satisfactory agreement, indicating that reactant consumption is significant for wood and also attesting to a successful solution of the physical problem.

In general, the mathematical analysis is developed in the following manner: The theoretical aspects of the problem are applied to the self-heating and ignition of wood which has previously been found[6] to conform to the partial differential equations:

$$\rho c(\partial T/\partial t) = K\nabla^2 T - \mathcal{Q}(\partial w/\partial t) \tag{1a}$$

and

$$\partial w/\partial t = -kw \exp(-E/RT), \tag{1b}$$

where ρ=density, c=specific heat, t=time, $\mathcal{Q}$=heat of reaction, w=concentration of reactive material, K=thermal conductivity, k=prefactor in Arrhenius rate expression, and T=temperature. These equations are normally solved with surface boundary conditions expressing heat input from the source of ignition or the flame, the highest temperature being at the wood surface. The present solution is based on another possibility arising from the exothermic nature of the decomposition. If the heat is not conducted away rapidly enough, the temperature can rise in the interior, accelerating the reaction rate, so that a thermal "explosion" occurs. The problem is analogous mathematically to the theory of thermal explosions in gases, extending the theory to include reactant consumption.

Equations (1a) and (1b) are converted to equations of dimensionless variables:

$$d\theta/d\tau = \delta\lambda \exp[\theta/(1+\epsilon\theta)] - A\theta \tag{2a}$$

and

$$d\lambda/d\tau = (-\delta/B)\lambda \exp[\theta/(1+\epsilon\theta)], \tag{2b}$$

subject to the initial conditions $\theta=0$, and $\lambda=1$ at $\tau=0$. The dimensionless quantities θ, λ, τ, δ, A, and B represent temperature, concentration, time, reaction rate, heat transfer coefficient, and adiabatic temperature rise. ($\epsilon=RT$ initial$/E$ is a small term that can be neglected.) Removing τ from Eqs. (2a) and (2b) by dividing gives

$$\frac{\lambda \exp[\theta/(1+\epsilon\theta)]}{B\{\lambda \exp[\theta/(1+\epsilon\theta)]-A(\theta/\delta)\}} \tag{3}$$

and the integral

$$\lambda=1-B^{-1}\int_0^{\theta}\frac{\lambda\, d\theta}{\lambda-(A/\delta)\theta e^{-\theta}} \tag{4}$$

which can be solved numerically by the trapezoid rule. The numerical solution determines the critical value of A/δ for a given value of B indirectly, but does not give an explicit formula for the critical curve. For this reason, Eq. (4) is also solved by the method of successive approximations for the critical and supercritical cases.

Squire concludes that the numerical method appears to be the best available for studying Eq. (2a) and (2b). He suggests that there may be an appreciable discrepancy between the full partial differential Eqs. (1a) and (1b) and both Eqs. (2a) and (2b) and Kinbara and Akita's linearization. To settle this point, he recommends that numerical solutions be obtained of the partial differential equations using a high speed computer.

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Subject Headings: ***Ignition, analysis of; Wood, time and temperature history of combustion.***

J. M. Singer

Martin, S. (U. S. Naval Radiological Defense Laboratory, San Francisco, California) and **Broido, A.** (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Thermal Radiation and Fire Effects of Nuclear Detonations," *U.S. Naval Radiological Defense Laboratory Technical Report 652* (10 May 1963)

This report presents a state-of-the-art review based on unclassified information available at the end of 1962. The purpose of the report is to assess the information available dividing it into correct, incorrect, and uncertain categories. The main subdivisions of the report deal with characteristics of thermal radiation, radiant exposure of distant surfaces, effects produced, formation, spread and control of fires, survival in fire zones, and conclusions.

The large yield nuclear weapons that are becoming available have increased substantially the fire damage effects far more than radiation and blast damage. These weapons present the possibility of high altitude detonations which would produce little blast effect and no early fallout, but maximum fire effects. The advent of these weapons has led to some extreme statements about their capability.

While all energy released in a nuclear explosion ultimately degenerates to heat, only that portion which is sufficiently intense to affect materials after passing through large distances in the atmosphere is of interest here. The large amounts of short wavelength energy produced by a nuclear detonation is absorbed in a short distance by the air and produces a fireball with a color temperature of about 6000°C. The resulting visible and near infrared energy is equal to about one-third of the detonation energy release for air bursts. This value falls to about one-fifth if the fireball touches the ground. Quantitative information about high altitude bursts, i.e., 100,000 feet and above, is less certain, but calculations indicate that the energy in the thermal state becomes a greater fraction of the released energy. However, the high altitude burst distributes the thermal energy over a greater time span so that the energy available for causing fires is less than in an equivalent air burst.

The radiant energy to which a material will be exposed will be a function of weapon size, distance from the source, orientation, and atmospheric transmission. A popular "rule of thumb" is that at a distance of one mile a surface normal to the ray path will receive one cal/cm^2 for each kiloton of yield. Beyond this point the radiation varies with the inverse square law. Air transmission is affected by dust and/or water vapor content. The air itself acts mainly as a scattering medium. Attempts have been made to express the transmission in terms of the meterological term "visibility". The relation of transmission to visibility is the most uncertain of the quantities needed to estimate radiation received. The models proposed produce variations of a factor of two for distances, and factors of five to ten for radiant exposure.

The biological effects produced will consist of retinal burns, temporary flash blindness, and flash burns. The severity of the last will depend upon weapon size, distance, and amount and kind of clothing worn. Small weapons are more effective than large weapons in producing burns. Clothing will in general provide protection except when dark and touching the skin.

The most fire-prone fuels are dried leaves, grasses, etc. Industrial trash and heavy wildland kindling are more resistant to fire and furnishing fabric, etc., are least fire prone. Most heavier materials are not ignited permanently by the nuclear thermal pulse. Ignition of the most susceptible material can be expected at a distance of ninety miles for a hundred megaton burst exploded at a fifty mile height. The start of a major fire will depend upon the distribution of combustible and its condition.

Spread of fires has been studied and is more affected by weather conditions in rural than urban areas. In either case humidity is of importance only in the early stages. Fire control action is best directed at (1) reduction of potential ignition, (2) provision of rapid extinguishment, and (3) reduction of fire spread potential.

Survival in a major fire would appear to be most favorable in an underground shelter located in an open area with an air vent placed so that it would not be buried by burning debris and that could be sealed for periods of an hour or two, which

would be the expected duration of the high intensity phase of a mass fire. A shelter of this type would also be effective against radioactive fallout.

Subject Headings: *Radiation, thermal, from nuclear explosion; Nuclear explosion, radiation;* Fire, effect of nuclear explosion.

H. N. McManus, Jr.

Martin, S. (U. S. Naval Radiological Defense Laboratory, San Francisco, California) "Ignition of Cellulosic Kindling Fuels by Very Brief Radiant Pulses," *U.S. Naval Radiological Defense Laboratory Technical Report 660* (15 July 1963)

In this study are reported the radiant exposures required for sustained, flaming ignition of cellulosic kindling fuels subjected to brief thermal radiation pulses. Exposure times are of the order of tens to hundreds of milliseconds. Such brief pulses are of interest now because of the current trend of weapons technology toward subkiloton-yield weapons discharged in the air and toward detonation of large-yield weapons at high altitudes. In these cases, the effective portion of the weapon's thermal energy is radiated in such brief spans. Accordingly, the U.S. Naval Radiological Defense Laboratory is studying their incendiary possibilities.

Samples of α-cellulose, newspaper, and kraft corrugated board were exposed in the carbon-arc, mechanical shutter system. The radiant energy source was a modified 36 in. paraboloidal mirror, carbon-arc source, equipped with a high speed, air-driven shutter. Minimum exposure time attainable was approximately 30 msec. Time of exposure was measured with a phototube circuit incorporating a fast counter–timer read-out.

The samples were exposed to irradiance levels of 50, 75, and 100 cal cm^{-2} sec^{-1} with the threshold ignition time determined by a bracketing approach. The irradiance level was then measured with a Mark VI Mod 2 calorimeter.

Ablation rates were determined for several samples exposed to 100 cal cm^{-2} sec^{-1} that failed to sustain ignition after exposures corresponding to the threshold of sustained ignition. The remaining thickness of such exposed samples was measured and the rate was calculated from the original thickness and the time of exposure.

In general, the radiant exposures required for ignition are relatively constant over times of exposure of such brevity. There is, however, a small but significant upward trend toward higher irradiances and shorter exposure times. This is probably less than a factor of two over an order of magnitude change in time. This trend may reflect the emerging preeminence of the ablation process and its endothermicity. It may result from the process becoming controlled by reaction rate rather than by heat diffusion. This question is being studied further.

In the ablation rate determinations, it was found that the remaining thickness of the samples was independent of their original thickness. This was expected in view of earlier work at NRDL indicating that at very high irradiance levels, the over-all energy requirement of the ignition process is dependent primarily on the thickness of the material and independent of exposure duration. Those studies had shown that intensely irradiated cellulose ignites but is not necessarily sustained

when the exposed surface temperature reaches a fixed point, probably in excess of 600°C. It was thought that sustained ignition occurs when the temperature of the back surface rises to 200° or 300°C. The temperature profile under the conditions of study here, is steep enough so that the back surface is not heated to sustained ignition temperature before the front surface has moved close to it.

At the 100 cal cm^{-2} sec^{-1} level, transient flaming occurs almost immediately but is not sustained until the material has ablated away almost completely. For even shorter pulses of higher irradiance, the sustained flaming threshold may lack significance.

The author also compares the efficiency of the air burst weapon pulse and that of the square-wave input.

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

G. S. Cuff

Thomas, P. H. and Bowes, P. C. (Joint Fire Research Organization, Boreham Wood, England) "Some Aspects of the Self-Heating and Ignition of Solid Cellulosic Materials," *British Journal of Applied Physics* 12, 222–229 (1961)

The authors review the published material on self-heating and ignition of fiber insulating boards,[1,2,3] first, in terms of a simplified mathematical theory of ignition and secondly, with respect to an analysis in which reactant depletion is accounted for.

The simple theory was originally developed by Semenoff[4] and others for certain gas mixtures, which depend for ignition on the balance between reaction heat and heat losses. The theory, which assumes that heating is due to a single reaction of nth order, that the Arrhenius law is obeyed, and the process is not diffusion limited, has been extended to account for the influence of convection cooling on δ_c the dimensionless heat generation rate by use of the methods of Frank-Kamenetskii.[5] By these methods it is shown that the ignition data of Mitchell,[1] Gross and Robertson,[2] and some new measurements by the authors can be well correlated.

However, when the peak temperature rise data from self-heating experiments of Mitchell are analyzed, it is found that heat generation rates are an order of magnitude greater than would be expected from the ignition measurements. If reactant depletion is accounted for, the discrepancy becomes larger.

The authors propose that previously-made assumptions of a simple reaction may not be justified. They provide some experimental data on the self-heating of a one inch cube of wood fiberboard to support this suggestion. From the shape of the temperature rise time curve resulting from this experiment, it is proposed that two or more reactions are involved. A comparison of ignition temperatures for different sizes of specimen will provide an indication of the activation energy for the second reaction, while measurements of the self-heating peak temperature rises provide that for the first reaction.

The data by Mitchell[1] on induction times have been plotted and appear to be inversely related to the square of the specimen radius. Since these data were obtained under conditions such that ambient temperature was from 2° to 10°C higher

than the critical ignition temperature it is reasonable to expect that these times would be quite insensitive to initial temperature of the specimen, although for these data, this was uniform and close to 25°C. Because of a systematic difference of about 40 between the induction period for cotton linters as compared with fiberboards, it is suggested that the cotton may contain a combustion inhibiting agent. This suggestion has formed the basis of several letters to the editor of this journal.[6]

It is concluded that there is significant evidence to show that a simple ignition theory based on a single reaction of the Arrhenius type is inadequate to explain the available data on ignition of cellulosic materials. The implication is that only under some situations is it possible to predict critical size and temperature conditions from small-scale experiments. It is recommended that both self-heating and self-ignition experiments be performed on small specimens to permit verification of the adequacy of the model for the proposed extrapolation to large scales.

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

A. F. Robertson

Cassel, H. M. and Liebman, I. (U.S. Bureau of Mines, Pittsburgh, Pennsylvania) "Combustion of Magnesium Particles. II. Ignition Temperatures and Thermal Conductivities of Ambient Atmospheres," *Combustion and Flame* **7**, 79–81 (1963)

The present report is a sequel to a previous one,[1] in which the ignition of single particles and of clouds of particles of magnesium and of 50% magnesium-50% aluminum was shown to follow closely the classical thermal theory. The "ignition temperature" of single particles was shown to be an inverse function of particle size, the dependence being quasi-hyperbolic. For dust clouds, however, the ignition temperature proved to be lower than for single particles of the same size, because the interior of the cloud is shielded from heat loss by the surrounding particles, and heat generated by reacting particles is transferred to neighboring particles. At large values of dust concentrations, however, the trend changes so that clouds of larger particles have higher ignition temperatures than do clouds of the smaller particles, at the same values of mass concentration. A significant finding was the fact that the ignition temperature was independent of oxygen concentration, thereby justifying the neglect of oxygen diffusion in favor of purely thermal conduction processes.

The present report continues the investigation into thermal phenomena, in which pure magnesium particles were ignited in air and in mixtures of $2O_2+8A$ and $2O_2+8He$, covering a fivefold range of thermal conductivity of the ambient atmos-

phere. Assuming an Arrhenius-type reaction law, the van't Hoff–LeChatelier theory of ignition predicted values of ignition temperature and of activation energy consistent with the experiments. The values of thermal conductivity of mixtures required to bring about this agreement agree with values calculated by the theory of Hirschfelder, Bird, and Curtiss. In this manner, it was found that the ignition temperature of single magnesium particles increase with decreasing particle size and with increasing thermal conductivity of the ambient atmosphere, as follows:

$$2O_2+8A<\text{air}<2O_2+8He.$$

Ambient atmospheres with higher thermal conductivities conduct away the heat more rapidly so that a higher temperature is required to make the reaction self-sustaining.

It appears that the primary reason for the consistency of results and good agreement with theory is the fact that such careful control of particle size and shape was maintained throughout the experiments.

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Subject Headings: ***Magnesium, ignition of; Ignition, of magnesium.***

J. K. Richmond

Bowden, F. P. (University of Cambridge, Cambridge, England) "The Initiation and Growth of Explosion in the Condensed Phase," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 499–516 (1963)

The Slow Decomposition of Explosive Crystals: Electron microscope studies show that the thermal decomposition of some explosive crystals, e.g., silver cyanamide, occurs primarily on the surface. With others, e.g., silver azide, the surface reaction is again important but there is evidence also for some decomposition within the crystal which can cause it to break up into many small fragments. There is also evidence that, for many of these explosives, an actual melting must occur—it is only in the molten phase that the reacting species have sufficient mobility for a rapid acceleration to take place.

The Effect of Fission Fragments and Nuclear Radiation: By choosing a crystal lattice which can be resolved in the electron microscope it has been possible to measure the extent of the damage with some precision. The damage depends upon the nature of the crystal and on other factors, but the track width may be approx. 100–120 Å. The disorder produced in the lattice and the holes and tunnels formed may be clearly seen. The damage may be interpreted on a thermal mechanism. The experiments at present suggest that even the intersection of two tracks would not produce explosion in an azide crystal. The intersection of three or more tracks within 10^{-11} sec is an unlikely event.

The Effect of Discontinuities in Promoting Shock Initiation: Recent experiments with single crystals emphasize the importance of very tiny defects in the initiation

of explosion by weak shock waves and the part they play in the growth process. A perfect crystal of silver azide is not initiated by a shock but a defect only a few microns in size will start reaction. This reaction in small crystals (0.01 to 1 mm) is a fast burning. With crystals greater than 2 mm it may grow to detonation. The defects may be present initially or may be introduced by a precursor stress wave moving at sonic velocity through the crystal. When a shock wave of appropriate intensity passes over a crystal containing multiple defects it can initiate a deflagration at each so that the forward movement of the deflagration is coupled to the shock wave. In this way a "pseudo-detonation" is set up. There is evidence that appropriately shaped cavities in liquids and solids can give rise to the formation of tiny Munro jets of high velocity. These might aid initiation by concentrating and increasing the velocity of impact and by breaking up the explosive.

Subject Headings: ***Explosives, ignition of; Ignition, of explosives.***

Author's Summary

Bruinzeel, C. (Koninklijke/Shell-Laboratorium, Amsterdam, The Netherlands) "Electric Discharges During Simulated Aircraft Fuelling," *Journal of the Institute of Petroleum* **49**, 125–135 (1963)

Aircraft fueling was simulated in large-scale equipment with the view of investigating the nature of the electrical discharges occurring, and means of preventing them. The experimental tank was 4×1×0.75m, divided into four compartments. Odorless kerosine was pumped from a storage tank through a filter into the experimental tank at measured rates ranging from 100 to 450 Imp gal/min. Provisions were made for measuring the charging rate, the charge density in the fuel flowing into the tank, the electric field in the tank, the quantity of charge transferred in a single discharge, the potential, and the lifetime of the discharge.

Photographs show the spark discharges are long and may follow irregular and even branched paths, similar to lighting. Corona discharges were also observed on sharp pointed objects in the vapor phase, sometimes occurring simultaneously with the spark discharges. Spark discharges occurred when the field strength at the roof of the tank was 400 to 500 kV/m, for no probe or a blunt probe. Corona discharges occurred to sharp pointed probes at average field strengths lower than this. Data on the charge transferred, the duration of the spark, the field strength, and the surface potential for a number of spark discharges are given. Oscillograms for some of the discharges are given; the discharges are rapid (a few microseconds duration). Sparks are most likely to appear in the first stages of filling, and when filling is nearly complete.

The author discusses the data and concludes that the observed discharges are long sparks. He notes that there seems to be no data in the literature concerning the energy–ignition relationship for long sparks. There are, he notes, extensive data for sparks between closely spaced electrodes. To test if sparks such as those observed would cause ignition, a local pocket of flammable gas (pentane–air) was created. When sparks discharged through this pocket the mixture was ignited, and this is illustrated by an excellent photograph. It is not yet clear, apparently, if

corona discharges will cause ignition. The duration of these is short (0.2 μsec) and the charge transferred ordinarily small. Nonetheless, the author advises against multiple corona discharges, sometimes suggested to bleed off the charge and prevent a hazardous spark.

Methods of reducing charge accumulation are discussed. One method would be to subdivide the tank into small compartments, but this is not a practical method. The method used is to increase the conductivity of the fuel. From his tests the author draws a curve of charge density at the tank inlet vs. rest conductivity of the fuel for sparking and nonsparking fuels, and concludes that the lower limit of conductivity for safety, except perhaps in very severe conditions, is 50 picomho/m. An appendix gives equations for the estimation of field strengths in a tank inlet compartment. An account of the discussion following the presentation of this paper is also given.

Subject Headings: *Sparks, static, during aircraft fueling; Ignition, by static sparks; Fuel, ignition of, by sparks.*

P. R. Ryason

Courtney, W. G., Clark, W. J., and Slough, C. M. (Texaco Experiment, Inc., Richmond, Virginia) "Ignition of Ethylene Oxide Vapor," *ARS Journal* **32**, 1530–1535 (1962)

Recent investigations of the decomposition flame of ethylene oxide indicate that the ignition energy and quenching distance are larger than those of hydrocarbon–air mixtures. Further, the burning velocity and flame temperature are smaller than the corresponding properties for hydrocarbon–air mixtures. The authors chose to study the behavior of ethylene oxide vapor decomposition flames as an appropriate test of the minimum ignition energy equation developed by G. Rosen and others. Ethylene oxide vapors were ignited in the absence of air in a constant-volume bomb by both spark and hot wire techniques. Single pulse overvoltage sparks were passed through the vapor in spark ignition. A constant energy pulse was passed through a small resistance wire totally surrounded by vapor in the hot wire ignition experiments. The initial temperatures of the ethylene oxide vapor were varied from 25° to 175°C and initial pressures from 0.125 to 6 atmospheres.

High speed schlieren motion pictures were taken of flame kernels. Reproducibility of the pictures of kernel formation and growth was not satisfactory for the case of capacitance spark ignition; flame kernels were irregularly shaped and turbulent. Multiple-type sparks often occurred even though single pulses of energy were sought. This contributed to poor reproducibility and was probably a result of the high spark energies required for ignition. Low voltage, medium inductance spark ignition gave better reproducibility. Much better reproducibility was obtained using the hot wire ignition technique; flame kernels were regularly shaped and laminar.

Space velocities of the flame kernels were studied using the hot wire ignition technique. They initially had moderately high space velocities but as the kernels grew, the space velocities slowed to a constant value which was identical to those

measured in spark-initiated kernels. The burning velocity of ethylene oxide vapor was determined from the data to be 4.8 cm/sec at 3 atmospheres and 175°C. This is in good agreement with previously reported flame velocities in ethylene oxide. Minimum ignition energies and quenching distances are also reported. The ignition of ethylene oxide vapor involves very high ignition energies, e.g., a minimum ignition energy of 1.5 J at 1 atmosphere and 25°C. The quenching distance for ethylene oxide vapor was found to be 1 cm at 175°C and 1 atmosphere which is much larger than the quenching distance for most hydrocarbon–air mixtures at the same conditions. It was concluded from this work that the equation of Rosen and others is useful for predicting ignition energies to a first approximation.

No photographic evidence of a preignition zone for ethylene oxide vapor was found. No evidence was found for a minimum-type ethylene oxide flame kernel that would propagate. It was concluded that the minimum embryonic ethylene oxide flame front that propagates must be essentially a steady-state flame front.

Subject Heading: *Ignition, of ethylene oxide.*

L. R. Griffith

III. Heat and Material Transfer

Anderson, J. E. and Stresino, E. F. (Linde Company, Indianapolis, Indiana) "Heat Transfer from Flames Impinging on Flat and Cylindrical Surfaces," *Journal of Heat Transfer* **85**, 49–54 (1963)

Prediction of the spatial distribution of heat transfer from a flame to a surface involves interaction of two complex and interdependent phenomena, the fluid mechanics of the flow, and the physical and chemical properties of the gas stream. It is necessary to specify the boundary conditions which in the case of a flame require knowledge of distribution of temperature, velocity, chemical concentrations, and similar quantities. In particular it is difficult to specify the thermal conductivity of a reacting gas. Due to the complexity of a rigorous theoretical approach, experimental investigations, as reported by the authors, are of interest.

Flames of four different fuel–oxidizer combinations (H_2–O_2, C_3H_8–O_2, C_2H_4–O_2, CH_4–air) impinged on two different geometries of surfaces (a flat plate and a cylinder). The flames were either low speed Bunsen-type or high speed jets similar to a miniature rocket. The flat copper plate was separated into two parts by a thin thermal insulator. The flame, with its axis parallel to the plate normal, was traversed along a path perpendicular to the insulator. Measurements of heat transfer to each portion of the plate were transformed mathematically in heat per unit area per unit time as a function of radial distance, i.e., $q(r)$. For the case of the cylindrical tube, which had water flowing inside, the flame axis, traversing line, and tube axis were mutually perpendicular.

Some of the qualitative observations were:

1) For flat plate q falls off rapidly with r; at about two jet diameters q is down tenfold;
2) For tube geometry $q(r)$ has a plateau with width comparable to flame diameter;

3) Maximum values of q varied widely depending on velocity and chemical constitutents; and
4) q depends on axial distance along the flame; within the cone on the flame axis q is less than for axial locations beyond the cone.

Curves of q as function of r are given for the different flames and for the different geometries.

For comparison the heat transfer to the tube was calculated by using the Nusselt number and Reynolds number correlation given by McAdams[1] for cylinders. To obtain the heat transfer coefficient from the Nusselt number, it is necessary to determine the thermal conductivity k. A simplified procedure for calculating k was adopted. The observed and calculated q for the tube were within a factor of unity except for one case.

The flat plate results could be correlated with the empirical formula

$$\log(q/q_E) = -4(r/D_F)\ \mathrm{Re}^{-0.34},$$

where q_E is a reference rate, D_F is the flame diameter, and Re the Reynolds number.

Reference

1. McAdams, W. H.: "Heat Transmission." McGraw Hill Book Co., Inc., New York, 1954.

Subject Headings: ***Flame, heat transfer to surfaces; Heat transfer, from flame.***

A. E. Fuhs

V. Combustion Principles

Sagert, N. H. and Laidler, K. J. (University of Ottawa, Ottawa, Canada) "Kinetics and Mechanisms of the Pyrolysis of *n*-Butane. Part I. The Uninhibited Decomposition," *Canadian Journal of Chemistry* **41**, 838–847 (1963)

The kinetics of the uninhibited decomposition of *n*-butane have been studied in the temperature range from 520° to 590°C and at pressures from 30 to 600 mm Hg. The main points of interest of this investigation were: the order of the reaction, the nature of the initiating and terminating steps of the chain mechanisms, and the role of the surface.

The apparatus has been described in previous papers. It consisted mainly of a quartz reaction vessel of 200 ml capacity supported in a large metal block, the temperature of which was electrically controlled to within 0.2°C. The reaction rate was followed by pressure changes, measured with a quartz spiral gauge, and by gas chromatography. The surface effect was studied by using an identical vessel packed with quartz tubing to give an 11.6-fold increase in the surface/volume ratio. The "conditioning" of the reaction vessel was carried out by pyrolizing butane in it at 300 mm Hg for 48 hours.

The reaction was concluded to be of the three half order in an unpacked vessel (somewhat lower in a packed one). The rate constant was found to be:

$$k_{\frac{3}{2}} = 3.24 \times 10^{15} \exp(-59{,}900/RT)\ \mathrm{cc}^{\frac{1}{2}}\ \mathrm{mole}^{-\frac{1}{2}}\ \mathrm{sec}^{-1}$$

The reaction was suggested to be largely homogeneous and to occur almost entirely by a free radical mechanism similar to the one put forward by Echol and Pease (1939). Some of the indications that the molecular components were of minor importance were given in the Part II of the paper where results of reaction inhibited by nitric oxide were presented. However, the authors found it difficult to explain the formation of 1 to 2 per cent butene found in the products by the proposed mechanism.

The initiating reaction was postulated to be the breakdown of *n*-butane into two ethyl radicals in its high-pressure first order region. The terminating step was then concluded to be the second order combination of the same radicals. Another possible initiation step was suggested to be the split of *n*-butane into a methyl and a propyl radical. This process was disfavored because it not only requires a slightly higher dissociation energy than the former process but also would result in termination steps occurring in their third order regions.

The reaction was found sensitive to surface. Both packing the vessel and "conditioning" it led to a decrease in the reaction rate and an increase in the activation energy. The surface effect was attributed to the surface catalysis of recombination of ethyl radicals, and to the abstraction of a hydrogen atom from butane by a surface atom in a manner similar to that by nitric oxide in an inhibited reaction.

Subject Headings: ***Butane, pyrolysis; Thermal decomposition, of butane.***

A. C. S. Ma

Beeston, G. (University of Sheffield, Sheffield, England) and **Essenhigh, R. H.** (The Pennsylvania State University, University Park, Pennsylvania) "Kinetics of Coal Combustion: The Influence of Oxygen Concentration on the Burning-Out Times of Single Particles," *Journal of Physical Chemistry* **67**, 1349–1355 (1963)

The authors report the results of their continuing experiments with single particles of coal. This phase of their work, primarily concerned with the second stage combustion of the solid carbon residue left after combustion of the volatiles, covers the influence of oxygen on the residue burn-out times. Carried out under precisely specified conditions, the experiments allow the authors to verify certain kinetic equations based on Nusselt's diffusion theory of reaction control.

Particles of sizes 1870, 1300, 928, 649, and 388 μ, derived from a single coal of a medium bituminous grade, were burned at oxygen concentrations ranging from 3 to 70 per cent. The coal particles were cemented to silica fibers and heated midway between two horizontal heating elements of electrical resistance wire to about 1000°C. The combustion unit was housed in a plexiglass box large enough so that oxygen depletion during combustion of a particle would be insignificant, leaving the ambient oxygen concentration effectively constant. The atmosphere was checked by Orsat analysis before and after combustion. Burning times were measured with a stop watch, and found to be quite adequate for the residue burning times.

Qualitatively, the particles burned in two stages with the first, the volatiles stage, acting quite irregularly, even failing ignition for the very small particles or

for low oxygen concentrations. The ignition delay, during which the particles heated up, increased as the oxygen content decreased. At 3 per cent oxygen, the particles failed to ignite. At high oxygen concentrations, the particles tended to decrepitate or explode.

Quantitatively, the authors were primarily concerned with combustion of the residues. The residue burning times (t_b) were found experimentally to obey the relation predicted from the Nusselt diffusion theory of particle combustion

$$t_b = m/\ln(1-p_0), \tag{1}$$

where p_0 is the ambient oxygen concentration and m is a constant. It is related to initial particle diameter d_0, thus

$$m = M^2 d_0^2, \tag{2}$$

where M is another constant. This second constant can be calculated from

$$M^2 = [(C_f/100)/f]\sigma/3\rho_0 D_0 (T/T_0)^{0.75}, \tag{3}$$

where C_f is the fixed carbon percentage, f is the swelling factor, σ is the solid particle density, ρ_0 is the s.t.p. density of air, D_0 is the s.t.p. coefficient of oxygen diffusing through nitrogen, T is the absolute temperature, and T_0 is the reference temperature of 273°K. Results were in good agreement with all of the relationships expressed above. In fact, the experimental and predicted values for M were identical. The burning constant K in the Nusselt expression

$$t_b = Kd_0^2 \tag{4}$$

was also calculated and found to be in adequate agreement with earlier values obtained for this same coal.

This experimental agreement with the theory based on Nusselt's analysis substantiates the assumptions he made, that: the rate controlling process was the diffusion of oxygen to the particle surface; reaction at the surface was effectively instantaneous; the surface reaction was also first order with respect to the oxygen partial pressure adjacent to the solid surface.

Establishment of the reaction order as unity at the low temperature of 1000°C was unexpected in terms of the available literature. The discrepancy is probably due to the fact that these experiments were carried out in effectively quiescent systems whereas the earlier work was done in flowing systems.

Subject Heading: *Coal, kinetics of combustion.*

G. S. Cuff

VI. Radiation

Callomon, J. H. and Gilby, A. C. (William Ramsay and Ralph Forster Laboratories, University College, London, England) "The Carbon Monoxide Flame Spectrum under High Resolution," *Journal of The Chemical Society*, 1471–1475 (March 1963)

The present work is a fine example of a crucial experiment which can successfully arbitrate between two divergent points of view—in this case the origin of certain

features of the carbon monoxide spectrum. For many years, spectroscopists have reported a strong continuum in this spectrum, extending from the ultraviolet into the infrared. It has required considerable skill on the part of theoreticians to explain a continuum, occurring at moderate temperatures and pressures, in the absence of solid particles. Some have doubted that this reported phenomenon was a true continuum, and the present authors have verified that it has indeed a very complex rotational fine structure, under high resolution.

Always present, distributed along the continuum, is a band structure which is also found in the spectrum from the afterglow of the reaction between atomic oxygen and carbon monoxide. In the latter case, the apparent continuum is absent. The authors also carried out careful experiments which tended to rule out the possibility that self-absorption might produce the apparent fine structure. As further evidence that the observed phenomena could not come from recombination reactions, involving non-quantized states, is the dependence of the intensity on pressure and temperature, which is in the wrong direction for such a mechanism to operate.

It is suggested that all the observed spectra comes from the carbon dioxide molecule in the excited state, as follows:

$$CO+O+M \rightarrow CO_2^*+M.$$

The excited CO_2 molecule can return to the ground state in the usual manner, and, in addition, intermediate states are likely in which the molecule is bent, as well as linear. This process can provide a large number of closely spaced vibrational states, although the details are too complex to permit a complete analysis.

Approximate analogies are pointed out in the visible spectra from BO_2 and from CS_2, where a fine structure was observed due to vibrational states, and where a dissociation continuum could be ruled out.

Subject Headings: *Carbon monoxide, flame spectrum; Flame spectrum, of carbon monoxide.*

J. K. Richmond

VII. Suppression of Combustion

Goodale, T. C., Hawkins, M. B., and Willoughby, A. B. (United Research Services, Burlingame, California) "Feasibility of Active Countermeasures for Thermal Radiation Effects of Nuclear Weapons," *Final Report on Contract OCD-OS-62-242 Office of Civil Defense* (July 1963)

Thermal radiation from nuclear detonations can cause large fires and inflict heavy damage to personnel and property, in the event of a nuclear attack. The fire hazards can be minimized in 3 ways: (1) Passive preattack countermeasures, which include whitewashing windows; installing noncombustible Venetian blinds; painting with noncombustible paints; and eliminating exposed trash, dry grass, and leaves. These fire-prevention measures are prepared in advance, and require no major action at the time of an attack. (2) Active preattack countermeasures, which require both advance preparation and major action at the time of an alert: for example, turning

on smoke screens or water sprinkler systems. (3) Postattack countermeasures, which are directed toward flame extinguishment rather than fire prevention.

This study deals only with the second class of thermal countermeasures, the active preattack countermeasures. Smoke screens are declared to be the only practical and effective absorbers of thermal radiation from nuclear blasts. They can be used to shield critical target areas, and attenuate the thermal radiation from nuclear weapons, reducing the incident energy to a safe level insufficient to kindle flames in the most susceptible fuels.

The direct ignition of materials by thermal radiation from nuclear detonations depends upon: (1) The weapon characteristics (total thermal energy, rate of energy delivery, spectral distribution); (2) The atmospheric transmission characteristics (visibility, amount of precipitable water vapor, geometry of cloud cover); and (3) The ignition characteristics of the kindling fuels (moisture content of dried leaves and grass, rotten wood or punk, forest litter, and crumpled newspapers). Heavy fuels and house sidings are not ignited directly by the blasts.

The primary purpose of active countermeasures is to prevent ignitions, as opposed to preventing skin burns or other biological damage. Two methods come to mind: (1) Installation and operation of water sprinkler systems; and (2) Erection and maintenance of smoke screens. Sprinkler systems are dismissed as impractical for large area protection because of the tremendous water requirement; and the inacceptability of soaking the exterior and interiors of buildings, including furnishings, during false alarms and practical alerts. On the other hand, smoke screens are effective, economically feasible, and not too great a nuisance.

Theoretical consideration of the interaction of thermal radiation with smoke screens shows that absorbing smokes composed of carbon or metal particles are much more efficient for shielding than scattering smokes such as oil fogs. Absorbing smoke particles in the 0.1 to 0.3 micron size range reduce the intensity of transmitted radiation by conducting heat to the surrounding air at a rate which must be nearly equal to the rate of absorption of the radiation. Scattering smokes reflect the same energy back and forth; and since all the energy that flows in must flow out, the radiation finds its way eventually to the target.

Horizontal, wind-erected smoke screens are recommended. Since no practical method is available for dispersing 0.1 to 0.3 micron dry powders into unagglomerated smokes, new smoke generators must be developed which employ vapor phase chemical reactions or organic chemical decompositions to form condensible solid products in the particle size range of interest. Present-day smoke pots give agglomerated smokes because the concentration of smoke inside the generators is high. Adequate protection can be obtained from a 100 meter thick carbon smoke, of about 0.2 micron particle size, and containing 2200 lb per square mile of particulate matter. This absorbing screen would reduce the normal incident radiation of the blast by about 90 per cent. (Visibility inside this smoke screen would be about 165 feet.) Such a smoke screen would contain about 5 mg of particles per meter, which is about 10 times the mean concentration in the atmospheres over Los Angeles, Detroit, San Francisco, and Washington, D.C. However, the fine particles would not fall out, as in ordinary smokes, but would diffuse and precipitate over a very large area. Hence the increase in general atmospheric contamination would be small, compared to the average air pollution.

Smoke screens are useful in a region around nuclear blasts extending from the 5 psi overpressure range (where destruction is so widespread that smoke screens

cannot be of much use) to an arbitrarily set lower limit (where the thermal energy is too low to constitute a danger). This is called the area of probable ignitions. Its size varies from 100 square miles for 1 megaton detonations at the earth's surface, to 15,400 square miles for 50 megaton detonations at 31 miles altitude.

Cost estimates for smoke screen installations depend upon the specified warning time (2 to 30 minutes); the wind speed (5 to 15 miles per hour); and the duration of the protection (6 to 24 hours). The estimated costs of complete systems vary from $100,000 to $31 million dollars per square mile. However basic wind-erected smoke pot systems can be installed for an initial cost of $150,000 to $300,000 per square mile.

Toxicity is a limiting factor in the selection of smoke screen materials. Carbon monoxide is a byproduct in the production of carbon smokes. It may not be present in harmful concentrations if the chemical reaction temperature in the smoke generators is kept below 600°C. However, the carbon monoxide produced during iron pentacarbonyl decomposition cannot be dismissed casually.*

The report concludes with a recommendation that a research and development program be undertaken to develop smoke screen systems.

Subject Headings: *Nuclear explosion, countermeasures; Smoke, as countermeasure to nuclear explosion; Ignition, prevention of, by smoke.*

G. Greifer

Friedman, R. and Levy, J. B. (Atlantic Research Corporation, Alexandria, Virginia) "Inhibition of Opposed-Jet Methane–Air Diffusion Flames. The Effects of Alkali Metal Vapours and Organic Halides," *Combustion and Flame* 7, 195–201 (1963)

The flame extinguishing power of sodium and potassium salts has long been recognized and exploited for suppression of mine-gas ignition and gun-muzzle flash and dry-powder extinguishment. The mechanism of the effect has been unexplained, although differences in effectiveness from one inorganic compound to another has implied a chemical mechanism. Previous analysis of a premixed flame had indicated a vapor-phase rather than a surface mechanism. To substantiate the indication of this analysis an investigation was undertaken to provide experimental evidence using a system where interactions of gaseous species with surfaces of solid or liquid particles could be eliminated.

Gaseous sodium and potassium were used in hydrocarbon–air diffusion flames, since premixing alkali vapors with air is not feasible. The opposed jet technique of Potter,[1,2] used for measuring the stability of diffusion flames, was employed. Since the opposed-jet technique had not previously been applied to the study of inhibition of diffusion flames, organic halides were first investigated to establish the validity of the opposed jet technique.

* The authors write, p. 66, that the carbon monoxide will probably be oxidized to carbon dioxide during the reaction. This reviewer feels that this cannot help much: carbon monoxide is a principal product of carbonyl combustion. See, "Dangerous Properties of Industrial Materials," N. Irving Sax, 2nd ed., page 906. Reinhold Publishing Co., 1963.

Methane was chosen as the test fuel. Sodium and potassium were formed by bubbling the methane through the molten metal in a nickel saturator device. The burner consisted of opposed coaxial vertical tubes of 3.86 mm bore and variable separation (generally about 1 cm). The lower tube carried fuel at about 460°C, the upper carried air at about 65°C. The appearance of a hole in the flame as flow was increased was used as the measure of flame strength. The ratio of volumetric fuel plus additive flow rate at the hole point to the pure fuel flow rate at the hole point in a companion control experiment was used as the parameter relating additive flow to inhibition effectiveness.

The experimental results demonstrating the applicability of the opposed-jet burner to inhibition studies showed that inert diluents, argon and nitrogen, have very little effect on the hole-point fuel-stream flow rate. Organic halides inhibited in the order $CH_3Cl < CCl_4 < CH_3Br = CF_3Br$. This agrees with the effect of additives in reducing flame-speed of premixed flames. These results were obtained with the fuel stream at room temperature. Further tests were performed with methyl bromide addition to methane at 460°C, as a preliminary to the alkali metal experiments. The inhibition effect was reduced at the higher temperature.

Addition of sodium to methane showed no detectable difference between hole-point behavior of the pure methane stream and the methane plus sodium stream at the same volumetric flow rate. Potassium produced the same results as sodium.

The addition of potassium salts to premixed flames reduces flame speed, as do bromine inhibitors, while elemental potassium has no inhibiting effect on the methane–air diffusion flame. The inhibitory effects of alkali metal salts are therefore hypothesized to arise from species other than alkali metal atoms. The gaseous metal hydroxide is proposed as the effective species. Equilibrium calculations for a stoichiometric premixed methane–air flame containing potassium show that gaseous potassium hydroxide and potassium are the only important potassium species. A second point is that atomized potassium hydroxide solutions, when sprayed on test fires, have been found slightly more effective than other potassium bearing compounds. A third point is that the important chain propagating radicals to be removed by the inhibitor are probably H, OH, and O. A fourth point is that these can be most readily removed by:

$$KOH + H \rightarrow HOH + K; \quad \Delta H = -36.6 \text{ kcal}$$
$$KOH + OH \rightarrow HOH + KO; \quad \Delta H = -13.7 \text{ kcal.}$$

Since both reactions are quite exothermic free-radial processes they should proceed quite rapidly. A fifth point is that potassium salts decompose early in the moisture-containing premixed flame to form KOH. The failure of elemental potassium to inhibit in the diffusion flame is attributed to the slow rate of conversion to KOH via the reactions possible in the diffusion flame.

References

1. Potter, A. E. and Butler, J. N.: *Am. Rocket Soc. J. 29*, 54 (1959).
2. Potter, A. E., Heimel, S., and Butler, J. N.: *Eighth Symposium (International) on Combustion*, pp. 1027–1034. Williams and Wilkins, 1962.

Subject Headings: *Inhibition, alkali metals on methane–air; Flame, inhibition of, by alkali metals; Methane, inhibition, by alkali metals.*

A. E. Noreen

Applied Physics Laboratory, The Johns Hopkins University "Flame Inhibition Research," *Quarterly Progress Report (1 May 1963–31 July 1963) MIPR No. ERDL-21-61 Project No. 8M76-05-001-03*

This is the eleventh quarterly progress report on a program of basic research on the mechanism of the inhibition of hydrocarbon–air flames by halogenated organic compounds. The general plan of the program is to study the methane–oxygen flame inhibited by a simple inhibitor in order to test current ideas on the mechanism of inhibition. The first inhibitor examined was hydrogen bromide. Subsequently methyl bromide, iodine, trifluoromethyl bromide, and trifluoromethyl chloride have also been studied.

The experimental approach has encompassed studies of the flame microstructure by the probe technique, temperature profile measurements, kinetics studies of elementary reactions related to flame processes, and computer analyses of the systems. A novel feature of the composition profile experiments has been the attempt to determine atom or radical concentrations by "scavenging" such species with an appropriate reagent, e.g.,

$$O+NO_2 \rightarrow NO+O_2.$$

By the above techniques it has been possible to obtain composition and temperature profiles for a hydrogen bromide-inhibited methane–oxygen flame for comparison with those of the uninhibited flame.

Most recently the application of molecular beams to the study of elementary reactions has been undertaken. An apparatus has been constructed for these studies during the present period, but experiments have not yet been performed. During the present period a sampling system was constructed which will permit the application of gas chromatography to analyses of the micro probe samples. Testing of various columns packings for their application to the expected products has also been performed. It is anticipated that gas chromatographic analysis should yield significant information about trace constituents of the flame gases.

Subject Headings: *Inhibition, of flame; Flame, inhibition of; Halogenated hydrocarbons, inhibition effects.*

J. B. Levy

Hall, A. R. (Rocket Propulsion Establishment, Westcott, England) "The Effect of Methyl Bromide and Trifluorobromomethane on the Limits of Flammability of the System Isopropyl Nitrate/Air," *Rocket Propulsion Establishment Technical Note No. 215* (January 1963)

This report describes a study of the effect of methyl and trifluoromethyl bromides on the limits of flammability of isopropyl nitrate–air mixtures containing from 2 to 100 per cent isopropyl nitrate. Isopropyl nitrate is in current use in Great Britain as a monopropellant in airplane engine starters.

The experimental method involved the preparation of isopropyl nitrate–air-additive mixtures in a 7.5 cm i.d. Pyrex tube, ignition of the mixture either by a spark or by a heated platinum wire and observation as to whether combustion was

propagated. The entire system was kept at 85°C in order to achieve the vapor pressures of isopropyl nitrate desired (b.p., 102°C).

The results fell into two groups: mixtures containing 2 to 10 per cent isopropyl nitrate and mixtures containing 10 to 100 per cent isopropyl nitrate. Since the stoichiometric mixture contains 6.06 per cent isopropyl nitrate it is clear that in the latter group the exothermic decomposition of the nitrate ester itself would be very important while the former group might behave like a hydrocarbon–air mixture.

It was found that for mixtures containing 2 to 10 per cent isopropyl nitrate the halogenated additives were more effective than nitrogen. For the stoichiometric mixture the amounts of additives required to yield a limit mixture stood in the ratios of 0.14:0.19:1.0 for trifluoromethyl bromide, methyl bromide, and nitrogen, respectively. Since the ratios expected merely on the basis of heat capacities would have been 0.33:0.4:1.0 it is clear that chemical inhibition is occurring.

For mixtures containing 10 to 100 per cent isopropyl nitrate the halogenated compounds were, if anything, less effective than nitrogen. Since it has been found[1] that additives of this type are not effective for methane–nitrogen dioxide flames, these results are not unexpected.

It thus does not appear that fire extinguishers containing halogenated organic compounds will be effective for isopropyl nitrate fires, or by analogy, for fires in-involving other nitrate esters (i.e., *n*-propyl or ethyl nitrates).

Reference

1. Rosser, W. A., Inami, S. H., and Wise, H.: "Study of the Mechanisms of Fire Extinguishment of Liquid Rocket Propellants," *WADC Technical Report 59-206, Stanford Research Institute* (April 1959)

Subject Headings: *Inhibition, effect of bromine compounds on isopropyl nitrate–air; Bromine compounds, inhibition.*

J. B. Levy

Meuresch, H. (Zurich, Switzerland) "Flash Point, Explosion Limits and Explosion Prevention," *Chemiker-Zeitung* **85**, 735–740 (1961)

There are three methods of extinguishing a fire:

1) Total or partial displacement of O_2 supply.
2) Insertion into the fire of substances that can absorb a lot of heat. This prevents the combustible material from reaching the minimum ignition point temperature.
3) Direct chemical intervention.

The halogenated hydrocarbons fit, in part, everyone of the above roles. They possess a high heat of vaporization and vapor density. They interfere with the normal chain processes in flames and explosions by supplying halogen radicals which act as chain arrestors. High dipole moments and consequently high polarizabilities are related to the effectiveness of a particular halogenated hydrocarbon as a fire retarder. Thus, CF_4 with zero dipole moment is a poor extinguisher. $CBrF_3$ and CBr_2F_2 with high dipole moments are good extinguishing agents. High dipole moments do not in every case correlate with extinguishing capability. We must also

look carefully at the polarizability of the carbon halogen bond. Thus the polarizability increases from C–F (lowest) to C–I (highest). The C–C bond weakens the polarizability of the C–X (X = halogen) bond. Thus the order of decreasing polarizability of the C–X bond is $C–X > C_2–X > C_3–X \cdots$.

The more halogen released in the flame the better the extinguishing capability. Pure halogens thermally decompose at high temperature. The degree of dissociation increases from F_2 to I_2.

Two basic conditions are necessary for an explosion to occur in a combustible gas mixture.

1) Concentration of combustible gas must lie between the boundaries of the upper and lower concentration limits.
2) A temperature has to be reached where self-ignition and consequent explosion will occur. At a proper temperature explosion can often be attained outside the normal concentration limits. As the temperature is raised, more free radicals are formed by thermal dissociation. Therefore the explosion limit drops as the temperature is raised.

In laboratory systems it is possible to fix the extinguishing limits as far as temperature and concentration are concerned. In real fires the extinguisher never reaches the source of the burning, precluding the formation of homogeneous gas mixtures. Despite this limitation, experiments were performed using ideal gas mixtures. A special apparatus was designed to ignite known quantities of fuel and inhibitor using two different ignition sources operating at 550° and 850°C, respectively. One was a burning candle at 550°C. The other a glow coil at 850°C. The lower explosion limit, or point of flame formation, was determined by observing an enlargement of the candle flame. The upper explosion limit or the extinction time was observed by the blowoff of the candle flame. The glow coil igniter offered no visible criteria for the values of the explosion limits although a slight extension of a weakly visible blue flame did occur at the lower limit. Mixtures tested included natural gas, vinyl chloride and $(C_2H_5)_2O$ with CCl_3F, CCl_2F_2 and CF_4. Results show lower explosion limits are greatly dependent on temperature. CF_4 proved to be a very poor inhibitor while CCl_2F_2 was better than CCl_3F. Pure fuels were first run alone for explosion limit determinations. Calculations can be made to predict the explosion limits and inhibitor concentration necessary to stop the chain reactions. The more inhibitor used, the greater the gap between the point of flame formation and explosion. The intensity of explosion decreases as inhibitor concentration rises until a point is reached where no flame appears prior to explosion.

Comparison of the 550° and 850° data shows only rough agreement. Errors in temperature measurement are unavoidably present when using the glow coil igniter. The flame gases are actually at a much lower temperature than that of the coil. The candle flame igniter values are on the other hand quite reliable. It can be stated that the presence of a very hot wire in a combustible gas mixture will ordinarily not cause the gas to explode, even if we have actually greatly exceeded the self-ignition temperature. This statement must not be taken too literally in view of the fact that the lower explosion limit is dependent on both the fuel concentration and the self-ignition temperature.

Subject Headings: *Halogenated hydrocarbons, inhibition; Inhibition, by halogenated hydrocarbons.*

P. Breisacher

Friedrich, M. (Karlsruhe Polytechnical Institute, Karlsruhe, Germany) "Fire Extinguishing Experiments with Aqueous Salt Solution Sprays," *Chemiker-Zeitung* **85**, 438–443 (1961)

Fine spray solutions of the sodium and potassium carbonates and bicarbonates were used to determine their effectiveness as fire extinguishers against a large number of pure liquid fuels. Solutions 1 to 10 per cent by weight carbonate were directed from a fixed distance at burning pools of fuel. The target area was located at fixed distances of 50 and 70 cm from the automatic electric spray nozzle. The solutions were ejected at 0.044 g/sec (50 cm) and 0.036 g/sec (70 cm). For comparative purposes a jet of distilled water was also directed at the firepool. The experiment was followed by high speed photography. The droplets formed in the spray nozzle are photographed and their size distribution determined. Between 1000 and 6000 drops are caught on a single plate. The drops are perfectly spherical no matter what the nozzle pressure. Changes in drop size are therefore not a factor in extinquishing ability. No difference in size distribution was noted between distilled water and salt solution sprays.

The fuels with highest enthalpy required the most solution to extinguishment. The effectiveness of these sprays was greatest at 10 per cent salt concentration. Below 5 per cent results were very poor. Two other methods of studying the drop shape and size were of little value. One method involves the capture of drops on a filter paper placed below the nozzle. Another method permitted the drop to fall into a cooled solution of butanol (−35°C) and determine the size by the sedimentation rate. Trouble occurred when drops congealed or broke up upon hitting the liquid surface.

The photographic results were good because the true shape and size of the drop was obtained. A pulsed spark discharge served as the trigger light source and film advancer.

The heat capacity of a kilogram of pure water is greater than 1 kilogram of 10 per cent salt solution. Therefore the inhibition effect is not due to heat extraction from the fuel charge. The salts appear to be the actual inhibitor in that they slow down the chain propagating properties of the peroxides present in the fuel gases. A chemical spot test using a dilute solution of ferric chloride and potassium ferrous cyanide was used to detect peroxide radicals. The flame is played upon the surface of this reactant with the result that an immediate color change occurs from yellow to blue. If aluminum stearate is spread over the surface of the reactant and a similar experiment performed no peroxide groups can wet the surface and pass through to the testing solution. This confirmed the validity and sensitivity of this peroxide test.

A typical test result showed that after 1 minute of distilled water spraying, no diminishing in the burning intensity of a pool of C_6H_6 was evident. When a 5 per cent salt solution was used the fire was out in 8 to 10 secs.

Some of the problems associated with the use of these salt solutions include:

1) When fighting fires around high voltage installations, problems could arise if a nonspray stream of the solution was used. The fire fighter would in effect be within a closed circuit if the highly conducting salt solution made contact with a high voltage source. Use of spray minimizes this problem since no ground loop is created.

2) Corrosion of metal parts is greatest with duraluminum and negligible for brass and sheet metal. Care should be taken in selecting associated equipment.
3) In cold climates the solution can be stored without freezing at temperatures of $-4°$ to $-15°$C depending on salt concentration.
4) Other alkali metal salts such as the oxalates would probably be superior to the carbonates. The limitation here is the low water solubility of these alternatives. Also the poisonous nature of the oxalates is a problem. The chlorides and nitrates are soluble enough but some of these salts would actually increase the concentration of combustibles in the flame system.

Subject Headings: *Sprays, salt, inhibition by; Inhibition, by salt sprays.*

P. Breisacher

Rosser, W. A., Jr., Inami, S. H., and Wise, H. (Stanford Research Institute, Menlo Park, California) "The Effect of Metal Salts on Premixed Hydrocarbon Air Flames," *Combustion and Flame* 7, 107–119 (1963)

It is known that some finely divided metal salts (e.g., $NaHCO_3$) can inhibit combustion to an extent which cannot be explained on the basis of dilution and heat loss alone.[1] In the present paper the inhibition mechanism is investigated for additives such as K_2SO_4, Na_2CO_3, NaCl, CuCl, $NaHCO_3$, $KHCO_3$, where the basic measurement is the reduction in methane/air flame speed. Those additives which chemically interfere with the combustion process typically cause a large decrease in flame speed with increased powder concentration until some critical concentration is reached. Beyond this point relatively small effects are produced. This critical concentration, which is particle-size dependent, is taken to be the measure of a particular additive's effectiveness.

The experimental configuration consisted of an agitated bed powder generator through which an adjustable fraction of the premixed combustible gases entered the system. The steady-state powder concentration was measured prior to each flame speed experiment by collecting the powder on a piece of glass filter paper through which the gas mixture was drawn. The flow was then interrupted and the enclosed mixture ignited by electrodes mounted in a long glass cylinder, 2 cm in diameter. The time required for the flame to travel between two fixed points in the vertical tube was recorded photometrically and used to compute the flame speed. Specific surface areas of the powders used were measured by optical transmission of dispersions in acetone. Mean diameters based on these specific area determinations ranged from 2.2 to 11 microns.

Heat transfer calculations based on a simplified laminar flame structure model revealed that particle surface temperatures were large enough for evaporation to occur even for materials not usually considered volatile. Indeed, the most effective inhibitors were found to be those which should suffer a high degree of evaporation in passing through the combustion wave. Conversely, those particles which could not be expected to evaporate were found to be poor inhibitors. It is then postulated that chemical inhibition is a function of the production of free atoms of sodium or potassium so that over-all effectiveness should depend not only on volatility but

also on the chemical availability of the alkali metal atom after evaporation. The metal atoms (e.g., Na) are believed to catalyze the rate of free radical (H, O, OH) recombination in accord with the reaction sequence:

$$R_1+Na+M\rightarrow(R_1Na)+M$$
$$(R_1Na)+R_2\rightarrow R_1R_2+Na,$$

where R_1, R_2 represent H, O, or OH and the molecule R_1Na must be sufficiently stable to make the second step kinetically important. The relative effectiveness of this over-all mechanism for a given radical R_1 should therefore depend on the local steady-state concentration ratio $[Na]/[R_2]$, which is shown to be of order unity for $R_2=O$, H. It is also conceivable that inhibition is the result of the deactivation of excited species such as O_2*, CO_2*, C_2*, CH* and OH* by sodium atoms. However, this mechanism was considered less likely in view of the uncertain role of these species in determining flame propagation rates.

Reference

1. Friedman, R. and Levy, J. B.: "Survey of Fundamental Knowledge of Mechanisms of Action of Flame-Extinguishing Agents," *WADC Report No. 56-568* (January 1957).

Subject Headings: ***Metal salts, inhibition of hydrocarbon flame; Inhibition, of hydrocarbon flame, by metal salts; Hydrocarbons, inhibition, by metal salts.***

D. E. Rosner

Neill, R. R. and Tuve, R. L. "An Evaluation of Certain Aspects of Multipurpose Powder Fire Extinguishing Agents," *NRL Report 5799* (July 16, 1962)

Multipurpose powder containing ammonium phosphate as the principal ingredient has become available on the market for use against all types of fires: Class A (wood, paper, etc.), Class B (flammable liquids, gases), Class C (electrical), and Class D (certain combustible metals).

Various fire extinguishing tests were devised in order to compare the effectiveness of three proprietary formulations of multipurpose powder with other extinguishing agents.

Class A fires of the wood-crib-type were modeled on a small scale and correlated with Underwriters' Laboratories tests on multipurpose powders. The weight of the powder actually effecting extinguishment was determined and compared to that of water required to extinguish a similar fire. Two of the powders appeared to be as efficient as water.

Rubber-tire fires which consist of various aspects of both Class A and Class B were extinguished in the laboratory using sections of rubber tires as fuel and in the field using whole rubber tires. Multipurpose powders when properly applied were found to be effective in extinguishing rubber-tire fires. A solution of wetting agent in water, however, appeared to be more effective than any of the powders.

The multipurpose powders were evaluated against sodium bicarbonate and potassium bicarbonate base dry chemical powders for use against large Class B fires. The experimental setup consisted of a steel tank, 8 ft 4 in. in diameter, containing $7\frac{1}{2}$ gallons of gasoline and a piped dry chemical application system. After a preburn

period of 15 seconds, the powder was discharged through a specially designed nozzle (located near the side of the tank) at a rate of 1.5 pounds of powder per second. The amount of powder required to extinguish the fire was recorded. The multipurpose powders were comparable in efficiency to the sodium bicarbonate base dry chemical. The potassium bicarbonate type was more effective than the other powders.

Subject Headings: *Powder, inhibition by; Inhibition, by powder.*

K. Sumi

Linacre, E. T. and Rhodes, A. C. (Safety in Mines Research Establishment, Sheffield, England) "The Extinction of Experimental Fires with Foam Plugs," *Safety in Mines Research Establishment Research Report No. 213* (1963)

The foam plug method of fighting coal mine fires, first described by Eisner and Smith (1956), is quantitatively evaluated by conducting ten fullscale experiments in the Buxton tunnel in Great Britain. The fuel for these fires consisted of (1) ordered stacks of wood each containing about 20 cwt completely filling the roadway, (2) lagging on the roof and sides of a 60 foot stretch of the tunnel, and (3) one fire of 15 cwt of coal spread on the roadway floor. For each fire, observations were made of the extent of visible combustion, the fire temperature and the downwind product gas composition during the extinction of the fire by the foam plug.

The foams were generated by spraying approximately 100 gal/min of foam-agent solution on a net stretched across the roadway upwind of the fire. The ventilation current supplied the air necessary to generate the foam plug and push it into the fire zone. The air velocity was controlled by adjusting a door across the ventilating fan's intake. Movement of the foam plug through the fire zone was observed by a camera downwind of the fire. Although photographic and temperature records may be used to confirm the presence of flames, firm evidence for the extinction of flaming combustion can only be provided from records of the gas analysis. From such records of the carbon dioxide concentration, it can be seen that the time taken for the rate of fuel consumption to decrease by one-third of its value at the time of application of foam to the fire zone was about 4 minutes for the stack fires and about 13 minutes for the lagging fires. The temperature downwind of the fire falls more rapidly than does the over-all fuel consumption rate as indicated by the carbon dioxide analysis. The largest concentration of hydrogen detected in the product gases was about one per cent for the wood fires and 0.1 per cent for the coal fires.

These results indicated that under the conditions of these experiments there is no risk of a water-gas explosion caused by the use of water foams on open fires. It was observed that when there was appreciable leakage of air past the foam plug at the roof, flames persisted in the roof area, burning in the air gap over the foam. In one experiment the roof fire actually increased with the onset of the foam plug. In the case of the coal fire, the foam cooled only the outer three inches, leaving the core of the fire red hot. However, the cool surface and reduced burning rate allowed a close approach of the fire fighters with shovels and hose. Occasionally the fires would revive after the application of foam even though all flames had disappeared; in such cases the revived fire was treated as a separate burning with renewed extin-

guishment procedures. The authors supply the reader with a liberal supply of graphs showing the histories of the temperature, carbon dioxide and carbon monoxide concentration, and ventilating velocity for each of the ten experiments conducted.

Subject Headings: *Foam, extinction of fire; Fire, extinction, by foam.*

H. E. Perlee

VIII. Model Studies and Scaling Laws

Ambrose, J. E., Eggleston, L. A., and Yuill, C. H. (Southwest Research Institute, San Antonio, Texas) "The Use of Models for the Investigation of Fire Spread," *Final Report DASA Project No. 12.024* (August 19, 1963)

This report is about fire spread in conflagrations or city fires. It refers to a program investigating the use of models for the study of fire spread in city fires and the use of modeling techniques for defining those factors which contribute to the development of mass fires.

A brief digression about the term "mass fires" is in order. This term obviously should be discouraged because, in this case, it has made it necessary for the authors of the paper to define mass fire as a fire produced by the interaction of numerous unit fires and the observation that the configuration of the unit fires will result in various types of mass fires, e.g., line fires, area fires, firestorms and conflagrations. The authors of the paper inherited the term "mass fires" from other users of the term, among them the reviewer. The term "mass fires" is relatively meaningless without exact definition and is simply not a good use of the language. On the other hand, a proper use of the same combination of words would be "fire masses." This paper is really about the modeling of "fire masses."

The paper reports on research which is very preliminary. It recommends two broad areas of further work: (1) theoretical and experimental studies of scaled models, and (2) the development of nondestructive methods. Both recommended approaches should be, the authors say, against actual mass fires to establish the degree of accuracy that reasonably may be expected.

The report includes a study of the 1922 conflagration in Astoria, Oregon. It observed that very few conflagrations have occurred in which adequate documentation of pertinent data was accomplished. The Astoria fire was studied to see what could be done in assembling published records of such a conflagration and supplementary testimony of eyewitnesses. The study concludes that securing case histories of conflagrations as indices of model performance is a practical technique even though some difficulties may be expected in unearthing the desired facts.

The authors of the paper do not make one suggestion which their conclusions suggest to this reviewer. Since wartime conflagrations are the subject providing motivation for these studies, it would seem desirable to collect data on certain wartime city fires. On these some data have been compiled. Much more could undoubtedly be assembled while records may be available and witnesses are alive to get together a picture of these fires. Particularly revealing might be a study of such cities as Hamburg, Kassel, and Darmstadt in Germany. In each of these cities, testimony supports the idea that a firestorm occurred. In final decisions on modeling techniques, it would be very helpful to have accurate information on building

dimensions and spacing at the time of the fire and also more exact information to establish the timetable of ignitions.

Subject Headings: *Fire spread, model of; Model, of fire spread.*

H. Bond

Nielsen, H. J., Tao, L., and Wolf, L. (IIT Research Institute, Chicago, Illinois) "Analysis of Convection Column above a Fire Storm," *Final Report for Office of Civil Defense Contract No. OCD-OS-62-82, Armour Research Foundation Project A6004* (August 1, 1963)

The purpose of the project reported in this publication was to include combustion effects in the analysis of a convective column. Two analyses are presented. In the first integral methods are applied to a convective column including the effects of combustion and radiation. In the second analysis a simple model is used to study diffusion effects.

In the treatment of the convective column it is assumed that the vertical convective column of hot gases is fed at its base by the products of pyrolysis of fuels on the ground. The products of pyrolysis move up into the column and burn as oxygen is entrained from the surrounding atmosphere. The appropriate conservation laws for mass, momentum, energy, and species are written. No attempt is made to include approximate expressions for the turbulent transport properties. Instead the conservation equations are integrated across the column and the profiles in the column are assumed. In the analysis given the profiles are taken to be square. In order to complete the specification of the problem it is assumed that the entrainment velocity is proportional to the vertical velocity. The chemical reactions in the columns have been approximated by a single over-all reaction: fuel and oxygen→product. It is also assumed that the reaction rate is controlled by the rate at which oxygen is entrained into the column.

In order to obtain a solution it is necessary to have the required boundary conditions at the base of the column. Data are included on the expected energy content available from the products of pyrolysis. Also required are the rate at which fuel is supplied to the base of the column and the size of the burning area. Computer calculations of the vertical velocity, temperature, column radius, and species concentration are given as a function of altitude for various initial column radii, fuel gas generation rates, and entrainment constants. The lapse rate of the surrounding atmosphere was also varied but the effect on the calculations was negligible.

In order to study diffusion the solutions for a point source in the atmosphere are considered. It is assumed that each building acts like a point source at which oxygen is being removed by combustion. Source strengths appropriate to a burning building are substituted and concentration profiles given. Since thermal effects are not included in this analysis, it is doubtful that the results are applicable to fire problems.

Subject Headings: *Fire storm, convection column; Convection column, of fire storm.*

D. S. Turcotte

Tarifa, S. C., et al. (Instituto Nacional de Tecnica Aeronautica, Madrid, Spain) "Open Fires and Transport of Firebrands," *Second Annual Report Grant FG Sp-114* (May 31, 1962–May 31, 1963)

This report contains a summary of the work done on two separate problems, as part of a continuing research effort.

Open Fires

The combustion of a liquid fuel contained in a vessel is considered in the first section. The theoretical model developed for this problem is based on the assumption that heat transfer is the dominant mechanism in so far as the burning rate is concerned. The combustion process is divided into four periods: first the fuel is heated from an external source (flame) until ignition occurs; next, combustion forces the fuel surface temperature to rise very rapidly until the boiling temperature is reached; third, combustion proceeds at constant surface temperature while the temperature within the fuel and the burning rate increase until a steady-state condition is reached; the fourth period is the time of steady combustion. As an analytical simplification, the first two periods are joined and it is assumed that negligible fuel consumption occurs during this time. The fuel enters the vessel at a temperature kept constant, and rises until it reaches the surface which is kept at a constant level either entirely by burning or by both burning and overflow tubes. The flow is assumed to be one-dimensional with negligible viscous and gravitational forces, and the fuel properties and density are taken to be constants. The heat transferred from the flame to the fuel is assumed known in the analysis and thus must be found experimentally. Finally, the momentum transfer in the fluid is neglected so that the pressure is constant.

With the above assumptions, the problem is reduced to the solution of the unsteady energy equation for a finite length of moving fluid with constant temperature at the inflow end and a known heat flux at the other. The general problem is divided into sub-problems consisting of a stationary process with or without overflow for the steady combustion, a transient heating process with no flow, and a transient combustion process. Well-known solutions exist for each problem except the last, for which an approximate superposition of solutions is employed. It is claimed that this linearization leads to small errors, although no proof is given.

Several plots of burning rate and temperature profile in the unburned fuel are given as functions of the various parameters of the problem. Also, the time to reach ignition and the variation of burning rate with time is presented for several parametric variations. It is shown that the fluid depth is an important parameter in designing meaningful experiments, and that since the temperature gradient is very large near the fuel surface a surface temperature sensor will measure an average temperature near the surface.

Since the experimental program has not been finished, only fragmentary data are available to compare with theory. A comparison of the amount of fuel evaporated and burned as a function of time for various overflow rates with that given by theory shows fair agreement. Since it was assumed that all the heat received by the fuel was due to radiation (only radiant energy transfer was measured for this case) it is very likely that the inclusion of heat transferred by conduction would reduce the difference between calculated and experimental results.

Transport of Firebrands

This section contains a report of the study of the flight trajectories of burning pieces of wood initially lifted by convective currents and then carried by horizontal winds. A simplified model of flight paths is established, which gives a good approximation to the actual flight path. In this model, the crucial assumption is that the firebrand always flies at its terminal velocity. That is, in terms of coordinate velocities, the relative horizontal velocity component is zero, and the relative vertical velocity component is the simple terminal velocity, for the case where the wind flow is steady. In order to prove this point several numerical integrations of the equations of motion are carried out for various types of wooden, spherical firebrands. In each case, the functional form of the sphere cross section to mass ratio is found from experimental studies. It is shown that the velocity components approach their terminal velocity values in times small compared to the burnout time. Hence, this approximation should be invalid only in those cases where the time of flight is also small compared to the burnout time. The maximum errors in the flight path introduced by the approximation are deduced for use in the event that this should occur.

With the simplification that the firebrand flies at terminal velocity, the flight path calculation reduces to a simple integration of this velocity as a function of time. The variations of velocity as well as weight and aerodynamic drag as functions of time are found experimentally in a wind tunnel. The firebrand is supported by a thin steel wire and the forces are measured with a strain gauge balance, or, otherwise the burning particle is allowed to hang freely from the wire and the tunnel velocity adjusted until the wire reaches a 45° angle from vertical, at which point the drag force and weight are equal and the tunnel velocity is the terminal velocity. In the latter case, the tunnel velocity is continuously adjusted as the particle burns, to maintain the wire angle at 45°. Flight trajectories are presented for spherical and cylindrical pine firebrands for various initial vertical convection currents and horizontal winds. It is concluded that a critical height at which the firebrand leaves the convection column exists for which the firebrand reaches a maximum horizontal distance while still burning. This, then, is the maximum distance from the flame front at which fire spread may occur due to firebrands. For certain conditions, this maximum fire spread range may reach values of several kilometers, even for small firebrands and moderate wind conditions.

While this report covers some very interesting research, it suffers from a complete lack of references which might aid the reader interested in pursuing these subjects further.

Subject Headings: ***Firebrands, propagation of fire by; Fire, propagation, by firebrands; Pool, analysis of fire in.***

T. C. Adamson, Jr.

Fahnestock, G. R. and Dieterich, J. H. (Intermountain Forest and Range Experiment Station, U.S. Forest Service, Ogden, Utah) "Logging Slash Flammability after Five Years," *Intermountain Forest and Range Experiment Station Research Paper No. 70* (December 1962)

This paper covers the final phase of research in the determination of flammability of slash for nine conifer species found in the northern Rocky Mountains. Results from previous studies for fresh-cut and 1 year old slash are included with the results obtained in the present study on 5 year old slash.

The characteristics of the slash on 63 0.01-acre plots after 5 years are described in detail in this paper. For most species tested virtually all of the needles fell and were found concentrated on or near the ground. However, some needle retention on branches in the lower portions of the white pine fuel beds were noted. Compaction of the fuel beds was found in all species except hemlock. Incipient branchwood decay occurred in varying amounts in all species but advanced decay in large limbs with ensuing break up occurred only in grand fir. Bark retention was noted for ponderosa pine and western larch; in other species varying degrees of bark disintegration were found.

The rate of fire spread for all species averaged 23 per cent of that found in fresh slash. The range was 8 per cent in grand fir slash to 36 per cent in lodgepole pine. Residual rate of spread percentages in 5 year old slash were essentially the same in western white pine, ponderosa pine, western hemlock, and lodgepole pine. The highest rates of spread were recorded in western white and lodgepole pine, followed by hemlock, ponderosa pine, red cedar, Douglas fir, Englemann spruce, larch, and grand fir.

From previous work in this study, rate of fire spread was related to fuel quantity per acre and relative humidity in both freshcut and 1 year old slash. These relationships showed that rate of fire spread increased with a decrease in relative humidity and increased with an increase in fuel quantity. In the present paper fuel concentration was found to have less apparent effect on rate of fire spread in 5 year old slash than in 1 year old. The apparent effect of relative humidity followed nearer that found in fresh slash than in 1 year old slash. The authors state, however, that these changes are not very significant since only two fuel weights were tested and in a few plots the results of fuel quantity were confounded by relative humidity.

A reduction in mean fire intensity as measured with radiometers was recorded in 5 year old slash dropping to about 27 per cent of the fresh slash level. In 1 year old slash the mean fire intensity was 36 per cent of fresh slash. These changes were approximately the same in medium (20 tons per acre) as in heavy (32.5 tons per acre) slash. The authors conclude that this supports a previous finding that fire intensity is essentially proportionate to rate of fire spread in any given kind of fuel.

Subject Headings: *Slash, fire spread in; Fire, spread in logging slash.*

W. Y. Pong

Ministere de l'Interieur, Service National de la Protection Civile, Paris, France
Forest Fires in France: Trensacq (April 1955); Caseaux, Luxey, and Reaup (April 1956)

The two main items in this collection of documents consist of a report on the experimental fire at Trensacq of 3.25 km², in April 1955, and a summary report of three fires at Caseaux (a deliberate burn off), Luxey and Reaup during April 1956, covering areas of 12, 10, and 8 km², respectively. Records of the progress of the fires are given together with plans and reports of the meteorological conditions in the neighborhood of each fire. These are of particular interest since, except at Trensacq, fire whirls were seen.

The height of the vegetation is given for the experimental fire at Trensacq and the fire load for the fires at Trensacq and Caseaux.

The Trensacq fire was mentioned by J. Faure at the International Symposium on the use of models in fire research, in Washington, D.C., 1961,[1] and the present report provides much useful extra information. The fire load (1.7 kg/m²) was wasteland covered with small bushes and gorse, about 1 m high, and the wind was about 5 to 8 m/sec. The area was approximately a triangle with the wind blowing from the apex almost normally to the opposite side. This downwind side was lit in $2\frac{1}{4}$ hours by flame throwers carried on jeeps, two groups starting from the center of the side. During this time the fire spread against the wind a distance, which can be estimated from the map of the progress of the fire, of about 140 m, i.e., an average rate of 1.7 cm/sec or, in terms of the average weight of fuel, of 0.3 g cm^{-1} sec^{-1}. The groups of jeeps then proceeded against the wind along the other two sides in 1 hour, during which virtually the whole of the fuel was burned. When the fires from the two sides met, the flames reached a height of 11 to 12 m and a "sudden recrudescence of flames took place." There are drawings of the smoke plume spreading downwind at a maximum height of 2300 m with an almost vertical mushroom reaching somewhat higher than this at the time when the two firefronts joined together.

It is stated that "the necessary time for a fire lighted in the direction of the wind to reach the opposite limit may be evaluated at 35 min." From this a burning rate of 2630 kg/sec is deduced. The "wind of combustion" was estimated to be of 10 to 15 m/sec near the edge of the fire. This, it may be noted, is of the same order of magnitude as the chimney effect of flames of 10 to 12 m high.

Taking 35 min for the downwind spread, gives a burning rate of about 1.1 m/sec or 19 g cm^{-1} sec^{-1}. The average burning rate per unit area of ground was 0.8×10^{-4} g cm^{-2} sec^{-1}. Extrapolating laboratory data on the basis of a $\frac{2}{3}$ power law between flame length and burning rate[2] leads to a value of about 29 m, about $2\frac{1}{2}$ times too large, though in view of the very much greater area burning, wind effects, and other differences, this is perhaps not surprising.

It is also interesting to compare the rate of spread with a value obtained from a crude heat balance assuming a specific heat of 0.34 cal g^{-1} $°C^{-1}$, a rise of temperature of 300°C for the fuel to ignite, a flame radiation level of 3 cal cm^{-2} sec^{-1} and flames of 11 m high. Neglecting the heat loss to the ground and all convection transfer, and assuming the radiation exchange factor to be $\frac{1}{2}$, as is appropriate to a vertical flame, leads to a burning rate of $(3\times1100\times\frac{1}{2})/(0.34\times300)$, i.e., 16 g cm^{-1} sec^{-1}. No doubt such good agreement is fortuitous and the exchange factor could easily be up to twice as high and the intensity somewhat lower or higher. There is

also some suggestion in the report that the quoted flame height is a maximum. On the other hand, the estimate of 0.3 g cm^{-1} sec^{-1} against the wind, in vegetation 1 m high, corresponds to a net heat transfer forward per unit cross section of fuel bed of about 0.3 cal cm^{-2} sec^{-1}. This is about $\frac{1}{2}$ that which can be deduced from the data obtained by Curry and Fons[3] for thin fuels in still air.

In the Caseaux fire the fire load was 2.25 kg/m^2 for $\frac{5}{6}$ of the area and 400 kg/m^2 for $\frac{1}{6}$ of the total area of 12 km^2. Against a wind of 10 to 12 m/sec the spread rate was 2.5 m/min, i.e., 4.2 cm/sec or nearly 1 g cm^{-1} sec^{-1}. This is about three times the rate at Trensacq against the wind, but further comparison cannot be made since the height of the vegetation is not given.

The area burned in the Luxey fire was over 10 km^2 and the ground level wind was 1.5 to 2.5 m/sec. Wind speeds and directions up to a height of 1000 m are reported for this fire, where a counterclockwise whirl having flames up to 20 m high was observed. The smoke was seen to rise spirally to 200 to 300 m.

The total area burned in the Reaup fire was 8 km^2 and wind speeds and directions up to a height of 1000 m are given in the range 3 to 5 m/sec. Three whirls were identified, one seriously burning three men and another "jumped the bank, crossed the stream and ignited a group of young pines on the opposite bank." This fire whirl progressed at about 25 km/hour and had a height of 4 to 5 m.

In its conclusion, the report discusses the meteorological conditions and recognizes their importance. Some qualitative discussion is given of the mechanism of whirling and there is a brief reference to vertical oscillations of the fires. Also the summary report states that it has been established that "water spray can be utilized for fighting large fires, this method being made feasible by the depression occurring in the center of the burning area," a reference presumably to a report of one of the fires not included in these documents.

It should be noted that the maps in copies of this translation, where the original scale is given as a fraction, e.g., 1/50,000, may not equal the original map in size; for example, the map of the Trensacq fire is about $\frac{3}{4}$ the linear size of the original map, and the actual scale has to be deduced from the quoted area of the fire.

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Subject Heading: *Fire, Transacq, France, analysis of.*

P. H. Thomas

X. Meteorological Interactions

Turner, J. S. (Radiophysics Laboratory, C.S.I.R.O., Sydney, Australia) "The 'Starting Plume' in Neutral Surroundings," *Journal of Fluid Mechanics* 13, 356–368 (1962)

Two main theoretical models have been employed to describe convection in the atmosphere and mixing, in and below cumulus clouds. The first is a jet model in which the cloud is assumed to behave like a steady turbulent plume. The other model is a bubble or buoyant vortex ring model. The bubble ("thermal") model ignores the possibility of a continuing source of heat and moisture at the base of the cloud, and the plume model does not take mixing into account properly. The author refers to a photograph of a grass fire which clearly shows a cloud formed on top of the smoke plume. He goes on to suggest that a proper model should incorporate features of the plume and of the "thermal" theory. A simple model is proposed of a vertical plume established by suddenly emitting buoyant fluid at a constant rate from a point source. The motion near the front of this plume is investigated theoretically and experimentally.

The theory is restricted to small clouds in which condensation effects do not play an important part. The specific model consists of a plume in a stationary fluid. The cap of the plume mixes with the surroundings, and draws up fluid from the plume, which adds extra buoyancy and momentum to the advancing spherical vortex ring (i.e., the cap). This is the "starting plume" model.

The dependence of velocity on height is different for a plume and a thermal, and the problem of matching the velocities is met by noting, experimentally, the motion is similar. The author assumes that the cap moves with a constant fraction of the velocity of the plume. A set of equations describing the motion of the plume and the cap is derived. The constants in the theoretical expressions were evaluated from data on plumes of salt water in fresh water. The power-law dependence of the position of the front with time was also determined and found to be in good agreement with the theory.

The author illustrates the use of this model to estimate the time required for a steady source of heat to produce a cloud at a known level. Alternatively, the theory can be used to compute the heating rate if the time for formation of a cloud is known. Provided the assumptions of the theory are satisfied, measurements on "starting plumes" produced by fires could afford an estimate of the area involved and the intensity of the fire. Relatively small fires in reasonably still conditions should be fitted by this model very well.

Subject Heading: ***Thermal, starting plume.***

P. R. Ryason

Turner, J. S. (Radiophysics Laboratory, C.S.I.R.O., Sydney, Australia) "The Motion of Buoyant Elements in Turbulent Surroundings," *Journal of Fluid Mechanics* **16**, 1–16 (1963)

This paper proposes a theory for motion of buoyant elements rising through the atmosphere. The theory is an extension of the model originally proposed by Priestley.[1] The buoyant element is taken to be a sphere which is interchanging fluid with its surroundings at a rate governed by the level of turbulence in the environment. As in previous work a spherical vortex is considered and the inflow into the vortex is taken to be proportional to mean vertical velocity. The present author also includes a loss term. An outflow velocity, u_0, is introduced which is assumed to be proportional to a velocity specified by the turbulence in the environment, in particular, the root-mean-square turbulent velocity $(\bar{u}^2)^{\frac{1}{2}}$. The loss terms, with u_0 taken to be a constant, are added to the equations previously used by Morton.[2] Numerical solutions for the size, height, and density of the buoyant element are given for stable, neutrally stable, and unstable environments. The stability parameter is $\gamma = -4\alpha GF_0/9u_0^4$, where α is the entrainment constant, G gives the stability of the environment, and F_0 is proportional to the buoyancy released initially. It is found that the buoyant element is absolutely unstable if $\gamma > 145$. If γ is smaller than this, the buoyant element reaches a finite height.

An experimental investigation to verify the assumption of constant outflow velocity u_0 is also reported. Buoyant elements of colored salt solutions were introduced into a water tank. Turbulence was introduced into the water by bubbling air up through the tank and using the residual turbulence when the air is turned off. The intensity of the turbulence was calibrated by photographing small objects as they moved through the tank. Measurements of the terminal heights of the buoyant elements were made for various turbulence intensities and buoyancies. The results correlated well with the theory if the inflow velocity is taken to be $\frac{4}{10}$ of the root mean square turbulent velocity.

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Subject Heading: ***Buoyant element, rise through atmosphere.***

D. S. Turcotte

Keffer, J. F. and Baines, W. D. (University of Toronto, Toronto, Canada) "The Round Turbulent Jet in a Cross-Wind," *Journal of Fluid Mechanics* **15**, 481–496 (1963)

This paper reports the results of a study of a jet directed normal to a steady cross wind. The analysis is based upon experimental observations, from which the various approximations are inferred. While the results are similar to those found in free jet studies, there are important differences.

The flow field is considered to be made up of two regions. The first is the zone of

establishment in which the maximum jet velocity is still constant and equal to the initial jet velocity. After the potential core is consumed, the maximum velocity along the jet center line decreases, and in general, the flow across the whole jet cross section is highly turbulent. This second region is termed the zone of established flow.

As a result of the cross wind, the jet is deflected. Generally, this deflection occurs in the zone of established flow and the only effect of the cross wind on the zone of establishment is to change the jet cross section shape from a circle to a kidney shape. However, for jet to cross wind velocity ratios less than four, deflection occurs in the first zone, and the given solutions do not apply. Aside from the deflection, this problem differs from the free jet case in the formation of a pair of vortices, attached to the jet, which increase in strength throughout the zone of established flow.

The experimental work was carried out in a wind tunnel in which a circular plate, from which the jet flowed, was placed above the tunnel floor in order to eliminate tunnel boundary layer effects. Flow measurements were made with a hot wire anemometer.

In the analysis, use was made of a natural coordinate system, fixed to the jet. Mass and momentum flux variations due to fluid entrainment were computed and the resulting equations were solved after simplification by judicious use of experimental observations. It was found that the dimensionless mass flux could be predicted satisfactorily as a function of dimensionless distance along the jet axis for moderate values of the mass flux. The error becomes progressively larger as the mass flux increases, but no reason for this divergence was found.

While it was not expected that true similarity would exist, as it does in a free jet, due to the presence of the vortices, it was reasoned that similarity might be found in an intermediate region before the vortices become dominant. Plots of various flow variables for different downstream locations indicate that this similarity does exist if the proper scaling factors are employed. This conclusion may be important in the analysis of other cases of free turbulence.

The results should be useful in such practical problems as gas flowing from chimneys.

Subject Headings: *Jet, round, in cross wind; Wind, effect on round jet.*

T. C. Adamson, Jr.

Browne, N. E. (U. S. Weather Bureau, Idaho Falls, Idaho) "Some Measurements of Diffusion Parameters from Smoke Plumes," *Bulletin of the American Meteorological Society* **42**, 101–105 (1961)

A method for obtaining diffusion coefficients from smoke plumes without recourse to assumptions regarding the percentage of axial concentrations that constitutes the visible plume edge was used to obtain lateral diffusion parameters from smoke photographs.

Applying a theory developed by Gifford[1,2] for plumes observed from a vertical distance, the author reports experiments carried out from a helicopter above the source during which instantaneous plume photographs were taken at 30-second or

1-minute intervals. Two different procedures were employed to obtain the required averaged plume. In the first, overlay tracings of the outline of individual plumes were combined from instantaneous pictures. The second procedure, preferred as more objective, involved combining the variance about a moving centerline obtained from the smoke photographs with the variance of the displacement of the centerline itself.

The photographs were used to measure maximum width of the instantaneous plume and the distance to the end of the visible plume. Values of turbulence intensity were calculated from Gifford's equations by using measurements from the points of maximum plume width. It was found that the values computed from measurements at the end of the plume were consistently greater than values obtained from points of maximum width. The author believes that these latter data are more reliable because the diffuse appearance at the end of the plume in the photographs made precise determination of the point difficult. When calculated mean-square particle dispersion was plotted as a function of time, considerable scatter of the data resulted. In the region near the end of the visible plume, however, the data were consistent with the assumption that mean-square particle dispersion is proportional to the cube of the time.

For wind speeds less than 5 meters per second, turbulence intensity measurements from smoke and wind vane were substantially equivalent to each other. At higher wind speeds there was considerable departure from linearity, with values of turbulence intensity from wind vane data found to be two or three times greater than those from smoke data. The author speculates on the possibility that this may have been caused by induced mechanical turbulence at the top of the tower where the wind vane was located. Another less likely speculation is that the picture intervals of 30 seconds and 1 minute were too long to permit detailed representation of the plume.

Finally, it is suggested that the method could also be applied to the vertical properties of smoke plumes by photographing them from the side, preferably by using time or multiple exposures to integrate the plumes.

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Subject Headings: ***Diffusion, in smoke plume; Plume, diffusion in.***

A. Strasser

Vaughn, L. M. (Stanford University, Stanford, California) "The Prediction of Atmospheric Diffusion by Using an Eddy Diffusibility Based on the Vertical Transfer of Heat," *Journal of Meteorology* **18**, 43–49 (1961)

In this paper the measured vertical profile of temperature and the concentration of a contaminate in the atmosphere[1] are compared with available theories. It is

assumed that the vertical turbulent diffusivity for matter is equal to that for heat conduction. It is also assumed that convective effects may be neglected because the measurements were carried out near the ground. Equations for contaminant concentration based on a power dependence of velocity and eddy diffusivity on height are given. By taking the experimental values for velocity and temperature profiles to give the power laws and required constants the concentrations are derived and compared with experiment. The agreement is excellent.

A relationship between the velocity and eddy diffusivity is also obtained, which may be used when no heat flux measurements are available. The logarithmic law for velocity is used along with the assumptions that diffusivities of momentum and species are equal and that the shear stress is constant. Again good agreement between theory and experiment was obtained. In addition, it was found that the ratio uz/K, where K is the mean vertical eddy diffusivity at a height z, is approximately equal to 20 over a wide range of stability at a height of less than 40 times the roughness parameter.

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Subject Headings: ***Diffusion, prediction based on heat transfer; Heat transfer, prediction of diffusion.***

D. S. Turcotte

Tritton, D. J. (Indian Institute of Sciences, Bangalore, India) "Transition to Turbulence in the Free Convection Boundary Layers on an Inclined Heated Plate," *Journal of Fluid Mechanics* **16**, 417–435 (1963)

In this paper an interesting set of experiments on transition in natural convection is reported. A heated, flat plate at various angles from the vertical was used and a quartz fiber anemometer was traversed to determine the presence of turbulent fluctuations in the boundary layer adjacent to the plate. The author reports the Grashof numbers for the first appearance of turbulent fluctuations and for full turbulence as a function of the angle of the plane from the vertical. On the lower side of the heated plate it is expected that turbulence would be inhibited since the natural convective boundary layer is stably stratified. This is what in essence the author reports.

Measurements on the initiation of the turbulent bursts were not repeatable and the author concludes from his own work and from the work of others that the initiation is strongly dependent on ambient conditions. With stable stratification on the lower side of the heated plate a large region was observed in which the flow was intermittently laminar and turbulent. For sufficient stable stratification the author concludes that an entire flow could occur which should be described as transitional, not laminar or turbulent. Such an intermittent flow made up of bursts

of turbulence might be expected in meteorological flows with stable stratification. The author correlates his results with observations of glacier winds.

Subject Headings: *Boundary layer, transition to turbulence; Turbulence, transition in heated boundary layer.*

D. S. Turcotte

Deardorff, J. W. (University of Washington, Seattle, Washington) "On the Direction and Divergence of the Small-Scale Turbulent Heat Flux," *Journal of Meteorology* **18,** 540–548 (1961)

By introducing turbulent fluctuations into the equations governing heat transfer in the atmosphere, terms equivalent to the Reynolds stresses of turbulent momentum transfer are obtained. In this paper such equations are derived and by multiplying the energy equation with a power of the potential temperature fluctuation and then averaging higher moment equations are obtained. Of course, such a procedure cannot yield a closed set of equations since additional unknowns are introduced. Such a procedure can be useful if extensive experimental evaluations of the velocity and temperature correlations are available, unfortunately this is not the case in natural convection problems. By rather gross approximations, the author of this paper is able to discard many of the terms in the second and third order moment equations and draws some conclusions from the remaining forms. For example, an estimate is given for the upward flux of heat when the potential temperature also increases upward in a sub-adiabatic layer.

The desirability of applying statistical theories on turbulence to the problems of atmospheric turbulence is certainly unquestioned. The mixing length theory, still rather widely used in natural convection problems has been largely discredited in forced convection problems for twenty years. Yet it is extremely difficult to obtain useful results from the statistical theory. The work reviewed here is a step in this direction but without extensive experimental measurements such work is of little value. Applications of the more complete statistical theories such as those given by Batchelor[1] to anything but homogeneous turbulence seems hopeless. A more fruitful approach would seem to be the application of similarity laws to atmospheric problems analogous to the similarity laws in forced convection, see for example, Coles.[2,3]

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Subject Heading: *Heat flux, turbulent.*

D. S. Turcotte

Fuquay, D. M. (Intermountain Forest and Range Experiment Station, U. S. Forest Service, Ogden, Utah) "Project Skyfire Progress Report, 1958–1960," *Intermountain Forest and Range Experiment Station Research Paper 71* (1962)

Lightning starts many forest fires; in the western United States it is the most frequent single cause of fires. A large number of fires may be started by lightning in a short period of time. The U.S. Forest Service is studying the meteorological problems associated with lightning-caused forest fires. The program, which is called "Skyfire", has two long range objectives. First, a better understanding of the occurrence and characteristics of lightning storms and lightning fires in the northern Rocky Mountain area is sought. Second, the possibility of eliminating or decreasing the number of lightning fires by means of weather modification is investigated.

The study was initiated in 1955 and is still in progress. Reported in *Research Paper 71* are the data and results for 1958 through 1960 along with a review of results for the period 1955–1957. As the program progressed the experiments were further developed and new experiments were added.

The weather-modification technique employed was seeding clouds with silver iodide. Airborne AgI generators were developed which produce 10^{15} nuclei/sec effective at $-20°C$. Ground-based silver iodide generators, which were built using the same design concepts as the airborne unit, were used to treat thunderstorms.

Weather modification is in its infancy so that there are not available a variety of modification techniques. This report considers only AgI seeding and does not consider or discuss any other scheme.

Thunderstorms were observed visually by fire lookouts over a wide area in Washington, Oregon, Idaho, and Montana. The number of thunderstorms, number of cloud-to-ground (CG) and cloud-to-cloud (CC) lightning discharges, and duration of storms were recorded. From the data the frequency distributions of storm duration, number of CG, and number of flashes per storm were determined. In addition maps showing the average annual number of thunderstorms and the average annual number of CG flashes per 1000 square miles were drawn.

Some of the information yielded by the study is the following: (a) average number of lightning storms per fire period ranged from 4 to 24, depending on location, (b) most lightning storms are short; only 4 per cent exceeded 30 minutes, (c) most storms produced a relatively small number of CG discharges; the few storms with large numbers of flashes account for a large fraction of the total flashes, (d) many lightning storms produce little precipitation, and (e) about 20 per cent of the storms yielded hail or graupel.

Electric field meters based on a design of Gunn[1] provided changes in electric field (E) due to a lightning discharge. By assuming a model of a point charge (the cloud) above an infinitely conducting plane (the earth), the changes in E could be interpreted in terms of changes in QH, i.e., the product of charge and elevation of charge. It was further assumed that the earth has a dielectric constant equal to free space. Several field meters were used so that CG discharges could be distinguished from CC discharges.

During the summer of 1958, weather modification by means of AgI seeding was tried. It is difficult to assess the effectiveness of seeding. There is no "standard" storm with which to compare the influence of modification attempts. A treated storm may have fewer flashes than an untreated storm; however, the storm may have had fewer flashes without the treatment. It is necessary to have many pairs

of treated and untreated storms and to apply statistical analysis in order to arrive at valid conclusions. Due to the fact that there were insufficient numbers of storms for analysis, the 1958 data did not indicate the effectiveness of weather modification.

Based on the information gained and the experience of the 1958 season the 1959 studies were conducted using more extensive equipment. The electric field meter network included five sites with synchronized measurements. A mobile radar was used. The aims of the 3 year program with the new meter network, starting in 1959, were to study (a) the frequency and distribution of lightning discharges during natural storms, (b) the quantity of charge carried by CG discharges, (c) the height of negative charge centers, and (d) the effect of silver iodide seeding from aircraft on some of the electrical and physical characteristics of lightning storms. The 1959 season had 40 per cent fewer storms than normal.

During the 1960 season measurements were made on 16 days providing data for 8 treated and 8 untreated storms. These 8 pairs of storms did not permit statistically significant conclusions. Preliminary analysis indicates that treatment does not cause marked difference between treated and natural storms.

In addition to the AgI generators and electric field meters mentioned previously, other equipment was used. This included a lightning spotting system which provided 360° coverage. Two weather radars gave information about location, elevation, and movement of storm centers.

Project Skyfire has provided valuable observations of thunderstorms that are natural or have been treated with AgI. Additional data is required for an evaluation of the effectiveness of AgI seeding.

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Subject Headings: ***Lightning, study of thunderstorm; Weather, modification of thunderstorm; Thunderstorm, lightning modification.***

A. E. Fuhs

Fuquay, D. M. (Intermountain Forest and Range Experiment Station, U. S. Forest Service, Missoula, Montana) "Mountain Thunderstorms and Forest Fires," *Weatherwise* **15**, 148–152 (1962).

This paper describes briefly in nontechnical terms the importance of lightning as a cause of forest fires, the general meteorological pattern leading to these fires in the Intermountain West, and the characteristics of thunderstorm clouds studied near Missoula, Montana, including base height and temperature, maximum height of radar echoes, accompanying precipitation, and frequency of lightning discharges.

Lightning causes 10,000 forest fires per year in continental United States and 70 per cent of all forest fires in the Rocky Mountain states. Lightning fire losses to forest resources in one year totaled an estimated 25 million dollars. Unlike man-caused fires, these usually occur in steep, inaccessible areas where suppression is more difficult.

In the Intermountain West, lightning often develops from surface heating, an

upper wave, or a front in a moist air mass that follows dry air which has dessicated the forest fuels. As a 5-year average on one national forest, thunderstorms occurred on 44 days during July and August. Counts of lightning flashes indicate some areas receive 1500 flashes to ground per 1000 square miles during these months. The peak of the lightning fire season from late July to a time before late August does not coincide with the earlier and later period of most intense thunderstorms which bring rain and hail.

Measurements during 3 summers near Missoula showed base elevations of incipient thunderstorm clouds to be 9000 to 18,000 feet above sea level, or normally more than 5000 feet above the ground. Such clouds had the same elevation on days with and without thunderstorms. Base temperatures were $-6°$ to $+9°$C and averaged $+2°$C.

During thunderstorms of one summer, cloud tops as indicated by maximum height of radar echoes ranged from 20,000 to 43,000 feet in height above sea level. These radar maxima averaged 33,000 feet. Visible cloud tops were estimated to be 3000 feet higher. Such storms over plains west and east of Missoula give much higher radar echoes. The author states that the minimum height of echo from tops of clouds producing lightning is about 21,000 feet, and as the height of tops increases as shown by the radar, the total number of lightning discharges increases. About 500 to 600 lightning discharges, of which about 150 went to the ground, occurred from the highest clouds. The average storm produced about 100 discharges with 40 per cent cloud-to-ground.

Stating that small areas of concentrated rainfall and lack of observing stations in mountains hinder reliable estimates of thunderstorm precipitation, the author assumed that the maximum precipitation measured in any one gauge in an area gave an approximation of the total. For 70 thunderstorm days a 5-gauge network with 2-mile spacing showed 50 per cent of all storms yielded less than 0.05 inch and 80 per cent yielded less than 0.2 inch. Storms having the higher cloud bases gave less precipitation.

Subject Headings: *Fire, relation to thunderstorm; Thunderstorm, effect on fire.*

W. G. Morris

Meese, A. D. and Evans, W. H. (Applied Research Laboratory, University of Tucson, Tucson, Arizona) "Charge Transfer in the Lightning Stoke as Determined by the Magnetograph," *Journal of the Franklin Institute* **273**, 375–382 (1962)

The charge transfer in 16 lightning flashes was measured with a magnetograph. The theory of the method is presented and the instrumentation described. The magnetograph measured the horizontal magnetic field anomally induced by a nearby vertical lightning discharge. The instrument used is of a ballistic type wherein the maximum deflection is proportional to the charge.

The calculated charge transfer in 16 strokes ranges from 23 to 1065 Coulombs. The average charge per stroke is 256 Coulombs with all strokes considered and 143 if the 2 largest strokes are omitted. These values compare favorably with those of

Hatakeyama[1] who, using both ballistic galvanometers and ballistic magnetometers, found the charge neutralized per flash to be greater than 100 Coulombs and occasionally reaching 300 to 400 Coulombs. The authors discuss the probable errors in measurement and conclude that these errors alone cannot explain the great discrepancy between their values and the generally accepted value of 20 to 30 Coulombs per stroke. They point out that magnetometers are integrating instruments and the only ones likely to include the prolonged smaller current that exists after the main surge of current.

Further discussion of the results reported by Meese and Evans appears warranted. In general, the accepted average charge transfer per ground flash is from 20 to 40 Coulombs.[2,3] Many different techniques were used to get these values; however, none were of the ballistic magnetometer type. In a more recent paper, Williams and Brook,[4] using a fluxgate magnetometer, found the average charge lowered to earth by continuing currents to be 31 Coulombs. If we consider that the average flash has 3 return strokes, neutralizing 3 to 5 Coulombs per stroke in addition to the continuing currents, we are still far short of the values reported by Meese and Evans.

Brook,[5] in commenting on the paper by Hatakeyama, noted that the 3-second period galvanometer used, when subjected to multiple strokes in a ground flash which could last over a 1.5-second period, could no longer be considered a ballistic galvanometer and would give higher values than for single flashes to ground. Another consideration is the physical dimensions of a cloud system which can store the charge. Workman, Brook, and Kitagawa[6] have shown that a discharge of 100 Coulombs would require an unusually large number of in-phase convection elements. About half the flashes reported by Meese and Evans exceeded this value with 2 flashes exceeding 1000 Coulombs.

This review has led to the following alternatives concerning the lightning data reported by Meese and Evans: the magnetometer system yields, for reasons unknown, charge transfer values much higher than those found by other commonly used methods; the magnetometer employed responded to only extremely intense discharges; the data reported included, by chance selection, only extremely intense and unusual discharges.

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Subject Heading: ***Lightning, charge transfer.***

D. M. Fuquay

Chandler, C. C. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Fire Behavior of the Basin Fire—Sierra National Forest, July 13–22, 1961," *Report of the Pacific Southwest Forest and Range Experiment Station* (October 1961)

The Basin Fire, which burned 17,000 acres on the Sierra National Forest in July 1961, was preceded by three consecutive years of drought. Logs and other heavy nonliving fuels probably had moisture contents much below normal. The moisture content of living fuels, such as brush, was unusually low and smaller twigs and branchlets were beginning to die early in July. The Basin Fire was a valuable fire behavior case study because (1) local weather data were available in considerable detail for the entire period of the fire (July 13–22), (2) local weather varied markedly during this period, and (3) there was a wide diversity of fuels and topography throughout the fire area.

A series of maps showing the fire boundary at 12-hour intervals indicates that approximately 2.0 or 2.5 square miles were burned during each of the intervals from July 13 to 16. However, on July 16, about 10 square miles burned between 6 a.m. and 6 p.m. About 8 square miles, or 30 per cent of the final area, were burned over between noon and 6 p.m. From the 16th to the 22nd the daily burning rate was somewhat less than from the 13th to the 16th.

On most days during the course of the fire, the maximum temperatures at the lower elevations in the general fire area were about 100°F and the relative humidities 20 per cent or less. The daily surface weather maps indicated that the general winds were light from July 13 to July 22. Local winds in the fire area showed more variation but were not strong at any time during the fire. The atmosphere in the general fire area was quite unstable from July 15 to July 21.

Since the range of elevation in the fire area was about 6000 feet, there was a wide range in major fuel types. These included grass woodlands, various types and densities of brush, and solid strands of fir at the higher elevations.

A selected group of questions concerning certain puzzling fire behavior or weather phenomena are presented and are accompanied by possible explanations. One of these relates to the spotting of the fire across the North Fork of the Kings River at 2 a.m. on July 16 for which there is no satisfactory explanation. Another question was why the high intensity burning, or "blow-up" occurred on July 16 rather than on July 15 or July 17 when the weather conditions were similar (or apparently similar). During the afternoon of the 16th when the area of the fire was increasing at a rate of nearly $1\frac{1}{2}$ square miles per hour, the height of the convection column was between 20,000 and 30,000 feet. To reach this height, the column probably was the free convection type* which accompanies most high intensity fires. The author attributes the high intensity of the fire and its convective buildup to topographic factors and the location of the fire front on the morning of July 16. These may have been contributing conditions but the structure of the wind field aloft may have had a pronounced effect. The towering column indicated low wind speeds aloft. This condition combined with either an appreciable wind speed at the surface, or a

* When the buoyancy forces in the column are greater than the inertial forces of the wind stream acting on the column, it will have the characteristics of free convection. However, both the shape of the column and the motions within will be distorted or modified somewhat from the free convection form which exists in a motionless atmosphere.

generally increasing land elevation in the direction of spread, would permit the strong convective buildup which occurred on July 16. Apparently data on the upper winds were not available for the Basin Fire.

Subject Heading: *Fire spread, Basin Fire, Sierra National Forest.*

G. M. Byram

"Proceedings of the Fire Weather Conference," Commonwealth of Australia, Bureau of Meteorology, Melbourne, July, 1958

This conference of top-level fire control administrators, forest fire researchers, and meteorologists had as its objectives "(1) to review the existing knowledge of the relationship between meteorological conditions in fires (2) to present and discuss reports of recent investigations in Australia on the subject, and (3) to examine the avenues of future research most likely to yield results of value to those engaged in fire prevention and control and fire-weather forecasting." The four sections of the program dealt respectively with the relation between meteorological factors and fuel moisture content, the direct effects of meteorological factors on fire behavior, the development and application of fire-danger measurement systems, and fire-weather forecasting. Papers varied in length from 8 to 40 pages and, as is commonly the case, value was not necessarily in direct proportion to length. Twelve of the papers were prepared by meteorologists, three by foresters.

Content of papers ranged from a straightforward and helpful discussion of sources of error in psychometric readings and calculations to a very complicated and inconclusive consideration of factors influencing the success or failure of prescribed burns. In some of the reported work, writers appeared to have become more interested in the methodology than in its outcome. Perhaps as a consequence, future efforts sometimes produced only very minor or questionable findings and in at least one instance, a conclusion by a meteorologist which was contrary to the observations of the fire control man present. In general, the nature and quality of the papers was such that American counterparts of the participants in the conference would have felt right at home. In the absence of substantial new information, only a few points appear to warrant comment.

The writers appeared to consider only fine, or "flash" fuels, presumably indicating thereby that such fuels strongly predominate in areas of heaviest fire business. Perhaps scarcity of coarser fuel particles to make long-burning fire brands accounts for the fact that a paper on the effect of wind considers spotting only in connection with gustiness. Although development of a strong convection column was discussed, its relation to long distance spotting did not receive attention. Citation of the need for learning more about chemical composition of fuels reflected the importance of species whose burnable portions contain large amounts of volatile constituents.

The consensus was that differences between fire danger measurement systems could be reconciled to provide a single compromise system acceptable nationwide. As in the United States, some conferees appear to have reservations on this score. The difficulty cited was application of a system developed for the very severe conditions of New South Wales to the situation in Tasmania—apparently about similar

to Southern California versus Southeastern United States. As in this country, systems devised for hot, persistently dry area placed more emphasis on temperature than did those for cooler, moister sections.

Papers on fire-weather forecasting revealed dissatisfaction with accuracy of predictions of atmospheric moisture and wind changes. These same problems plague the fire-weather forecaster in the United States, of course, but parts of Australia appear to have especially great difficulty by reason of the alternating influence of the sea and the hot, dry interior.

An excellent feature of the conference was the preparation and circulation of papers prior to the conference. Wider adoption of this practice would lead to far more intelligent and searching consideration of the information presented than is the rule at scientific work conferences. In the present instance the appearance of only 22 pages of discussion to 260 pages of papers is disappointing, and suggests that either the papers were not very well received or adequate means for recording discussion were not available.

Subject Headings: ***Fire weather, Conference; Weather, Conference on effect on fire.***

G. R. Fahnestock

XI. Operational Research Principles Applied to Fire Research

Chandler, C. C., Storey, T. G., and Tangren, C. D. (Pacific Southwest Forest and Range Experiment Station, U.S. Forest Service, Berkeley, California) "Prediction of Fire Spread Following Nuclear Explosions," *Final Report Contract OCD-OS-62-131—U.S. Forest Service Research Paper PSW-5* (1963)

The Office of Civil Defense in a joint contract with the Forest Service and United Research Services, Inc., Burlingame, California, ordered the preparation of a mathematical model of mass fire spread compatible with the damage assessment system. This is a final report covering the activities of the Forest Service whose task it was to isolate and identify the specific parameters significant to the spread and intensity of mass fires, to suggest methods of measuring and codifying these parameters and to collect specific input data to be used in testing a predictive model of fire spread. The authors assumed that (1) small fires will occur as a consequence of nuclear explosions, (2) fire spread following a nuclear attack would be controlled by natural factors and be relatively independent of fire-fighting efforts and (3) the rate of spread of mass fires following nuclear attack will be identical to the rate of spread of large area conflagrations that have occurred in the past in identical fuel, weather, and topographical situations. As a consequence of these assumptions, the principal methods they used were to review the fire spread literature, to analyze the reports of about 2000 large wildland fires and urban conflagrations dating back as far as the great Chicago fire and, finally, to rely on the views of experienced fire chiefs and mass fire experts.

The authors emphasize that the most likely situation following a nuclear detonation is one in which several mass fires are scattered throughout a larger area rather than the picture often given of hundreds of square miles going up in flames at once.

They point out that even under the most severe situation imaginable, in which hundreds of square miles of unbroken, homogeneous fuels are ignited simultaneously, the period of active burning will not exceed a few hours and once the central area has burned out, the remaining fire perimeter will spread in the same way as any other wildfire.

A most valuable aspect of this report is the collection and evaluation of data on the spread of conflagration fires under known conditions of fuel, topography, and weather. After being forced to discard about 90 per cent of the fire reports because of incomplete data, the authors carefully tabulated all the remaining data. Parameters listed include time and duration of spread, wind velocity and direction, temperature, relative humidity, fuel moisture and type, length and degree of slope, profile of topography, and type and rate of spread. They report that in cities the mean rate of fire spread was about 0.12 miles per hour while wildland fires spread at a mean rate of about 0.16 miles per hour. Standard deviations of the spread rate were such that this difference was not significant. Additionally, it was shown that the rate of spread depends on the length of time over which spread was measured. In general, the shorter durations of spread yielded higher rates of spread both for urban and wildland fires.

Following a discussion of small wildland and urban fires which are shown to be influenced primarily by surface weather phenomena, the authors point out the importance of convective activity in large fires which produce the massive convection columns accompanying these mass fires. Reports of air entrainment into fires have been inconsistent. Indrafts have usually been observed, but outdrafts have not been uncommon both from stationary and moving fires. The unpredictability of the increased air flow out of a fire is noted with the remark, supported by some evidence, that such outflow may be a common feature of large fires. The relative roles played by atmospheric stability, total fuel weight, and topography are also briefly discussed.

As far as requirements for a predictive model of fire spread are concerned, the report details the data which are available and further data which are needed. Data collected for further mathematical model studies included the length of time natural fuels might be expected to burn, weather conditions for no significant forward spread, and for extinguishment of a forest fire without effective fire-fighting action. Similar data were collected for urban fires, although in general these data were harder to come by. Much of the material reported here was a collection of the educated opinions of fire-fighting experts. For example, detailed figures for burning times of specified fuel types from grass to timber in wildlands and from light residential to civic center and massive manufacturing areas in cities are generally the product of a consensus of expert opinion. Nevertheless, within these limitations, there was a fairly successful effort to verify the fire spread criteria from available records.

The appendixes to the report, which contain all the fire spread data, will be the source from which further modeling studies will be continued. In addition, the appendixes contain a discussion of the estimators of fire modeling parameters obtainable from aerial photographs as well as case histories of an urban and wildland fire which indicate how fire spread data may be obtained from such sources.

Subject Headings: *Nuclear explosion, prediction of fire spread; Fire spread, from nuclear explosion.*

A. Strasser

Countryman, C. M. and Chandler, C. C. (Pacific Southwest Forest and Range Experiment Station, U.S. Forest Service, Berkeley, California) "The Fire Behavior Team Approach in Fire Control," *U.S. Forest Service Fire Control Notes* **24,** 56–60 (1963)

The authors of this article have been leaders in the development and application of the job of the *fire-behavior* officer in the forest-fire suppression organization. Although the proposed organization has not as yet been adopted as standard for the Fire Service, it points to a way of possible future organization. The basis for this organization is that the fire-control men require an accurate evaluation of the effect of the prevailing weather and fuels on forest-fire behavior, often sector by sector. The supplying of this type of information is the responsibility of the fire-behavior officer and his team who have the required training in both fire behavior and meteorology to provide the fire-control men the needed information.

Briefly, the fire-behavior team consists of the following, beginning with the "front-line" men and terminating with the fire-behavior officer:

1. *Meteorological Observers*—Men obtained from the fire-control force who are capable of operating meteorological instruments in the fire area.
2. *Senior Meteorological Observer*—This man is responsible for the meteorological equipment and, in addition, obtains and compiles the meteorological observations made in the fire area by the observers. These observations are submitted to the fire-behavior officer and the meteorologist (the Fire Weather Forecaster).
3. *Fire Weather Forecaster*—This man prepares weather forecasts for the fire-behavior officer.
4. *Fire-Behavior Officer*—This man functions as an advisor to the fire-control Plans Chief and Fire Boss. He must integrate information on local weather, fuels, topography, and anticipated fire control action into a forecast of probable fire behavior.

Subject Heading: *Fire control, team approach.*

R. A. Gorski

Bruce, D. (Pacific Northwest Forest and Range Experiment Station, U. S. Forest Service, Portland, Oregon) "How Many Fires?," *U.S. Forest Service Fire Control Notes* **24,** 45–50 (1963)

Being able to predict how many fires may occur on a specific land management unit is an important step toward better fire control planning and prediction of average levels of fire business. This article describes how negative binomial distributions can be used to describe past fire occurrence in a given area much in the same way that they are used to describe a variety of things that are counted in equal units of space or time.

Fire occurrence records for a 7-year period from the former Clark National Forest in Missouri are used to show how the frequency distribution of fires can be estimated by computation. The data used in this example includes 1052 days of record on seven ranger districts for seven years of spring and fall fire seasons.

A table is used to show the comparison of actual to estimated fire frequencies in terms of number of days, having various numbers of fires in each danger rating class. From this table a graph is prepared that shows the per cent of the total days in each fire danger class plotted as cumulative per cent over the average danger rating for the class. Using the estimated fire frequencies rather than the actual appears to smooth out the plotted curves on the charts.

To complete the discussion, formulas are presented showing how to compute the expected fire frequency using basic fire occurrence and danger rating information for specified areas.

Subject Heading: *Fire, prediction of frequency.*

J. H. Dieterich

Hogg, J. M. (Joint Fire Research Organization, Boreham Wood, England) "Fires Involving Liquefied Petroleum Gas," *Joint Fire Research Organization Fire Research Technical Paper No. 8* (1963)

The author analyzes the annual frequency of fires involving liquefied petroleum gas in the years 1947 through 1961 to ascertain whether use of liquefied petroleum gas is becoming intrinsically more dangerous in the United Kingdom, or whether the increase in the number of fires might be solely attributable to the increased usage of this fuel.

Data summarized for the years 1947 through 1961, in two figures, show that:

a) The total number of fires involving liquefied petroleum attended by fire brigades increased from 35 to over 630 per year, with the greater part of the increase occurring in the period of 1957 through 1961.
b) Deliveries of the liquefied gas, exclusive of deliveries to gas plants, increased from about 20,000 to 130,000 tons per year.
c) The rate of fire incidents per thousand tons of liquefied gas delivered increased from 2 to nearly 5, with the upward trend apparent in the period of 1957 to 1961.

In addition, tabulated data for the years 1947 through 1957 show an increase in incident rates wherein the liquefied petroleum gas applicance was the source of ignition, and a decrease in incident rates wherein gas leaking from storage cylinder fittings and values was initially ignited. Ten tables are included to present the survey analysis. In the period studied it is deduced that liquefied petroleum torches used in dwelling construction and repair contributed significantly to the increased fire incident rate. Use of liquefied petroleum gas in cooking and the industrial application of cutting torches also contributed significantly to the number of fires involving this fuel in 1957. Personal injuries in liquefied gas fires were largely associated with fitting and valve leakage, and a decrease in the rate of injury is reported for the year 1957.

Although the author does not so state explicitly, we may conclude from the

analysis of data presented that the use of liquefied petroleum hand torches (cutting, burning, paint removing, etc.) requires good fire preventive practice.

Subject Heading: ***Fire, in petroleum gas.***

J. E. Malcolm

O'Neal, N. C. and Holtby, B. E. (U. S. Forest Service, Washington, D. C.) "The Fire Control Simulator," *U.S. Forest Service Fire Control Notes* **24,** 25–31 (1963)

For several years the Washington Office of the Forest Service, Division of Fire Control has been looking for new and better ways to train personnel in the difficult task of wildfire management. Simulation has been tried and found effective in space-age training, and since simulation is nothing more than a concerted effort to represent a real situation in which operations are carried out, the application to fire control situations appeared logical.

In 1962 the International Electric Corporation in Paramus, New Jersey was awarded a contract to develop the Fire Control Simulator. Preliminary construction was completed in 1962, and the first exercise run was made in December 1962. Since that time the Simulator has been in nearly constant use across the country—either at fire control training sessions or for demonstration purposes. The most effective demonstration of the Simulator capabilities comes from a well-planned exercise with active participation by all but a very few observers.

The Simulator's portable walls enclose an area of approximately 720 square feet. There is a Trainee Area for those participating in the exercise and a Control Area where direction of the operation takes place. The projection system is an important part of the over-all unit. The visual action takes place on a $8' \times 12'$ screen in view of the trainees, on which an actual scene is projected in color. Through an additional system of projection equipment flames, smoke, suppression equipment, and burned area are all realistically superimposed on the basic scene. Communications equipment is available that includes intercom, telephone, ground–air radio and ground–ground radio and connects the trainees with the Training Director and role-players.

The Training Director during the course of an exercise may grant certain degrees of success or failure to the trainees and he ensures that realistic messages are transmitted to the fire boss through the role-players. A section of fireline may be lost; some equipment may fail or be burned, or crews may become trapped. These stress situations help to make the exercise more realistic and call upon the trainees to make responsible, accurate decisions.

An important part of the Simulator exercise is the de-briefing session that follows. Here, trainees, instructors, and role-players come together to discuss fire control strategy, placement of men and equipment, and the consequences of major decisions.

This unit appears to be an excellent training tool, but as with any training device it requires absolutely that (1) the exercise be well planned and realistic, and (2) the role-players, Simulator operator, and Training Director be completely familiar with their duties and operate as a team during completion of the exercise.

Subject Headings: ***Fire control, simulator; Simulator, fire control.***

J. H. Dieterich

XII. Instrumentation

Bradshaw, P. and Johnson, R. F. (National Physical Laboratory, Teddington, Middlesex, England) "Turbulence Measurements with Hot Wire Anemometers," *National Physical Laboratory Notes on Applied Science* No. 33 (1963)

The hot wire anemometer is essentially an instrument for measuring fluctuating velocities and for the study of turbulence. In order that the upper limit of frequency of velocity fluctuation may be extended to 100 kilocycles/second, it is necessary to use sophisticated electronic compensation for the thermal inertia of the wire, and for generating particular functions of velocity, such as the root mean square value. This booklet is intended to give guidance to aerodynamicists with limited electronic knowledge on the circuits and units involved, as well as provide information on the theory of operation, method of construction, and mode of operation of hot wire anemometers. Some addresses of manufacturers of apparatus in use at the National Physical Laboratory are also given.

The heat transfer from a hot wire depends on the square root of the velocity, and for purposes of measurement the wire may be operated at constant temperature (resistance) or constant current. Wires can be made from platinum or tungsten with diameters 0.00005 to 0.0003 in. Diameters as small as these are obtained either by drawing down a composite bar of silver with a platinum core and removing the silver by etching with nitric acid or by etching alone in the case of tungsten. Platinum may be used up to 250 ft/sec air velocity and tungsten up to the speed of sound. Platinum alloys have been used at higher velocities. The wires are soldered to steel prongs fastened to the probe body in such a manner that no vibration occurs when in use, which would generate spurious signals. Details of the method of construction are given together with photographs and ways of calibration are described.

After some general hints on the operation of electronic equipment, a description of constant current and constant temperature compensation equipment is given. Many circuits of the constant temperature type can prove to be unstable, giving rise to the idea that constant current apparatus is easier to use. Many investigations in which the intensity of turbulence is high are described, e.g., in turbulence jets or close to the wall of a duct. The apparatus for constant temperature compensation described here is said to be extremely reliable and simpler to use than many constant current systems.

It is possible to generate functions of velocity fluctuation and to perform mathematical operations on the result by electronic systems in the form of analogue, digital, or data logging techniques. The systems described here have all been tested and used in research investigations, and circuit diagrams are included.

This note, together with its bibliography forms a most useful base reference for those investigators embarking on turbulence studies.

Subject Headings: *Anemometer, turbulence measurement; Turbulence, measurement.*

P. L. Start

Hill, K. and Hornstein, B. (Thiokol Chemical Corporation, Denville, New Jersey) "Detection of Hydrogen-Air Fires and Explosions in Aerospace Vehicles via OH Band and Water Band Emission," *Technical Documentary Report No. ASD-TDR-63-113, Contract AF33(657)-8969, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio* (April 1963)

In manned aerospace vehicles carrying stored liquid hydrogen, fuel can leak into a vented or closed compartment and burn or explode with air. For safety it is necessary to detect the presence of hydrogen and fill the compartment with inert gas before ignition takes place. If ignition does occur the resulting fire or explosion must be reliably detected, under all flight conditions, so that effective suppression or safety measures can be taken in time before damage occurs.

Flame properties such as temperature, ionization or reaction product appearance can be detected only when the reaction zone or burnt gases are in contact with the detector element. The property selected as most suitable for detection is the emitted radiation from the reaction zone. For the H_2-air system this comprises principally the OH radiation in ultraviolet and the water bands in the near infrared. Radiation can be detected at a distance from the reaction zone and burnt gases and emitted radiation can be detected from any point in a solid angle viewed by a detector such as a photomultiplier tube.

A comprehensive survey of the literature relating to the properties of both premixed and diffusion hydrogen–air flames is presented. Properties include deflagration and detonation, ignition energy by spark and hot surface, flammability limits, quenching distances, and burning velocities. Previously published work shows that the OH radical appears in substantial concentration in the initial phases of the H_2–air reaction and the reaction mechanism, hence the appearance of OH is the same for flames, high order deflagrations, and detonations. Further, the OH radiation is sufficiently intense to be of interest as a detectable property and can have a concentration greater than the calculated equilibrium value. Data on the radiant intensity of OH emission versus flame size, flow rate and pressure of H_2–air flames are found to be lacking as are data on the radiant intensity of OH emission versus time for H_2–air explosions. A detailed experimental program has been carried out to provide these data. The H_2–air diffusion flame was chosen as the radiation source. Measurements of the absolute value of the radiant intensity against all the variables, i.e., hydrogen flow rate, part diameter and pressure from 760 to less than 20 mm Hg, were made over the OH bands of the ultraviolet and the water bands in the infrared. A surprising result was the increase in OH radiant intensity with decreasing pressure. For explosions, mixture ratios as well as pressure were varied, the rate of increase of emission and rise of pressure after ignition were measured to determine the detection lead time, that is, the time between detection and the pressure reaching an assigned value dependent upon the suppressive action to be taken. Results are presented as fundamental quantities which can be applied to a variety of design situations.

The H_2O band infrared emission is not considered to be a suitable property for flame detection due to its decrease with decreasing pressure and background interference.

A critical survey of detection equipment suitable for installation in aerospace vehicles is presented.

Subject Headings: *Fire, detection; Detection, of fire.*

G. L. Isles

Chleck, D., Cucchiara, O., and Donaghue, T. (Parametrics Incorporated, Waltham, Massachusetts) "Detection Techniques for Hazardous Vapors of Elemental Propellants," *Technical Documentary Report No. ASD–TDR–63–294 Contract AF 33(657)-8916, Air Force Systems Comand, Wright-Patterson Air Force Base, Ohio* (July 1963)

This report describes an investigation into techniques capable of being developed into simple, direct, inexpensive, field devices for detecting hazardous vapors of hydrogen and fluorine, or fluorine-containing oxidizers. Goals for detection limits were one-fourth or less of the lower explosion limit (LEL) for hydrogen and the threshold limit value (TLV) for fluorine.

The results of an extensive literature search of detection techniques are presented. It is concluded that only indirect methods exist and they do not otherwise meet the program objectives.

Three new systems for fluorine are evaluated as well as another technique of potential dual-gas detection capability.

1. The fluorescence of aluminum morin paper, under ultraviolet excitation, is quenched by hydrogen fluoride. Assuming HF is coexistent with elemental fluorine, this effect leads to a sufficiently sensitive, stable and direct system without further development.

2. A hydroquinone–Krypton-85 clathrate compound releases radioactive Krypton-85 gas in proportion to the oxidation of hydroquinone. Thus, a radioactivity counter can determine the oxidizer concentration. A "sensitized" clathrate of improved characteristics was developed that displayed satisfactory response to 0.05 ppm of fluorine (compared to the TLV of 0.1 ppm for 8 hours exposure), was independent of flow rate, except for very short residence times, and was simple and effective for long times.

3. Chemiluminescense results from oxidation of a rhodamine B–silica gel surface. This light excites a photomultiplier tube signal which is proportional to the fluorine oxidizer flux (i.e., concentration times flow rate) passing the detector surface. Response is less than one second for all fluorine concentrations and adequate for determining TLV for 8 hour intervals.

4. The final technique examined makes use of radioactive Krypton-85 incorporated into a solid, i.e., a kryptonate. Fluorine reacts with the surface layers of kryptonates, causing release of Krypton-85. The effluent radioactive gas is directly proportional to fluorine concentration and is measured by a Geiger counter. The highest sensitivity is obtained using kryptonated pyrographite. Its response is adequate for continuous detection of fluorine in the atmosphere. (Kryptonated boron also is considered satisfactory although less sensitive.)

In adapting kryptonates to hydrogen detection, the decreased radioactivity of

the source is monitored. The escape of Krypton-85 comes about from the reduction of the kryptonated surface by hydrogen and is proportional to the partial pressure of hydrogen in the gaseous environment. Excellent response and sensitivity to hydrogen in air is obtained by use of a mixture of molybdenum trioxide and kryptonated platinum oxide. The former acts as a coating to inhibit oxygen–hydrogen reactions and allows hydrogen to diffuse through to the kryptonated surface. (In a nonoxygen containing atmosphere, kryptonated copper oxide and platinum oxide can be used for hydrogen detection.)

Subject Headings: *Detection, of vapors; Vapors, detection of.*

K. M. Foreman

Murray, J. R. and Philpot, C. W. (Pacific Southwest Forest and Range Experiment Station, U.S. Forest Service, Berkeley, California) "The Fuel Temperature Counter," *U.S. Forest Service Research Note PSW-10* (1963)

In this paper an electronic recording instrument for measuring fuel temperature is described. Fuel temperature appears to have an important bearing on fire ignition and spread—particularly in the very early stages of a fire and the data collected using this counter help provide a better understanding of temperature changes in surface fuels.

The instrument consists of three fuel-temperatures sensors, a pulse generator, a timer, and an accumulating counter. It has good portability for field use, will operate effectively for two weeks on a low power requirement (24-V battery).

The temperature sensing elements are made from three thermistors, wired in series, each placed in a hole drilled through a wooden dowel to stimulate the fine fuel. The timing mechanism permits readings to be made for any length of time to obtain an average fuel temperature. The sensors are calibrated in a controlled oven and a curve is plotted indicating the relationship between fuel temperature and resistance. The number of pulses per unit of time may then be interpreted in terms of temperature of the fuel.

Charts and diagrams are presented that show the relationship between resistance, pulse per 15 minutes, and fuel temperature. A schematic diagram of the pulse generator–amplifier is also included.

Subject Heading: *Temperature, determination, of fuel.*

J. H. Dieterich

Hirsch, S. N. (Intermountain Forest and Range Experiment Station, U. S. Forest Service, Missoula, Montana) "Infrared as a Fire Control Tool," *Proceedings of Annual Meeting, Western Forest Fire Research Committee Western Forestry and Conservation Association, Seattle, Washington* (December 11, 1962)

The application of infrared techniques to the detection and mapping of fires, particularly forest fires is discussed. The possibility of observing fires by electro-

matic radiation (light) is presented. Since an infrared system provides a thermal map of the terrain such additional uses as determining the fire perimeter, spot fires outside the perimeter and rate of spread are evident.

On the basis of radiation emitted from the fire, the solid fuel, flame, gases and smoke, and problems of atmospheric adsorption it is shown that observation of emitted infrared in the ranges of 3.6 to 4.1 and 4.5 to 5.5 microns is most feasible. Either range could be used for nighttime observations but in the presence of daylight only the longer wavelength would be practicable.

In the observation of forest fires, detection from an aircraft is generally required. The wavelengths of useful infrared is beyond the limit of direct photography. Hence, a suitable system would employ an electronic infrared detector and then either electronic display or a infrared-visible light converter with photographic recording.

One anticipated problem in observing fires at or near ground level is the blockage of the actual fire by trees and smoke. Tests made of the screening of heat sources by trees on the ground showed a wide variation, from 0 to 86 per cent, depending upon tree basal area, but not dependent upon timber type among Douglas fir, ponderosa pine and Engelmann spruce.

Infrared visibility through smoke cannot be predicted because of the wide variation of solid particle content and smoke density. However, flight tests over prescribed fires showed them to be visible to the infrared system while visual observation was completely cut off by dense smoke above the fire.

The results prove the potential of infrared detection in the observation of forest fires. Present equipment however is not suitable for operation by a fire patrol. Further development is required to yield a simple, convenient, and easily portable piece of equipment.

Subject Headings: *Infrared, detection of fire; Fire, detection, by infrared.*

R. W. Ziemer

Adams, J. L. (Department of Forestry, Ottawa, Canada) "Wind Measurement with Hydrogen-Filled Balloons," *U.S. Forest Service Fire Control Notes* **24**, 69–72 (1963)

In view of the importance of wind velocity and direction measurements in fire research and because of the possibility of finding the use of tethered balloons as an economical but reliable method for measuring these parameters, the author undertook a program to determine the feasibility of such measurement by inflating tethered toy and standard 3″ meteorological balloons with hydrogen and determining which combination of balloon (type and size) and tether length (using No. 8 linen thread) gave the more reliable results. The meteorological balloon inflated to 7 to 14 inches in diameter tethered 2 to 10 feet above the ground appeared most suitable for wind velocity and direction measurement based upon the "angle of lean" measurement.

Subsequent trials around test fires (small bonfires and a small-scale burn in a plantation) led to the conclusion that the use of tethered, hydrogen-filled balloons

will not provide reliable and accurate measurement of wind speed or direction near the ground. The tethered balloons may be used for qualitative applications, however. Reasons for these conclusions were: (1) the "angle of lean" was difficult to measure since the balloons bobbed and weaved too much, (2) the "angle of lean" was not sufficiently reproducible with all controlling variables being constant, (3) the balloons were no more accurate in indicating the wind direction than using the "dampened-finger" method, (4) there was no discernible correlation between indrafts and ambient winds, and (5) the balloons are more prone towards indicating instantaneous air velocities than average velocities as measured by standard anemometers.

Subject Heading: *Wind, measurement, by balloon.*

R. A. Gorski

Danckwerts, P. V. and Wilson, R. A. M. (University of Cambridge, Cambridge, England) "Flow-Visualization by Means of a Time-Reaction," *Journal of Fluid Mechanics* **16,** 412–416 (1963)

A rather novel method for visualizing liquid flow fields is described. Reactants are introduced steadily into a continuous flow. The reaction is designed in such a way that, at a definite time, θ, after the reactants are brought into contact, the reaction causes the liquid to turn blue instantaneously. The time, θ, can be varied by varying the initial concentration of a critical reactant. In this manner, the mean flow residence times can be measured visually as a function of position in a chamber during steady flow.

A few experiments and photographs are shown for cylindrical chambers with various inlet and outlet arrangements. The effects of diffusion seem to preclude quantitative interpretation of the results. However, any new tool for studying complex turbulent flows is important.

Subject Heading: *Flow, visualization by reaction.*

F. A. Williams

XIII. Fire-Fighting Techniques, Equipment

Harmathy, T. Z. (Division of Building Research, National Research Council, Ottawa, Canada) "A Treatise On Theoretical Fire Endurance Rating" *Special Technical Publication No. 301, ASTM,* 10–40 (1961)

Fire endurance ratings are assigned to elements of buildings by code or rating officials on the basis of performance of the element when exposed to a standard fire endurance test.[1] The title of the paper is unfortunate in that the subject is more nearly confined to an exploration of numerical methods for computing heat flow through such building elements under the conditions commonly used for fire tests.

It is suggested that prior methods proposed for prediction of thermal behavior of structures exposed to fires have all been of limited usefulness because of the necessity of assumption of thermal properties which are independent of temperature. Such limitations can, however, be largely obviated if enthalpy, specific heat, and thermal conductivity, as well as surface transfer coefficients are treated as temperature dependant variables. This will, of course, require rather extensive information on these properties for materials commonly used in building construction. Some information of this type is presented for bricks and gypsum over the temperature range from 0 to 2000°F. Surface heat transfer coefficients which combine both radiation and convection losses are presented in graphical form for both vertical and horizontal surfaces over a temperature range of 0 to 1500°F.

The numerical computation method described is essentially that of Dusinberre[2] but includes provisions for treating temperature-dependent properties as variables. As used by the author the problem is handled with the use of a desk calculating machine, the solution of the problem being developed in tabular form. Migration of moisture is recognized and discussed but not allowed for in the solution. Moisture is assumed to be lost as steam, once the heat of vaporization appropriate for a given section has been absorbed. The author further recognizes and mentions that while a fire test of a structure may involve failure by mechanical rather than heat transfer causes, the latter only is considered in this paper.

Three problems are analyzed and discussed in the paper:

1. The influence of moisture content on fire endurance of brick walls. Three wall thicknesses are considered: $2\frac{1}{4}$, $3\frac{3}{4}$, and 8 inches. These are assumed to have uniform moisture content of 0, 5, 10, and 15 per cent. Application of the computation method shows that the time for limiting temperature rise on the unexposed surface is linearly related to moisture content, but that on a percentage basis, the increase in fire endurance resulting from water is greatest for the thin walls. For these the incorporation of 15 per cent moisture is shown to double the fire endurance.

2. The effectiveness of air gaps as heat barriers. Two walls comprising two layers $3\frac{3}{4}$ in. thick are analyzed. In one wall the layers are in intimate contact while in the other a one inch air space separates the two layers. It is shown that the insertion of the air space may significantly extend the time required to reach a limiting temperature rise on the unexposed surface.

3. The dependence of fire endurance on the surface to which fire is subjected in an asymmetrical construction. It is pointed out that the formula proposed by the National Bureau of Standards,[3] because of lack of advice on handling of asymetrical constructions, may be misleading. For example, several cases of such constructions are analyzed; in the first a brick wall built of two layers (a) and (b) were analyzed. Layer (b) was assumed to have similar properties as conventional brick layer (a) but twice the thermal conductivity. With an assembly of this type it was shown that about 18 per cent greater fire endurance resulted when the layer of lower conductivity was exposed to the furnace fire. Analysis of a brick wall with plaster on one side shows that best results are obtained when the plaster is on the unexposed wall surface.

This paper forms a valuable contribution to the fire research literature. There are still many gaps to be filled but the basic computational methods proposed will undoubtedly prove useful in solution of heat transfer problems of the transient type involved.

References

1. *ASTM Standard Methods of Fire Tests of Building Constructions and Materials, E-119.*
2. DUSINBERRE, G. M.: "Numerical Analysis of Heat Flow." McGraw Hill, New York, p. 114, 1949.
3. *National Bureau of Standards, Building Materials and Structures Report BMS 92, Appendix B.* U.S. Government Printing Office, 1942.

Subject Heading: *Fire endurance rating.*

A. F. Robertson

"Chemicals for Forest Fire Fighting," *A Report of the National Fire Protection Association Forest Committee* (1963)

This publication presents a brief summary of the use of chemicals in forest fire control through 1962. It is a compilation of information from research reports and field experience on the selection, mixing and handling, and application of chemicals to forest fires from both ground equipment and aircraft. The information is presented in handbook form and reference to the original reports is made when appropriate.

The contents of the publication are presented under the following headings and the contents of each chapter are summarized below.

Chapter 1—Maximum desirable characteristics.
Chapter 2—Short-term retardants.
Chapter 3—Flame-inhibiting chemicals (long-term retardants).
Chapter 4—Effects of forest fire fighting chemicals.
Chapter 5—Application of chemicals from the ground.
Chapter 6—Equipment for mixing chemicals.
Chapter 7—Pumps for handling chemicals.
Chapter 8—Distribution systems for handling chemicals.
Chapter 9—Storage of mixed and unmixed chemicals.
Chapter 10—Measuring instruments.
Chapter 11—Permanent chemical mixing plants.
Chapter 12—Portable (temporary) chemical mixing stations.
Chapter 13—Safety.
Appendix

Chapter 1 presents a list of desirable characteristics for chemicals based on recommendations of the California Air Attack Coordinating Committee. This list includes costs, effectiveness on fires, toxicity, corrosion, handling, etc. In addition the special desirable characteristics of a chemical for its use as a suppressant and/or a retardant are listed. An outline of a suggested testing procedure for new chemicals is also presented.

Chapter 2 describes and compares the use of water, "wet water", viscous water, gels, and bentonite clay as suppressants and short-term retardants (effective as long as the water is retained). A physical description of the chemical–water mixtures, mixing ratios and resulting viscosities, purchase costs, and particular desirable and

undesirable characteristics are presented for algin (sodium alginate), CMC (sodium carboxymethyl-cellulose), calcium alginate gel, and bentonite clay.

Chapter 3 presents information similar to that given in Chapter 2 for borate (sodium calcium borate), DAP (diammonium phosphate), algin–DAP, CMC–DAP, pectate–DAP, and the combination of ammonium sulphate and attapulgite clay.

Chapter 4 examines the state of knowledge of the effects of chemicals on fires, vegetation, humans and animals, and mixing and handling equipment. A brief section examines the effects on men and equipment of dyes used as coloring in bentonite and viscous water combinations.

Chapters 5 through 9 present and discuss representative components of the equipment system for mixing, transporting, and storing of chemicals to be used for ground or aerial application to a fire. Chapter 5 discusses also equipment for applying chemicals to a fire from the ground.

Chapter 10 describes and briefly discusses the use of various instruments for measuring viscosity, gel strength, acidity and alkalinity, and temperature of a chemical slurry in both the laboratory and the field.

Chapter 11 presents a discussion and design recommendations for establishing permanent chemical mixing plants at airports.

Chapter 12 briefly presents a discussion and design recommendations for portable chemical mixing stations which are used for supplying helitankers and ground tankers.

Chapter 13 lists safety precautions which should be observed by operators of chemical mixing plants.

The appendix contains summary tables for water mixing ratios for the chemicals described in the text and approximate mixing times for these chemicals for eight different mixers. The latter table presents mixing times for all of these chemicals for only two of the eight mixers listed. A list of commercial sources of the chemicals is also presented. The list of reference reports quoted in the text is presented at the end of the appendix.

No information on the design or testing of aircraft equipment for aerial delivery of chemicals to a fire is presented in this publication.

Subject Headings: ***Forest fire, chemical control; Fire, chemical control, in forest.***

A. W. McMasters

Crosby, J. S. (Central States Forest Experiment Station, U. S. Forest Service, Columbus, Ohio), **Johansen, R. W., and Cooper, R. W.** (Southern Forest Fire Laboratory, U.S. Forest Service, Macon, Georgia) "A New Machine for Forest Fire Control: The Model II Michigan Sand Caster," *U.S. Forest Service Research Paper CS-2* (May 1963)

The Model II Michigan Sand Caster is a new type of machine designed to cast a large volume of sand at high velocity for fire suppression. Model II can cast as much as 4 cubic yards per minute from a trench it digs in the ground over which it is towed.

Trials were conducted in Michigan, Georgia, and Florida primarily to evaluate

the principle of sand casting in fire suppression, but also to evaluate the machine itself.

Results showed that sand cast in sufficient quantity is capable of extinguishing flames. Used to pretreat fuels, it increases their resistance to ignition and reduces both fire intensity and rate of spread.

The Model II Michigan Sand Caster is a pilot model and should point the way towards a more dependable machine. It operated successfully in open areas with little debris or dense vegetation. However, as the amount of debris and vegetation increased, breaking of shock load shearpins, clogging, and maneuvering proved troublesome. As a result, operations close to the front of an intense fire became risky. Effective direct attack on flames with this machine must be made from 50 feet or less. Although direct ground attacks with other equipment must be made even closer to the fire front, distance still limits the kind and number of fires on which direct sand-cast attacks can safely be made.

Pretreating fuels with a sand cover for indirect fire control was generally quite successful and may offer the greatest promise for the use of this model. Sand casting may also be beneficial in bringing some crown fires to the ground, in corralling the flanks of wildfires, and for work on the rear of fires that require much mop-up.

This machine appeared to perform better in Michigan than in the more complex fuels of Georgia. For effective use in most fuels when only one cast was made the full capacity of the machine was needed; in the more complex fuels even a full-capacity single cast was often inadequate for complete control.

Subject Headings: *Forest fire, sand caster; Fire, sand caster in forest control.*

E. C. Woodward, Jr.

Peterson, H. B., Tuve, R. L., Gipe, R. L., and Porter, J. W. (U. S. Naval Research Laboratory, Washington, D.C.) "A Vacuum Pneumatic Process for Filling Large Dry Chemical Fire Extinguishers," *NRL Report 5942* (April 10, 1963)

In the process described, a four hundred pound dry chemical extinguisher is filled by a pneumatic method in six minutes, as compared to forty-six minutes which is required by hand-pouring.

A 1.5 h.p. commercial vacuum cleaner takes suction on the extinguisher through a special dual-passage closure. Dry chemical is directed vertically downward and air is withdrawn from near the top to minimize intermixing and carry-over.

The special nozzle on the chemical suction hose is placed in the open chemical container and moved about until all chemical is removed. Transfer rate decreases from 1.14 to 0.43 lb/sec, as the cleaner bag becomes filled. The carry-over, normally under 4 per cent is periodically emptied and recovered.

Powder is more dense when filled by this method than with hand filling, so that the amount charged must be watched to avoid overfilling.

Pneumatic filling appears particularly desirable for large crash-rescue "air-lift" extinguishers, where timesaving may be important.

Subject Heading: *Fire extinguishers, filling of.*

O. W. Johnson

XIV. Miscellaneous

"Discussion on Dust Explosions," *Report of Conference Proceedings, College of Mineral Industries, The Pennsylvania State University, University Park, Pennsylvania* (September 4 and 5, 1962)

This Conference* was called to organize a concerted effort in behalf of research on and prevention of dust explosions.

Dr. Hylton Brown, former chairman of Committee on Dust Explosions of N.F.P.A., presented a historical background of the subject and Professor M. W. Thring of the University of Sheffield, England, outlined a program of applied research on dust explosions and prevention measures. Messrs. Donald S. Kingery and John Nagy of the U.S. Bureau of Mines contributed facts and figures on dust explosions. Dr. Raymond Friedman of the Atlantic Research Corporation treated certain fundamentals of dust flames as a problem of heterogeneous reaction kinetics. Emphasizing the difference from gas flames due to volatilization and radiative transfer, he proposed determinations of ignition limits, burning velocities as influenced by turbulence, explosion limits, and of mechanisms of dust flame inhibition as prerequisites of a successful attack on the elimination of dust explosion hazards. Basically along the same lines were proposals of experiments on dust explosions suggested by R. H. Essenhigh.

A contribution of practical value to the investigation of explosions under reproducible, though very specific, conditions was made by P. Laffitte and R. Delbourgo, University of Paris, France. A simple apparatus, consisting of a vertical, 2-m-long pyrex tube, 2.5 cm in diameter, into which weighted quantities of dust are dropped on the top, and (after dispersion) spark-ignited from the bottom, serves for a great variety of studies. On the basis of experience thus gained the authors recommend control of relative humidity in dusty atmospheres as a means of reducing the occurrence of hazards, particularly in the food processing industries. T. W. Moodie, Chairman, Sub-Committee on Electrical Dust Hazards, Instrument Society of America, discussed progress in the design of equipment for dust sampling. In his opinion, the principal lack is a continuously recording instrument in the proper range for the classification of hazardous materials and areas.

There emerges from this conference the need for solutions to the following problems:

1) Coordination in planning and execution of basic research, experimental as well as theoretical;
2) Collection of information on procedures, data, and conclusions, and their earliest dissemination to those concerned, possibly through a new periodical or a section of an existing one, exclusively devoted to pulverized fuel combustion and dust explosions;
3) Elaboration of safety codes and regulations; and
4) Education and training of industrial personnel.

Subject Headings: ***Dust, explosion; Explosion, dust.***

H. M. Cassel

* For summary, see Fire Research Abstracts and Reviews *5*, 55 (1963).

Annual Reports, 1962, *U.S. Forest Service Forest Experiment Stations.*

Lake States Forest Experiment Station, St. Paul, Minnesota

M. B. Dickerman, Director

Forest fire research has been revitalized in the Lake States in recent years to meet the increase in hazard and risk caused by bigger timber harvests, the huge expanse of vulnerable plantations, and a spectacular increase in recreational use.

Study of forest-fire fuels in plantations will show potential fire behavior and intensity in the undisturbed stand and will permit calculation of the logging slash that will result from any type of cutting. Twenty-year-old, well-stocked, red pine plantations may contain, on an average, 27½ tons of fuel per acre, exclusive of main tree stems (56 per cent green branches and foliage, 19 per cent dead branches, and 25 per cent litter and duff).

Use of soil sterilants promises to reduce the cost of maintaining firebreaks, a job heretofore accomplished by mechanical means. Because chemicals are somewhat selective as to vegetative cover type and soil type, research is being concentrated on jack pine sand plains, dense grass on sandy loams, and ferns and hardwoods on heavy soils.

Prescribed burning can be used effectively in certain forest types to reduce fire hazard and accomplish various timber- and game-habitat management objectives. Current research on prescribed burning aims mainly to find out (1) how various vegetation types respond to fires of different intensities, and (2) how to select conditions for burning that will give the desired fire intensities. So far it appears that (1) summer burns in jack pine cutovers, after 6 to 8 dry days, effectively prepare the site for seeding or planting; (2) summer burns after about 2 weeks of dry weather can eliminate much brush and expose mineral soil for regeneration; (3) hazard reduction can be accomplished by burning after 3 or 4 days without appreciable rain.

Pacific Southwest Forest and Range Experiment Station, Berkeley, California

K. Arnold, Director

Study of fire environment and behavior is now concentrating on identification, measurement, and prediction of the conditions under which burn the 3 to 5 per cent of California's fires that account for 95 per cent of the damage. Measurement of green-fuel moisture is being intensified. Analysis of 1962 and earlier studies is showing how invasion by marine air affects both atmospheric moisture and wind patterns in the coastal range. An important sideline to the meteorological studies is the development of new sensory instruments, recorders, and a data collection and processing system.

Screening and subsequent field tests of chemical fire retardants have shown solutions of diammonium phosphate (DAP), thickened with pectin or sodium carboxymethyl cellulose (CMC), to be highly effective. Certain mixing and coloring problems still require solution. Algin gel has shown promise for use by aerial tankers, especially helicopters.

A questionnaire sent to 2 per cent of California hunters revealed quite high knowl-

edge about forest fire prevention. Surprisingly, differences in level of knowledge were not related significantly to such social characteristics as age, occupation, or residence. Much of the hunters' fire prevention information was obtained from mass media; therefore, response of selected subjects to widely-used signs is being studied experimentally.

Research on techniques and economics is contributing to a major effort to reduce conflagration potential by breaking up extensive fuel bodies in ways that are compatible with multiple-use management of wildlands. Operations research has produced a preliminary mathematical model of fire growth for use in studying requirements for initial attack. Basic research on combustion is mainly concerned with the influence of chemical additives on the thermal degradation of certain carbohydrates and the effect of mineral content on combustibility of vegetation.

Intermountain Forest and Range Experiment Station, Ogden, Utah

J. F. Pechanec, Director

Over a 5-state area, during several years of observation, summer lightning storms were found to be high, relatively dry, mostly of short duration, and quite variable in number by year and location. About half produced 10 or fewer strikes to ground; only 5 per cent produced 100 or more. Number of discharges varied with maximum height, as indicated by radar. Extent of structural damage by lightning to individual trees increased with tree size.

To test possibilities for improving forest fire detection through use of electronics, a sferics direction-finding system is being developed to track lightning storms, and infrared sensors will be tried for locating fires. These sensors have demonstrated their utility for mapping fires through dense smoke, day or night.

Laboratory tests with ponderosa and western white pine needles showed that rate of fire spread had a linear relation to fuel moisture contents between 5 and 15 per cent. Rate of spread in field test fires depended somewhat on fuel loading but much more on wind. Temperature distribution in flames and convection columns resembled that measured in the laboratory. Convection column velocities sometimes exceeded 20 mph. Long plots ignited at one end appeared preferable to center-fired circular or square plots.

Western white pine and ponderosa pine needles were found to be almost identical chemically, but after exposure to weathering ponderosa needles had nearly twice the ether extractables and dried to a lower equilibrium moisture content. Sphagnum moss, with the least ether extractables, had the highest equilibrium moisture content.

Work is underway on modification of lightning storms, fire danger rating, and use of fire, but significant results are not reported for 1962.

Subject Headings: *Forest fire, research on.*

G. R. Fahnestock

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ABSTRACTORS

THOMAS C. ADAMSON, JR.
University of Michigan

GEORGE A. AGOSTON
Stanford Research Institute

JOHN J. AHERN
General Motors Corporation

THOMAS P. ANDERSON
Northwestern University

RAJAI H. ATALLA
Newark, Delaware

LOREN E. BOLLINGER
The Ohio State University

PETER BREISACHER
Aerospace Corporation

FREDERICK L. BROWNE
Madison, Wisconsin

GEORGE M. BYRAM
Southern Forest Fire Laboratory
U. S. Forest Service

HANS M. CASSEL
Silver Spring, Maryland

WELBY G. COURTNEY
Texaco Experiment, Incorporated

OWEN P. CRAMER
Pacific Northwest Forest and Range Experiment Station
U. S. Forest Service

GLADYS S. CUFF
Ethyl Corporation

DANIEL DEMBROW
National Aeronautics and Space Administration

J. H. DIETERICH
Lake States Forest Experiment Station
U. S. Forest Service

G. DIXON-LEWIS
The University, Leeds (England)

R. H. ESSENHIGH
The Pennsylvania State University

GEORGE R. FAHNESTOCK
Southern Forest Experiment Station
U. S. Forest Service

FELIX FALK
Applied Physics Laboratory
The Johns Hopkins University

K. M. FOREMAN
Republic Aviation Corporation

ALLEN E. FUHS
Aerospace Corporation

ARTHUR L. GOLDSTEIN
Ionics, Incorporated

ROBERT A. GORSKI
E. I. duPont de Nemours & Company

BERNARD GREIFER
Atlantic Research Corporation

L. R. GRIFFITH
California Research Corporation

GEOFFREY L. ISLES
The University, Leeds (England)

OLIVER W. JOHNSON
Johnson-Williams, Inc.

WILLIAM C. JOHNSTON
Westinghouse Research Laboratories

IRVING R. KING
Texaco Experiment, Incorporated

WILLIS G. LABES
Illinois Institute of Technology

JOSEPH B. LEVY
Atlantic Research Corporation

RONALD LONG
University of Birmingham (England)

A. S. C. MA
Imperial College (England)

JAMES E. MALCOLM
Office of Chief Engineers
U. S. Army

D. G. MARTIN
Imperial College (England)

HOWARD N. McMANUS, JR.
Cornell University

ALAN W. McMASTERS
Pacific Southwest Forest and Range Experiment Station
U. S. Forest Service

C. C. MIESSE
Westinghouse Electric Corporation

WILLIAM G. MORRIS
Pacific Northwest Forest and Range Experiment Station
U. S. Forest Service

A. E. NOREEN
Boeing Airplane Company

CLEVELAND O'NEAL, JR.
National Aeronautics and Space Administration

HENRY EDGAR PERLEE
U. S. Bureau of Mines

M. G. PERRY
University of Sheffield (England)

WEE YUEY PONG
Pacific Southwest Forest and Range Experiment Station
U. S. Forest Service

LOUIS A. POVINELLI
National Aeronautics and Space Administration

J. KENNETH RICHMOND
Boeing Airplane Company

DANIEL E. ROSNER
AeroChem Research Laboratories, Inc.

WILLIS A. ROSSER, JR.
Stanford Research Institute

P. R. RYASON
California Research Corporation

R. H. SABERSKY
California Institute of Technology

R. G. SIDDALL
University of Sheffield (England)

JOSEPH M. SINGER
U. S. Bureau of Mines

PHILIP L. START
University of Sheffield (England)

ALEXANDER STRASSER
U. S. Bureau of Mines

K. SUMI
National Research Council (Canada)

CLAUDE P. TALLEY
Texaco Experiment, Incorporated

DONALD L. TURCOTTE
Cornell University

FORMAN A. WILLIAMS
Institute of Defense Analysis

HENRY WISE
Stanford Research Institute

E. C. WOODWARD
University of South Carolina

F. H. WRIGHT
California Institute of Technology

RICHARD W. ZIEMER
Electro-Optical Systems, Inc.

E. E. ZUKOSKI
California Institute of Technology

THE FIRE RESEARCH CONFERENCE

H. C. Hottel, *Chairman*	Director, Fuels Research Laboratory Massachusetts Institute of Technology
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Joseph Grumer	Project Coordinator, Flame Dynamics Explosives Research Laboratory U.S. Bureau of Mines

Volume 6 Number 2

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Committee on Fire Research
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FOREWORD

Two papers in this issue deal with ignition of materials by radiation. The review by Martin effectively summarizes results which have been accumulating for over ten years. The paper by Passel and Miller predicts radiation intensities from high-altitude nuclear explosions.

They are outgrowths of the intense interest in nuclear-weapons effects and are representative of a sophisticated effort to understand a particular facet of the fire problem. They show what can be achieved once a specific problem has been identified and when capable people and adequate resources are made available to explore it for an extended period. The result is an understanding of radiation fluxes from nuclear explosions of various sizes and locations in space and a wealth of design data on ignition characteristics of materials that make it possible to predict what initial fire effects may have to be dealt with in case of nuclear war.

Such a vigorous effort is still relatively rare in other areas of fire research. The close and continuing interaction between fire technology and advanced methods of research—as suggested by the NAS–NRC Committee on Fire Research in the "Proposed Fire Research Program" [FRAR 1, 1 (1959)]—is still largely unfulfilled.

The recently published Directory of Fire Research in the United States (NAS–NRC Publication 1189) reflects this situation. In 1963, a questionnaire was sent to government agencies, private and industrial laboratories, and universities requesting a summary of work-in-progress that was considered "fire research." The response was impressive, with 77 laboratories identifying 320 projects. A closer inspection of the replies shows, however, that less than 10 per cent of the projects deal with fundamental questions of specific relevance to fires which have led to published results. Of this number only a fraction is supported by funds specifically identified for fire research.

This shows that the interest in universities, from which, traditionally, one expects the largest contribution to research and scholarship, is still small. This has, in turn, an effect on the number of people who are being trained for a career in fire research. There are no easy solutions to this dilemma. The situation is better than it was five years ago. However, a broadly-based and meaningful research attack is yet to be mounted and problems of continuing funding, of communications, of education, etc., remain to be resolved.

W. G. BERL
Editor

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ERRATA

Volume 6 Number 1

1. Dr. R. Delbourgo has requested that the following correction be made with regards to the summary of the Dust Explosion Conference held at State College, Pennsylvania State University [Fire Research Abstracts and Reviews *6*, 82 (1964)]:

> "The summary is misleading as regards the paper I gave with Professor Laffitte. I had, at that time, explained that we had no personal experience of Dust Explosions, but that we had developed a reliable method for the introduction of a given sample of dust into a flame or into a gaseous mixture. I merely said that this method—in my opinion—*could* usefully be extended to the study of explosive dusts."

2. The caption to Figure 4 of the review on "Current Fire Research Problems" [Fire Research Abstracts and Reviews *6*, 10 (1964)] should read:

> FIG. 4. Vortex column in the lee of a fire plume generated by 100 burners regularly spaced over an area 125 × 125 meters, burning 1 ton of fuel per minute. The smoke tube is about 10 m in diameter, 200 m long, and about 525 m from the fire. Horizontal wind speed 100 m/min (Ref. 24). (Photo reproduced from *Nature* with permission of the publisher.)

REVIEWS

Ignition of Organic Materials by Radiation

S. MARTIN

U. S. Naval Radiological Defense Laboratory, San Francisco, California

Early History of Ignition Studies

Although the subject of ignition of organic solids by thermal radiation has always had a degree of pertinence to the mechanics of fire propagation, it only began to receive the close scrutiny of the scientific community following the first wartime use of nuclear energy. Along with radioactivity, the nuclear weapon exhibited a novel characteristic—the release of awesome amounts of visible and infrared radiation having the capability of burning the skin and setting fires in combustible materials. The lessons learned earlier in the war about the fearful destructiveness of massed conventional incendiary attack on population centers took on an enhanced level of significance. There were arguments as to the importance of fires caused directly by the thermal radiation relative to secondary fires caused by blast, and a measure of the controversy survives to this day. But few knowledgeable people will deny that the thermal radiation from the fireball of a nuclear-weapon burst has great incendiary potential and that the hazard has become proportionately greater compared to blast effects with increased weapon yields and with the development of the thermonuclear bomb.

In the years immediately following the war, the major effort in this field was given to measuring the characteristics of the thermal radiation emitted by nuclear devices as they were tested in the Nevada and Pacific proving grounds. As a result of this program an extensive technology developed which provided the empirical relationships and "scaling laws" necessary to the development of appropriate laboratory simulation. But before much of this information was available (and concurrently with the field measurements which generated it), thermal radiation sources were already being developed for laboratory work. The primary impetus derived from the need for facilities for calibrating the instruments to be used in the field measurements. Because of its high radiant output and desirable spectral distribution, the high-current (cored) carbon arc was the almost unanimous first choice. Many of these sources (and much of what was learned about them) found use directly in the more sophisticated simulation facilities later.

Fundamentally, simulation facilities are nothing more than intense sources of thermal radiation (usually approximating a 5000°–6000°K black body) with optical systems which provide small (usually less than 1 in. diameter) spots of uniform irradiance, and with a means of controlling the over-all level of irradiance and of varying the irradiance as a function of time to provide a pulse having a temporal pattern like the one emitted by the weapon.

The early work on the effects of intense thermal radiation on materials was largely given to observing the kinds of responses and the corresponding radiant exposure levels (in cal cm^{-2}) for an almost endless list of household items, building materials, military goods, forest vegatation, etc. Most of this random exploratory

testing was conducted using a fixed duration of exposure. It soon became evident that the only effect of genuine concern was the ignition of thin, cellulosic kindling fuels, i.e., materials igniting at less than that about 20 cal cm^{-2}. It was also discovered that the radiant exposure required to ignite a material is a function of exposure duration, i.e., the efficiency depends upon the rate of delivery of energy. Literally hundreds of kindling fuels were tested at one or more levels (usually unspecified) of moisture content and at one or more exposure durations (typically 1 and 3 sec). From these results there was a general trend in evidence of increasing radiant exposure for ignition with moisture content, thickness, and duration, but there were many notable exceptions. Among these, the most perplexing were the cases of longer exposures requiring less radiant exposure to ignite. The task of experimentally determining the ignition radiant exposures of all kindling fuels for a variety of conditions and a wide range of weapon yields appeared as a formidable, if not impossible, undertaking. Experience and intuition suggested that, with minimal experimental work on a model kindling fuel and the use of similitude theory, a generally useful technology of the ignition of kindling fuels might be generated; one which could successfully predict the response of untested materials to untried situations.

Theoretical and Physical Models

The ignition of most organic solids actually occurs in the gas phase where the volatile pyrolysis products, generated by the local application of heat to the surface of the solid, mix with air under conditions amenable to the development of an accelerating rate of reaction between the fuel constituents and the oxygen of the air. Accordingly, a complete description of the process would include heat transfer, fluid mechanics, and chemical kinetics. In detail, such factors as the deposition of heat in the solid and how the decomposition of the material is influenced by the transient temperature distribution, the diffusion of the volatile pyrolysis products, the mixing of the issuing volatiles with the surrounding air, the kinetics and thermochemistry of the oxidation reactions, and the combined heat losses of the system during the course of the ignition process, would have to be considered. Very often, however, in complex situations like this much can be learned using an analytical model which does not attempt to consolidate all of the factors involved. The heat transfer, fluid mechanics, and chemical kinetics parts of the process can frequently be decoupled and individually scrutinized to discover which (if any) exerts the greatest control on the system under experimental study. A model based on the controlling mechanism (if one exists) will often correlate experimental data and reveal in the nonideality of the incomplete model, the importance of missing factors. In principle this procedure could be applied to ignition of organic solids by thermal radiation; in practice, a somewhat less direct route was travelled.

In 1956, Sauer (at that time with the California Forest and Range Experiment Station, U.S. Forest Service) attempted to correlate all of the existing data on the behavior of wood undergoing charring and weight loss.[1] Prior to this, several investigators[2,3] proposed correlations using dimensionless groupings from heat conduction theory and based on specification of a "charring temperature". Sauer argued that such an approach is quite artificial, that thermal decomposition is a time-dependent as well as a temperature-dependent phenomenon. On the assumptions that, first, temperature profiles in wood during heating with a constant flux are as predicted by

the solution of the heat-conduction equation with suitable boundary conditions (but ignoring losses and internal sources and sinks) and, second, that the thermal degradation of wood is kinetically first order, he set up a differential equation for the charring process the (symbolic) integration of which yields dimensionless groups which do not explicitly contain a "charring temperature." Of these groups, the two containing the heat-transfer parameters were found to adequately correlate all existing data on char depth and weight loss, i.e., the charring process is controlled primarily by the diffusion of heat over the range of conditions considered.

The usual starting point in a theoretical evaluation of the thermal decomposition of an organic solid is the postulate of an nth order (usually first order) reaction rate with Arrhenius temperature dependence. Several investigators[1,4,5] have demonstrated that over a limited temperature range, at least, cellulose losses weight w in a kinetically first-order manner, viz.,

$$-dw/dt = \bar{\mu}(w - w_f) \exp(-\bar{E}/RT),$$

where t is the time, T the temperature (absolute), $\bar{\mu}$ and $\bar{E}$ the kinetic constants for the over-all weight-loss process, R the universal gas constant, and the subscript f refers to the final state after an indefinitely long period of heating. Bamford, *et al.*[4] employed such a concept in their well-known mathematical treatment of the ignition process.

On the assumption of dimensional stability, the extensive property, weight, may be transformed into the intensive property, density. This change permits the writing of a more generally useful expression for the change in density ρ at any fixed position x

$$(\partial\rho/\partial t)_x = -\bar{\mu}[\rho(x, t) - \rho_f] \exp[-\bar{E}/RT(x, t)],$$

where both density and temperature are continuous functions of position and time.

The temporal variation of the temperature profile during irradiation with a constant flux is approximated by the solution of the heat-conduction equation for the opaque, semi-infinite solid with the boundary conditions

$$T = T_0 \qquad \text{at } t = 0 \quad \text{and} \quad 0 < x < \infty,$$

and

$$-k(\partial T/\partial x) = aH \qquad \text{at } t > 0 \quad \text{and} \quad x = 0,$$

where k is the thermal conductivity, a the absorptance, and H the incident flux.

The solution is a function of only two dimensionless parameters (as, for example, $\Delta T(k\rho c)^{\frac{1}{2}}/aH(t)^{\frac{1}{2}}$ and $x/(\alpha t)^{\frac{1}{2}}$, wherein c is specific heat and α is thermal diffusivity). In reality, the nonsteady-state temperature distribution in a cellulosic fuel is not accurately represented by the theoretical expression because the boundary conditions are not perfectly satisfied and the profile is perturbed by heats of reaction and phase change. Nevertheless, Gardon,[6] Williams,[2] and, later, Martin and Ramstad[7] demonstrated that under conditions of irradiation appropriate to the study of ignition, the actual temperature profiles can be expressed as functions of the same dimensionless parameters derived from the solution of the heat conduction equation.

α-Cellulose as a Model Kindling Fuel

Encouraged by the successful correlation of char-depth and weight-loss data using dimensionless parameters representative of heat diffusion only, Sauer proposed

a cooperative research program on ignition of cellulosic materials between the California Forest and Range Experiment Station and the U.S. Naval Radiological Defense Laboratory. He suggested using a specially prepared α-cellulose as a model of the broad class of kindling fuels. He proposed that the data from such a material, having constant chemical properties but with considerable latitude for variation in physical properties, might be correlated using dimensionless groups of variables derived from heat-conduction theory. The resulting correlation, then, by relating ignition thresholds to exposure parameters and fuel properties, would serve to fill in the gaps in the weapons effects picture, but, more importantly, it hopefully would reveal the basic causalities of ignition phenomena.

The idealized kindling fuel was prepared by the Forest Products Laboratory, USDA, in Madison, Wisconsin. These "papers" were produced from a single batch of pure alpha wood pulp. They were made up with varying amounts of carbon black added to provide gradations in optical properties from white to black, and in a range of thickness from 0.002" to 0.03". They were provided in two densities (originally 0.55 and 0.73 g cm^{-3}) which caused them to possess two different sets of heat-conduction properties.

The initial research program[8] was limited in scope to a study of ignition of the black α-cellulose when irradiated with square-wave (constant irradiance) exposures of 2–25 cal cm^{-2} sec^{-1} irradiance levels. The use of the black paper only for the initial work was to avoid any absorptivity or diathermancy effects. The geometry of exposure was carefully designed and the use of square-wave pulses was chosen to satisfy as nearly as possible the conditions imposed on the theoretical model, i.e., unidirectional heat flow and constant heat flux across the exposed surface. Intuitively, it was expected that subsequent weapon–pulse correlations would be similar in character to the square-wave correlations and experimentally square-wave exposures are much more convenient to deal with. No effort was made to control the moisture content, but it was measured and found to remain relatively constant in the 4–5 per cent range.

Reasoning from the char-depth work[1] whose data were well correlated over a wide range of irradiance levels and exposure duration by the relationship

$$\mathcal{Q}R/\rho c d E = f(\alpha t)^{\frac{1}{2}}/d,\ E/RT_0);$$

where $\mathcal{Q}$ is the radiant exposure, and noting that char penetration d to the total thickness L of the sample appeared to be a necessary condition for sustained ignition, Sauer expected that ignition data would correlate through the use of the functional relationship

$$\mathcal{Q}R/\rho c L E = f'((\alpha t)^{\frac{1}{2}}/L,\ E/RT_0).$$

This turned out to be so over much of the range of values of the Fourier modulus $(\alpha t)^{\frac{1}{2}}/L$. Thus it appears that much of ignition phenomenology is governed by diffusion of heat.

One of the significant findings of this early work was the existence of several distinct kinds of ignition and of their relationship to one another in terms of irradiance level and duration of exposure. Transient-flaming ignition, a familiar phenomenon in thick fuels, was observed for even very thin kindling fuels at small values of the Fourier modulus and was found to be separated from persistent-flaming ignition by a clearly defined threshold. Glowing ignition (always persistent) was recognized as a separate phenomenon which, over part of the range of values

of the Fourier modulus, occurred at lower radiant exposures than flaming ignition, but the data were inadequate to permit delineation of the difference.

The concept of a critical irradiance, the irradiance level below which ignition would not occur regardless of the length of exposure, was advanced to explain the behavior (particularly the lack of correlation with thickness) at large values of the Fourier modulus, but again insufficient data prevented detailed evaluation. Sauer believed that both transient and persistent ignition were limited by the same critical irradiance threshold. He also concluded that the threshold radiant exposure for persistent ignition increased in proportion to the one-quarter power of the exposure duration starting at a Fourier modulus of 0.8 and ending abruptly at the critical irradiance. In this he was supported by the findings of Bates and Monahan.[9] This conclusion spawned the popular notion, still devotedly held by some, that the energy threshold for ignition scales as the one-eighth power of weapon yield (for sea-level bursts). Neither the conclusions about the threshold of transient ignition nor the simple quarter-power relation of energy to time survived subsequent scrutiny of more extensive data.

Details of Ignition Behavior

Following Sauer's lead, Butler, Martin and Lai[10] proceeded to acquire the very large amount of ignition data necessary to clarify the ignition behavior picture in detail. They chose, however, to reject the use of E/R or other kinetic or thermochemical group in the energy modulus, arguing that this is nearly as artificial as the use of an "ignition temperature". Its only potential advantage, they claimed, aside from the largely asthetic value of the dimensionlessness it imparts to the parameter group, might be to provide for the correlation of noncellulosic materials if the appropriate kinetic or thermochemical quantity could be discovered. Values of $\bar{E}$, the "over-all weight-loss activation energy" exhibit about as large a variation among the various cellulosic materials as they do between cellulosic and noncellulosic materials such as silk. Considering the complexity of ignition behavior it seems

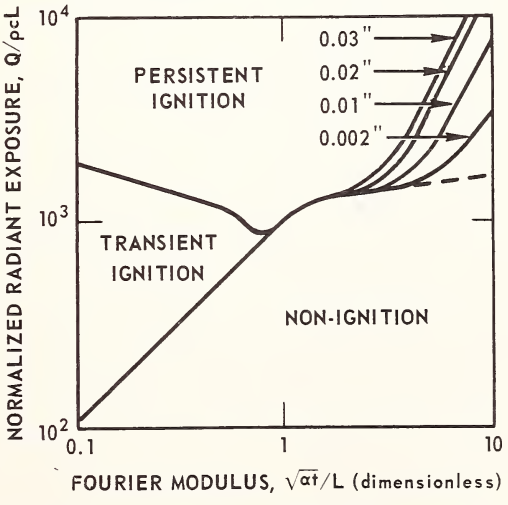

FIG. 1. Generalized ignition behavior of cellulose.

rather unlikely that any one such parameter could successfully correlate ignition data for very dissimilar materials.

The final ignition behavior pattern for square-wave exposure of black α-cellulose is shown in Fig. 1. It will be noted that at small values of the Fourier modulus (short times or thick materials) transient ignition occurs at the smaller values of radiant exposure and is followed at higher radiant exposures by persistent ignition. The threshold of spontaneous flaming ignition in this region is found to be independent of sample thickness. The threshold line is given by the expression

$$H(t^{\frac{1}{2}})/(k\rho c)^{\frac{1}{2}} = \text{a constant},$$

which suggests that the criterion for ignition is the attainment of a constant high temperature at the exposed surface (estimated to be at least 600°C). Recent radiometric measurements by Alvares[11] indicate that the temperature of the exposed surface at the instant of ignition lies between 600° and 650°C, independent of the irradiance level and independent of sample thickness so long as it is sufficiently great that no appreciable rise in back-surface temperature occurs prior to ignition.

At larger values of the abscissa, flames persist after exposures which terminate at the earliest appearance of flame. At still larger Fourier moduli, flaming ignitions are frequently preceded by or entirely replaced by glowing ignitions. At this point there occurs a transition from ignitions controlled primarily by diffusion of heat into the solid to ignitions governed by fluid mechanics, i.e., convective heat losses and/or convective mixing of fuel and air become increasingly important in the process. For this reason the correlation technique based only on heat conduction fails to correlate the data and there occurs a separation into a family of curves for different thicknesses. These curves approach a asymptotic value of 0.5 cal cm^{-2} sec^{-1} which is the critical irradiance as defined earlier. This may well represent the combined heat losses from both surfaces of a cellulosic sheet at a temperature which, for very slow heating, corresponds to ignition. Accordingly, this temperature would be about 300°C (for an 0.75-inch-diameter circular sample with surfaces vertical and having an emissivity of 0.9) which is in good agreement with measurements of ignition temperatures for furnace heating and the like.[12,13] This regime of ignition behavior has received the attention of several investigators among whom, the most notable perhaps, is Simms[14] in England.

It is of some interest to attempt to interpret the ignition-behavior curves in terms of temperature profiles attained during exposure. First, let us consider very short exposure durations, i.e., $0<t<0.1L^2/\alpha$ (this corresponds to exposures of about 10 msec or less for materials as thin as newsprint). If the material is reasonably opaque, the energy is deposited in a very thin layer of material at the surface causing very high temperatures. The result is violent ablation, and ignition occurs almost instantly, but it persists only after the solid has suffered extensive ablation. At the other extreme, for long, low irradiance exposures, i.e., $t>4L^2/\alpha$, the material is (dimensionlessly) too thin to maintain a gradient. The result is a uniform, low temperature which is slowly attained. The material is smoothly converted to char and often glows instead of flaming because it runs out of gaseous fuel (which is relatively poorly combustible anyway because of its high CO_2 and H_2O concentration) before temperatures rise high enough to induce ignition. As indicated earlier, ignition at long times depends upon heat losses and certain, as yet ill-defined, geometric factors.

For intermediate durations of exposure the nature of the response is governed by

thermal diffusion. Persistence of flames (or glowing combustion) at the conclusion of exposure depends upon the thickness and volumetric heat capacity of the material. It is convenient to divide this region into two sub-regions. In the first ($0.1 < \alpha t/L^2 < 0.6$) energy is distributed throughout the sample by conduction causing the unexposed surface to exhibit a small but finite temperature rise, but the exposed surface reaches the ignition temperature, say 600°C, before the average over-all temperature is high enough (in excess of 300°C at least) to sustain the flow of volatile fuel. Clearly if the temperature profile existing at the end of the exposure relaxes to a value of only 150°C, for example, the flow of volatiles, for all practical purposes, will cease and flaming will abruptly end. Therefore, transient flaming is the threshold effect and only after a somewhat greater radiant exposure will ignition be sustained. In the second case ($0.6 < \alpha t/L^2 < 4$) the average or "relaxed" temperature of the material exceeds a value sufficient to maintain the flow of volatiles by the time the exposed surface reaches the ignition temperature and flames always persist. The major characteristics of ignition behavior can be explained, at least qualitatively, on the basis of the foregoing discussion.

Subsequent square-wave work on α-cellulose containing varying amounts of carbon black in atmospheres of controlled relative humidity clarified the influence of optical properties and moisture content on the ignition behavior.[15] It was found that for most kindling fuels (absorptivities of about 0.5 and higher) the ignition behavior is described by the correlation pattern of Fig. 1 after allowance is made for the heat capacity of the moisture contained and by multiplying the radiant exposure values by the radiant absorptance of the material corresponding to a spectral distribution for the appropriate source temperature. Therefore, to estimate ignition radiant exposure for a variety of cellulosic kindling fuels under a wide range of conditions, corrections can be readily applied to values computed for dry, black α-cellulose using the expression

$$\mathcal{Q}_{a,m} = 1/a(1+3.2m)\mathcal{Q}_{1,0},$$

where $\mathcal{Q}_{a,m}$ is the radiant exposure required to ignite a cellulosic material having a radiant absorptance a (lying between about 0.4 or 0.5 and 1.0), and a moisture content m (expressed as a fraction of the dry weight of the material), and $\mathcal{Q}_{1,0}$ is the radiant exposure required to ignite cellulose having unit absorptance and zero moisture content. For more detailed information the original references[15] [16] should be consulted.

Ignition by Nuclear Weapon Pulses

With the square-wave pulse correlation well in hand, attention was next directed toward achieving a similar correlation which could be applied directly to weapons-effects problems. The experimental work[17] was basically a repetition (though less extensive in scope) of the earlier measurements but a pulse designed to simulate the effective portion of the thermal pulse of low-altitude nuclear-weapon air bursts (see Effects of Nuclear Weapons, U.S. Government Printing Office, 1962 edition, p. 359) was used instead of the square-wave. The correlation necessarily had to be modified in one important respect. Since the duration of nuclear-weapon pulses cannot be rigorously defined, it was necessary to use the time to peak irradiance in the Fourier modulus. By the same token the total radiant exposure is somewhat indefinite. Experimentally, with the laboratory-simulated pulse, the peak radiant

power H_p, the time to peak power t_p and the radiant exposure $\mathcal{Q}$ can be measured and are found to be related by

$$\mathcal{Q}=\int_0^{10t_p} H(t)\ dt=2.07H_pt_p.$$

However, the laboratory pulse does not include the long, low tail of the weapon pulse which includes some 20 per cent of the energy. From field measurements we estimate the *total* radiant exposure to be

$$\mathcal{Q}_T=\int_0^{\infty} H(t)\ dt=(2.6\pm0.5)H_pt_p.$$

Consequently, this difference should be considered whenever attempting to apply laboratory data to weapons-effects problems. Because of the still unsettled state of scaling relationships, the only really reliable and generally useful weapon–pulse ignition data are those which are reported in terms of both H_p and t_p.

As anticipated the ignition behavior for weapon pulses was found to be remarkably similar to that for square-wave exposure. Contrary to the case for charring of wood, however, no simple square wave–weapon pulse equivalence was to be found Quantitatively similar responses are observed when the weapon–pulse peak irradiance is roughly 3 times the irradiance level of the square wave,

$$H_p/H=2.7\pm0.2,$$

but the weapon pulse is significantly more efficient (20–40 per cent less radiant exposure required) than the square wave for short exposure and significantly less so for long exposures.

From the resulting correlation it is possible to predict the radiant exposures required to ignite a variety of kindling fuels under a wide range of conditions and over a wide range of weapon yields and burst heights, knowing only the properties of the fuel and the appropriate weapon yield–t_p scaling. The job of measuring the necessary physical properties of every material of interest is not as formidable as it might at first seem since the more difficult to measure properties such as diffusivity, heat capacity, and moisture content, exhibit a regular dependence upon such readily determined properties as thickness, weight per unit area, and the relative humidity of the environment. Again details are to be found in the original references.[16,17] The estimates made in this manner are strictly applicable only to low altitude detonations (sea-level air bursts). The use of a scaling equation such as

$$t_p=(W\rho/\rho_0)^{\frac{1}{3}},$$

where W is in megatons, ρ is air density at burst altitude, and ρ_0 is air density at sea level, can be used to extend ignition estimates to burst heights up to about 20 miles, but the higher-altitude estimates are not as reliable because of uncertainties in the air density–t_p scaling and because the thermal pulse is not accurately duplicated by the laboratory pulse on which the estimates are based.

The Practical Ignition Problem

In the practical problem of evaluating the incendiary threat of nuclear-weapon attack, numerous complicating factors must be considered in applying the results of

laboratory ignition work. In addition to such factors as attenuation of the atmosphere and the field of view, distribution, and location relative to other combustibles of the kindling fuels in a target area, none of which will be treated here, there are other complicating factors involving area and uniformity of exposure and the geometrical complexity of real kindling fuels.

Laboratory exposures are necessarily idealized. Because of the limited area and depth of field of the uniform spot of most simulation facilities, laboratory studies are necessarily limited to flat samples of small exposure area (usually apertured) which are usually exposed with surfaces in a vertical plane normal to the optical axis of the source. This type of exposure ignores any possible influences of sample attitude, geometry and area, and of nonuniformity of exposure.

Hottel[18] has pointed out that in the regime where diffusion-controlled ignition gives way to ignition governed primarily by convective heat loss, i.e., for long exposures, the radiant exposures required to ignite materials like newsprint should depend upon the area of the heated specimen. Measurements in a muffle furnace indicated to him that the temperature required for ignition rises as the heated area is decreased, suggesting a diluting effect in addition to increased convective heat loss for small specimens. Moreover, at a given temperature, small specimens were observed to glow while larger specimens flamed. Taken together, these results indicate that the previous carbon-arc exposure results for long-duration exposures tend to overestimate the radiant exposures for ignition and to predict glowing ignitions where flaming ignitions would in fact occur.

Our experience definitely supports the latter contention, but it is not clear yet whether this is the result of increased area or of nonuniform irradiation. Simply removing the aperture from a given type of specimen frequently causes flaming ignition to occur for an exposure which otherwise would have resulted in glowing. Bending part of the sample back away from the spot or casting the penumbra of an opaque object on part of the exposure area causes the same result.

Recent studies at both Naval Applied Science Laboratory and NRDL using large area sources (banks of incandescent–tungsten, tubular-quartz-envelope lamps) show the same significant lowering of flaming thresholds (frequently down to the previous glowing thresholds), but the lowest ignition radiant exposures fail to drop significantly below previously reported values, i.e., critical irradiances for black α-cellulose remain at about 0.5 cal cm^{-2} sec^{-1}, newspaper about 1 cal cm^{-2} sec^{-1}.

On the other hand, geometrically complex specimens, crumpled, wrinkled, folded, multiple sheets, etc., have significantly lower ignition thresholds at long times of exposure than their plane-sheet counterparts. A loosely folded newspaper, for example, appears to have a critical irradiance level of about 0.5 cal cm^{-2} sec^{-1} compared to 1 cal cm^{-2} sec^{-1} for a single sheet. This small difference in asymptotic value can have a major effect on estimates of ignition radiant exposures at long pulse durations. Figure 2 illustrates the current estimates of ignition thresholds for newspaper as a function of weapon yield (modified by air density). The bottom of the band estimates the values for dark-printed single sheets or for loosely folded or crumpled sheets with ordinary text printing, whichever is lower, while the top of the band estimates thresholds for ordinary-printed single sheets. Moisture contents are those for relative humidities in the 40–50 per cent range.

There is one other complicating factor which should be mentioned before leaving the subject of the practical ignition problem, partly because it is "the fly in the ointment" when it comes to using purified-cellulose ignition data to predict the

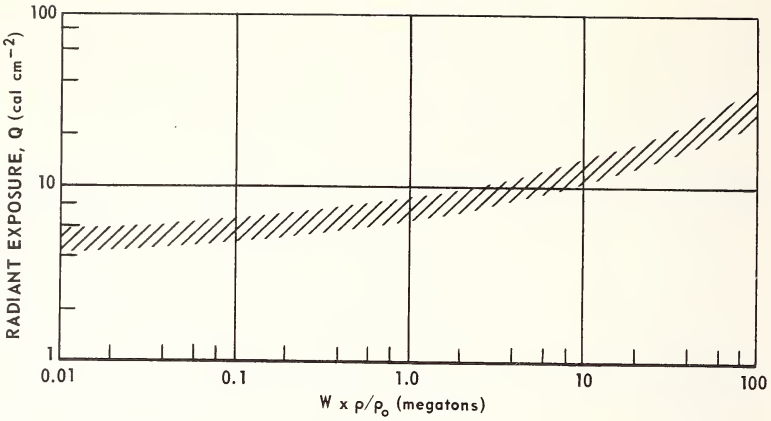

Fig. 2. Ignition of newspaper.

behavior of impure, natural cellulosic substances, and partly because it gives some (as yet far from fulfilled) promise of a practical countermeasure to incendiary attack. Trace amounts of certain inorganic substances have a profound influence on both the ignition behavior and the thermal decomposition of cellulose.[19] Such substances appear to catalyze reactions whose final products are mainly char, water, and the oxides of carbon. This, in turn, promotes the glowing combustion of a radiantly exposed fuel, often to the exclusion of flaming ignition. The process is not, as yet, well understood, but it is receiving a good deal of attention by Broido and coworkers at the Pacific Southwest Forest and Range Experiment Station in Berkeley.[20]

Ignition by Very Brief Pulses

The current interest in the incendiary capability of very-high-altitude detonations has sparked a flurry of theoretical and experimental work directed toward the assessment of ignition behavior for very short pulses of very high radiant power. The previous lack of experimental data for these short exposures is due, in large measure, to the radiant-power limitations of simulation facilities. Megaton-yield weapons detonated at altitudes between about 20 and 50 miles are expected to radiate the effective portion of their thermal energy in times of the order of tens to hundreds of milliseconds. Anticipating radiant-exposure values for the sustained ignition of typical kindling fuels to be on the order of 10 cal cm^{-2}, we, therefore, expect to need irradiance levels on the order of 10^2–10^3 cal cm^{-2} sec^{-1} to properly simulate high-altitude bursts of high-yield weapons. Carbon-arc sources, at best, provide irradiances extending only into the lower part of this range. Xenon flashtubes have the capability of very high radiant power levels, but their pulse durations are generally less than 1 msec with a consequently inadequate radiant exposure level.

Certain theoretical analyses indicated that the persistent ignition thresholds would exhibit a very strong time dependence for exposures of high radiant power, that they would rise precipitously to very high radiant exposure levels as pulse durations are made increasingly shorter. For example, Siddons[21] used as a computational model a kinetically simple, first-order, chemically reacting system whose temperature history is given by the solution of the heat-conduction equation for

the inert, opaque slab irradiated on one face and being cooled convectively and radiatively at both faces. The threshold of persistent ignition was taken as that point where the volatile content of the material falls to some arbitrary, low level. Despite the relative elegance of this model, no account was taken of surface ablation and unreasonably high surface temperatures were calculated, leading to overestimates of radiation cooling.

On the experimental side, xenon flashtube measurements made at NASL[22] showed no evidence of a sharp upturn in the ignition threshold for pulses intended to simulate a 1 ton low-altitude nuclear burst or a 4 megaton detonation at 250,000 feet. The flashtube pulse, which peaked at about 1 msec with an intensity of at least 1500 cal cm^{-2} sec^{-1} and was virtually out by 10 msec, ignited closely printed classified pages of newsprint with a radiant exposure of 4.6 cal cm^{-2}. (Compare with values of Fig. 2.)

Meanwhile, Martin at NRDL[23] extended the square-wave correlation for cellulose to smaller values of the Fourier modulus (included in Fig. 1) using a more intense carbon-arc source than was previously used, which provides useful exposures down to 20 or 30 msec duration. Ignition radiant exposures were found to retain their proportionality to the ρcL product increasing less than a factor of two over an order of magnitude reduction in exposure duration.

Hochstim and McLain at the Institute for Defense Analyses[24] obtained short-pulse ignition data from an ingenious Fresnel lens system which utilizes solar radiation. Their data generally support the NRDL results.

Mechanisms of Ignition and Thermal Decomposition of Cellulose

The point has been made that the radiant ignition of cellulose, as well as many other organic solids, is controlled (at least superficially) over a wide range of conditions by diffusion of heat into the solid. Numerous ignition criteria and ignition theories have been advanced in an attempt to provide a more fundamental, mechanistic picture of the process. Objective evaluation of such proposals has been hindered by a lack of information on evolution rates and chemical composition of pyrolysis products. Some significant gains have been made recently and will be reported here briefly.

There is a growing body of evidence which indicates that, rather than a single first-order pyrolysis reaction, there are several consecutive and competitive routes by which cellulose can decompose, each (with very different products) having its own temperature regime and some being catalyzed by certain inorganic agents. A complete discussion of the relevant evidence is beyond the scope of this paper, but briefly it includes information on the differences in differential-thermal-analysis and thermogravimetric-analysis patterns and the amounts of tar and char resulting from different heating histories and added inorganic materials in trace amounts.[20]

In this connection, it has been recognized for some time that when cellulose is heated slowly (or when it has a significant mineral content) a large fraction of the original weight remains as carbonaceous residue (char) after the evolution of highly oxygenated products such as H_2O and CO_2 while rapid heating (particularly of ash-free cellulose) leaves little or no char and the volatile products are, on the average, correspondingly richer in carbon.

Many investigators agree that there are at least two basic modes of cellulose decomposition at temperatures above about 250°C. The first of these amounts to a

depolymerization to levoglucosan (1,6-anhydro-β-D-glucopyranose). Under ideal conditions, more than 75 per cent of the original cellulose may appear in the tar fraction of which about 80 per cent is levoglucosan.[25] Madorsky, *et al.*[26] suggest that this is the result of random scission of the 1,4-glycosidic linkages, but recent Russian work[27] gives evidence of an unzipping mechanism following an initial random decomposition (with poor levoglucosan yield) to 200 D.P. (average) residues. These last results indicate a possible morphological influence on mechanism.

The second basic mode of cellulose degradation is often described as "char formation" and is clearly a result of more drastic changes in molecular structure such as ring scission or extensive elimination of the residual hydroxyl groups of the intact glucosan units of the cellulose molecule.* In all probability, there are numerous elementary reactions contributing to the process called "the char-forming reaction." They do, however, have products with certain characteristics in common. These two basic modes of decomposition from a rational basis for postulating that there is a set of competitive reactions which gives rise to an apparent change in mechanism with increased heating rate. At whichever stage the competition occurs, in the mechanism of the primary decomposition of the intact cellulose molecule or in the secondary stage of "boil off" versus destruction of a product such as levoglucosan, the result is the same—the distribution of products is a function of the manner in which the cellulose is heated.

Measurements of the volatile pyrolysis products of cellulose exposed to intense radiant energy (in an inert atmosphere) show a maximum in the rate of evolution at a time close to the instant of ignition (in air).[28] Levoglucosan, the main volatile-fuel component, increases in yield from about 25 per cent of the theoretical upper limit early in the exposure to about 75 per cent at the ignition time (the actual values depending to some extent upon irradiance). However, no evidence was found of an ignition criterion based on a threshold rate (or amount) of volatile-fuel evolution.

Calculations of the rate of surface decomposition, based on assumed first-order kinetics, indicate that, over a wide range of irradiance levels, the surface is well-charred prior to ignition.[28] On this basis it seems likely that the role of the exposed surface in spontaneous ignition is as a site for secondary reactions. Hydrogen, methane, ethylene, and ethane first appear and increase rapidly in amount at about the time when spontaneous-flaming ignition would occur in air. They are almost certainly products of secondary reactions in the incandescent char layer of the exposed surface. While their quantities are always relatively small, their sudden appearance suggests the distinct possibility of ignition being "triggered" by reactive intermediates.

Product analyses of nearly identical exposures of thick and thin specimens indicate that the persistence of flaming depends only upon achieving a temperature profile during exposure whose relaxed value is sufficient to maintain the flow of flammable volatiles and not on any unique composition of them.[28]

The current ignition program at NRDL seeks more definitive information about the basic chemical reactions which precede and accompany the ignition of cellulose.

* For the sake of completeness we must mention the possibility of char being formed from the glucopyranose or glucofuranose elimination products (e.g., levoglucosan) which fail to escape the high temperature environment. In this connection, the minor product, hydromethylfurfural, is a logical intermediate in dehydration of levoglucosan to char. It is our belief, however, that this represents a very small part of the over-all char-forming process.

The inherent difficulties of working with a hard-to-characterize natural polymerlike cellulose are amplified manifoldly by the temporally and spatially nonisothermal history which results from radiant heating of the surface. An attempt is being made to repeat the analytical measurements described above but under conditions of high temperature, isothermal heating of the solid. In addition, both the residual solid and the tar fractions will be analyzed in considerably greater detail. Along with this work, we are attempting to observe, with a time-of-flight mass spectrometer, the pyrolytically generated, transient species which may be responsible for spontaneous ignition.[29] Finally, the character of the transient combustion process is being explored by studying the effect on ignition times and temperatures of such changes in the atmospheric environment as total pressure, oxygen partial pressure, and inert diluents other than nitrogen.

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Radiative Transfer from Nuclear Detonations Above 50-Km Altitude

T. O. PASSELL AND R. I. MILLER

Physics Division, Nuclear Physics Department, Stanford Research Institute, Menlo Park, California

The transfer of energy from a nuclear detonation above 50 km to the earth's surface occurs chiefly by radiation. Two main radiative processes can occur: (i) fast fluorescence, and (ii) thermal emission from incandescent air. Herein, we considered only the latter process. Major assumptions are: (a) four-fifths of the nuclear detonation energy yield is emitted initially as x rays with an energy spectrum equivalent to that of a black body around 10^7 °K; (b) air in the temperature range 5000 to 20,000°K emits photons with an energy distribution equivalent to that of a black body; (c) the emissivity of air varies with temperature but is constant with photon wavelength; and (d) the transmissivity of the earth's atmosphere is about the same for sunlight as for thermal radiation from nuclear detonations in the wavelength region of 0.31 to 1.9 microns.

With the above assumptions and the additional assumption that 10 cal/cm² delivered in 1 sec are required for ignition of commonly exposed materials, the ignition radius for a 1000-megaton detonation at 50 km is found to be about 250 km. At 240-km burst height the ignition radius becomes zero km for 1000 megatons.

A fireball ceiling at around 80 km altitude is shown to exist, i.e., as the detonation height h rises above 80 km the fireball remains behind in the form of a pancake 10 to 20 km thick and $h-80$ km in diameter. Just above the 80-km level a sudden decrease in radiative transfer efficiency occurs because only those x rays emitted within 45° of straight down contribute significantly to creation of the incandescent fireball.

Introduction

A study of the fire-starting potential of nuclear weapons revealed much diversity among the current estimates of energy pulses from high-yield (greater than 1 megaton) weapons detonated at high altitudes (above 50 km). To resolve this diversity, the problem was reinvestigated. This report explores the basic physical laws that will govern energy transfer from pulsed, point sources at temperatures near 10^7 °K, the temperature-assumed characteristic of nuclear weapons.[1]

Much is already known and published regarding energy transfer in the form of shock waves and thermal radiation for bursts at altitudes to 30 km.[1] Above 30 km, shock effects diminish rapidly so that at altitudes above 50 km they are not significant, leaving thermal radiation as the chief mechanism of energy transfer to the earth's surface.

In this report we consider only altitudes above 50 km to explore theoretically the radiative energy-transfer processes free of major shock-wave effects. Experimental data in this altitude region is sparse, coming only from the Teak (77 km) and Orange (43 km) shots. Thus, the theoretical model developed here should be roughly consistent with the general observations reported on Teak and Orange.[1]

The main features of nuclear detonations above 50 km which affect radiant energy transfer are:

1. The instantaneous emission at time zero of a pulse of x-ray photons representing up to four-fifths the yield, with mean energy in the region of 1 to 10 keV.

2. When the burst occurs at an altitude between 50 and 80 km, the absorption of most of the energy of the x-ray photon pulse by a roughly spherical volume of the surrounding air having a raidus ~1 mean free path for 1- to 10-keV x-rays.
3. The transfer of the absorbed energy into adjacent cold air by radiative transfer until a roughly uniform temperature of 20,000°K is reached.
4. Radiative cooling of the fireball from 20,000° to ~5000°K with a substantial fraction of the radiated energy reaching the earth's surface.
5. Cessation of radiant emission as a major cooling mode below 5000°K.
6. The rapid change from a nearly spherical fireball to one of pancake shape as burst height is increased beyond 80 km, the level of the pancake remaining always near 80-km altitude.
7. The loss of well over three-fourths the total x-ray energy for all detonations above 80 to 90 km, because of radiation into space or to regions heated below the threshold of incandescence.

In this study it has been convenient to differentiate between two altitude regions: (i) the 50- to 80-km region where fireballs are roughly spherical—called the *upper atmosphere* (UA), and (ii) the region above 80 km which has been designated *above the atmosphere* (AA). These two regions (AA and UA) will be treated more or less separately in this development of a theoretical model.

In this analysis, details of the initial energy deposition by x-ray absorption for UA and AA detonations are discussed and radiating properties of hot air (assuming thermal equilibrium) are described. Considered next is the relative disposition of the radiant energy into three chief energy bands: (i) the O_2 absorption band, (ii) the ozone absorption band, and (iii) the atmospheric transparency band. This is followed by a discussion on the geometry and transmission factors which influence the distribution of the energy relative to ground zero. Finally, general curves for calculating energy fluxes received at the ground as a function of yield and detonation height are shown, along with ignition circle radius–altitude profiles for three different yields.

Absorption of Black Body X-Ray Spectra by Air

In the energy range from 100 eV to 20 keV the x-ray mass-absorption coefficient of air is well approximated by

$$\mu_{x\ ray} = [(4\times 10^3)/E^3]\ \text{cm}^2/\text{g}, \tag{1}$$

where E is the incident energy in keV.

In addition, the atmospheric density as a function of altitude above the earth's surface may be approximated by

$$\begin{aligned} \rho &= 1.36\times 10^{-10} \exp(-Z/28)\ \text{g/cm}^3, \quad 147 < Z < 320 \\ &= 1.225\times 10^{-3} \exp(-Z/7)\ \text{g/cm}^3, \quad Z < 147, \end{aligned} \tag{2}$$

where Z is the altitude in km.

For a given x-ray spectrum $F(E)$, the energy intensity $I(X)$ transmitted by an absorber of thickness X is given by

$$I(X) = I_0 \int_0^\infty F(E)\ \exp[-\mu(E)X]\ dE. \tag{3}$$

A black body source of absolute temperature T_x emits radiation with the energy distribution

$$F(E) = \frac{15}{(\pi kT_x)^4} \frac{E^3}{[\exp(E/kT_x) - 1]} \tag{4}$$

so that Eq. (3) becomes

$$I(T_x, X) = I_0 \int_0^\infty \frac{15}{\pi^4} \frac{u^3}{[\exp(u) - 1]} \exp[-\mu(ukT_x)X]\, du, \tag{5}$$

where $u = E/kT_x$.

The quantity $I(T_x, X)$ is plotted vs. absorber thickness in Fig. 1.[2]

For atmospheric attenuation, X represents the mass surface density, $P(\mathbf{b}, \mathbf{r})$, where the mass surface density from the burst point $\mathbf{b}(0, 0, h)$ to the point of interest $\mathbf{r}(r, \theta, Z)$ is given by

$$P(b, r) = \int_0^1 \rho[Z + x(h - Z)]\, |\, \mathbf{b} - \mathbf{r}\, |\, dx \text{ g/cm}^2, \tag{6}$$

where x is the fractional distance from $\mathbf{r}$ to $\mathbf{b}$.

For an AA detonation, we are most concerned with those x rays coming from a detonation height $h > 125$ km straight down to the denser air at a height $Z < 100$ km, so that

$$P(\mathbf{b}, \mathbf{r}) = P(h, Z) \approx P(Z) = 7 \times 10^5 \rho(Z) \text{ g/cm}^2. \tag{7}$$

For a nonvertical path, $P(Z)$ from Eq. (7) must be multiplied by the secant of the angle that the nonvertical direction makes with the vertical.

Equation (5) thus becomes, in the case of a vertical path as described above

$$\frac{I(T_x, Z)}{I_0} = \int_0^\infty \frac{15}{\pi^4} \frac{u^3}{[\exp(u) - 1]} \exp\left[\frac{-\mu(kT_x)}{u^3} P(Z)\right] du. \tag{8}$$

For a UA detonation, the x rays are absorbed in the atmospheric gases immediately about the detonation point. From the plot of $I(T_x, X)/I_0$ vs X given

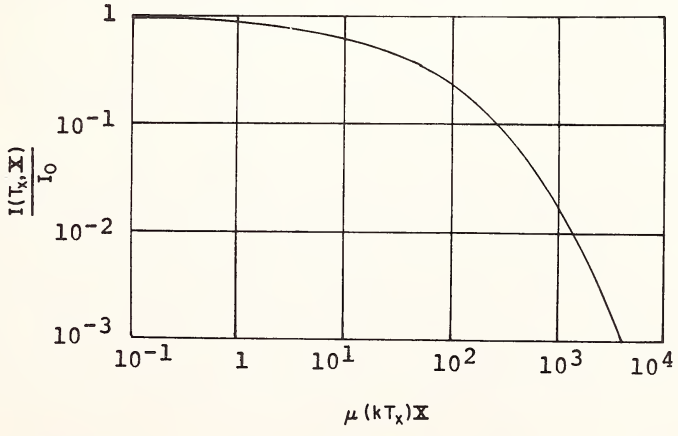

FIG. 1. X-ray transmission vs absorber thickness for an incident black-body source (absorber thickness is given in terms of the mean free path for monoenergetic x rays of energy kT_x).

in Fig. 1 and Eq. (1) we see that $(1-1/e)$ of the energy is absorbed in a distance $L_{1/e}$ given by

$$L_{1/e}=10(kT_x)^3/(\rho/\rho_0)\ \text{cm}; \tag{9}$$

where $\rho_0=1.225$ g/cm^3 (NTP) and (kT_x) is in keV.

Since it follows from Eq. (7) that above a given altitude there is only the equivalent of one scale height (7 km) of air at the density corresponding to that altitude, it is seen that as $L_{1/e}$ becomes comparable with a scale height, the x-rays from the detonation leaving in the upward direction are no longer significantly absorbed. Their energy is therefore "lost to space." Thus it is seen that the condition

$$[\rho(Z)/\rho_0]<1.43\times10^{-5}(kT_x)^3 \tag{10}$$

essentially determines the height Z above which the x rays from the detonation are no longer absorbed in the immediate vicinity of the detonation point. Altitudes below this height have been defined as the UA; and altitudes above this height have been defined as AA.

For an initial incident black-body temperature (kT_x) of 1 keV, $\rho(Z)/\rho_0=1.43\times10^{-5}$, determining $Z=81$ km as the height below which most of the x-ray energy is absorbed within a scale height of the detonation point, and above which only those x rays directed towards the earth are absorbed.

Temperature of X-Ray Heated Air

The internal energy of heated air may be approximated by

$$E_I=3.5\times10^2T^{\frac{3}{2}}(\rho/\rho_0)^{0.9}\ \text{ergs/cm}^3(T>10^4\ ^\circ\text{K}), \tag{11}$$

$$E_I=10T^2(\rho/\rho_0)\ \text{ergs/cm}^3[10^3<T<10^4\ ^\circ\text{K}\quad\text{and}\quad(\rho/\rho_0)<10^{-3}], \tag{12}$$

where T is the temperature of the heated air volume in °K.[3]

For a UA detonation, $(1-1/e)$ of the x-ray energy of the detonation will be deposited within an air mass whose volume is roughly given by $\frac{4}{3}\pi L^3_{1/e}$, so that the average temperature in this volume (the x-ray fireball) will be given by

$$3.5\times10^2T_{RR_0}^{\frac{3}{2}}(\rho/\rho_0)^{0.9}\tfrac{4}{3}\pi L^3_{1/e}=(1-1/e)4.18\times10^{22}Y\ \text{ergs/cm}^3, \tag{13}$$

$$T_{RR_0}=[(6.8\times10^{10})/(kT_x)^6](\rho/\rho_0)^{1.4}Y^{\frac{2}{3}}\ ^\circ\text{K}\quad(T>10^4\ ^\circ\text{K}), \tag{14}$$

where Y is the yield (in megatons) of the detonation and T_{RR_0} denotes the initial temperature of the irradiated-air volume after x-ray energy deposition. For $\rho/\rho_0=1.43\times10^{-5}$ (corresponding to a detonation height h of 81 km) and an incident black-body temperature of 1 keV (kT), we see that any yield over 2.5 megatons will heat the surrounding air to a temperature T_{RR_0} of at least 2×10^4 °K. It will be shown below how such superheated air radiatively cools from these temperatures.

For the absorption of energy by the atmosphere for AA detonations, we must consider the differential deposition of energy at each altitude as x rays proceed toward the earth. The temperature at a given point directly above ground zero is determined by equating the internal energy of the air E_I (known as a function of temperature) at a given altitude with the x-ray energy deposited at that altitude,

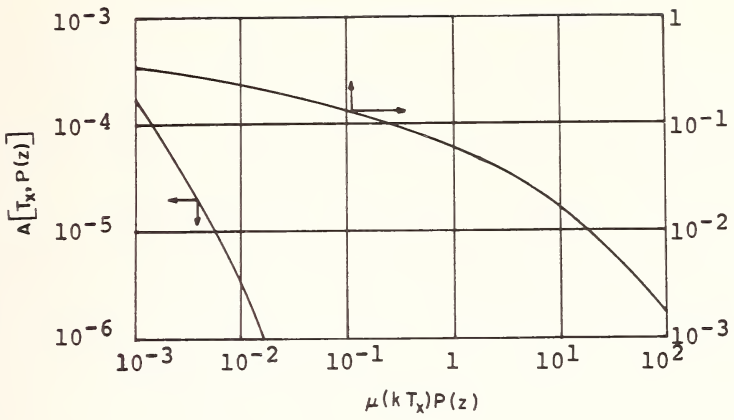

FIG. 2. Derivative of x-ray transmission with respect to absorber thickness vs absorber thickness.

so that there follows

$$E_I = dI[T_x, P(Z)]/dZ \text{ ergs/cm}^3$$

$$= I_0\mu(kT_x)P(Z)\int \frac{15}{\pi^4}\frac{\exp\{[-\mu(kT_x)/u^3]P(Z)\}}{\exp(u)-1}\,du. \qquad (15)$$

Figure 2 shows a plot of

$$A[T_x, P(Z)] = [I_0\rho(Z)\mu(kT_x)]^{-1}\{dI[T_x, P(Z)]/dZ\} \qquad (16)$$

vs. absorber thickness (mass surface density) as obtained from a differentiation of Eq. (8) by graphical and numerical methods.

With the stated assumption that four-fifths of the initial energy of the detonation appears as x rays, it follows that

$$T^2_{RR_0} = \frac{1.38\times10^{11}\,A[T_x, P(Z)]Y}{(h-Z)^2(kT_x)^3} \quad (10^3\ ^\circ\text{K} < T < 10^4\ ^\circ\text{K}). \qquad (17)$$

Similarly,

$$T^{\frac{3}{2}}_{RR_0} = \frac{1.20\times10^9\,A[T_x, P(Z)]Y}{(h-Z)^2(kT_x)^3}(\rho/10^{-8})^{0.1} \quad (T > 10^4\ ^\circ\text{K}), \qquad (18)$$

where $h-Z$ is in km, kT_x is in keV, and T_{RR_0} is in °K.

From Eqs. (17) and (18) it is seen that the yield Y, required to heat air at a given density (and therefore at a given altitude) to a required temperature T_{RR_0}, varies as $[(kT_x)^3/A(T_x, P(Z)]$.

Thus for *AA* detonations the initial temperature of the device determines to what altitude level the x rays will penetrate and deposit their energy. In Fig. 3 three possible levels within the feasible range for devices at initial temperatures around 10^7 °K, or 0.862 keV,[1] are considered: 70, 83, and 95 km—corresponding to arbitrarily chosen air densities of 10^{-7}, 10^{-8}, and 10^{-9} g/cm³, respectively.

It is seen that air at a density of 10^{-9} g/cm³ is most effectively heated by an AA detonation in which the incident black-body spectrum is described by $kT_x = 0.6$

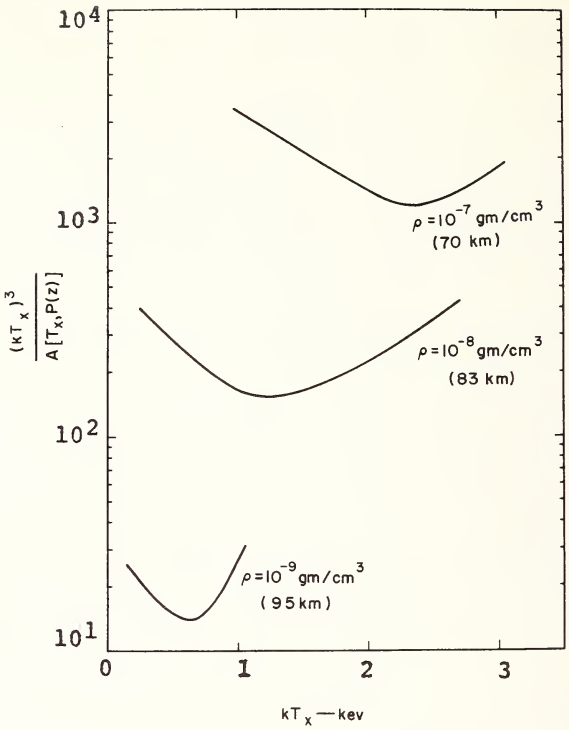

FIG. 3. A quantity proportional to the yield required to heat air to a given temperature vs the black-body temperature of the incident spectrum for air densities of 10^{-7}, 10^{-8}, and 10^{-9} g/cm^3.

keV; at 10^{-8} by a spectrum described by $kT_x = 1.25$ keV; and at 10^{-7} by a spectrum described by $kT_x = 2.4$ keV; and that the amount of energy required to heat any given layer to a specified temperature is roughly proportional to the air density at that layer. In addition, most of the energy absorbed by the atmosphere in an AA detonation will be absorbed within a couple of scale heights of the optimally heated altitude.

Radiation of Heated Air

In this discussion it will be assumed that the air heated by x-ray deposition radiates its energy as if it were a black body. The emissivity (and hence the opacity) of this black body is determined by the composition of the air at whatever temperature corresponds to thermodynamic equilibrium.

The equation of radiative transfer for an atmosphere in thermodynamic equilibrium is given by[4]

$$dN_\nu/ds = \mu'_\nu(B_\nu - N_\nu) \text{ ergs cm}^{-3} \text{ sec}^{-1} \text{ (unit frequency in sec}^{-1})^{-1} \text{ sterad}^{-1}, \quad (19)$$

where N_ν is the emitted energy flux per unit solid angle per unit projected area, per unit frequency band; s the distance in cm; B_ν the black-body spectrum given

as a function of the frequency ν by

$$B_\nu = (2h\nu^3/c^2)\,[\exp(h\nu/kT)-1]^{-1} \text{ ergs cm}^2 \text{ sec}^{-1} \text{ (unit frequency in sec}^{-1})^{-1} \text{ sterad}^{-1}; \tag{20}$$

μ'_ν is the reduced absorption coefficient of air corrected for induced emission, and is given by

$$\mu'_\nu = \mu_\nu(Z, T)\,[1-\exp(-h\nu/kT)] \text{ cm}^{-1}; \tag{21}$$

and μ_ν is a function of both the temperature and density of the atmosphere.

For detonations in the upper atmosphere (below about 80 km) the radiating volume surrounding the detonation point is approximately spherical in shape. In AA detonations the radiating volume can be considered, to a first approximation, to be a plane circular layer a few scale heights in depth.

To solve Eq. (19) we integrate from a point where the intensity in a required direction equals zero to the outer surface of the radiating volume. For UA detonations, the net radiated intensity in any given direction equals zero at the detonation point; for AA detonations, the downward-radiated intensity equals zero at the top surface of the radiating layer (neglecting the radiation from the rarer, and therefore less effective radiating volumes closer to the detonation points). Thus, we can solve Eq. (19) to obtain

$$N_\nu(s) = \int_0^s \mu_\nu' B_\nu \exp[-\mu_\nu'(s-s')]\,ds', \tag{22}$$

where we have assumed radiating bodies of constant temperature and density. The integral term sums the contributions to the directed emitted energy flux from the radiating volumes between $s'=0$ and the position s', correcting for absorption between the radiating volumes and s.

For all but the lowest black-body photon energies, which will be absorbed by water and other infrared absorbers in the air and so will not affect the radiation observed on the ground, $[1-\exp(-h\nu/kT)]=1$, and therefore $\mu'_\nu=\mu_\nu$. The radiation coming from a heated region of dimension s will thus be given by

$$N_\nu(s) = [1-\exp(-\mu_\nu s)]B_\nu \simeq \mu_\nu s B_\nu \tag{23}$$

for any $\mu_\nu s$ much less than 1, i.e., a gas layer which is relatively transparent to its own radiation. In both UA and AA detonations, the absorption coefficient μ_ν is such that the radiating air mass is opaque to the incoming x rays but transparent to its own longer wavelength reradiation.

For UA detonations s in Eq. (23) is replaced by R, the mean radius of the radiating fireball. In AA detonations, s in Eq. (23) is replaced by d, the depth of the effective radiating plane layer. To obtain the rate at which energy is radiated across a given surface we must integrate Eq. (23) over all frequencies and over all solid angles. For a perfectly diffuse surface, the integration over all solid angles merely introduces a factor of π so that the result is given by

$$\begin{aligned} I(s) &= \pi\bar{\mu}s(\sigma T^4/\pi) \text{ ergs cm}^2 \text{ sec}^{-1}, \\ &= \bar{\mu}s\sigma T^4, \end{aligned} \tag{24}$$

where $I(s)$ is the total amount of radiant energy flux crossing the surface area element dA of the radiating surface at s, $\sigma = 2\pi^5k^4/15c^2h^3$ is the radiation constant

and is equal to 5.67×10^{-5} ergs/[cm^2 sec (°K)^4], and

$$\bar{\mu}=\frac{15}{\pi^4}\int \mu_u u^3 \exp(-u)\ du \text{ cm}^{-1} \tag{25}$$

is the mean absorption coefficient over the Planck distribution.

A more convenient quantity to work with is $d\mathcal{E}/dt$, the energy radiation rate per cubic centimeter of radiating volume, which is obtained from Eq. (24) by multiplying by the radiating area and dividing by the volume, so that

$$d\mathcal{E}/dt=(\bar{\mu}sA_R/V)\sigma T^4 \text{ ergs cm}^{-3}\text{ sec}^{-1}. \tag{26}$$

For UA detonations with a radiating fireball, $A_R=4\pi R^2$, $V=\frac{4}{3}\pi R^3$, $s=R$, and Eq. (26) becomes

$$d\mathcal{E}_{UA}/dt=3\bar{\mu}\sigma T^4 \text{ ergs cm}^{-3}\text{ sec}^{-1}. \tag{27}$$

For AA detonations with a thin reradiating layer, $A_R=2A$, $V=Ad$, $s=d$, and, neglecting the radiation from the edges of the layer, there follows

$$d\mathcal{E}_{AA}/dt=2\bar{\mu}\sigma T^4 \text{ ergs cm}^{-3}\text{ sec}^{-1}. \tag{28}$$

The equilibrium composition of air to 2.4×10^4 °K is given by Gilmore.[3] With the aid of these results, the absorption coefficients for air have been computed by Meyerott and Sokoloff[5] in the range 10^3 to 1.2×10^4 °K and by Armstrong, Holland, and Meyerott[6] in the range 2.2×10^4 to 22×10^4 °K. In particular, Kivel and Bailey[7] have computed the Planck mean absorption coefficient and the volume-emission rate for air in the range 10^3 to 1.8×10^4 °K. Their results for the energy radiated per second per cm^3 by a thin planar sheet are given in Fig. 4. These results can be approximated by

$$\bar{\mu}\sigma T^4=4.1\times10^{11}(\rho/\rho_0)^{1.5}(T/10^4)^9 \text{ ergs cm}^3\text{ sec}^{-1}(3\times10^3<T<1.5\times10^4 \text{ °K}) \tag{29}$$

$$\bar{\mu}\sigma T^4=5.0\times10^{15}(\rho/\rho_0)^2 \text{ ergs cm}^{-3}\text{ sec}^{-1}\ (T>1.5\times10^4 \text{ °K}). \tag{30}$$

Beyond 2.5×10^4 °K, $\bar{\mu}$ very roughly has a value of $10^2(\rho/\rho_0)^2$ cm^{-1} (see Armstrong, Holland, and Meyerott[6]) so that the radiation rate again increases with

$$\bar{\mu}\sigma T^4=5.7\times10^{-3}(\rho/\rho_0)^2T^4 \text{ ergs cm}^{-3}\text{ sec}^{-1}\ (T<2.5\times10^4 \text{ °K}). \tag{31}$$

Twice this quantity, corresponding to a thin planar sheet, is plotted in Fig. 4.

The equilibrium temperature of the radiating air mass as a function of time is then determined from the equation

$$d\mathcal{E}/dt=dE_I/dt, \tag{32}$$

where E_I has been given in Eqs. (11) and (12). This equation is then solved for T as a function of time, the result being given in Fig. 5 for an initial temperature T_{RR_0} of the reradiating volume much greater than 2.5×10^4 °K.

Reradiation Efficiencies into the Atmospheric Passband and Time Dependence of the Thermal Radiation

Atmospheric Absorption Bands and Passbands. Because of infrared absorption by H_2O vapor and CO_2, and ultraviolet absorption by O_2 and O_3, the atmosphere is

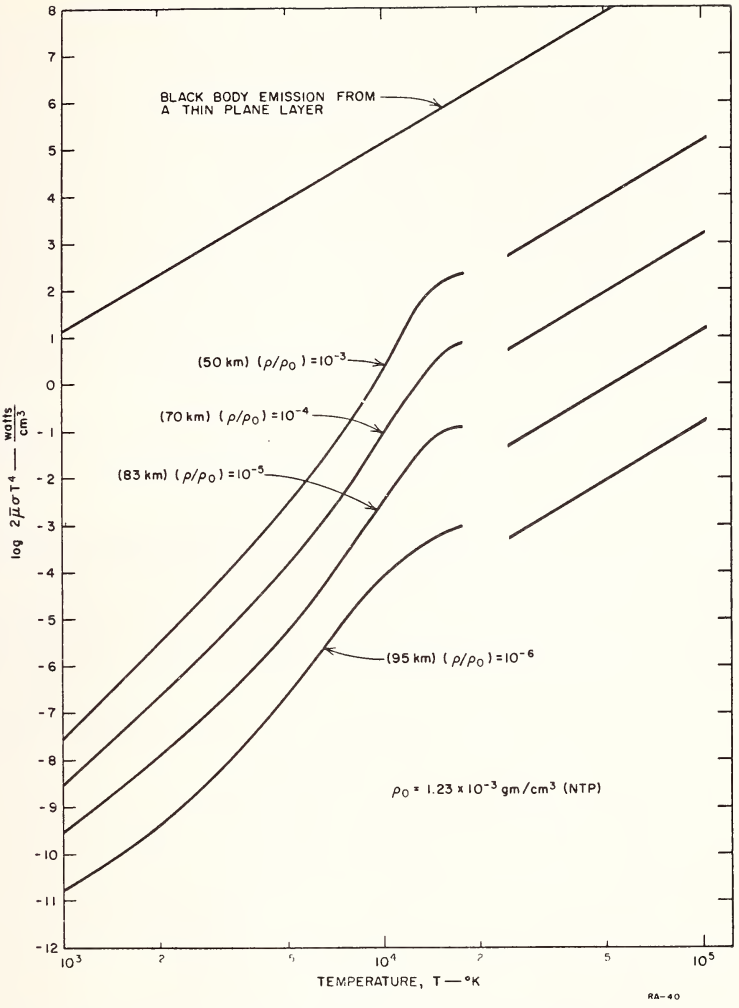

FIG. 4. Total emission from a plane thin layer of air as a function of temperature.

transparent to photon energies lying between, roughly, 0.65 and 4 eV. From 4 to 6 eV, radiation is absorbed by O_3, which is concentrated in the atmosphere between 20 and 40 km. Above 6 eV, radiation passing though the atmosphere is absorbed principally by O_2 but also by N_2.[8] The O_2 absorption coefficient for energies greater than 6 eV is so large, in fact, that even at 10^{-5} normal atmospheric density any radiation of greater than 6-eV energy has an absorption mean free path of less than an atmospheric scale height (7 km), so that the air immediately surrounding the reradiating volume will be able to absorb sufficient energy to heat itself to temperatures comparable with the original fireball and thus itself become part of the radiating volume.

In Fig. 6 are plotted those fractions of energy of a black body that lie within the O_2 and O_3 absorption bands, and also that fraction which lies within the at-

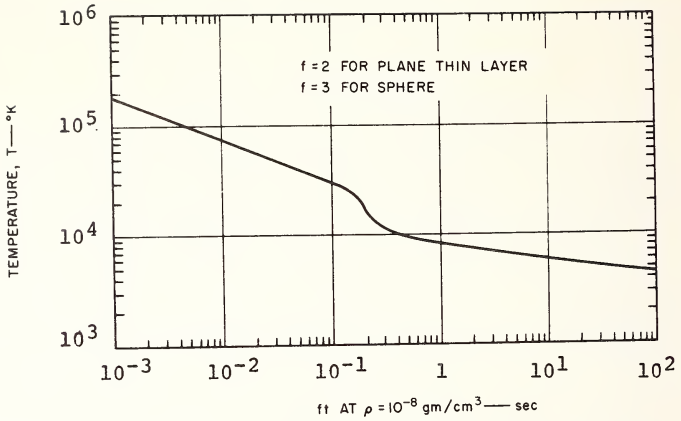

FIG. 5. Temperature vs time for air at a density of 10^{-8} g/cm^3 and an initial temperature greater than 2.5×10^4 °K.

mospheric passband as a function of black-body temperature.[9] (Two assumed atmospheric passbands are shown, 0.65 to 4 eV and 0.65 to 3.6 eV.)

By inspection of Fig. 6, it is seen that for black-body temperatures greater than 2×10^4 °K, >50 per cent of the reradiated energy will be absorbed by the surrounding O_2 and therefore will increase the radiating volume. Below 2×10^4 °K,

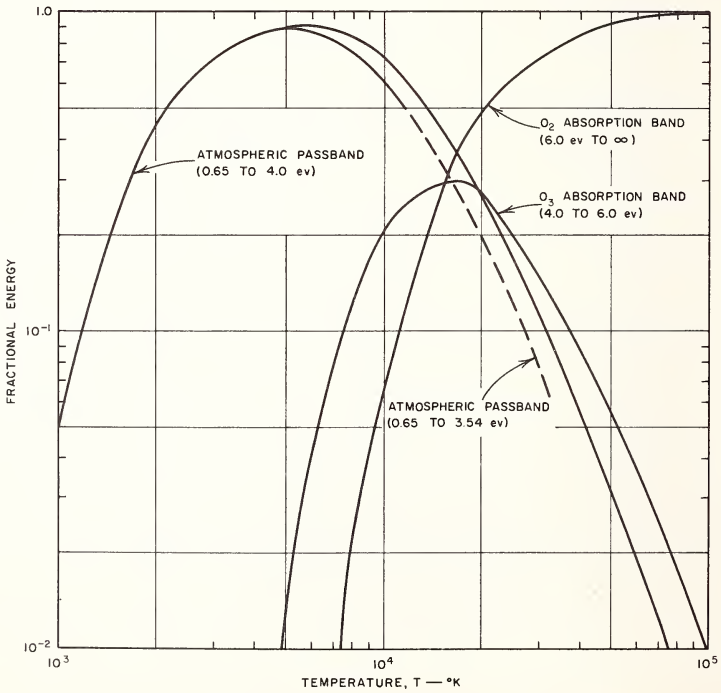

FIG. 6. Fractions of black-body energy in relevant energy ranges as a function of black-body temperature.

>20 per cent of the black-body energy will lie in the atmospheric passband and so will be transmitted to the ground. Thus, the radiation-transfer process can be considered in two steps when the initial reradiation temperature T_{RR_0} is greater than 2×10^4 °K. In the first step, which will take place in about 0.05 sec at $\rho=10^{-8}$ g/cm³ (see Fig. 5), the radiating volume will cool down by radiative expansion until it has an average temperature of about 2×10^4 °K; in the second step, this enlarged fireball will then cool down from 2×10^4 °K by radiation into the atmospheric passband and the ozone absorption band. Since it has already been shown that, for UA detonations, any yield over 2.5 megatons will result in an initial fireball temperature of greater than 2×10^4 °K, it follows that the energy radiated into the atmospheric passband for UA detonations greater than 2.5 megatons, will be linear with the yield and will have an efficiency and time dependence roughly corresponding to a 2×10^4 °K radiating volume at the detonation height h.

From Fig. 6 it is seen that the fraction of black-body energy in the atmospheric passband can be approximated by

$$\int_{0.65\text{ eV}}^{4\text{ eV}} \frac{E^3}{[\exp(E/kT)-1]}\,dE \Big/ \int_0^\infty \frac{E^3}{[\exp(E/kT)-1]}\,dE$$

$$\approx 0.85 \quad (3000<T<10{,}000\ ^\circ\text{K}), \tag{33}$$

$$\approx (5.4\times10^6)/T^{1.7} \quad (10{,}000<T<20{,}000\ ^\circ\text{K}), \tag{34}$$

so that the energy radiated into the atmospheric passband E_R as a function of T,

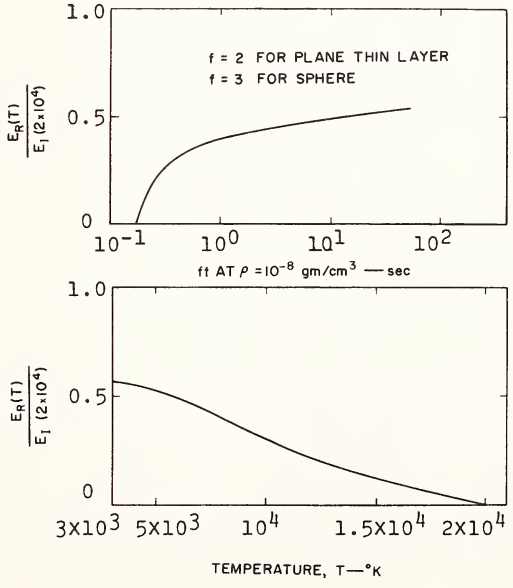

FIG. 7. Fractional energy radiated from a 2×10^4 °K air mass as a function of temperature and time (air density of 10^{-8} g/cm³).

for $T_{RR_0}=2\times10^4$ °K, is given by

$$E_R(T_{RR_0}=2\times10^4\ °\text{K},\ T)=\int_{2\times10^4\ °\text{K}}^{T}\frac{5.4\times10^6}{T^{1.7}}\,dE_I(T)\quad(T>10^4\ °\text{K}),\qquad(35)$$

where E_I has been given in Eqs. (11) and (12). Figure 7 shows a plot of the ratio

$$E_R(T_{RR_0}=2\times10^4\ °\text{K},\ T)/E_I(T_{RR_0}=2\times10^4\ °\text{K})$$

as obtained from solving these above two equations. By reference to Fig. 5, this same ratio is plotted vs. ft at $\rho=10^{-8}$ g/cm^3, where it has been assumed that the initial fireball was much hotter than 2×10^4 °K, and that negligible atmospheric passband radiation occurred before this temperature of 2×10^4 °K was attained. From Fig. 7 it is seen that roughly half of the energy of a 2×10^4 °K UA fireball is radiated in the atmospheric passband. Half of this half has radiated by the time the fireball has cooled to 10^4 °K.

Efficiencies of Radiative Transfer into the Atmospheric Passband

To obtain an estimate of the over-all efficiency for the conversion of x-ray energy into energy reradiated in the atmospheric passband, there are two additional factors to be considered: (i) ozone absorption in the lower atmosphere, which will absorb about one-quarter of the reradiated energy of the fireball during the first-step cooling-down process to 2×10^4 °K (see Fig. 6); (ii) energy which is absorbed too far from the center of the reradiating volume to heat the air to a radiating temperature. (This effect occurs for both initial x ray and also that reradiated energy greater than 6 eV absorbed by the surrounding O_2.) The latter factor will account for another effective loss of about one-quarter of the original x-ray energy. Thus, UA detonations will have an efficiency of about 25 per cent for converting the original energy of the detonation into radiation within the atmospheric passband. One-quarter is lost in O_3 absorption, one quarter is ineffectively absorbed too far from the reradiating fireball to give those temperatures necessary for radiation into the atmospheric passband, and of the remaining one-half, only one-half again is radiated into the atmospheric passband. This result is in agreement with the reported efficiency for UA detonations of 25 to 35 per cent.[1]

The time dependence of the power radiated for a UA detonation can be obtained by combining the information in Fig. 5 with Eqs. (29)–(31). For example, in the important temperature range below 1.5×10^4 °K, the time dependence is approximately

$$d\mathcal{E}/dt\propto t^{-1.3}.\qquad(36)$$

Radiation into the atmospheric passband will take place even during the first step of the cooling process in which the radiating volume is cooling down to an average temperature of 2×10^4 °K, since even a black body of temperature T greater than 2×10^4 °K has a finite amount of energy in the atmospheric passband. In addition, even at the earliest times the fireball will have outer sections at the more effective radiating temperatures (for the atmospheric passband) of less than 2×10^4 °K, since in reality the fireball is not uniform in temperature. These factors will produce radiation in the first step of the cooling-down process but will neither significantly increase the total amount of energy reradiated nor affect the radiation rate for times when the fireball is more uniform in temperature. Thus, the over-all

result is that the energy radiation rate at early times is more constant than the above analysis would indicate.

Two significant facts describing the situation at these earlier times are: (i) roughly one-fourth of the energy eventually radiated to the ground (see Fig. 7) by a body initially heated to any temperature $>2\times10^4$ °K has been emitted before the body cools to 1.5×10^4 °K; (ii) the time required for the heated air to cool to 1.5×10^4 °K is roughly the same as the cooling time from 1.5×10^4 °K to 10^4 °K (0.1 sec at $\rho=10^{-8}$ g/cm^3).

In AA detonations, the reradiating volume is no longer spherical because the air immediately surrounding the detonation point is too rare to absorb enough of the energy of the detonation to be a significant radiator. In the AA case, the altitude at which the x-ray energy from the detonation is absorbed is dependent upon the black-body temperature of the device. For the purpose of the following calculations, a device temperature $kT_x=1.25$ keV is assumed. This is the optimum

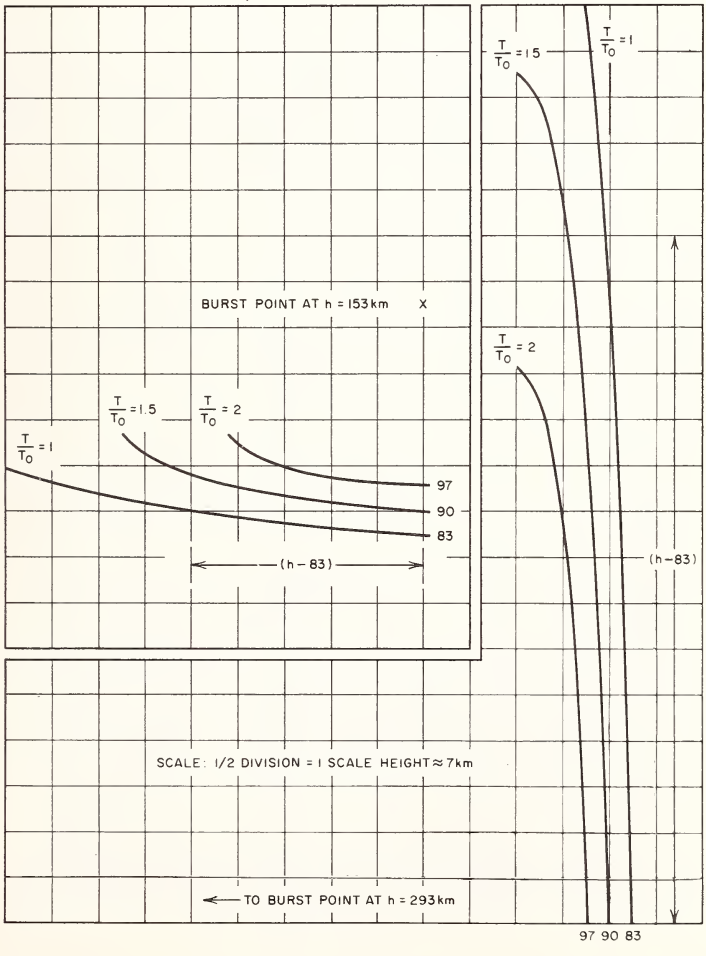

FIG. 8. Isothermal contours for above-the-atmosphere detonations at two detonation heights.

temperature for heating air at about the 10^{-8} g/cm^3 (83 km) level (see Fig. 3). This temperature assumption represents a rough maximization for reradiation efficiencies into the atmospheric passband. A higher device temperature would result in the x-ray energy being deposited in a higher density layer which would require correspondingly larger detonation yields (which are already in the tens of megatons range for $kT_x=1.25$) to heat the air to incandescence. The possibility of a lower device temperature being more efficient is ruled out by the fact that the lower-density air in which the x-ray energy would then be absorbed would take excessively long (tens of seconds) to radiate a significant function of its energy to the ground. In addition to nonradiative dissipation by convection, which can occur within such time periods as many seconds, these longer times drastically reduce the potential ignition hazard for a given integrated energy flux.

From Eqs. (17) and (18) it is seen that the isothermal surfaces for an AA detonation are described by

$$A[T_x, P(Z_0)]/(h-Z_0)^2=A[T_x, P(Z) \sec\theta]/(h-Z)^2, \tag{37}$$

where z_0 is the height directly above ground zero of a point on a given isotherm, θ the angle that the line from the detonation point to the required point on the isotherm makes with the vertical, and z the height of the point in question on the isotherm. In Fig. 8 are plotted isotherms determined from a graphical solution

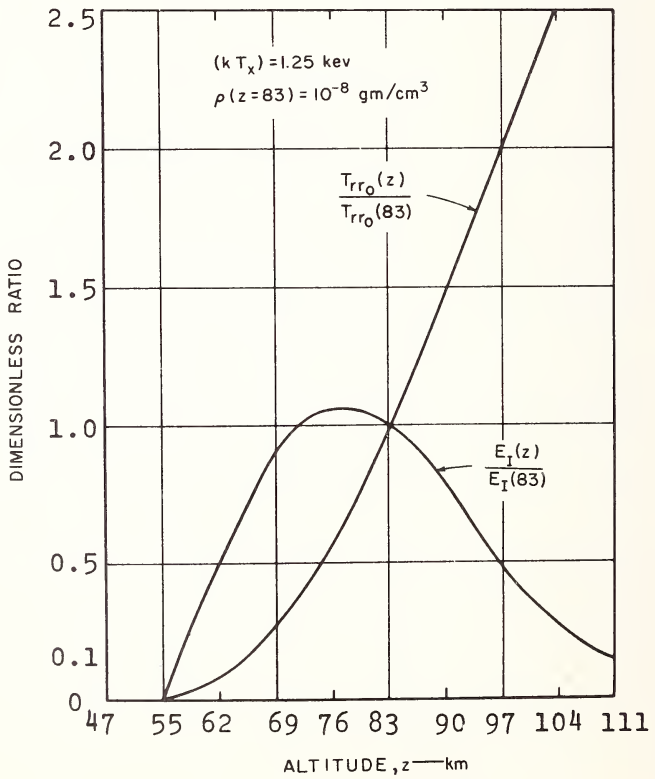

FIG. 9. Energy and temperature distribution of the air directly below an AA detonation (for an initial x-ray black-body temperature of $kT_x=1.25$ keV).

of Eq. (37) for two detonation heights—153 and 293 km. It is seen from this figure that the shape of the isotherm is such that an upper limit of approximately $\pi(h-z_0)^2/4\pi(h-z_0)^2 \leq \frac{1}{4}$ of the x-ray energy of the detonation is effective in heating air which can then radiate a significant fraction of its energy into the atmospheric passband. We have assumed the edge of the fire pancake to be that radius at which a given isotherm has risen one scale height.

A further loss of efficiency for AA bursts compared with UA bursts results from the fact that less than four-fifths of the energy of the detonation goes into x-rays,[1] and thus into heating of the lower lying air. For UA detonations, essentially all the energy of the detonation—in the form of both x rays and the kinetic energy of the fragments—is absorbed by the radiating air immediately surrounding the detonation point.

To find the efficiency with which x rays are absorbed and converted into atmospheric passband radiation for an AA detonation, the absorption and reradiation of

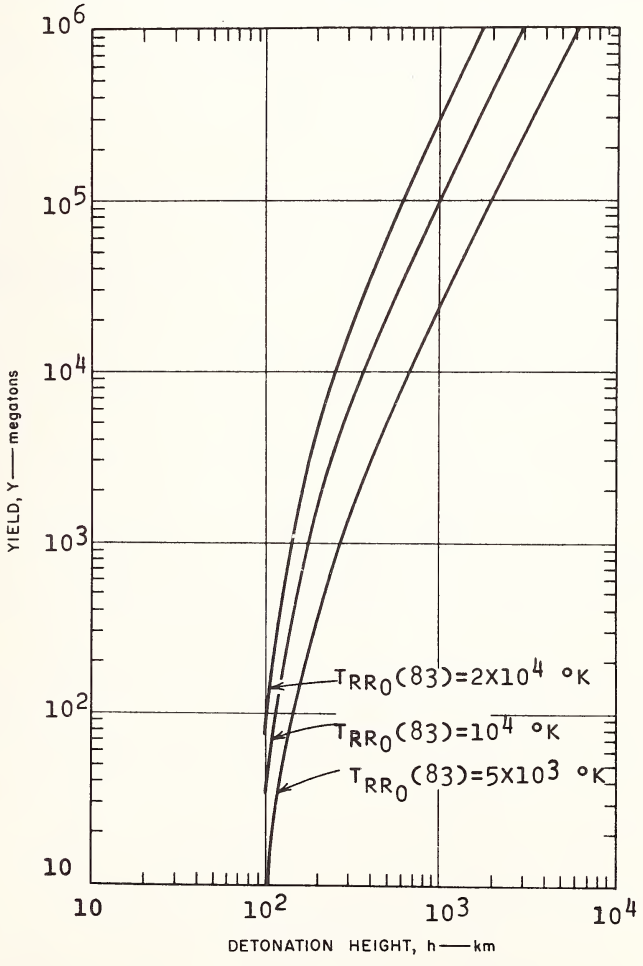

FIG. 10. Yield required at a given height to give an initial reradiation temperature at 83 km ($\rho = 10^{-8}$ g/cm^3) of 5×10^3, 10^4, and 2×10^4 °K.

the x-ray energy directly above ground zero is considered. From Eqs. (11) and (18), Fig. 9 is obtained, giving the temperature and internal-energy distribution in the heated lower-air layer for a detonation sufficiently high above the heated layers that the layer thickness is small compared with its distance from the detonation points.

Figure 9 shows the temperature and energy distribution as a function of altitude directly below the burst point for an x-ray burst characterized by $kT=1.25$ keV. Because of a change in the temperature dependence of the internal energy of air below 10^4 °K [see Eqs. (11) and (12)] the temperature distribution of Fig. 9 will decrease more sharply with decreasing altitude for altitudes below the layer heated to 10^4 °K. However, the energy distribution curve will remain unchanged.

The area under the $E_I(z)/E_I(83)$ curve in Fig. 9 is proportional to the incident x-ray energy flux from the detonation directly above ground zero, so that the fraction of this energy radiated into the atmospheric passband will give the efficiency of radiative transfer to the ground.

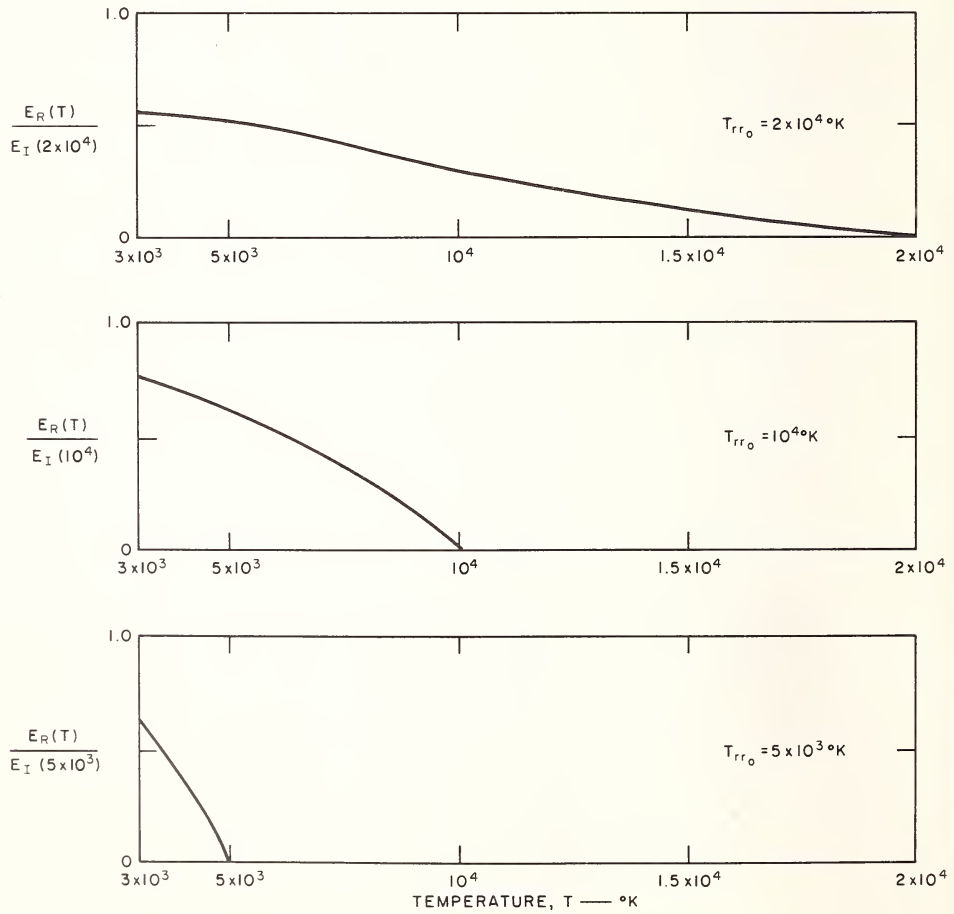

FIG. 11. Fractional energy radiated from 2×10^4, 10^4, and 5×10^3 °K air masses as a function of temperature.

To determine this efficiency it is first necessary to determine the initial temperature (T_{RR_0}) of the radiating air. This is readily determined from Eqs. (17) and (18) and the temperature distribution plot of Fig. 9. For $kT_x=1.25$ keV, $z=83$ km, $\rho=10^{-8}$ g/cm^3, there follows

$$T^2_{RR_0}(83\text{ km})=\frac{9.2\times10^8 Y}{(h-83)^2} \quad (10^3\text{ °K}<T<10^4\text{ °K}), \tag{38}$$

$$T^{\frac{3}{2}}_{RR_0}(83\text{ km})=\frac{8.0\times10^6 Y}{(h-83)^2} \quad (T>10^4\text{ °K}), \tag{39}$$

where Y is in megatons, h in km, and T_{RR_0} in °K. In Fig. 10, Y is plotted vs h for $T_{RR_0}=5\times10^3$, 10^4, and 2×10^4 K°.

In Fig. 11 there is plotted the fraction of the total x-ray energy reradiated, E_R/E_I, for $T_{RR_0}=2\times10^4$, 10^4, and 5×10^3 °K as a function of T. From Fig. 5 an estimate of the time dependence of T can then be obtained for these three cases.

To give an idea of the variation of reradiation efficiency with detonation yield Y, Table I gives a rough estimate of the fractional energy ϵ reradiated in the atmospheric passband in 0.1, 1.0, and 10 sec for $T_{RR_0}=2.5\times10^3$, 5×10^3, 10^4, and 2×10^4 °K.

Table I was obtained by first determining from Fig. 9 the energy percentage and the average temperature of layers a scale-height thick (7 km) at heights of 69, 76, 83, 90, 97, and 104 km; the fraction of the energy reradiated into the atmospheric passband within 0.1, 1.0, and 10 sec from each of these layers was obtained from Figs. 5 and 11.

An estimate of the over-all efficiency within a given time is then obtained by multiplying the values given in Table I by $0.8\times0.25=0.2$ (four-fifths of the device energy is assumed in x rays and of that, less than one-quarter is absorbed in the reradiating layers). As opposed to the UA detonation case, in which the efficiency of transfer to the ground did not change with the yield for any yield greater than about 2.5 megaton, in the AA detonation both the efficiency and time dependence of the reradiation are functions of the temperature of the heated air as shown in Table I and thus are functions of the yield (see Fig. 10).

From Table I, a rough estimate of the time behavior of the reradiation energy can be obtained. It can be seen that for times greater than 1 sec the power goes roughly as $t^{-1.3}$ in agreement with the UA case [see Eq. (36)].

Table I. Fraction of absorbed x-ray energy (ϵ) reradiated in the atmospheric passband in 0.1, 1.0, and 10 sec

$T_{RR_0}(83)$, °K	Fraction (ϵ) at		
	0.1 sec	1.0 sec	10 sec
2×10^4	0.12	0.22	0.38
10^4	0.06	0.19	0.33
5×10^3	0	0.07	0.16
2.5×10^3	0	0	0.1

Geometry Factors

The radiation received on the ground can now be determined from a consideration of the geometry factors involved and the transmission of the atmosphere for radiation within the atmospheric passband.

For the UA detonation, the geometry factor is given simply by $(4\pi r^2)^{-1}$, where r is the distance from the detonation point to any other point in question. It will be convenient to consider the ground effects at those points on the ground n burst heights away from ground zero, for which case r^2 becomes

$$r_n^2 = (n^2+1)h^2, \tag{40}$$

where h is the burst height. If we let F_n represent the transmission factor corresponding to the path from the burst point (UA detonations only) to the ground point at nh, then the integrated energy flux, S_n^{UA}, received at the ground point n burst heights from ground zero on a surface normal to the ray to the detonation point is given by

$$S_n^{UA} = \frac{2\times 10^3 F_n Y}{(n^2+1)h^2} \text{ cal/cm}^2 \quad (h<80 \text{ km}), \tag{41}$$

where Y is in megatons, h in km, and an over-all efficiency of 25 per cent for the conversion of the initial energy of the detonation into energy reradiated into the atmospheric passband has been assumed. In particular S_0^{UA} gives the effect at ground zero.

In AA bursts, the geometry is slightly more complicated, since the radiating surface approximates a flat circular cone rather than a sphere. To determine the ground-zero effect it is considered (from the properties of a cone) that the reradiating layer has an average distance from ground zero given by

$$R_0^2 = \{83^2+[\tfrac{1}{2}(h-83)]^2\} \text{ km}, \tag{42}$$

since the radiating air is approximately centralized about a height of 83 km ($\rho = 10^{-8}$ g/cm^3), and the median radius of the conical pancake is approximately $\frac{1}{2}(h-83)$ km. For a ground point nh km from ground zero, the radiating volume can again (as for the UA detonation) be taken as concentrated at the center of the radiating layer, so that the distance to the ground point is given by

$$R_n^2 = (83^2+n^2h^2) \text{ km}^2 \quad (n>1). \tag{43}$$

The energy flux, S_n^{AA}, received at the ground point r_n normal to the ray to the center of the radiating layer is thus given by

$$S_n^{AA} = \frac{1.6\times 10^3 \epsilon(T_{RR0}) F'_n Y}{R_n^2} \text{ cal/cm}^2 \quad (h>100 \text{ km}), \tag{44}$$

where Y is in megatons, h in km, and ϵ is given in Table I for various relevant times and representative initial reradiating temperatures, T_{RR_0}. (In Fig. 10, these initial temperatures, T_{RR_0}, are related to a required yield at a given burst height.) $F'_n = F_n$ as defined in Eq. (40) for $n>1$; however, $F' \neq F_0$, as F'_0 is the transmission factor corresponding to the path from ground zero to the median radius of the reradiating layers, as given in Eq. (42).

The ratio of the energy flux received at a ground point nh km away from ground

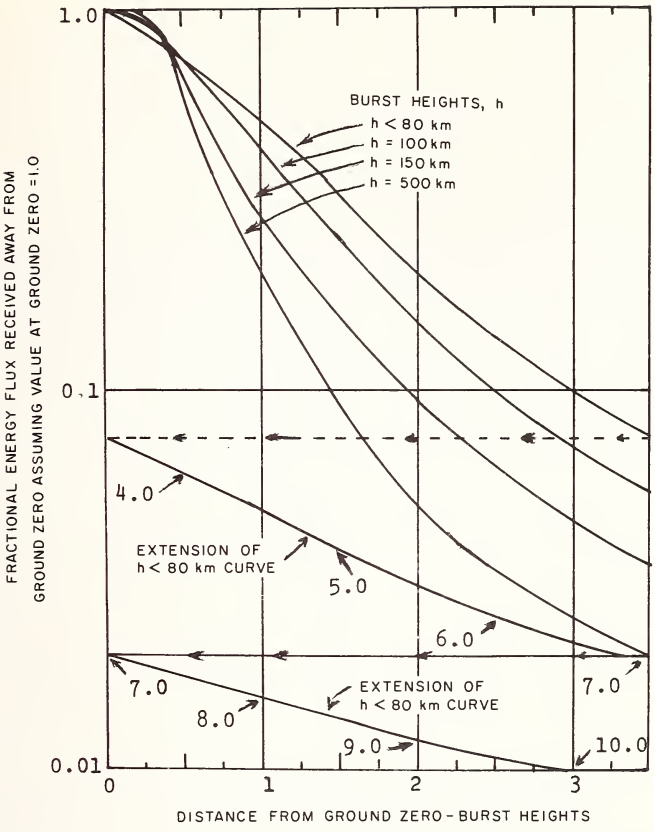

FIG. 12. The relative energy fluxes arriving at optimally oriented surfaces at various distances from ground zero (atmospheric attenuation neglected).

zero to that energy flux received at ground zero is thus given by

$$S_n^{UA}/S_0^{UA} = (F_n/F_0)\,(n^2+1)^{-1} \quad (h<80 \text{ km}), \tag{45}$$

$$S_n^{AA}/S_0^{AA} = (F_n/F'_0)\,(R_0^2/R_n^2) \quad (h>100 \text{ km}), \tag{46}$$

where R_0^2/R_n^2 and $1/(n^2+1)$ are plotted in Fig. 12 as a function of the distance on the ground from ground zero (in units of the burst height h for various representative burst heights).

Curves for Computing Ground Effects

The numerical results for ground effects are summarized in Figs. 12 and 13. These figures contain all the information needed to compute the energy flux received at any point on the ground from a nuclear detonation above 50 km altitude. The energy flux calculated is that which would be received on a surface oriented to receive the maximum possible radiation, i.e., facing the fireball. Figure 13 gives the yield required at a given burst height for energy fluxes at ground zero of 100, 10, and 5 cal/cm², assuming 100 per cent transmission by the atmosphere within

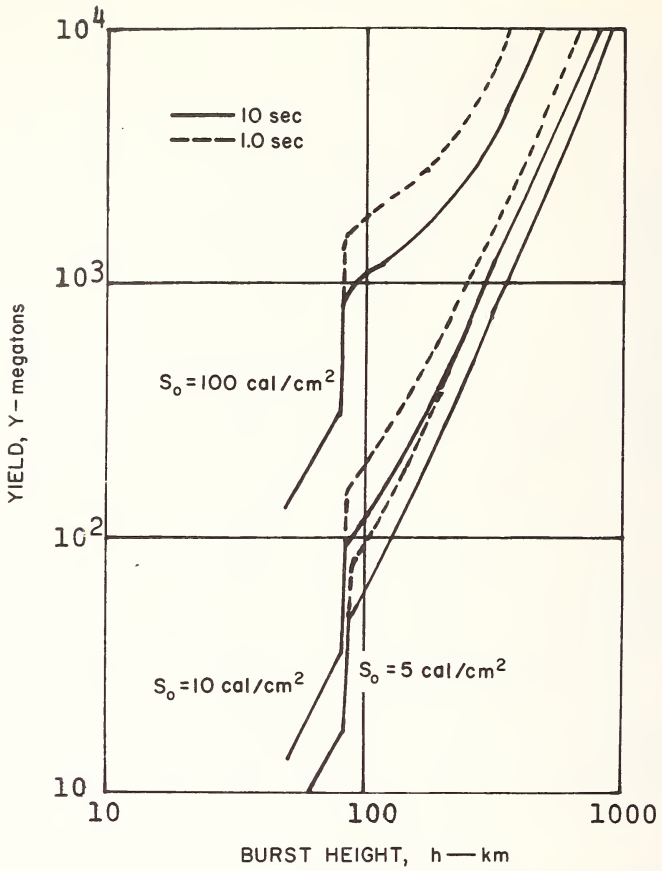

FIG. 13. The yield required at a given burst height for energy flux delivered at ground zero within 1 and 10 sec after detonation (horizontal surface, atmospheric attenuation neglected).

its assumed transparent window (3100 A to 19,000 A). Since the time behavior of the energy arrival is often of interest, separate curves are given for the energy arriving in the first 1-sec period and in the first 10-sec period, respectively, after detonation.

Figure 12 gives the fractional energy flux received at all points on the ground relative to that received at ground zero. The distance of the particular point of interest from ground zero is given in units of burst heights. For example, if the burst height were 100 km, the number 1 on the abscissa of Fig. 12 would correspond to a point 100 km from ground zero.

To illustrate the use of Figs. 12 and 13, consider a specific example: suppose a device of 100 megatons yield is detonated at 80 km altitude. To what distance from ground zero do optimally oriented surfaces receive 10 cal/cm² in the 1 sec following detonation? Entering Fig. 13 on the vertical line at 80-km burst height, we observe that the 1-sec and the 10-sec curves have merged and that 320 megatons gives 100 cal/cm² at ground zero. Since the S_0 curves are linear with yield below 100 km, S_0 for 100 megatons becomes $100/320 \times 100$ or 31.3 cal/cm². Now that we have the value for ground zero, we wish to know how far from ground zero one

must proceed to reduce the energy flux to 10 cal/cm². The relative reduction is to 0.32 or 32 per cent of the value at ground zero. Using the $h < 80$-km curve of Fig. 12, we observe that reduction to 0.32 occurs at 1.5 burst heights from ground zero or $1.5 \times 80 = 120$ km. The radius of the circle on which 10 cal/cm² is received the first second after detonation is thus 120 km.

The above analysis assumed 100 per cent atmospheric transmission within

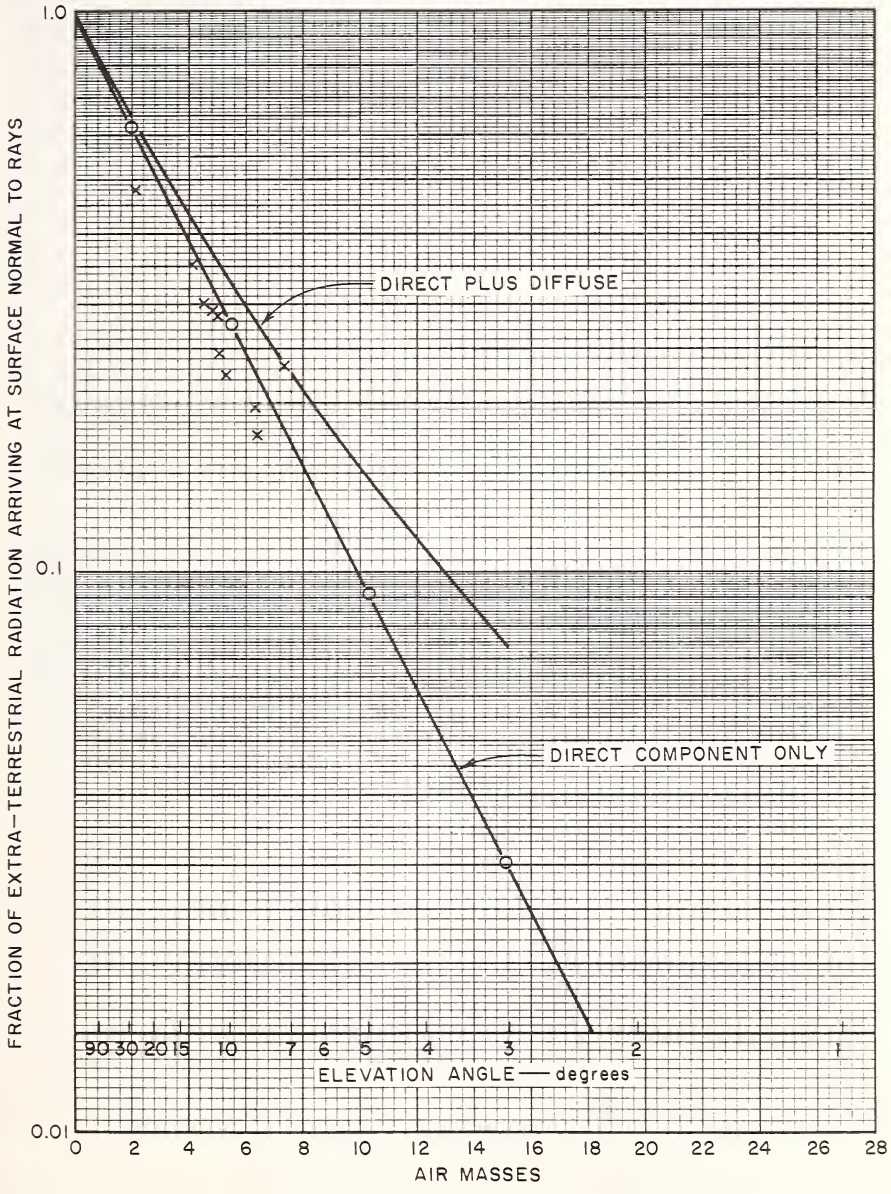

FIG. 14. Atmospheric attenuation factors as a function of elevation angle of the ray for the average clear day at sea level.

the atmospheric passband. Hence, the circle radius obtained is definitely an upper limit. We now consider the effect of atmospheric attenuation.

Atmospheric Attenuation. One common atmospheric condition for which attenuating properties are reasonably well known is "the average clear day at sea

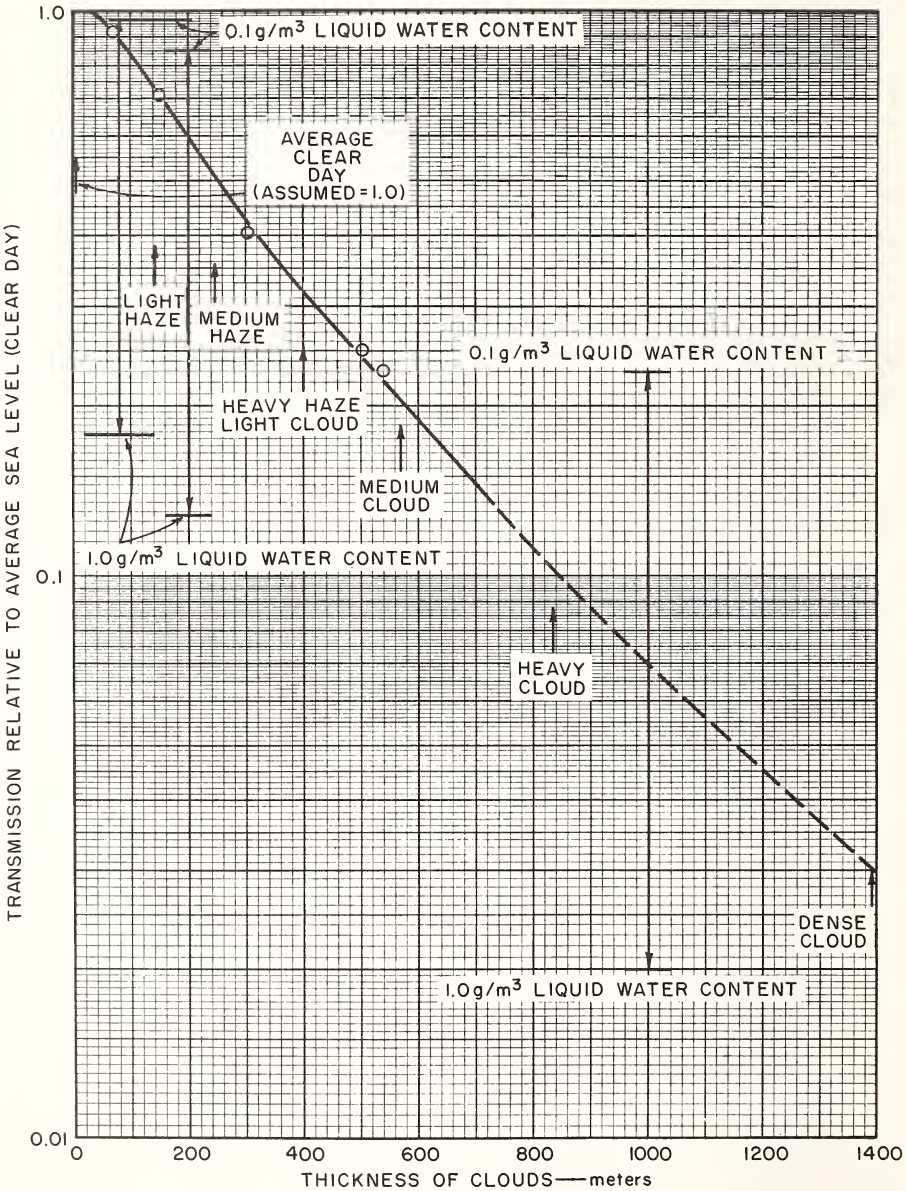

FIG. 15. Atmospheric attenuation factors as a function of cloud thickness and/or cloud density as visually judged.

level." For such an atmosphere, Jones and Condit[10] give transmission factors for the luminous fraction of solar energy which they derived from the earlier work of Moon.[11] If the radiation from high-altitude nuclear detonations is transmitted to the same degree as the luminous flux from the sun, we may use the data of Jones and Condit[10] without alteration as replotted for our purposes in Fig. 14. Note that one must determine the source elevation angle in order to apply the transmission factors of Fig. 14.

Having applied the transmission factor for the average clear day at sea level, an additional factor can then be applied to account for the attenuation due to haze, cloud, or fog. Figure 15 shows a combination of information on cloud transmission (assuming a value of 1.0 for the average clear day at sea level) taken from Jones and Condit,[10] Neiburger,[12] and Hewson.[13] The long vertical bars show the range of transmission values computed by Hewson[13] for clouds having 0.1 and 1.0 g/m^3 of liquid-water concentration. However, the values in Fig. 14 correspond to transmission to a horizontal surface. Since the transmission to an optimally oriented surface is always less than that to a horizontal surface, these values are upper limits.

In Fig. 15, the cloud thicknesses shown on the abscissa apply to experimental data obtained by Neiburger[12] in California coastal stratus and to the vertical bars representing theoretical calculations of Hewson.[13]

Jones and Condit[10] described clouds entirely in the verbal terms given near the appropriate transmission values in Fig. 15 (for an optimally oriented surface).

Calculation of Ignition Radii for Average Clear Day at Sea Level. The information

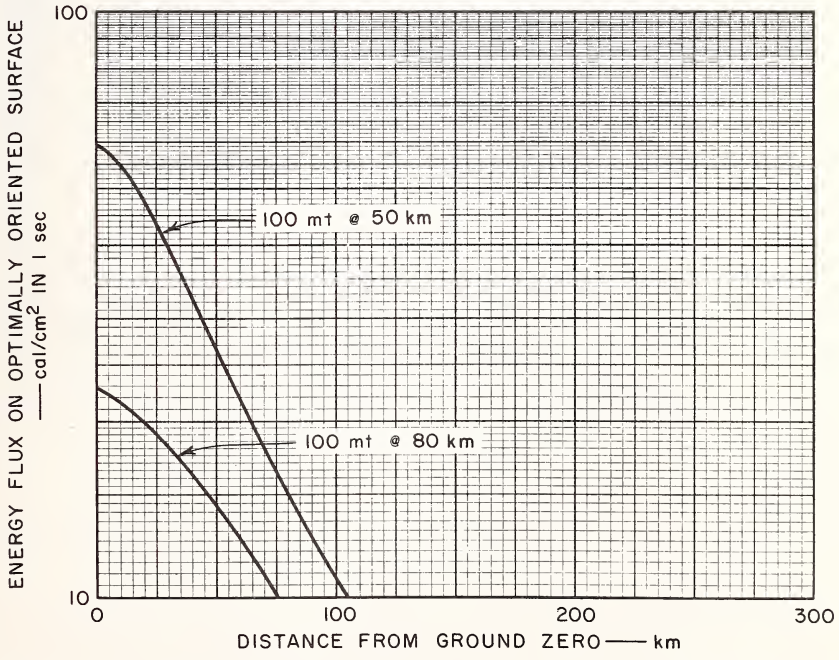

FIG. 16. The energy flux arriving at ground level in 1 sec from 100 megatons at two altitudes (average clear day at sea level, optimally oriented surface).

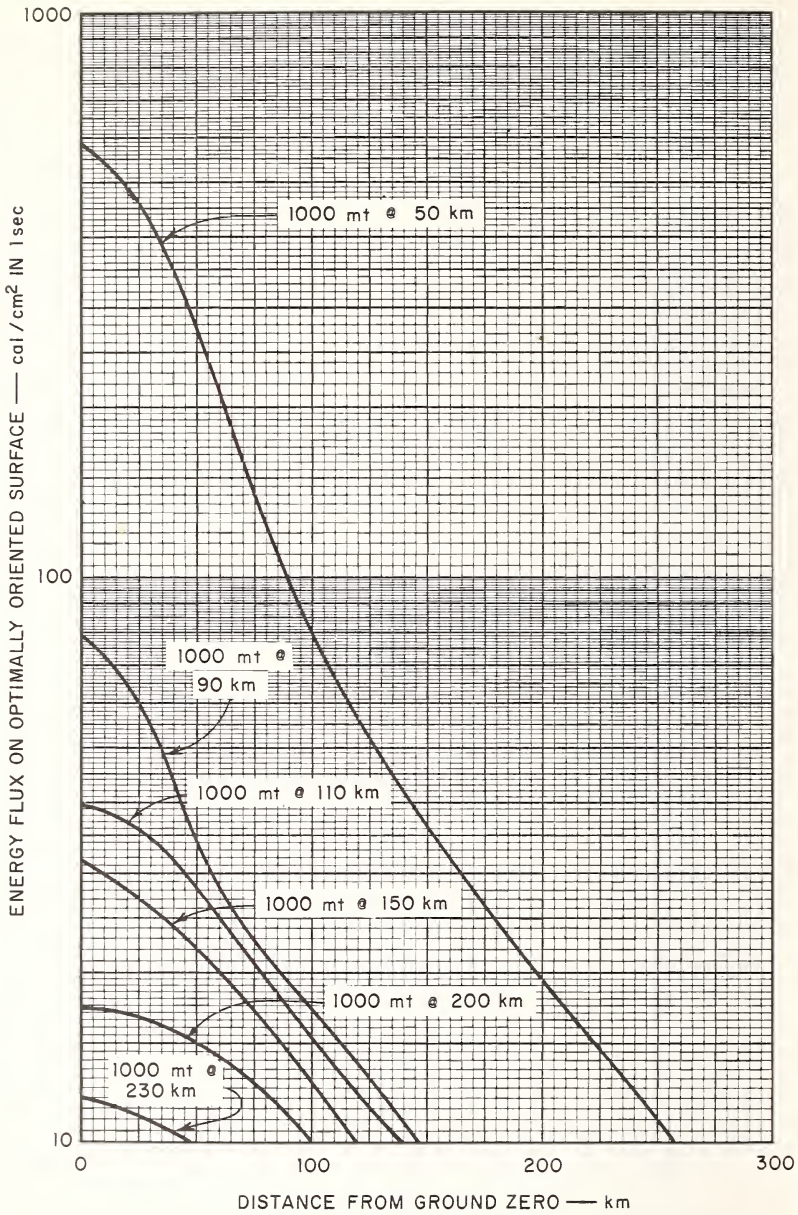

FIG. 17. Energy fluxes in 1 sec at ground level for a 1000-megaton detonation (average clear day at sea level optimally oriented surface).

in Figs. 12, 13, and 14 may now be combined to calculate energy flux as a function of distance from ground zero and, from this information, ignition-circle radii can be determined, provided the energy flux required for ignition is known. It will be assumed that ignition requires 10 cal/cm² delivered within 1 sec.

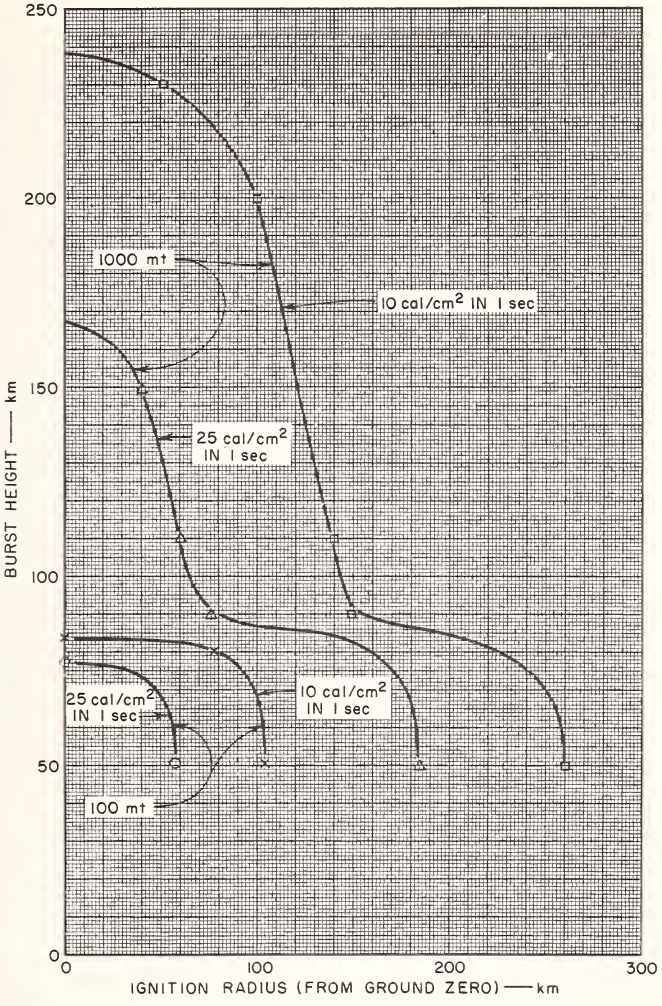

FIG. 18. Two ignition radii as a function of burst height for 100 and 1000 megatons (average clear day at sea level, optimally oriented surface).

Energy flux in 1 sec as a function of distance from ground zero is shown for several detonation heights for 100- and 1000-megaton yields in Figs. 16 and 17, respectively. From these figures and the specification of 10 cal/cm² in 1-sec energy flux required for ignition, ignition-circle radii as a function of burst height can be derived as in Fig. 18.

To obtain ignition radii for various conditions of cloudiness, Figs. 16 and 17 can be used with Fig. 15 and new ignition radii determined for each specific detonation height. For example, it is clear from observation of Fig. 16 that reduction of the energy flux by a factor of 6 would reduce the ignition radius to zero for 100 megatons detonated at 50 km. From Fig. 15 it is seen that a cloud condition described as "medium cloud" would give almost the required reduction.

Conclusions

The existence of a fireball ceiling in the altitude region around 80 km is perhaps the primary conclusion of this study. That is, regardless of the burst altitude the incandescent region capable of radiating within the atmospheric transparency window cannot be above ~80 km for initial detonation temperatures around 10^7 °K.

Fireball shape undergoes a sharp change as the burst height increases above ~80 km. Below 80 km the fireball is approximately spherical. Above 80-km burst height the fireball assumes the approximate shape of a flat circular disk centered about the 80-km level and parallel to the earth's surface. The radius of the disk is roughly equal to the burst height in km −80.

The 80-km upper limit for the fireball (or fire disk) altitude limits the area of the earth's surface which can receive radiant energy. This restriction comes about from the fact that the extreme limit of the ground range from a point at 80 km altitude is about 1000 km. Since atmospheric absorption has been neglected, the radius of the largest circle of irradiated earth from a single detonation is in fact always less than 1000 km.

There is a marked change in the efficiency for energy transfer from bursts that occur around 80 km altitude. For bursts below 80 km altitude (and above 50 km) intense thermal pulses less than 1 sec long occur at ground level for all yields above a few megatons. Within the 10 or 20 km above 80 km, the efficiency for conversion of energy to that which can reach the earth's surface suddenly drops from ~25 per cent to ~5 per cent. A further increase in altitude diminishes this efficiency even more, so that eventually the only radiation received at the ground is the flash fluorescence (a few microseconds in length) which has an efficiency of ~1.5 per cent (Meyerott, Landshoff, and Magee,[14] and Hartman and Hoerlin[15]).

Aside from a purposeful attempt to establish upper limits to ground effects throughout the study, the major uncertainty in the study is the assumption of thermal equilibrium within the incandescent layer, especially for detonations above 80 km. It is the author's opinion that this uncertainty will only be resolved by an experimental program to determine how fast x-ray flash-heated air reaches thermal equilibrium.

By applying empirical transmission data obtained from published studies of the sun to these theoretical calculations of energy fluxes from nuclear detonations, a series of curves of ignition-circle radius versus detonation height can be drawn. From one such curve, it is seen that the ignition-circle radius (10 cal/cm^2 in 1 sec assumed to be required for ignition) for a 1000-megaton detonation varies from 250 km at 50-km burst height to 0 km at 240-km burst height.

Acknowledgments

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ABSTRACTS

I. Ignition Phenomena

Simms, D. L. (Joint Fire Research Organization, Boreham Wood, England) "On the Pilot Ignition of Wood by Radiation," *Combustion and Flame* **7**, 253–261 (1963)

Spontaneous ignition of wood by radiation has been studied previously under conditions where the rate of heating is high enough for volatiles to be emitted from the surface, to mix with air and give rise to a flame, which then flashes down to the surface. The condition where the volatiles produced by a heated surface are ignited by a pilot flame has received less attention, although this system is of great practical importance. In the spread of fire the heat transfer may be by a radiation process while the volatiles emitted may be ignited by a burning brand simulated in experiment by a pilot flame.

It is upon such considerations that the safe separation distances between buildings will depend, based upon the minimum intensity of radiation at which pilot ignition can occur in addition to the maximum radiating temperature of the fire.

The time taken for irradiated wood to be ignited by a pilot flame depends not only upon the density of the wood and the intensity of radiation but also, at any given intensity, upon the position and possibly the size of the pilot flame. Two forms of ignition by pilot flame have been distinguished: one where the flame is not in contact with the irradiated surface (pilot ignition) and the other where flame spreads over the surface from the flame in contact with it (surface ignition). It has been confirmed that ignition occurs much sooner, and at much lower intensities of radiation with surface than with pilot ignition.

Reports by two authors who attempted correlations of the experimental results relating the ignition time to the intensity of radiation for different densities of wood are reviewed.

In a series of experiments described a number of woods of various densities have been subjected to a range of intensities of radiation and a pilot gas flame positioned at different distances from the irradiated face of the wood. The ignition time is measured for each case. The variation in ignition time with the position of the pilot flame shows that the concentration of volatiles in the air stream is not constant. This implies that relatively little mass diffusion occurs and that the flow in the volatile stream is laminar, not turbulent. This is in agreement with the theoretical treatment.

Ignition times can, however, be correlated by simple heat transfer theory, using a different surface temperature for each position of the pilot flame. At each of these correlating temperatures the rate of production of volatiles at the surface produces a flammable mixture at the pilot flame. The correlations are not complete because a small variation coupled with density remains and the behavior of fiber insulating board is anomalous, probably because self-heating is significant under some experimental conditions.

Consideration is made of the critical intensity of irradiation at which ignition is theoretically just possible; this is in effect the rate at which heat is lost from the surface at the temperature calculated. The minimum intensity at which ignition

occurs is higher than the critical intensity because the estimate of critical intensity neglects the fact that the supply of volatiles is limited.

The mean value of the critical intensity for pilot ignition is about 0.3 cal cm^{-2} sec^{-1} for unprotected dry wood. In practice, wood used in building is painted and contains moisture so that this figure can be used to calculate safe separation distances with a reasonable margin of safety.

Subject Headings: *Wood, ignition, by radiation; Ignition, of wood, by radiation; Radiation, ignition, of wood.*

G. L. Isles

Rothbaum, H. P. (Dominion Laboratory, Wellington, New Zealand) "Spontaneous Combustion of Hay," *Journal of Applied Chemistry* **13**, 291–302 (1963)

An experimental program was carried out to investigate factors which influence spontaneous combustion of hay and to clarify the conditions under which microbial heating can pass into chemical heating and eventually to ignition. Results indicate that under particular conditions of relative humidity the hay is heated slowly to about 75°C due to the action of thermophilic bacteria, then by chemical reaction which can cause ignition of the hay.

Tests were carried out under both adiabatic and isothermal conditions. Heat output, carbon dioxide production, and temperature rise, in the adiabatic tests, were measured. In adiabatic experiments relative humidity, which was carefully controlled, was shown to be of crucial importance. At values below 95 or above 99 per cent the hay temperature failed to exceed 70°C. The carbon dioxide production indicated only modest microbial activity at the lower humidities and, thus, insufficient heat was generated to appreciably raise the temperature. At the higher humidities, especially with excess water present, the carbon dioxide generated was quite high. However, the higher thermal conductivity provided by the water and water vapor permitted the dissipation of heat which prevented the temperature from rising from 70°C. Between 95.5 and 97.5 per cent relative humidity the temperature of the hay rose to and exceeded 75°C.

Above 75°C it was shown that further heating was neither caused by nor affected by the presence of microorganisms. A sample of hay, sterilized with a spray of 0.1 per cent mercuric chloride solution, showed no production of heat or carbon dioxide when left in a thermostat at 97.5 per cent humidity and 30°C for 2 days. This same sample when held in a 90°C thermostat produced carbon dioxide at a rate equal to that produced by a nonsterilized sample that had been permitted to heat itself adiabatically to 90°C. Thus, chemical heating is independent of previous biological activity.

Finally, the effect of the presence of water on the chemical heating was investigated. It was found that between 90° and 130°C the carbon dioxide generated in dry hay is significantly less than that in wet hay. Between 150° and 200°C the rates approach each other, indicating that the heating of wet hay merges into dry heating, which raises the temperature to the ignition point.

Thus, the spontaneous ignition of hay is crucially dependent on relative humidity. Microbial heating will raise the temperature above 70°C only under conditions of

95 to 97.5 per cent relative humidity. Chemical heating, which becomes significant above 75°C, is insufficient in dry hay to cause appreciable temperature rise. With moisture present the temperature can rise to 150°–200°C at which point the hay is dehydrated and further heating and ignition is not dependent on water content.

Subject Headings: *Hay, spontaneous combustion; Ignition, spontaneous, of hay.*

F. Falk

II. Thermal Decomposition

Simms, D. L. (Joint Fire Research Organization, Boreham Wood, England) "Damage to Cellulose Solids by Thermal Radiation," *Combustion and Flame* **6**, 303–318 (1962)

Radiant heat, the chief means of heat transfer in a well-established fire, damages such cellulosic materials as wood by (1) charring, (2) ignition, or (3) thermal destruction when charring or flaming persists. Ignition may be (a) spontaneous when enough flammable volatiles are emitted and mix with air, (b) pilot when an independent flame or spark sets off the combustible gases, or (c) surface when an independent flame touches the wood.

The heat balance in a dry, non-reflective solid involves: (a) external heating, assumed to be radiant with impulse either constant in time or of form similar to a nuclear explosion and absorbed over a range of thickness of diathermanous solid (natural wood) or in an infinitesimally thin surface layer of opaque solid (blackened or charred wood); (b) conduction normal to the surface within the solid; (c) thermal capacity of the solid; (d) convective transfer by volatiles moving within the solid (effectively zero before charring); (e) heat generated by decomposition of the solid; (f) surface cooling (assumed Newtonian). From these, assuming external heating of an area linearly much greater than the depth of heating and heating normal to the surface, the differential equations are derived for the thermal balance and the chemical balance in the solid and from these equations several dimensionless groups are obtained for use in correlating experimental results.

The general analysis is too complicated for practical use but it is usually possible to neglect one or more terms and thereby obtain useful simplifications. For opaque solids all terms containing the attenuation coefficient for diathermanous material drop out. If internal chemical heating can be neglected terms containing heat of reaction, gas constant, activation energy, and frequency factor are eliminated and temperature becomes the dependent variable, dependent only on the conventional conduction parameters for an inert, diathermanous material. Rearrangement of the Fourier number term gives a dimensionless time variable, the ratio of the rate of conduction of heat away from the surface to the rate of retention of heat, which measures the "age" of the problem—when small indicates that the material is effectively of infinite depth, and when large that the material is effectively thin. The dimensionless Biot number term is essentially the ratio of surface to internal resistance. The equation for an opaque, inert material can be simplified and sometimes solved by combining the terms for Fourier number and Biot number; for semi-infinite solids the thickness is unimportant and if the resulting term is small surface

heat losses may be neglected, for thin slabs with a quasi-stationary state the conductivity is eliminated and the mean temperature rise can be expressed in terms of this parameter and the energy modulus. If the heat losses are large the energy required to produce a certain level of thermal damage increases with the time of exposure.

The criteria suggested by various authors (38 references are cited) for the onset of the different kinds of thermal damage are examined. These criteria are: (1) a given type of thermal damage occurs when the temperature of the solid reaches a fixed value of either RT/E (gas constant, absolute temperature, activation energy, respectively) or T; (2) continued burning occurs when volatiles are evolved at a critical rate; (3) charring begins at any depth when the volatile content there falls to a certain value; (4) a similar weight loss criterion; (5) for thin materials continued burning occurs when the mean temperature reaches a certain value. There follows detailed discussion of charring and weight loss problems, spontaneous ignition time under constant intensity of radiation, the threshold condition for spontaneous ignition under radiation varying with time as in a pulse, pilot ignition, surface ignition, continued burning, and thermal destruction.

It is concluded that, if chemical heating is negligible compared with the external heating, and if the onset of thermal damage is rapid, then, provided conditions in the volatile stream can be ignored, equations defining chemical criteria for thermal damage may be neglected and materials may be assumed to have "thermal damage temperatures". Experimental results for the onset of charring, for spontaneous ignition (both for ignition times and threshold conditions), for pilot and surface ignition and for continued burning are correlated in this way. This method is not applicable at very high rates of heating when the rate of chemical reaction in the solid presents a limiting condition and at low rates of heating when the supply of volatiles may be exhausted.

Subject Headings: *Cellulose, damage, by thermal radiation; Radiation, damage, to cellulose; Wood, radiation damage; Ignition, of cellulose.*

F. L. Browne

III. Heat and Material Transfer

Rasbash, D. J. (Joint Fire Research Organization, Boreham Wood, England) "Heat Transfer between Water Sprays and Flames of Freely Burning Fires," *Proceedings of the Symposium on the Interaction between Fluids and Particles*, The Institution of Chemical Engineers (London, 20–22 June 1962)

This paper presents measurements of the heat transfer to water droplets in a flame and measurements on the extinction of flames using water sprays. A theory for the penetration of a water spray into a hot gas is also developed. In the measurements of heat transfer rates water droplets were suspended on fine quartz fibers of different diameters in a Bunsen burner flame. By extrapolation, times of evaporation were determined for a hypothetical fiber of zero diameter. Based on these data the empirical equation for heat transfer to droplets given by Ranz and Marshall[1] was

modified to the form

$$\frac{hD}{k}=\frac{\lambda}{\lambda+0.4\beta}\left[2+0.6\left(\frac{c\mu}{k}\right)^{0.33}\left(\frac{\rho vD}{\mu}\right)^{0.5}\right], \tag{1}$$

where h = heat transfer coefficient, D = drop diameter, k = thermal conductivity of the gas, λ = heat required to vaporize unit mass of water, β = enthalpy increase of the water vapor, c = specific heat of the gas, μ = viscosity, ρ = gas density, and v = velocity of the flow.

A theory is developed to translate the heat transfer to a single droplet into the volume cooling of a flame with a spray of water droplets. The change in velocity of the droplets after they enter the flame is considered, using an empirical equation for the drag coefficient. Also, the change in size of the droplets is determined until the droplets disappear. The heat lost by the flame per unit time and volume, X, is given by

$$X=(6\dot{m}/\rho_L vD)h\,\Delta T, \tag{2}$$

where $\dot{m}$ = mass flux of droplets of diameter D, ρ_L = density of water, and ΔT = temperature difference between the flame and the droplets. Calculations show that X increases as the diameter of droplets decreases; however, 0.005 mm droplets

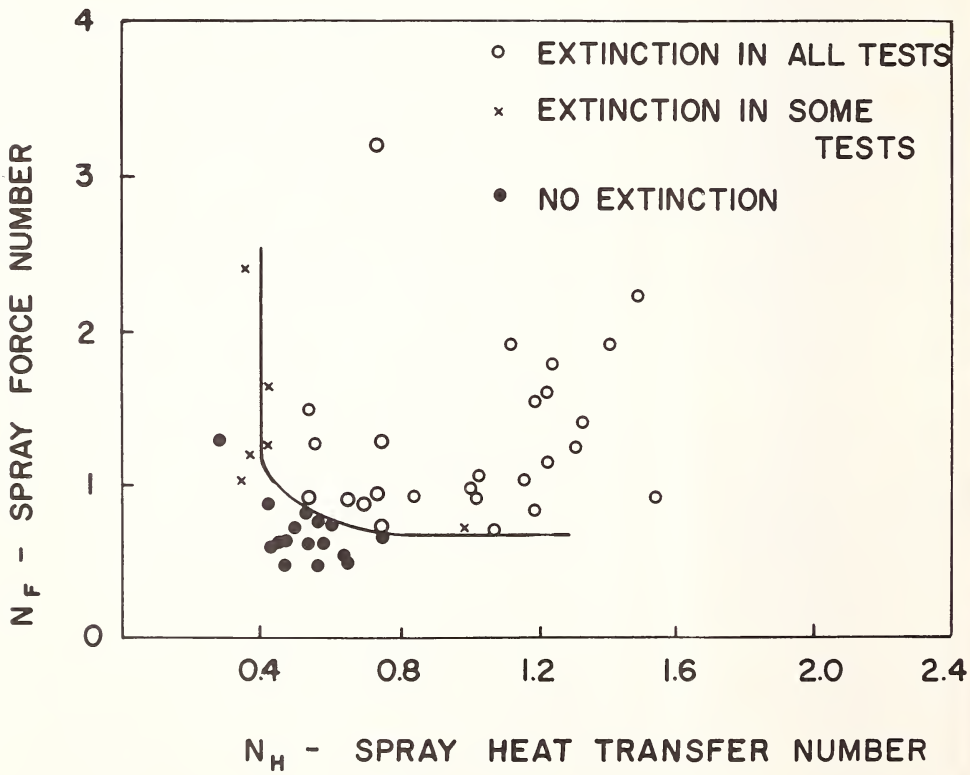


FIG. 1. Extinction of flames of burning hydrocarbons with water spray.

penetrate only 1 cm into the flame while 0.020 mm droplets penetrate 22 cm for the conditions considered.

Experiments were carried out to determine under what conditions a burning pan of fuel could be extinguished when sprayed from above with water. Kerosene, gasoline, and benzole were burned in a 30-cm-diameter vessel. The data were correlated using two dimensionless variables. The first was the spray heat transfer number,

$$N_H = XV/MH, \tag{3}$$

where V = volume of the flame, M = mass of fuel burned in unit time, and H = heat of combustion of the fuel. N_H represents the ratio of the rate at which the flame imparts heat to the spray to the rate at which heat is being produced in the flame. The second dimensionless variable is the spray force number

$$N_F = (\rho_a v_a^2/[\rho_a - \rho_f]gx) \ , \tag{4}$$

where ρ_a = ambient air density, v_a = velocity of air entrained in the spray, and x = height of the flame. N_F is proportional to the square root of the ratio of the downward force of the spray and the upward force of the flame. The results of the experiments are shown in Fig. 1. Reliable extinction took place only if N_F and N_H were greater than 0.4 and 0.7, respectively. In order to extinguish a flame a spray must be capable of abstracting a certain critical value of heat from the flame. In addition, however, the spray must be capable of penetrating the flame.

Reference

1. Ranz, W. E. and Marshall, W. R.: *Chem. Eng. Progr. 48*, 141 (1952).

Subject Headings: *Heat transfer, from water sprays; Water, heat transfer, from sprays; Fire, heat transfer to, from water sprays; Sprays, heat transfer, to fires; Flame, heat transfer to, from sprays; Droplets, heat transfer from, to fires.*

T. C. Turcotte

Cahill, J. P., Gauvin, H. P., and Johnson, J. C. (Air Force Cambridge Research Laboratories, Bedford, Massachusetts) "Effective Transmission of Thermal Radiation from Nuclear Detonations in Real Atmospheres," *Air Force Surveys in Geophysics No. 144* (April 1962)

How can one predict the thermal heat load, on man and machine, imposed by a nuclear explosion?

If you are faced with this task, this report offers a simple and comparatively realistic predictive technique. However, the manner in which this work is cast makes it more directly valuable to the user, rather than the receiver, of a nuclear device; data presentation is in terms of such parameters as burst altitude and slant range which would best be known by those controlling the initiation of the explosion.

Nevertheless, this inquiry into the effectiveness of representative real atmospheres to transmit heat, is a valuable compilation of fact and analysis beyond the

revealed characteristics (unclassified) of the special heat source motivating the report.

The atmosphere attenuates radiation primarily by absorption and scattering. All radiant energy transmission in this study is considered between the atmospheric transmission cutoff wavelength of 3200 Å and the explosion source intensity limit of 3.57 microns. Absorption in this spectral range is principally by water vapor and carbon dioxide components of the atmosphere, with minor oxygen absorption in the 7000–8000 A band.

Scatter by suspended atmospheric particles decreases in magnitude with altitude and becomes a Rayleigh scattering process, at 30 kilometers altitude, which varies as the inverse fourth power of the wavelength. Along the horizontal range, scattering decreases inversely with surface visibility, but because of the larger number of suspensoids rather than particle size.

Pertinent test data on nuclear explosions are summarized in the report. The fireball of air bursts is treated as a spherical black body at a surface temperature of 8000°K. In contrast, surface bursts are considered a hemispherical source at 5800°K temperature. Although the actual thermal pulse "spikes" rapidly and then declines before slowly rising to a second maximum (followed by a slow decay), only the latter maximum is considered the important thermal energy source. The fireball radius R_s for a surface burst of yield W is approximated by $R_s = 180W^{\frac{1}{3}}$ at the time of this second maximum (R_s in feet, W in kilotons of TNT).

The ratio of total weapon yield to radiation yield is the thermal partition, F_T; it is a function of burst type and nature of reflecting boundary. The authors conclude from weapon test data that $F_T = 0.49$ for an air burst, 0.32 for a surface burst over water, and "somewhat lower" than 0.32 for a surface burst over land.

The specific radiant energy detected from the two kinds of bursts is shown to vary only by a geometric factor $(1+\cos\theta)$, where θ is the angle between the slant range R and the vertical.

Surveys of meteorological data from semitropical islands and mid-continent stations reveal 72 combinations of parameters affecting atmospheric transmission. These have been grouped into six basic atmospheric models: Tropic (ocean and land surface), Temperate (ocean and land surface), and Arctic (snow field and solid cloud undercast), for use in the computations.

With these thermal source data and atmospheric attenuation characteristics, the authors have formulated a finite difference equation for effective transmission factor τ, which has been programmed for IBM 704 machine computation. This transmission factor is, in essence, the ratio of maximum specific radiant energy $\mathcal{Q}$ (received by a detector) to the energy which it would receive in the absence of a real attenuating atmosphere and reflecting surface $\mathcal{Q}_0$. (The detector is characterized as a flat, perfectly absorbing surface at slant distance R from the thermal source.)

The digital computer results are summarized by 18 graphs of smoothly varying transmission factor contours for the six synthesized cloudless atmospheric models, horizontal and vertical distances of up to 100,000 feet, bursts at zero, 5000, and 30,000 feet altitude, and visibilities of 2, 10, and 50 miles.

It is found that the most sensitive parameters affecting the value of transmission factor are the scattering factor and the albedo factor. At distances where survival is considered possible, the least important attenuating mechanism is water vapor absorption in the infrared. However, the major source of inaccuracy in using the

graphical results is the admitted lack of precision associated with the information available about atmospheric scattering.

Subject Headings: *Nuclear detonation, transmission of radiation; Radiation, transmission, from nuclear detonation.*

K. M. Foreman

Steen, H. K. (Pacific Northwest Forest and Range Experiment Station, U. S. Forest Service, Portland, Oregon) "Relation between Moisture Content of Fine Fuels and Relative Humidity," *U.S. Forest Service Research Note PNW-4* (1963)

Data on diurnal changes in relative humidity and corresponding changes in moisture content of fine forest fuels are presented in this paper. The data were collected at the Wind River Experimental Forest near Carson, Washington.

Relative humidity and moisture content measurements were taken from early morning to late evening over a four-day period. The fuels tested were common in the Pacific Northwest and included rotten wood of Douglas fir, duff from an overmature stand of Douglas fir and western hemlock, dead needles from ponderosa pine litter, dead cheatgrass, and dead western bracken. The fuels were exposed in trays or pans on the ground in a sunny location. Moisture contents were determined using the ovendry weight method, and relative humidity and temperature were measured with a hygothermograph located near the test site.

The diurnal pattern of relative humidity and moisture content were found to be very similar. Sudden changes in relative humidity resulted in like response in moisture content. Though the diurnal trends were similar, the fuel moisture content for a given relative humidity was found to be quite variable. This was especially true where the relative humidity was rising or falling. A more consistent relation between relative humidity and fuel moisture occurred in afternoon than in the morning.

Of the fuels tested, bracken generally had the highest moisture content. During midday, cheatgrass and rotten wood had the lowest. The most reponsive fuel to humidity change was cheatgrass while pine needles and duff showed less response. In general, a relative humidity of 50 per cent nearly always resulted in a fine fuel moisture of 10 per cent or less; humidities near 30 per cent resulted in a 5 per cent moisture content.

The author states that, at many locations in Oregon and Washington, diurnal changes in humidity similar to those analyzed in this paper will result in similar trends in fuel moisture. He concludes that in localities where weather conditions are similar to the study area, these relations can be used to estimate the moisture content of fine fuels. Differences in patterns of fuel moisture will result from the presence or absence of dew formation, temperature differences, amount of solar radiation, and location of recording instruments.

Subject Headings: *Fuel, moisture content and humidity; Humidity, relation with moisture content; Moisture content, of fuels.*

W. Y. Pong

IV. Diffusion Flames

Gross, D. and Loftus, J. J. (National Bureau of Standards, Washington, D. C.) "Surface Flame Propagation on Cellulosic Materials Exposed to Thermal Radiation," *Journal of Research of National Bureau of Standards* 67C, 251–258 (1963).

Results and analysis are given of a standardized flamespread test in which a cellulosic material is exposed to thermal radiation, and the subsequent flame propagation measured in terms of an arbitrary flame-speed index. The propagating flame is taken to be analogous to a series of progressive surface ignitions of the thermally irradiated material. The data are treated to delineate the important physical and thermal properties for surface flame propagation on simple and composite slabs.

The test procedure has been described in an earlier paper published in this review.[1] An inclined 6″ wide × 18″ long specimen is irradiated by a vertical panel of porous refractory material in which a premixed gas–air flame burns to give a black body temperature of 670°C. The combustible gases that rise along the surface of the specimen are ignited by a pilot igniter of acetylene–air placed at the upper edge. Progress of the flame downward along the specimen surface, and the temperature rise of thermocouples are measured.

The flame speed index I_s is computed as the product of the flame-spread factor F_s and the heat of evolution $\mathcal{Q}$, where

$$F_s = 1 + t_3^{-1} + (t_6 - t_3)^{-1} + (t_9 - t_6)^{-1} + (t_{12} - t_9)^{-1} + (t_{15} - t_{12})^{-1}$$

and

$$\mathcal{Q} = 0.1\Delta\theta/\beta.$$

The symbols t_3 to t_{15} correspond to time in minutes from beginning of specimen exposure to arrival of the flame front at positions 3 to 15 inches, respectively, along the length of specimen. $\Delta\theta$ is the observed maximum thermocouple temperature rise minus the maximum temperature rise observed with a thick asbestos-cement board substituted for the specimen; β is a calibration constant.

Equations of analyses of the radiation induced ignition process are given for thin and thick materials following the approximations of Simms.[2] The solutions are of the form

$$\theta = (I/H) f(x/l,\ kt/\rho c l^2,\ Hl/k),$$

where θ is the temperature rise of the opaque inert slab of thickness l, density ρ, thermal conductivity k, and heat capacity c; x is the distance in the slab measured from the irradiated surface, t the time, I the irradiance falling on one face, and H the Newtonian cooling coefficient of both faces. The approximate equations are

(1) for thin materials:

$$\theta_s = (I/2H)[1 - e^{-Ht/\rho cl}]$$

(2) for thick materials:

$$\theta_s = (I/H)[1 - e^{b^2}\ \mathrm{erfc}\ b]$$

where

$$b = \mathrm{H}(t/k\rho c)^{\frac{1}{2}}$$

and

$$\text{erfc}\ (b) = 1 - \text{erf}(b) = \frac{2}{\sqrt{\pi}} \int^{\infty} e^{-\xi^2}\, d\xi.$$

Since the flame-spread factor F_s consists of a series of reciprocal time periods, an inverse hyperbolic relationship exists between F_s and ρcl for thin materials and between F_s and $k\rho c$ for thick materials.

An approximate solution for the temperature rise of a composite slab is also given. The equation for thick-skin material reduces to

$$\theta_s = (2I/\sqrt{\pi})(t/k_1\rho_1 c_1)^{\frac{1}{2}}$$

and for the critical thickness as $l_1' = (\pi\alpha_1 t)^{\frac{1}{2}}$, where α is the thermal diffusivity $= k_1/c_1\rho_1$.

The above theoretical equations are followed approximately by the measurements of surface propagation and computed values of the flame-spread factor. The data for thin panels (veneers of balsa wood ranging in thickness from 0.071 to 1.26 cm and hardwood from 0.081 to 0.635 cm) are represented by $F_s = 5 + (1.5/\rho cl)$; the data for thick panels (from 0.6 to 1.2 cm thick) by $F_s = 5 + (0.003/k\rho c)$. For the composite assembly of a thin veneer over a semi-infinite substrate, F_s is a function of the thermal inertia of the substrate to veneer in accordance with the functional relationship. The substrate in combination with the thinnest veneer and with the greater $k\rho c$ difference from the veneer are shown to have the most effect upon the surface temperature. The relationship $I_s = 100 + (0.02/k\rho c)$ is shown to be able to represent the data of all thick cellulosic materials.

The correlations achieved, especially for thin and thick materials, support the concept that flame propagation on surfaces of cellulosic materials exposed to thermal radiation consists of progressive ignition of the solid when a characteristic temperature is reached.

References

1. Gross, D. and Loftus, J. J.: Fire Research Abstracts and Reviews *3*, 151 (1961).
2. Simms, D. L.: *Combust. Flame 4*, 293 (1960).

Subject Headings: *Cellulose, flame propagation; Flame, propagation, on cellulosic materials; Radiation, effect, on flame propagation.*

J. M. Singer

Powell, F. and Taylor, T. W. (Safety in Mines Research Establishment, Buxton, England) "The Propagation of Flame over a Coating of Lydopodium Spore Dust on the Interior Surfaces of 7 cm and 14.5 cm Diameter Horizontal Perspex Tubes," *Combustion and Flame* **7**, 207–208 (1963) Letter to the Editor.

As part of an attempt to determine the mechanism by which dust explosions propagate horizontally, the authors noticed that in lydopodium spore dust a flame would propagate at about 50 cm/sec without disturbing the dust, presumably by the mechanism of distillation of the volatiles ahead of the advancing flame front.

With the tube closed at one end, propagation rates as high as 250 cm/sec were obtained. In large tubes, only the upper half of the tube needed be dusted to obtain propagating conditions. Attempts to propagate a flame over coal or cork dust were unsuccessful.

Subject Headings: *Flame, propagation, on lydopodium spore dust; Dust, flame propagation on.*

D. Dembrow

V. Combustion Principles

Spalding, D. B. and Jain, V. K. (Imperial College, London, England) "A Theoretical Study of the Effects of Chemical Kinetics on a One-Dimensional Diffusion Flame," *Combustion and Flame* **6**, 265–273 (1962)

This paper is concerned with the study of a particular, idealized hydrocarbon–air diffusion flame. The general problem of a one-dimensional diffusion flame has been studied by several authors, each of whom approximated the reaction-rate mechanism differently. As a result, the solutions, while showing the same general results, differ in specifics and are quantitatively valid only for relatively restricted reaction mechanisms. In the same spirit, this analysis contains an approximate reaction mechanism which is considered to be more realistic for hydrocarbon–air flames than those employed heretofore.

In the problem considered, fuel flows through a porous plate into one end of an adiabatic duct. At the other end, air is blown across the duct in a direction perpendicular to the fuel flow. A reaction zone exists in the duct toward which fuel and oxygen diffuse and from which the products of combustion diffuse. Conservation equations are written for the enthalpy, fuel mass fraction referred to the unburned state of the mixture, and for the oxygen and secondary fuel concentrations. Secondary fuel refers to carbon monoxide and hydrogen. The Lewis number is taken to be unity and the exchange coefficients are assumed to vary linearly with temperature.

In approximating the actual hydrocarbon–air reaction mechanism, three specific assumptions are made. First, the reaction between carbon dioxide and water vapor with the primary hydrocarbon fuel is very fast, giving carbon monoxide and hydrogen as combustion products. Second, the slower rate-controlling reaction is the combustion of carbon monoxide and hydrogen with oxygen. Finally, the rate of consumption of secondary fuel is of second order, depending on the oxygen and secondary fuel concentration, with an activation energy of 39.6 kcal/g mole.

The equations were transformed such that the fuel mass fraction became the independent variable, and a numerical solution was obtained for a particular idealized case. The results illustrate the conditions under which extinction results, a phenomenon which occurs when the fuel flow rate is increased to such an extent that the chemical reaction cannot keep pace and the flame is extinguished. Also, it is shown that relatively large quantities of unburned fuel escape through a diffusion flame. Finally, by equating the maximum fuel consumption rate per unit area with

the fuel consumption rate per unit area for a laminar premixed stoichiometric flame, an approximate relation is derived for the parameter which characterizes the diffusion flame extinction. While this relation gives favorable results when compared with the parameter value obtained in the numerical solution, more comparisons should be made before it can be applied with confidence.

Subject Headings: *Flame, effect of chemical kinetics; Diffusion flame, effect of chemical kinetics.*

T. C. Adamson, Jr.

Chase, J. D. and Weinberg, F. J. (Imperial College, London, England) "The Acetylene Decomposition Flame and the Deduction of Reaction Mechanism from 'Global' Flame Kinetics," *Proceedings of the Royal Society* **A275,** 411–430 (1963)

Surmounting many difficulties, acetylene decomposition flames have been stabilized above a novel flat burner and burning velocities (7.3 to 17.0 cm/sec) measured over a necessarily narrow range of pressure (2.5 to 3.3 atm) and temperature (1493° to 1693°K). To safely accomplish the potentially hazardous measurements the authors had to employ several new techniques. The arrangements included: (1) several flashback arrestors and bursting discs, (2) a fail-safe solenoid valve, (3) novel flowmeters consisting of variable assemblies of sintered plates, (4) a new type of laboratory acetylene compressor consisting of parallel strands of flexible tubing cyclically squeezed by a rotor, and capable of delivering stable gas flow rates at selected discharge pressures, and (5) a three-stream concentric tube burner, the core of which delivered acetylene, the middle annulus a small acetylene–air flow which served as a pilot to stabilize the edge of the main flame, and the outermost annulus a shroud of inert gases which swept away soot formed in the decomposition flame. Flame velocities were determined from particle tracks illuminated by interrupted light, and temperatures were measured by optical pyrometry. The results are interpreted within the framework of the Zeldovich, Semenov, and Frank-Kamenetskii theory of flame propagation, as are subsidiary data obtained in propane-air and ethylene-air flames to test the experimental procedure. The expressions employed by the authors to deduce over-all—or "global"—reaction order (1), and activation energy (2) are

$$\ln S_u = \tfrac{1}{2}(n-2)\ln P + K_1, \tag{1}$$

$$\frac{E}{RT_b} = \ln \frac{S_u^2 (T_b - T_u)^{n+1}}{T_b^{m+n+1} T_0^2} - K_2, \tag{2}$$

where S_u is the burning velocity (apparently referred to T_0—presumably 273°K, although this is nowhere stated in the paper), P is pressure, n is the effective over-all reaction order, E is the over-all activation energy, T_b and T_u refer to the final and initial flame temperatures, m is the temperature coefficient of thermal diffusivity (3/2 for an ideal gas), and for a given mixture K_1 and K_2 are constants at either fixed temperature or pressure, respectively.

For ethylene and propane, use of Eqs. (1) and (2) led, respectively, to over-all reaction orders of from 1.64 to 1.68 and from 1.35 to 1.41, and over-all activation

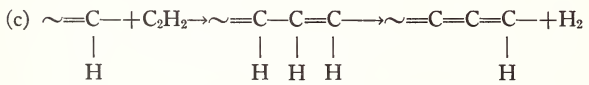
energies of from 43 to 46 and from 21 to 27 kcal/mole. However, when T_b was replaced by the temperature corresponding to the combustion of reactants to CO and H_2O, i.e., the temperature prevailing before the onset of CO afterburning, the data fitted Eq. (2) equally well. Values for E obtained by the latter procedure were from 4 to 8 kcal/mole which, as stressed in the paper, are in order of magnitude in accord with those to be expected if the hypothetical single rate limiting step implicit in the derivation of the Semenov flame propagation theory is identified with the destruction of fuel molecules by a free radical reaction. This result is significant in that it indicates that burning velocity data can be treated by either procedure, one yielding "effective kinetics," of empirical value, and the other yielding a perhaps more fundamental accounting of the basic flame reactions. The authors, however, consider the method to be inferior to more direct methods of investigating chemical kinetics in flames such as, for example, the use of scavenger and microprobes.

In the acetylene decomposition flames reaction orders of 1.2 ± 0.5 at 1633°K and 1.4 ± 0.3 at 1493°K were obtained. The authors interpret these results as indicating an essentially first-order reaction, consistent with the large excess of C_2H_2 in the flame. E was more accurately determined as (21.6 ± 2.8) kcal/mole, based on $n=1$, or (25.9 ± 3.9) kcal/mole for $n=2$. These results are in sharp conflict with the findings of both shock tube and low-temperature pyrolysis studies, which overwhelmingly favor a reaction order of 2, and appreciably higher activation energies (30 to 51 kcal/mole). The authors propose that in the absence of competitive heterogeneous mechanisms, the decomposition of acetylene at flame temperature occurs by the following (partial) mechanism:

(a) $H+C_2H_2\rightarrow C_2H+H_2$, $\Delta H=+9$ kcal/mole (Ref. 1); $E=1.5$ (*sic*) kcal/mole

(b) $C_2H+C_2H_2\rightarrow C_4H_2+H$, $\Delta H\approx-43$ kcal/mole; $E\ll26$ kcal/mole

followed by steps of the general type

(c)


Reaction (b) is thought to be rate controlling. H-atom participation is proposed to explain the authors' inability to ignite acetylene with a hot wire at temperatures up to 1200°K in the absence of a pilot flame and for the disagreement between over-all kinetics in these flames and in low-temperature pyrolysis. Similarly, the discrepancy with shock-tube studies is explained away by the inability of H atoms to significantly diffuse ahead of rapidly moving shock fronts. In all of these cases the authors believe the principal mechanism to be different from that dominating in the flames. They propose that one such alternate mechanism involves Reaction (c), in which solid reaction intermediates may participate. Heterogeneous reactions complicated these experiments seriously when soot deposition on the burner was not prevented.

The authors interestingly speculate that in cases where flame behavior is determined by diffusion upstream of reaction products, slow homogeneous reactions and reactions in shock-tubes may not bracket flame conditions but, in spite of temperature and residence times, may both lie to one side.

Reference

1. Bernecker, R. R. and Long, F. A.: *J. Phys. Chem. 55*, 1565 (1961).

Subject Headings: *Flame, acetylene decomposition kinetics; Acetylene, decomposition of*

S. C. Kurzius

Fenimore, C. P. and Jones, G. W. (General Electric Research Laboratory, Schenectady, New York) "Destruction of Acetylene in Flames with Oxygen," *The Journal of Chemical Physics* **39**, 1514–1518 (1963)

Using quartz microprobe and thermocouple techniques, the authors extend their study of stable and free-radical species concentration profiles in low-pressure hydrocarbon flame fronts to the acetylene-oxygen system. From the profiles obtained for C_2H_2, O_2, H_2, H_2O, CO and CO_2, the local rates of consumption or formation of C_2H_2, O_2 and CO_2 are deduced as a function of distance from the burner surface, employing diffusion corrections made on the basis of diffusivities extracted from the pre-flame front concentration profiles. The authors then interpret these data to determine the reaction partner by which C_2H_2 is destroyed, viz., either OH, H, O or O_2. This is accomplished in part through use of the comparison reactions

$$H+O_2 \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} OH+O, \quad k_1=4\times10^{14}\exp(-18\ \text{kcal}/RT)\text{cm}^3\ \text{mole}^{-1}\ \text{sec}^{-1} \tag{1}$$

$$CO+OH \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} CO_2+H, \quad k_2\cong5\times10^{12}\exp(-6/RT), \tag{2}$$

the rate constants given being those used in the paper.

As long as C_2H_2 was present, the formation of CO_2 was observed to be essentially irreversible, so that*

$$[CO]^{-1}\, d/dt\, [CO_2]=k_2[OH].$$

The authors reason that if C_2H_2 were destroyed primarily by OH with a rate constant k_2, then

$$-[C_2H_2]^{-1}\, d/dt\, [C_2H_2]=k'[OH]$$

and the ratio of the specific rates of reaction yields the ratio k'/k_2. Values for k' determined by this procedure for a C_2H_2+2.68 O_2+8.54 CO+5.14 Ar flame at 30 Torr led to an impossibly high pre-exponential factor for k'. On the basis of this result, it is concluded that C_2H_2 is not predominantly destroyed by reaction with OH. Similarly, the local O_2 consumption rate, when compared with the specific rate of C_2H_2 consumption also led to an impossible rate constant for the reaction of C_2H_2 with H atoms. Reaction of C_2H_2 with O_2 could also not be made consistent with the data.

* No direct evidence is yet available from hydrocarbon flames for the nature of the reaction forming CO_2. In explosion limit studies, however, Reaction (2) has been well verified. In flames, only the reverse of Reaction (2) has been studied.

The consumption of O_2 early in the reaction zone conformed to

$$-[O_2]^{-1}\, d/dt\, [O_2] = \text{constant} \times k_1,$$

indicating that [H] was constant in the early flame front. Based on the assumption that the H atom concentration remains fairly constant in the entire flame front (checked in some of the flames by scavenging with N_2O), i.e., that the forward rate of Reaction (1) is described by $d[O_2]/[O_2]\, dt$ as determined in the early flame front, the authors deduce values for [O] by taking the difference between the forward and observed specific rates of O_2 consumption, and equating the resulting rate to the reverse of Reaction (1). To obtain [O], [OH] was estimated from k_2 and the observed rate of formation of CO_2. In this way, the authors are able to fit their data for the destruction of C_2H_2 in 7 different flames to the reaction

$$O+C_2H_2 \rightarrow C_2H_2O^* \rightarrow CH_2+CO \quad \text{or} \quad H+HC_2O,$$

for which a very large rate constant of 1 to 2×10^{13} is reported. The temperature in these flames varied from 970° to 1660°K, and the pressure from 20 to 30 Torr. No trend with temperature was observed in the rate constant and ketene was not observed in the reaction products collected by the microprobes.

The destruction of C_2H_2 in flames contrasts with the destruction of the saturated molecules CH_4 and C_2H_6 by H or OH; but is consistent with the previous findings of the authors that the unsaturated molecule C_2H_4 is also destroyed in flames primarily by O atoms.

A valuable confirmation of the derived O-atom concentrations would have been their direct determination through the use of scavenger probes, as described, for example, by Fristrom.[1,2] Notwithstanding this omission, the work reported adds significantly to our widening knowledge of the details of combustion chemistry.

The authors have previously shown that the consumption of O_2 occurs primarily through Reaction (1).

References

1. Fristrom, R. M.: *Science 140*, 297 (1963).
2. Fristrom, R. M.: *Ninth Symposium (International) on Combustion*, p. 560, Academic Press, 1963.

Subject Headings: ***Acetylene, destruction in flame; Flame, destruction of acetylene.***

S. C. Kurzius

VI. Radiation

Simms, D. L. and Coiley, J. E. (Joint Fire Research Organization, Boreham Wood, England) "Some Radiation Characteristics of a Gas-Fired Panel," *British Journal of Applied Physics* **14**, 292–294 (1963)

An experimental investigation was carried out to measure the distribution of intensity of radiation from a proprietary-type gas-fired panel, the spectral formation of which is close to that of a black body and has an emissivity (ϵ) of 0.7.

The intensities (I) were measured at positions in several specified planes and compared with the corresponding values calculated using configuration factors (Φ), which assumes that Lambert's cosine law holds and may be computed from tables (McGuire 1953), by the expression

$$I = \epsilon\Phi\sigma(T^4 - T_0^4),$$

where σ is the Stefan–Boltzmann constant, T and T_0 the absolute temperatures of the radiator and the enclosure.

Hence, the constancy of I/Φ for any output of the panel is a measure of the uniformity of the panel and how well it obeys Lambert's law.

Three sets of results giving the values of I/Φ as functions of position and of radiant temperature are given. It was found that Lambert's law holds where the heat transfer is solely radiative. However, near the panel, convective heat transfer may amount to as much as that of radiative transfer. The intensity of radiation is uniform (to at least 90 per cent of the maximum) over an area of 50 cm² within 20 cm of the panel, beyond which the size of the area increases rapidly with distance.

Subject Heading: *Radiation, from gas-fired panel.*

A. S. C. Ma

VII. Suppression of Combustion

Miller, D. R., Evers, R. L., and Skinner, G. B. (Monsanto Research Corporation, Dayton, Ohio) "Effects of Various Inhibitors on Hydrogen–Air Flame Speeds," *Combustion and Flame* **7**, 137–142 (1963)

The effects of small amounts of eighty compounds (gases and vaporized liquids) on the speeds of some hydrogen–air flames were measured. The burning velocities were measured by dividing the area of the schlieren cone of the flame (on a slightly converging nozzle) into the gas-flow rate. The flame speed of the uninhibited mixture was a maximum at an equivalence ratio of 1.75.

Tables of data are given showing efficiencies of a large number of inhibitors when the equivalence ratio was at this value; while for several of the better inhibitors the effect of varying the equivalence ratio is shown graphically. Most of the inhibitors are more effective in rich than in lean mixtures.

The inhibitors were classified as:

Good: Saturated and unsaturated hydrocarbons, monohalogenated hydrocarbons, brominated hydrocarbons, metal carbonyls, some metal chlorides.

Fair: Hydrogen halides, inorganic sulfur compounds, partially fluorinated and chlorinated hydrocarbons, some metal halides.

Poor: Halogens, fully fluorinated and chlorinated hydrocarbons, oxides of carbon and nitrogen, silicon and boron halides.

Within each hydrocarbon series the effectiveness increased with the size of the alkyl group. The most efficient inhibitor studied was 1.3-butadiene, two per cent

of which reduced the burning velocity of the mixture with equivalence ratio 1.75 from 300 to 27 cm sec^{-1}.

Because of the comparatively small concentration of additives needed (<4 per cent), the inhibiting effects are assumed to be kinetic in origin, resulting in rich mixtures from replacement of reactive species like hydrogen atoms by, for example, less reactive alkyl radicals.

Subject Headings: *Inhibitors, effect on flame speed; Flame speed, effect of inhibitors.*

G. Dixon-Lewis

Palmer, K. N. and Tonkin, P. S. (Joint Fire Research Organization, Boreham Wood, England) "The Quenching of Flames of Various Fuels in Narrow Apertures," *Combustion and Flame* **7**, 121–127 (1963)

An extension of earlier work[1] on the quenching of propane–air flames, this paper gives the results of experiments on flame quenching using various hydrocarbon fuel flames. The fuels were hexane, acetone, acetaldehyde, ethyl acetate, benzene, diethyl ether, and ethylene.

The liquid fuels were vaporized into an air stream at the required rate and the stoichiometric air–fuel mixture was then cooled before being passed into the explosion tube. The tube was 6.4 cm internal diameter Perspex with a 0.6 cm wall thickness. For the tests it was closed at one end and mounted horizontally, except for some of the cool-flame experiments when it was vertical. The flame trap of perforated sheet or blocks was fixed across the tube, at a distance from the ignition source which was varied between 11.4 cm and 313 cm. A spark gap or small flame (for cool flames) served as the ignition source.

The perforated sheeting holes were rectangularly spaced at center spacings from 1.4 cm to 0.11 cm. The thickness of the sheeting varied from 0.124 cm to 0.046 cm. The blocks were 1 cm thick with holes 0.175 cm in diameter in the same pattern as the sheeting and they could be combined in packs with the apertures accurately aligned. Flame velocity was measured photographically, except in the case of the rather dim cool flames which were visually measured.

Using a formula[1] giving a relation between the critical flame velocity and the gas and aperture parameters the authors are able to compare the results with those obtained in the earlier work on propane–air flames. The results showed that the ease of quenching flames propagating in stoichiometric vapor–air mixtures was similar but not identical to that of propane–air mixtures at the same velocity. Part of the difference could be attributed to variation in the thermal properties of the flames.

Ethylene–air flames propagated through perforated sheeting and blocks with aperture diameters above 0.10 cm at lower critical velocities than the other fuels, the equation overestimating the required velocity by a factor of eight. The authors suggest that this may be due to the fact that the standard quenching diameter for stoichiometric ethylene–air flames is close to the aperture diameters used. In this case, only part of the surface of the apertures in the sheeting is involved before the flame regenerates by propagating into further unburned mixture.

Cool flames with fuel-rich mixtures of acetaldehyde and diethyl ether could be

quenched by perforated sheeting with relatively large holes, similar to those required for normal flames propagating at the same slow velocity.

Reference

1. PALMER, K. N.: The Quenching of Flames by Perforated Sheeting and Block Flame Arresters, *Symposium on Chemical Process Hazards with Special Reference to Plant Design*, p. 51, Institution of Chemical Engineers, London, 1961.

Subject Headings: *Flame, quenching, in narrow passages; Quenching, of flame, in narrow passages.*

M. G. Perry

Fittes, D. W. and Richardson, D. D. (Joint Fire Research Organization, Boreham Wood, England) "The Influence of Alcohol Concentration on the Effectiveness of Protein Foams in Extinguishing Fires in Gasoline Alcohol Mixtures," *Journal of the Institute of Petroleum* **49,** 150–152 (1963)

Recognizing that special "alcohol-type" foam suitable for extinguishing fire in water-miscible solvents may not always be readily available where the storage is predominantly of hydrocarbons, it was desired to determine the applicability of normal protein-based air foam to fires in blended fuel containing up to 20 per cent of alcohol.

Foam (expansion 8, shear strength 250 dyne/cm^2) made from 4 per cent foam liquid solution was applied at varying rates to fires in a two feet diameter pan. The fuel was a "narrow boiling-point range" petroleum distillate blended with 0, 1, 5, and 20 volume per cent of 95 per cent ethyl alcohol.

Gentle application employed a T-shaped applicator close to the fuel surface. Jet application was by a horizontally directed nozzle 2 ft horizontally and 1 ft vertically above the center of the fuel surface, the nozzle diameter being selected to give a constant efflux velocity.

The fires were considered controlled when the combined effect on 3 symmetrically spaced radiometers was reduced to one-third of the initial value.

With gentle application, the critical application rate below which control could not be achieved was found to be increased negligibly for 1 to 5 per cent of alcohol in the fuel, and by threefold when the fuel contained 20 per cent alcohol, the actual range being 0.016 to 0.05 gal/sq ft/min.

With jet application the critical rate increased rapidly from 0.016 to 0.13 gal/min/sq ft with increasing alcohol content. One test with a foam of substantially greater shear strength (stiffness) showed only nominal improvement in performance.

It is concluded that fires in fuels containing up to 20 per cent alcohol may be extinguished with gently applied normal protein-based foam, by an appropriate and often attainable increase in foam quantity and application rate over the requirements for unblended fuel. Jet application will apparently be impractical for high alcohol content fuels.

It is implied that the observed critical application rates and times for control

may be used to calculate the requirements for a large tank fire. Such extrapolation appears to the reviewer to be questionable.

Subject Headings: *Foam, effectiveness, in presence of alcohol; Fire, gasoline–alcohol, extinguishment by foam; Extingusihment, of gasoline–alcohol fuels, by foam.*

O. W. Johnson

Markels, M., Jr., Friedman, R., Fry, O., Macek, A., DuZubay, E., and Eichbauer, R. (Atlantic Research Corporation, Alexandria, Virginia) "A Program to Advance the Technology of Fire Extinguishment," *Technical Documentary Report No. ASD-TDR-62-526, Contract AF33(616)-8110, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio* (September 1962)

The report describes an investigation of possible methods of suppressing and extinguishing fires and explosions resulting from accidental spills of liquid hydrogen in the presence of liquid oxygen. The basic objectives and program and the facilities available have been outlined in previous abstracts.[1]

As a basis for extinguishment tests, burning rates of liquid hydrogen were measured in stainless steel Dewars of 2.5, 2.75, and 7.375 inches diameter, and for spill fires in steel pans of 9, 13, and 20 inches diameter. Burning rates in shallow Dewars were approximately equal to the evaporation rates without ignition. Extrapolation of the Dewar burning rates to zero depth/diameter rates indicated a steady burning rate on a flat surface of about 1.65 in./min. In the steel pans the rates were about 3.0 in./min due to the higher evaporation rate caused by heat leakage.

The extinguishment tests were first conducted on fires in small Dewars, and the more promising agents were then employed on spill fires. The most promising technique, which also appeared to be practical for larger fires, was the application of mechanical foam to cover the fire, followed by potassium bicarbonate. The rates of application were, for foam with an expansion ratio of 25 to 1, 0.35 gallon of contained water/min/sq ft while the potassium bicarbonate was applied at 0.7 lb/sq ft sec. This produced extinguishment in less than 5 seconds. Potassium bicarbonate and carbon dioxide, separately, also extinguished Dewar fires at application rates of 3.0 and 1.0 lb/sq ft sec, respectively, but these rates are too high for use with large fires. The important feature for extinguishment is *rate* of application: fires were either extinguished rapidly or not at all. For the foam–potassium bicarbonate combination, the rate of foam application is a minimum effective rate, while that of bicarbonate may be slightly above the minimum. The bicarbonate should be applied with a rapid fanning motion parallel to the fire surface. Neither sodium bicarbonate, ABC powder, steam water fog, bromotrifluoromethane, nor nitrogen were effective on Dewar fires. Potassium oxalate was effective on the single occasion on which it was used, but the powder caked and plugged the extinguisher.

A second phase of the investigation concerned suppression of detonation in the gaseous hydrogen–oxygen system. Ten additives were investigated: nitrogen, methane, methyl chloride, methyl bromide, methyl iodide, carbon tetrachloride, bromine, iron pentacarbonyl, tetramethyl lead, and water. Methane and methyl chloride both inhibited appreciably, but the best inhibitor was iron pentacarbonyl,

although it is probably too toxic for consideration as an extinguisher. With 2.2 per cent of the latter, detonation could not be initiated with 47 joules initiation energy, compared with 12 joules for the uninhibited mixture. Carbon tetrachloride sensitized the detonation. An attempt was made to extend the investigation to mixtures of solid oxygen and liquid hydrogen, but was discontinued following a gaseous explosion above the mixture.

Finally, a number of recommendations are made. First, if liquid hydrogen is spilled on the ground, extends to a depth of 2 inches or less, and ignites, extinguishment effort is useless. Evaporation and burning occur in less than one minute. If the spill is contained, however, in pools several inches deep, foam and potassium bicarbonate will cause extinguishment. Due to the low radiation level from hydrogen flames compared with hydrocarbon flames, danger to neighboring structures is diminished and, indeed, application of extinguishers will increase the radiation. Hence, spills on flat surfaces (particularly gravel) should be allowed to burn out, using water sprays to prevent spread. No attempt should be made to fight fire where liquid oxygen is spilled with liquid hydrogen, because of the danger of detonation in the condensed phase. The application of methyl chloride in small-scale fires as a detonation suppressant may be of some merit.

Reference

1. Fire Research Abstracts and Reviews *4*, 148 (1962).

Subject Headings: ***Hydrogen, suppression of detonation; Extinguishment, of hydrogen fires; Fire, suppression, of hydrogen fires; Detonation, suppression in hydrogen–air.***

G. Dixon-Lewis

Markels, M., Jr., Friedman, R., Macek, A., Haggerty, W., and Eichbauer, R. (Atlantic Research Corporation, Alexandria, Virginia) "A Program to Advance the Technology of Fire Extinguishment (Hydrogen-Oxygen)," *Technical Documentary Report No. ASD-TDR-62-526, Part II (Contract No. AF 33(616)-8110) Air Force Systems Command, Wright-Patterson Air Force Base, Ohio* (March 1963)

This paper is the second in a series on the inhibition and extinguishment of hydrogen–oxygen combustion. In the first paper, a systematic study of extinguishing liquid-hydrogen fires and the suppression of gaseous hydrogen–oxygen detonations was carried out. The present paper continues the work on gaseous detonations. In addition, methods for controlling liquid-hydrogen combustion and the extinguishment of liquid hydrogen–metal slurry fires are investigated.

In the gaseous-detonation suppression studies, the minimum initiation energy is the quantity used to determine whether the detonation is affected. If the energy increases, then the additive inhibits development of a detonation. In many cases, however, the minimum energy was lowered indicating promotion of the reaction. Experiments with gases were carried out in the apparatus used previously. The hydrogen–oxygen mixture of 62 per cent and 38 per cent, respectively, was used as a

standard or calibrating mixture throughout. This mixture was studied exclusively in the first phase. Reproducibility of data was good.

A total of sixteen gases were added to varied mixtures of hydrogen and oxygen. These included saturated, unsaturated, and halide-substituted hydrocarbons. It was found that methane and methyl chloride showed equal inhibiting power, while carbon tetrachloride and chlorine proved to be promoters. Because of the similar action of CH_4 and CH_3Cl, further experiments were performed in an attempt to explain the result. Addition of chlorine to the detonable mixture showed the strongest promoting effect encountered thus far. Extremely small amounts of this gas was effective, as indicated by the prolonged pumping required to assure reproducibility after an experiment with Cl_2. Absence of methyl radical was checked out by adding chloroform in amounts of 1 to 5 parts per hundred parts of mixture, and was found to be a promoter as expected. The methyl radical at this point was thought to be responsible for inhibition where CH_4 and CH_3Cl were employed. This belief was tested using di-tertiary butyl peroxide. This is an unstable compound, and it should provide a large number of CH_3 radicals. The compound promoted the detonation, but the authors conclude that the result is difficult to interpret since this molecule contains a large amount of oxygen.

The experimenters reasoned that compounds with many CH_3 groups should be better inhibitors than methane. Consequently, five saturated hydrocarbons from methane to isobutane were tested in hydrogen-lean mixtures. All of the compounds had a similar effect, the minimum energy was increased. The unsaturated hydrocarbons proved more interesting. Ethylene was found to be a promoter, while propylene, isobutene, and transbutene-2 were very good inhibitors. Butene-1 was less effective as an inhibitor. In fuel-rich mixtures (70 per cent H_2:30 per cent O_2), it was shown that isobutene is a much better inhibitor than any of the saturated compounds.

Two halogenated hydrocarbons (bromotrifluoromethane and 1,2-dibromotetrafluoromethane) promoted the detonation, but they are known to be good flame inhibitors. Combining these halogenated compounds with pure hydrocarbons as additive also failed to inhibit the detonation. There were a few experiments with solid powders. About 0.5 gram per liter was uniformly dispersed and the mixture was ignited before the material settled. Little conclusive evidence resulted, but it did appear that the reaction was inhibited slightly by addition of the powders.

Some comparisons are noted for inhibition results involving both flames and detonations. The pertinent observations are the following:

1. Ethylene inhibits a flame, but it is a good promoter of detonations.
2. Chlorine is a promoter in both cases, while pentacarbonyl iron is an inhibitor for both.
3. The two halogenated compounds tested inhibit flames, but they promote a detonation.

Results from the hydrocarbon studies enabled the authors to remark on the reaction kinetics. They conclude that the important step in the reaction mechanism is the capture of chain carriers by molecules and not by radicals. It is further stated that the inhibition effectiveness of hydrocarbons is directly related to the ease of removal of a hydrogen atom from the hydrocarbon molecule.

The remainder of this paper is devoted to the control of liquid-hydrogen fires. The practical concern here is the leakage hazard when using or handling the com-

bustible. Experiments were of two types: (1) those concerned with leakage into small confined spaces, and (2) those where leakage occurs in large confined spaces. For small spaces, the amount of combustion suppressant in air required can be obtained from flammability limit curves of the ternary mixture. The experiments dealing with large spaces merely identified certain compounds that are effective for extinguishment of these fires. The most efficient suppressor was a finely divided solid such as potassium bicarbonate. Halogenated hydrocarbon liquids also functioned well. Liquid hydrogen–metal slurry fires were found to be very much the same as combustion involving liquid hydrogen alone. Using coated aluminum particles, two tests showed absolutely no burning of the solid.

The paper contains a two-part appendix that could be helpful to some; (A) graphs of the results on small confined spaces, and (B) a detailed description of liquid-hydrogen facilities. In addition, the text is sprinkled liberally with graphs and illustrations.

Subject Headings: ***Hydrogen, suppression of detonation; Extinguishment, of hydrogen fires; Fire, hydrogen, suppression of.***

C. O'Neal, Jr.

Landesman, H. and Klusmann, E. B. (The National Engineering Science Co., Pasadena, California) "New Chemical Extinguishing Agents for Rocket Propellant and Metallic Fires," *Technical Documentary Report No. RTD-TDR-63-4208, Contract AF 33(657)-8015, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio* (December 1963)

The extinguishment of fires of metals such as the alkali metals, and of high energy fuels, often called "exotic" fuels, can be effected as far as is known at present, only by what might be called physical mechanisms. Either the extinguishing agent must blanket the fuel from its oxygen supply, or it must cool the fuel below the temperature where it will sustain combustion, or it must dissolve in the fuel and dilute it enough so that it is no longer flammable.

For agents that are to be applied to fires of this sort, in addition to the questions as to the thermal stability and flammability of the agent itself, various physical properties, such as viscosity, solubility in the fuel to be studied, etc., are of crucial importance.

The present report describes the synthesis of a series of fluoroalkyl esters of inorganic acids which, since similar compounds had shown some effectiveness in magnesium fires, offered promise as potential extinguishing agents. It also describes the investigation of the properties pertinent to their application as extinguishing agents for fires of metals and exotic fuels.

A series of esters of boron, silicon, sulfur, and phosphorous, where the alkyl part of the ester was of the type $H(CF_2CF_2)_xCH_2O$, with x varying from 1 to 4, was synthesized. Unsuccessful attempts to prepare esters of aluminum are described. Details of the synthetic methods are given. Standardized tests were set up to evaluate these compounds on a relative basis for thermal stability, hydrolytic stability, corrosivity to metals, and compatibility with nonmetallic materials (polyethylene, Teflon, rubber, neoprene, and silicone rubber). Solubilities in pentaborane, nitrogen

tetroxide, unsymmetrical dimethylhydrazine, and JP–4, were determined as were vapor pressure data, specific heat, NMR spectra, infrared spectra, mass spectra, and gas chromatographic retention times. In addition the film-forming properties of the compounds were compared by pouring molten aluminum at red heat (~660°C) into the liquid ester and examining the cooled metal for film formation.

Plans to conduct tests on small-scale fires were abandoned when it became evident that reproducible application rates could not be attained with conventional spraying system nozzles because of viscosity differences.

The report summarizes the properties listed above for the esters synthesized.

Subject Headings: *Extinguishment, of propellant fires; Fire, rocket propellants, extinguishment of; extinguishment, of rocket propellants.*

J. B. Levy

VIII. Model Studies and Scaling Laws

Thomas, P. H. (Joint Fire Research Organization, Boreham Wood, England) "The Size of Flames from Natural Fires," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 844–859 (1963)

This paper discusses the length of the turbulent flames rising from burning fuel in terms of both a dimensional analysis and the entrainment of air into the turbulent flame. Beginning with the conventional plume relationship for nonreacting hot gases, the nondimensional excess temperature along the axis is given by

$$\Theta = \frac{\theta_c D^{5/3}}{(H^2 T_0/\rho_0^2 c^2 g)^{1/3}} = f(z/D). \tag{1}$$

The unspecified function $f(z/D)$ depends upon the shape of the source. For a point source, or for an extended source in the region where $z \gg D$, and $f(z/D) \propto (D/z)^{5/3}$, it is found that

$$\theta_c \propto H^{2/3}/z^{5/3}. \tag{2}$$

If for a line source $H = H'D$ and $f(z/D) \propto D/z$, then similarly the result is

$$\theta_c \propto H'^{2/3}/z. \tag{3}$$

Under these conditions, the temperature distribution along the axis θ_c is found to be independent of the characteristic source dimension D. Since heat is generated in flames, it is pointed out that the conservation of sensible heat in conventional plume treatments must be modified to allow for the progressive release of heat as a result of mixing with air.

Considering the flame zone as a region of uniform temperature θ_{fl}, it is shown that the characteristic mean upward velocity $\bar{w}$ for similarly shaped flames, where the initial fuel velocity w_1 is negligibly small, is of the form $(gL)^{\frac{1}{2}}$. Including a shape factor for differently shaped flames,

$$\bar{w} \propto (gL)^{\frac{1}{2}} F(L/D). \tag{4}$$

Following Taylor,[9] it is assumed that, if air enters a rising column by entrainment, the entrainment velocity v is proportional to the local rising velocity w_z. Introducing a shape function $G(L/D)$ affecting the surface area of the flame envelope, the total air flow into the rising plume may then be represented by

$$\mathcal{Q}_0 \propto \bar{v} G(L/D) D^2. \tag{5}$$

Replacing $\mathcal{Q}_0$ by $\mathcal{Q}_0'$ for the two-dimensional flame from a strip source, and representing the flame area per unit length of strip by $G(L/D)D$, Eq. (5) for this case changes to

$$\mathcal{Q}_0' \propto \bar{v} G(L/D) D. \tag{5a}$$

Considering that the total quantity of air $\mathcal{Q}_0$ is proportional to the quantity of fuel $\mathcal{Q}_1$, together with the relation $v \propto w_z$ in combination with Eqs. (4) and (5), the following relation is obtained:

$$\mathcal{Q}_0 \propto \mathcal{Q}_1 \propto (gL)^{\frac{1}{2}} F(L/D) G(L/D) D^2. \tag{6}$$

In like manner, combining Eq. (4) and (5a) for a two-dimensional flame gives

$$\mathcal{Q}_0' \propto \mathcal{Q}_1' \propto (gL)^{\frac{1}{2}} F(L/D) G(L/D) D. \tag{6a}$$

As a result of the above discussion, it is shown that for any one fuel the height of a turbulent diffusion flame is related to the volumetric flow rate of fuel $\mathcal{Q}_1$, and the characteristic source dimension D, as described by

$$L/D \propto (\mathcal{Q}_1^2/gD^5)^{1/(2q+1)}. \tag{7}$$

In the above relation, the exponent varies from $\frac{1}{3}$ to $\frac{1}{5}$ as L/D increases, until at high values of $\mathcal{Q}_1^2/gD^5$ it tends to zero and L/D becomes constant. For strip sources the relation becomes

$$L/D \propto (\mathcal{Q}_1'^2/gD^3)^{1/(2q+1)} \tag{8}$$

in which case the value of (q) is 1 when L/D is $\gg 1$ and the index of $\mathcal{Q}_1'^2/gD^3$ is $\frac{1}{3}$. Thus neither for long flames from finite burners, nor from infinite line burners does theory suggest that L depends on D.

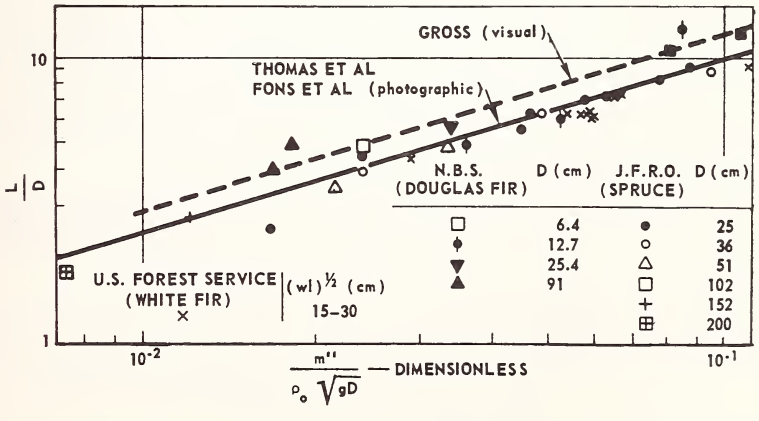


FIG. 1. Correlation of flame height data (still air—approximately radially symmetrical).

In applications it is convenient to employ the mass flow rate m_1 instead of $\mathcal{Q}_1$, and use is made of the relations

$$m_1''D^2 \propto m_1 \propto \rho_1\mathcal{Q}_1,$$

from which

$$\mathcal{Q}_1^2/gD^5 = m_1''^2/\rho_1^2gD = m_1''/\rho_1(gD)^{\frac{1}{2}}.$$

With open wood cribs as a laboratory fuel source, a correlation was made of flame height data obtained by Thomas, *et al.*,[23] Gross,[15] Fons, *et al.*,[16] the results of which are shown in Fig. 1, plotted in dimensionless form as L/D in terms of $m''/\rho_0(gD)^{\frac{1}{2}}$. Using the density of air (1.3×10^{-3} g/cc) to plot the results, the best equation for the photographed flames is given as

$$L/D = 42[m''/\rho_0(gD)^{\frac{1}{2}}]^{0.61}. \tag{9}$$

The above laboratory fire data is compared with various other flame height data in Fig. 2, including a whiskey warehouse fire, Blinov and Khudiakov's data[17] for liquid fuel fires ($D<80$ cm), the Camps Park fire reported by Broido and McMasters,[18] and the Trensacq test reported by Étienne[19] and Faure,[20] the last two being flames resulting from piles of wood distributed over a large area. Also included in the plot of Fig. 2 is the Putman and Speich data[21] for natural-gas flames, modified to make it comparable to the data for wood fires; in the range $100<L/D<200$, the data are represented by the equation

$$L/D = 29(\mathcal{Q}_1^2/gD^5)^{\frac{1}{5}}. \tag{10}$$

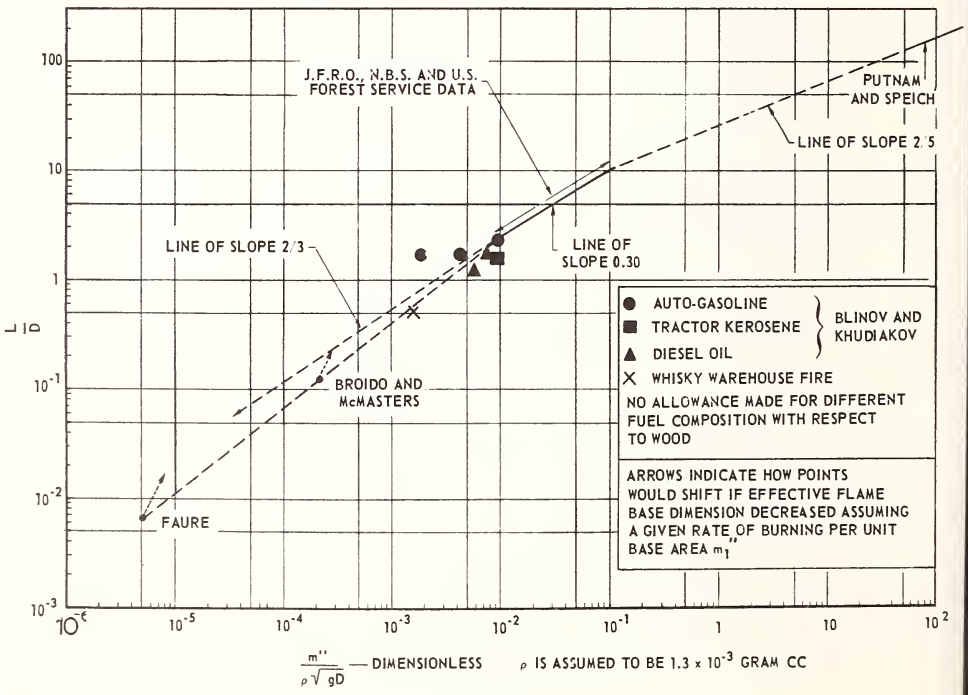


FIG. 2. Flame height correlation.

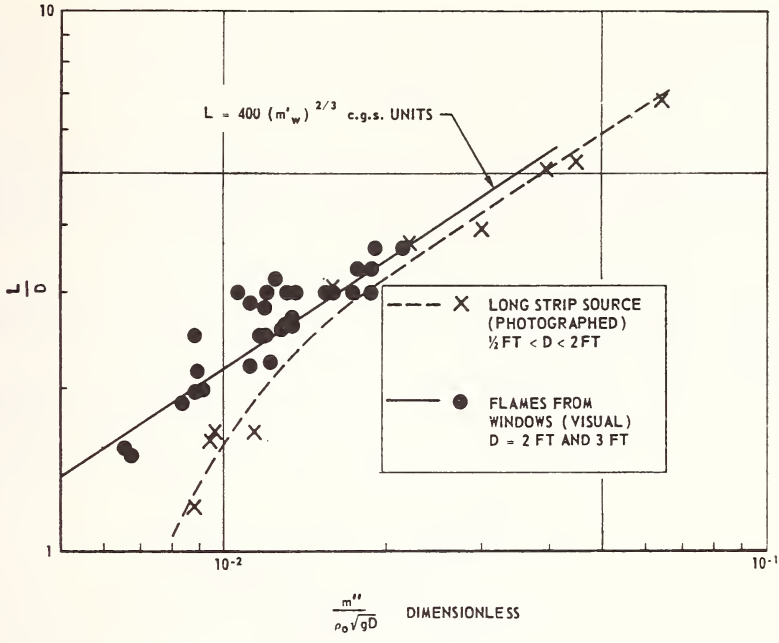


FIG. 3. Flames from long strips and windows.

These results indicate that the index $1/(2q+1)$ increases above $\frac{1}{3}$ for *small* values of L/D associated with the breakup of flame from a large fire into a number of flame envelopes.

Data on flames from long strips and windows are given in Fig. 3. As predicted by Eq. (8) with $q=1$, the equation of the line in Fig. 3 is (in cgs units)

$$L=400\ m_w'^{\frac{2}{3}} \tag{11}$$

for the ranges $1.5<L/D<4$. It is pointed out that these results do not apply where there is a vertical "wall" above the window, the wall acting as a plane of symmetry. According to Eq. (11), a one-sided flame would be 1.6 times taller than a two-sided flame for the same value of m_1'.

It is shown that the mean mass rate of air entrainment per unit area in the vertical plane of the flame envelope is given (in cgs units) approximately by

$$m_0'' \doteq 0.06_2 \times 10^{-3}(gL)^{\frac{1}{2}}. \tag{12}$$

Regarding a strip fire, the total mass rate of air entrainment per unit length is then (in cgs units)

$$m_0' \doteq 0.06_2 \times 10^{-3}(gL)^{\frac{1}{2}} \times 2L. \tag{13}$$

Combining Eqs. (11) and (13) gives the air–fuel ratio m_0'/m_w' as 31, which is shown to correspond to a flame-tip temperature rise of about 470°C. Following a similar procedure, the total rate of air entrainment for an idealized square-based fire is given (in cgs units) approximately by

$$m_0 \doteq 0.06_2 \times 10^{-3}\ 2DL(gL)^{\frac{1}{2}}. \tag{14}$$

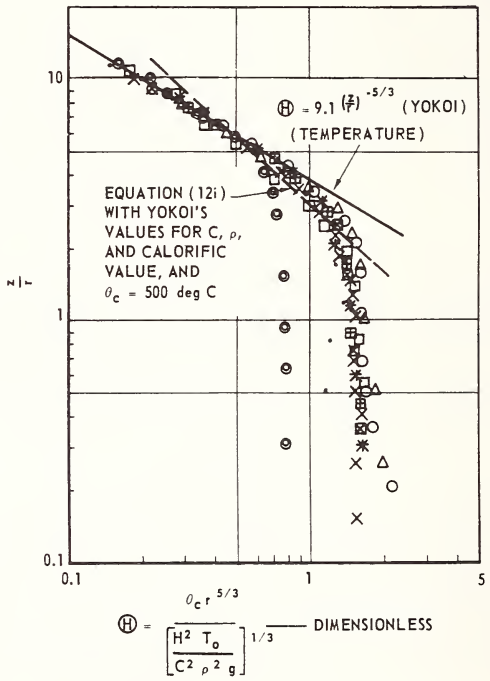
For comparison of theory and experiment, the slope of the line through the data of Fig. 1 is modified from 0.30 to $\frac{1}{3}$, and Eq. (9) is put in the form (in cgs units)

$$L/D = 420(m_w^2/D^5)^{\frac{1}{3}}. \tag{15}$$

Combining Eqs. (14) and (15) gives the air–fuel ratio m_0/m_w as 33, which corresponds to a flame-tip temperature rise of about 510°C. Considering the assumptions and approximations made in each case, these flame-tip temperatures of 470° and 510°C compare satisfactorily with each other, as well as with the value of 500°C used by Yokoi.[1]

An application of entrainment theory is made to a problem involving the roof venting of a large fire, for which satisfactory agreement is shown between the experimental results and the calculated values presented.

Yokoi[1] measured temperatures at various heights above alcohol fires of different sizes, and used a dimensionless relation similar to Eq. (1) to obtain flame heights



CONTINUOUS HEAT SOURCES

SYMBOL	$\frac{r}{cm}$
⊙	3.3
•	6
×	9.9
⊠	14.3
□	18.85
⊞	23.8
✱	37.5

DISCONTINUOUS HEAT SOURCE

SYMBOL	$\frac{r}{cm}$
△	16
○	20

FIG. 4. Correlation for horizontal circular and square heat sources.

defined by a 500°C temperature rise. In Fig. 4, Eq. (9) has been superimposed on Yokoi's results, indicating a discrepancy in trend between the two sets of data, but agreement in the region of z/r in the range 2 to 3 corresponding to the heights of flames for Yokoi's experiments.

Cribs of white-pine sticks were burned in wind speeds of 5–15 ft/sec (3.4–10.2 mph), the loss in crib weight was recorded, and flame length and inclination measured. The results given in Fig. 5 are represented by the equation

$$L/D = 68(m''^2/\rho_0^2 gD)^{0.43}\ (U^2/gD)^{-0.11}. \tag{16}$$

For comparison the data from Fig. 3 are also shown with $(U^2/gD)^{0.11}$ nominally constant at 0.82. It is of interest to note that the index 0.43 is somewhat larger than was found in any of the preceding correlations; and that the effect of wind speed on flame length is relatively small. It is suggested that the reduction in flame length with increasing wind speed is likely a result of better mixing.

A modification of Eq. (16) was made to provide a tentative equation for a line source in a wind as follows:

$$L(g\rho_0^2/m'^2)^{\frac{1}{3}} = (55 \pm 5)[U\rho_0^{\frac{1}{3}}/m'g)^{\frac{1}{3}}]^{-0.21}. \tag{17}$$

Equation (17) was compared with a dimensionless correlation obtained from Rankine's data,[28] as shown in Fig. 6. The author indicated that this will be described in detail elsewhere.

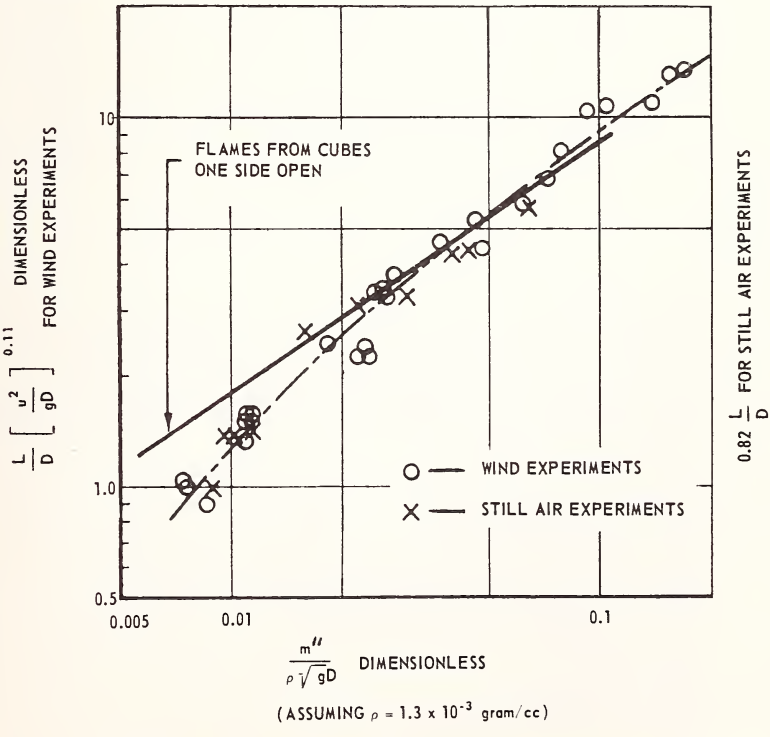


FIG. 5. Effect of wind speed and burning rate on flame length.

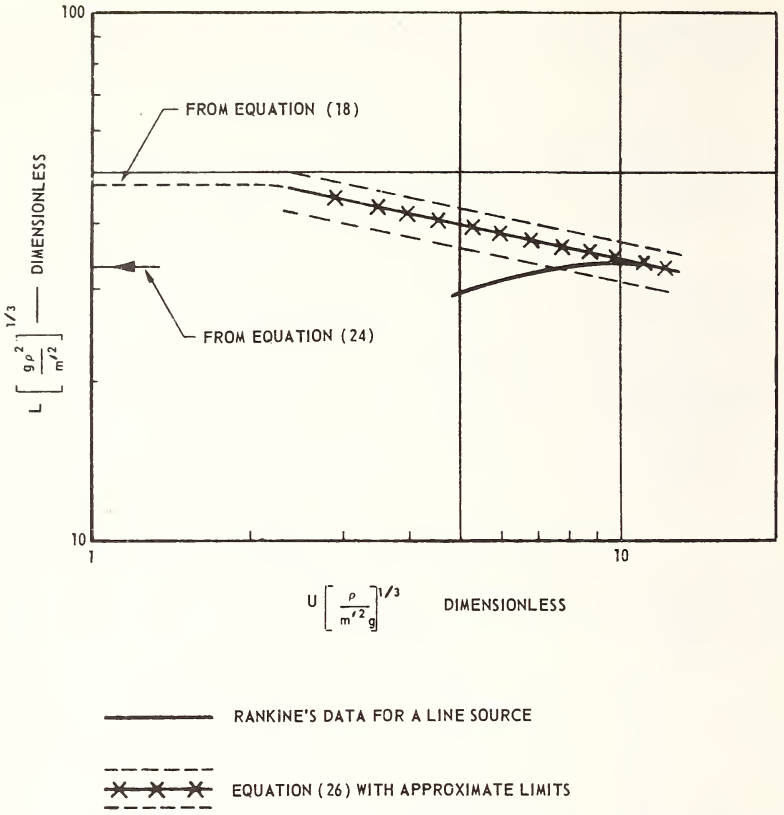


FIG. 6. Estimated correlation for a line source; ρ is assumed as 1.3×10^{-3} gram cm^{-3}.

Nomenclature

A	Area of vent
D	Characteristic dimension, side of square, diameter, or width of infinite strip
F	Shape function of L/D affecting velocity of rising gases
G	Shape function of L/D affecting surface area of flame envelope
H	Convective heat flux
L	Flame length
$\mathcal{Q}$	Volumetric rate of flow
T	Absolute temperature
U	Wind speed
W	Width of rectangular burning zone, width of window
X	Modified dimensionless flame length
a	Curtained area
c	Specific heat
d	Depth of curtain
f	A function of (general)
g	Gravitational acceleration

h	Height of building
l	Length of reactangular burning zone
m	Mass flow rate
n	Shape factor
p	Curtain perimeter
q	Index
r	Yokoi's characteristic dimension, effective radius
s	Distance along the trajectory
v	Sideways velocity of entrainment
w	Upward velocity on central vertical axis
x	Horizontal length
z	Height
μ	Viscosity
ρ	Density
ν	μ/ρ
θ	Temperature rise
Θ	Dimensionless temperature
Ω	Dimensionless wind speed
Re	Reynolds number

Subscripts

1	Fuel at burner
0	Surrounding air
c	Center-line of plume or flame
t	Flame tip—instantaneous
fl	Flame zone
w	Wood
$'$	Per unit length of line or strip
$''$	Per unit area

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Subject Headings: *Fire, size of flame; Flame, size of.*

W. G. Labes

Putnam, A. A. (Battelle Memorial Institute, Columbus, Ohio) "Area Fire Considered as a Perimeter-Line Fire," *Combustion and Flame*, **7**, 305–307 (1963) Letter to the Editor.

It was hypothesized that an area fire acts as a line fire with air supplied from only one side and that recirculated products of combustion are supplied from the other side.

Data were studied from natural gas fires arranged in a line and from six in a hexagonal pattern. Dimensionless flame heights were graphed as a function of dimensionless spacing raised to the two-thirds power. These data were extrapolated to large numbers of sources in line for comparison with those of the hexagonal array.

When the hexagonal array becomes more compact, the dimensionless flame height reaches a value of $6^{\frac{2}{3}}$. The transition from an area-type fire to the compact single-source flame appears to be quite abrupt. The author believes that the hypothesis is justified based on this correlation and analysis.

Subject Heading: *Fire, area and perimeter analysis.*

L. E. Bollinger

Strasser, A. and Grumer, J. ((U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Air Flows into Uncontrolled Fires," *Final Report No. 3909* (January 8, 1964)

This is an aptly named final report on a project motivated by a desire to find out something about fire storms. The program is experimental. A number of original laboratory experiments were carried out, and various experiments performed by others were reconsidered in an effort to gain from model studies an understanding of the underlying mechanisms producing large, intense fire storms. Much of the original research is intrinsically quite valuable. But its relationship to fire-storm phenomena is tenuous at best (except insofar as all basic fire research has a bearing on the behavior of fire storms).

A buoyant helium plume issuing at 360 cm/sec from a 10.2 cm i.d. pipe into atmospheric air was studied by observing photographically the motion of fine dust deposited in the vicinity of the plume and by measuring helium–air composition profiles with a Pauling analyzer. The two methods of measurement agreed in yielding average horizontal air-inflow velocities of the order of 6 cm/sec. The interpretation of the experimental results is entirely in terms of mass-average motion. Turbulent diffusion processes appear to be of dominant importance in these experiments, but turbulent diffusion is not mentioned by the authors.

Wooden blocks held in wire baskets in various ordered and unordered arrays, were ignited by burning methyl alcohol, and the burning rate (gm/sec, obtained by continuously weighing the fuel bed) and air inflow rates (cm/sec, obtained by photographing the motion of fine dust) were recorded during burning. Wood (Douglas fir or pine) was chosen instead of charcoal or bituminous coal for these experiments because wood was observed to have the highest maximum burning rate and the shortest total burning time. The experiments differ from previous wood-burning experiments (which were primarily concerned with fire propagation or spread) in that the entire fuel bed was ignited simultaneously. The unordered arrays employed cubes 2 to 9 cm on an edge, dumpted into baskets 30, 57, and 100 cm in diameter, in depths ranging from 15 to 60 cm. The ordered arrays were rectangular with uniform distances (varied from one test to another) between each fuel element; typical fuel elements were sticks 4 cm square and 22 cm long.

Measured air-inflow rates (which ranged from 2 to 10 cm/sec) were correlated by employing a momentum balance for a buoyant column (the height of which was assumed to be equal to the depth of the fuel bed) and by assuming that the air inflow into the fuel bed conformed to a theory of fluid flow through packed porous beds developed in 1951 by other workers at the Bureau of Mines. Theory and experiment appeared to agree in showing that the air-inflow velocity is inversely proportional to the square root of the radius of the fuel bed. Except when the number of blocks in the bed became small, theory and experiment also appeared to agree insofar as the magnitude of the induced air velocity was concerned. The scatter in the experimental data is a factor of about 2.

Experiments in which air was blown (at velocities of 220, 880, and 2700 cm/sec) into the burning fuel beds were also performed. These showed that forced air flow into the fire column above the fuel bed had little effect upon the burning rate. On the other hand, forced air flow into the fuel bed markedly increased the burning rate (by factors as large as 6 or 7). The increase was, however, not as large as one would calculate by assuming that all of the air blown into the bed reacted completely with fuel.

A few other measurements were made. Gas composition analysis of samples from the flame indicated that most of the heat release occurred within the fuel bed. Observations of the burning rates of two fires separated by various distances inside the wire basket indicated that convective heat transfer is much more important than radiative heat transfer in affecting the burning characteristics of these piles of wood. Experiments with ordered fuel beds supported this view. Placing a pipe above the fire to act as a chimney had no effect upon the burning rate unless the pipe enclosed the fuel bed, and even then the effect was not large. Static pressure measurements within fuel beds showed pressure depressions in the center that reached a maximum of a few tenths-of-a-millimeter of water at the time of maximum air-inflow velocity (which occurs somewhat later than the time of maximum burning rate because of time-dependent heating effects).

The authors discuss fire storms, fire whirls, etc., quoting a number of valuable references on these topics. They conclude that their experiments do not uncover any mechanism for fire-storm development and suggest that a superadiabatic lapse rate in the atmosphere, capable of being triggered into instability by a fire-convection column, may be necessary for the occurrence of fire storms.

To the reviewer, it seemed clear in advance that the experiment, as originally designed, can have little to do with fire storms. The height to diameter ratio of a city afire is between 10^{-3} and 10^{-1}; the experimental height to diameter ratio was between 0.16 and 1. There are many more open spaces in a burning city than in the experimental fuel bed. The packed-bed model appears to be excellent for their experiments. But for fire storms, air will usually be entrained by turbulent mixing from above, and the packed-bed picture will be inapplicable. Large-scale turbulence and buoyant plumes have long been known to be essential in fire storms. The present study reconfirms this view.

Subject Headings: *Fire, air flow into; Fire storm.*

F. A. Williams

Faller, A. J. (Woods Hole Oceanographic Institution, Woods Hole, Massachusetts) "An Experimental Study of the Instability of the Laminar Ekman Boundary Layer," *Journal of Fluid Mechanics* **15,** 560–576 (1963)

This paper concerns the stability of a laminar Ekman boundary layer for which there is an exact analytical solution. Laminar Ekman flow was obtained by generating a vortex in a large rotating tank of water 4 meters in diameter. The vortex was produced by withdrawing water from the center of the tank and replacing it at the rim. In the steady state, the flow consisted essentially of (1) a tangential circulation in the main body of the fluid whose speed varied inversely as the radius and (2) the boundary-layer flow near the bottom which accounted for the entire radial transport. The speed of the fluid relative to the rotating tank was small. At some critical value of the radius r_c, for which the corresponding critical Reynolds number was Re_c, perturbations formed in the boundary layer. They appeared as bands or "waves" in the inward spiraling flow of the boundary layer which was made visible by dye crystals placed near the outer rim of the tank. Streaks from the dye crystals formed nearly equiangular spirals very close to the 45° predicted by theory. The

average angle between the instability bands and the tangential direction was between 10° and 15°. The actual value for any one experiment appeared to be related to Ro_c, the value of the Rossby number Ro when $r=r_c$.

The theory of the basic circulation takes into account nonlinear inertial terms in the equations of motion by obtaining an iteration solution based upon an expansion in powers of a Rossby number Except for a region of adjustment near the outer rim, and a region for which the radius was less than the critical r_c, the observed values of the circulation were in fairly good agreement with the second-order theory. For values of r less than r_c, instability may have caused the observed circulation to depart from the theory. However, the second-order solution is not reliable for the large values of Ro which occur at small values of r; this may have been a factor contributing to the deviations.

A partial correlation analysis was made to determine the degree to which the departures of the nondimensional normalized circulation from theory were independently related to Re and Ro. These departures, designated as ΔV, were related independently only to Re; there was no significant partial correlation between ΔV and Ro. ΔV was closely correlated to Re for which the critical value Re_c was about 136. Below this value, ΔV was essentially zero but increased linearly with Re when $Re > Re_c$.

Subject Heading: ***Boundary layer, instability of Ekman.***

G. M. Byram

Khosla, P. K. and Murgai, M. P. (Defence Science Laboratory, Delhi, India) "A Study of the Combined Effect of Thermal Radiative Transfer and Rotation on the Gravitational Stability of a Hot Fluid," *Journal of Fluid Mechanics* **16,** 97–107 (1963)

The problem of the stability of an incompressible fluid enclosed between two horizontal surfaces with the lower surface at a higher temperature has been the object of considerable experimental and theoretical study since 1900. This paper, which deals with the effects of thermal radiation and rotation on the stability of a fluid in a gravitational field, is an extension of previous work by the same authors. The reader will find that the present paper is difficult to follow unless he refers frequently to an earlier paper[1] which concerns the effect of thermal radiation and a magnetic field on the gravitational convection of an ionized fluid.

The basic equations are linearized by using the method of small perturbations. In this procedure the behavior of the system is examined when it is disturbed from its initial state of equilibrium which is characterized by no convection. A small temperature perturbation θ is accompanied by perturbations ρ and ϕ in the pressure and radiative heating per unit volume, respectively. The boundary conditions are not affected by radiation and the boundary surfaces are free.

The equations for marginal stability (characterized by $\partial/\partial t=0$) are developed for the optically thin case $k^2d^2 \ll a^2$ and the optically thick case $k^2d^2 \gg a^2$, where k is the absorption coefficient, d the distance between the horizontal planes, and a is a dimensionless number characterizing the cell size and shape. The minimum value of the Rayleigh number R is determined by the use of a variation principle for each

of the two cases. However, this principle is valid only when the boundary surfaces are free.

The critical Rayleigh number R_c for the onset of convection is expressed in terms of the Taylor number T and the dimensionless quantities λ and χ which are characteristic of the absorption coefficient, the distance between the horizontal planes, the temperature in the equilibrium state, and the rotation. Criteria are developed for determining which type of instability (convection or over-stability) will arise first. Radiation does not affect the condition under which convection will arise or the necessary condition for the validity of the principle of the exchange of stabilities. Rotation and radiation both have an inhibiting influence on the thermal instability of the fluid.

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Subject Headings: ***Radiation, stability effect on fluids; Rotation, stability effect on fluids.***

G. M. Byram

X. Meteorological Interactions

Turner, J. S. (Division of Radiophysics, CSIRO, Sydney, Australia) and **Lilly, D. K.** (U. S. Weather Bureau, Washington, D. C.) "The Carbonated-Water Tornado Vortex," *Journal of Atmospheric Sciences* **20,** 468–471 (1963)

Tornado vortices formed by the convective concentration of pre-existing angular momentum is modeled by the release of gas bubbles in carbonated water. The process closely resembles the release of buoyancy by condensation in the atmosphere. A plastic cylinder of carbonated water, 6 inches in diameter and 18 inches deep, is placed in solid rotation at 90 rpm. When suitable nuclei are placed in the water, vigorous effervescence occurs as the bubbles come out of solution. The resulting convection produces a central vortex the exact nature of which depends on the number, position, type, and size of nuclei and also on the amount of gas remaining in the water.

If small nuclei of common salt are put in at the top, the vigorous convection prevents the particles from falling to the bottom. A strong vortex containing bubbles will grow from the top to the bottom of the beaker but does not remain attached to the bottom. When heavier particles are dropped in the top, some reach the center of the bottom and a vigorous vortex seems to appear suddenly at all levels. It remains attached to the bottom until the nuclei at the base of the vortex have all dissolved.

Still larger particles dropped onto the bottom can produce vortices even though there is no release of buoyancy in the liquid above but the result is not as vigorous as when convection is present in the upper liquid as well. However, in either case the mechanism of formation seems to be a concentration of the mean angular momentum by an influx to the center of the vortex near the bottom boundary as a

result of a decrease in pressure. In deeper tanks of rotating soda water, large nuclei placed anywhere on the bottom can set up a strong vortex at the center not linked to the position of the nuclei.

The importance of high-level convection can also be demonstrated by bubbling air from a fine tube pushed part way down the center of the tank. With a suitable depth and strength of bubbling, an intense steady vortex can be formed which extends right to the bottom. A vertical circulation is also present which can be observed by introducing particles and colored tracers into the flow. Crystals of dye placed near the center of the tank bottom show a converging region of upward-flowing fluid along the axis. Dye introduced at the top of the tank shows an annular region of downward flow which surrounds the region of upward flow. Thus, all of the convective motions are contained within the ring of downflow.

Subject Headings: *Vortex, modeling of tornado; Models, of tornado vortex.*

G. M. Byram

Turner, J. S. (Radiophysics Laboratory, CSIRO, Sydney, Australia) and **Yang, I. K.** (Dong Kook University, Seoul, Korea) "Turbulent Mixing at the Top of Stratocumulus Clouds," *Journal of Fluid Mechanics* **17**, 212–224 (1963)

When cloudy and unsaturated air are mixed at the top of a turbulent cloud layer, the evaporation of the cloud into relatively dry air near its top can cause cooling with a consequent density change. Mixing thus may produce fluid which is not intermediate in properties between the two components but has a density greater than either. It is the purpose of this paper to describe and interpret model experiments which help explain how the rate of mixing is affected by such nonlinear density changes.

Using the nonlinear density behavior of modified mixtures of methyl alcohol and water in a transparent tank in which the lower layer of fluid could be stirred mechanically, the authors have observed visual analogies with cloud mixing and have also arrived at some quantitative conclusions. For example, between the visible top of a stratocumulus cloud and the dry clear air above, there is a moist, turbulent, inversion layer which may be regarded as dynamically part of the cloud. In the experimental work, a similar intermediate layer was produced with the nonlinear mixtures of fluids. The mechanism of formation of this intermediate layer is examined in terms of spatial differences of concentration and a qualitative analogy with cloud observations is adduced.

Quantitative results were obtained by measuring the concentration of the upper fluid in the lower as a function of time, thus obtaining the density difference and mixing velocity. Comparing the results of these experiments with experiments performed on mixtures with linear characteristics, it was found that the latter all showed an increasing mixture velocity with time while the nonlinear cases can have velocity either increasing or decreasing with time.

The effect of viscosity changes in the liquid mixture makes the analogy with cloud mixing less than perfect, as the authors admit. However, by using the measured maximum change in viscosity of 20 per cent, they have put an upper limit on

changes in rate due to viscosity alone. This modifies the quantitative results but does not negate their conclusions.

Order of magnitude estimates in comparing the laboratory data with data from clouds lead to plausible numbers. Basing a Richardson number on the length of the stable layer, the authors conclude that the velocity of the interface with one per cent density difference will be about 1 cm/sec for clouds where the turbulent velocity scale is of the order of 1 m/sec.

Finally, it is pointed out that these results are applicable only in cases where the mixing is due to turbulence driven by processes independent of evaporation. Nevertheless, the relatively simple technique employed has produced interesting results and emphasizes a feature of mixing that has been previously neglected—the nonlinear changes.

Subject Heading: *Mixing, turbulent, in clouds.*

A. Strasser

XI. Operational Research Principles Applied to Fire Research

Chandler, C. C. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "A Study of Mass Fires and Conflagrations," *U.S. Forest Service Research Note PSW-N22* (1963)

This report presents a preliminary analysis and interpretation of a study on mass fires and conflagrations conducted by the U. S. Forest Service for the Office of Civil Defense. Major findings summarized in this report are based on a literature review on fire spread, report analysis on 1621 wildland fires and 254 urban conflagrations, interviews with more than 30 rural and city fire chiefs, and correspondence with mass-fire experts in three foreign countries.

The author first presents a picture of conditions in and around mass fire areas. He states that mass fires differ from the usual city and wildland fires in that large areas are actively burning at the same time. He discounts the assertion that mass fires following nuclear attack will exhibit unusual behavior characteristics and rates of spread. He contends that the behavior and spread of these fires will be governed by the same factors which affected larger fires in the past. Several reasons were given by the author to support this contention.

Mass fires in heavy concentration of fuel can exhibit fire storm characteristics in the absence of strong natural winds. The fire storm is characterized by violent indrafts around the fire area, centering on a rotating column of flame and smoke. Normal wind movement is blocked by the intense combustion in the fire storm, and air flows into the fire from all sides. Hurricane indrafts are not continuous and uniform around the fire perimeter, however. This was aptly brought out in the case history of the Hamburg fire storm where successful fire fighting was possible at certain locations around the fire perimeter, and heavy smoke was reported outside the fire area.

The author states that mass fires in the suburbs and in forested areas will probably behave differently from those in heavier fuel concentration areas. Fire storms will result only under the most exceptional meteorological conditions. Conflagrations (moving fire fronts) can be expected with dry fuels. When winds are strong fires will be spread by burning brands and will advance in surges. A more steady and slower spread will occur in the absence of a strong wind.

The total fire picture following a nuclear explosion is summarized by the author as one with the countryside sprinkled with mass fires, some moving, others stationary, and interspersed with burned and unburned areas. Except for fire storms in areas of dense fuel, the author feels that this picture differs from past conflagrations only in scope and not in kind. Because of this there appears to be no reason to believe that civil defense measures are impossible or impracticable.

The broader relations developed in this study from data obtained from case histories, supplemented by the judgment of experienced fire chiefs, are discussed next by the author.

The expected burning times of various fuels under selected weather conditions were determined for three distinct burning regimes. These were described as: (1) violent burning time, (2) residual burning time, and (3) potential threat time. A table showing the burning times for urban and wildland fuels under dry weather conditions with light winds is given in the paper.

Burning conditions under which fires could be expected to exhibit no significant outward or forward spread were determined for various forest fuel types. Fire spread in these types depend mainly on weather conditions. In cities, fire spread is less dependent on weather and more dependent upon spacing between buildings and across streets and type of construction. Because of this, rules for fire spread in cities are much more difficult to devise. The probability of urban fire spread for various values of fuel loading, exposure distance, and wind is presented graphically.

The free rate of spread of large fires under known conditions of weather, fuel, and topography is discussed in the final section of this paper. Data from 133 fully documented fires from which 1687 rates of spread were obtained during 364 burning periods were analyzed. These data showed:

1. Fire spread, measured over a period of 6 hours or longer, was much slower than popularly assumed. City fires spread at about the same rate as forest fires.
2. Rates of spread were strongly time dependent. That is, the measured rate depended on the length of time over which the measurement was taken. In both urban and wildlife fires, a decrease in mean rate was recorded with increasing duration of spread.
3. Over long time periods, the fastest travelling fires occurred on level ground, following by those moving predominantly upslope, with the slowest moving downslope.
4. The head of a conflagration had speeds which were on the average 3 times that of the flanks and 7 times that of the rear.

Subject Headings: *Mass fire, and conflagration, analysis of; Conflagration, and mass fire, analysis of.*

W. Y. Pong

Jewell, W. S. (Operations Research Center, University of California, Berkeley, California) "Forest Fire Problems—A Progress Report," *Operations Research—Journal of the Operations Research Society* **11**, 678–692 (1963)

A progress report on a study of the potential applications of operations research techniques to the problem of forest fire control is presented in this paper. The study, one of the first of its kind, is the result of a cooperative program undertaken in 1961 by the U. S. Forest Service and the Operations Research Center of the University of California, Berkeley, California.

The initial stages of the program were devoted to the definition and exploration of the following problem areas: initial attack planning; man and equipment mobilization; economics of detection systems; fire camp organization; fire agency communications.

Since the initial attack on a fire is of great importance in minimizing fire damage, a simple flame spread model was designed to analyze relationships among several relevant parameters affecting the initial attack. In the model, a fire front of length L was assumed to be moving at velocity V_f through homogeneous fuel. It was assumed that the fire would be extinguished by constructing a fire break of length L and width W at an appropriate distance downstream from the head of the fire. Once the head of the fire was contained at the break, the remaining weaker portions could be extinguished.

Using the simple flame spread model as a basis, the following expressions for the optimum size of a suppression force, the optimum time to control the fire, and the minimum total cost of fire suppression and damage were derived:

Optimum suppression force x^*, number of men,

$$x^* = L[V_f(C_B'/C_S)(W/\alpha)]^{\frac{1}{2}},$$

Optimum fire control time T^*, number of hours,

$$T^*[(1/V_f)(C_S/C_B')(W/\alpha)]^{\frac{1}{2}},$$

Minimum total cost $C(x^*)$, dollars,

$$C(x^*) = C_F + C_H LW/\alpha + 2L[V_f C_S C_B'(W/\alpha)]^{\frac{1}{2}},$$

where C_B' = cost of values burned, dollars/sq ft; C_S = cost of suppression and mobilization, dollars/man; α = fire-break clearing rate, sq ft/man-hour; C_F = fixed costs of suppression and force and detection, dollars; and C_H = hourly suppression costs, dollars/man-hour. The cost equation minimizes the expense of two counteracting effects: the cost of values burned, which decreases with the size of the suppression force; and the cost of mobilization and suppression, which increases with the size of the suppression force.

Although the model described above has severe limitations as far as direct application to the majority of fire control problems is concerned, it does serve as the basis for further investigation and improvement of fire spread and fire attack theory. Some of the more complex variables being given current consideration in the Operations Research Center program are: fire geometry; rate of fire spread; fire acceleration; efficiency of various methods of fire fighting and suppression; incorporation of the factors of risk associated with poor estimating or unrecognized changes in fire characteristics; problems of reinforcement when initial attack forces

are inadequate; relationships of the fire attack variables in dynamic multiple-fire situations.

Man and equipment mobilization play an important role in initial attack planning. Shorter mobilization time will generally be reflected in smaller fires thereby requiring fewer suppression forces and resulting in lower total suppression and damage costs. Time for mobilization may be decreased by staffing seasonal or year-round "ready crews" and by keeping men and equipment on standby status during periods of high fuel danger. Faster means of transport and improved access to forest areas are other potential improvements.

The methods of fire detection used are also important to the minimization of mobilization, suppression, and damage costs. Detection systems that are overly complex or elaborate can cost more than losses from the fires themselves. The detection system employed must be determined from an analysis of the value of the area to be protected, the probability of fire and false alarm, the search and scanning patterns of the equipment, and the costs of the system.

Fire agency organization and communication are being investigated to help improve the information retrieval and decision-making procedures of the fire fighters Studies are also being made on large versus small camp operations.

Although the application of operations research technique and theory have not as yet played a significant role in forest fire control programs, the initial progress of the study at the Operations Research Center indicates that many important solutions may be forthcoming in the years ahead.

Subject Headings: *Forest fire, application of operations research to; Operations research, application to forest fire.*

A. L. Goldstein

McArthur, A. G. (Forestry and Timber Bureau, Canberra, Australia) and **Luke, R. H.** (New South Wales Forestry Commission, New South Wales, Australia) "Fire Behavior Studies in Australia," *Fire Control Notes 24*, 87–92 (1963)

From analysis of fire reports, much experimental burning, and case studies of major fires, the Commonwealth Forestry and Timber Bureau has devised national fire danger tables that are used by most protection agencies and the Commonwealth Bureau of Meteorology. Development of the tables was facilitated by the relatively small range of climate, topography, and vegetation.

The basic fire danger index is derived on the assumption that (1) lesser vegetation is completely cured and (2) heavy fuels are free of the residual wetting effects of past rains. The index ranges from 0 to 100 with variations in air temperature, relative humidity, and wind; the entire scale is adjusted for amount of recent rainfall, elapsed time since rainfall, and degree of curing of grass fuels. A rating of 100 represents the worst possible condition in 5 tons of surface fuel per acre—approximately equivalent to eucalypt forest unburned 10–15 years. The fire danger tables have been converted to slide-rule form similar to Forest Fire Danger Meter Type 8–100–0, developed for southeastern United States.

Rate of advance of headfires is directly proportional to the fire danger index in a given fuel type, and to weight of fuel per acre at a given level of fire danger index.

Fire intensity and fire damage likewise are proportional to fire danger index and fuel weight.

The demonstrated relation of fire spread, intensity, and damage to fuel weight has created widespread interest in hazard reduction through prescribed burning. Guidelines for obtaining controlled fires with the desired characteristics were derived largely from the same studies that gave rise to the fire danger tables.[1]

Fire behavior studies were made with an eye to early application of results by general foresters. Thus, in New South Wales fire danger tables have been put in convenient form for field use, belt weather kits have been provided, and fuel-type photographs have been issued.

Reference

1. McArthur, A. G.: Control Burning in Eucalypt Forests, *Forestry and Timber Bureau Leaflet No. 80*, 1962.

Subject Heading: *Fire, danger rating, in Australia.*

G. R. Fahnestock

XII. Instrumentation

Simms, D. L. and Hinkley, P. L. (Joint Fire Research Organization, Boreham Wood, England) "An Absolute Radiometer for the Range 0.1–2.5 cal cm^{-2} sec^{-1} (0.4–10 w cm^{-2})," *Journal of Scientific Instruments* **40**, 216–220 (1963)

Radiation is the principal method by which heat is transferred in fully developed fires. The intensities of radiation vary from 4 cal cm^{-2} sec^{-1} near a building fire to 0.1 cal cm^{-2} sec^{-1}, which is the lowest intensity likely to cause damage to the surface of cellulosic material. A reliable instrument to cover this range was desired. Accuracy closer than 5 per cent was not required.

The rate of rise of temperature of a block of copper exposed to radiant heat transfer was selected as the basic measurement. Although the principle is simple, several difficulties had to be overcome. It was necessary to insure, first, that only the front face received radiation; second, that all the incident radiation, or a known fraction of it was absorbed; third, that the temperature of the block was measured accurately; and fourth, that the cooling conditions were carefully controlled.

The following design was intended to overcome these difficulties. The front face of the copper block was set flush with the front face of a water-cooled screen and the sides of the block were separated from the surrounding screen by an air gap about 0.016 cm thick. This prevented radiation from striking the edges of the block. Cooling water from a constant temperature source first flowed around the center of the screen and then out towards the edge at a rate sufficiently fast to prevent appreciable temperature rise. The surface of the copper block was treated with black lacquer and soot to insure maximum absorbtivity. The temperature of the center of the block was measured by a thermocouple, installed to assure minimum heat loss from the wires.

Calculations showed that the block was essentially isothermal for temperature

rises of the order of 100°C and for times greater than 50 sec. The intensity of radiation was computed by

$$I=(MC/A)(\theta-\theta_0)\{b/[1-\exp(-bt)]\},$$

where I is intensity of radiation (cal cm^{-2} sec^{-1}), M is mass of block = 178 g, C is specific heat of copper = 0.092 cal g^{-1} $°C^{-1}$, A is area of the block exposed to radiation = 13.75 cm^2, θ is temperature of block (°C), θ_0 is temperature of block at equilibrium with air and cooling water (°C), b is cooling constant of copper block = 0.0048 sec^{-1}, and t is time (sec). The cooling constant b is determined as the slope of log $(\theta-\theta_0)$ plotted against t for the cooling period.

The error in measuring radiation intensity was analytically estimated to be about 3 per cent. Copper-block radiation measurement showed good agreement with calculated intensities and experimental measurements using a water-cooled thermopile exposed to a gas-fire radiant panel operating at about 1000°K.

Subject Heading: ***Radiometer, absolute.***

A. E. Noreen

"Unusual Thermocouples and Accessories," *Instruments and Control Systems*, **36**, 110–113 (June 1963), 99–103 (July 1963), 130–133 (August 1963)

The staff of *Instruments and Control Systems* prepared this noncritical survey of the features of unusual or less well-known thermocouples and accessories developed, relatively recently, by 46 different listed U.S. manufacturers. The value of this series lies in the concise description, aided by 43 illustrations, of special purpose equipment.

These fill specific needs ranging from rugged, fast response, 6000°F thermocouples to highly sanitary designs for food-processing use, and from microsecond time constant, 2000°F surface thermocouples to a precision temperature reference cell based on the equilibrium triple-point of pure water.

Considering the obvious scope of this handy summary, one wonders why the manufacturers' addresses were omitted.

Subject Heading: ***Thermocouples, review on.***

K. M. Foreman

Traub, A. C. (Fenwal Incorporated, Ashland, Massachusetts) "Fiber Optic in Aerospace Vehicle Hazard Detection," *Technical Report No. ASD-TDR-62-731-Contract No. AF 33(616)-8165) Air Force Systems Command, Wright-Patterson Air Force Base, Ohio* (December 1962)

The use of fiber optic systems is considered for the detection of fires, smoke, or overheat conditions within aerospace vehicles. This report rather comprehensively reviews the technology of fiber optics and discusses at length the basic physical properties of fibers and fiber bundles. Such topics are covered as optical, mechanical,

and thermal properties of individual fibers; and optical image transmission, color distortion, incoherent transmission, mechanical properties, thermal properties, and vibration resistance of fiber bundles. Discussed in detail are fiber optic systems with information on terminal lenses, light and image detectors, scanning devices, bundle to bundle couplings, and self-cleaning windows. Thus, the major portion of this large report is actually a compilation of technical information and data on the state of the art of fiber optics. For this aspect alone, the report is very useful, being almost a handbook.

An evaluation is made of the feasibility of using fiber optics for the detection, and particularly, the identification of certain flight hazards. A photodetector can warn that light is being emitted, say, for example, within a closed engine nacelle. This is a primary alarm device. The use of fiber optics would give the pilot immediate information in the form of a visual image as to whether the light is coming from a fire or an engine overheat condition. In addition, the quality of images obtainable is sufficient that the exact location and extent of a fire can be ascertained. Many other advantages of being able to "directly" observe in remote and critical areas of a vehicle are presented and discussed.

The conclusion of the study is that fiber optics can be very useful in the detection of certain malfunctions resulting in fires. Good images can be transmitted for distances of 50 to 100 feet under ordinary viewing conditions. The use of electronic image tubes can extend the capability considerably further. A detailed evaluation of the capabilities and limitations of a particular system, however, can only be defined when the particular hazards to be monitored and the environmental conditions are known. Moreover, the effectiveness of a complete detection system is primarily dependent upon the quality that one chooses to design into the system compromising cost and complexity with the sensitivity and resolution of the final image sufficient to yield the necessary information. Most of the data necessary to make such an evaluation of a particular application can probably be found within this report.

Subject Headings: *Fire, detection, by fiber optics; Fiber optics, detection of fire.*

R. Ziemer

Fish, A., Franklin, N. H., and Pollard, R. T. (Imperial College, London, England) "Analysis of Toxic Gaseous Combustion Products," *Journal of Applied Chemistry* **13**, 506–509 (1963)

The combustion of many fire- or heat-resistant materials often generates undesirable toxic product gases. Among the latter are CO, HCl, Cl_2 and $COCl_2$. The rapid analysis of these gases is necessary under real disaster conditions. A gas-chromatographic method employing a 6 ft column of silica gel (28–60 mesh) operating at 56.5°C with nitrogen carrier gas flow of 30 ml/min was used to analyze, in order of retention times (in minutes) H_2 (1), CO (2.5), CH_4 (2.9), C_2H_6 (7.0), $COCl_2$ (9.9), CO_2 (11.1), C_2H_4 (12.1), HCl (13.3), Cl_2 (28.5), C_2H_2 (31.6). The inlet and outlet pressure of the column was 770 and 320 mm, respectively.

The gases were produced by burning a fire-retardant paper containing 21.1 per cent C, 3.03 per cent H and 19.6 per cent Cl. The remainder was principally oxygen

and trace metals. The combustion was conducted in a range of 400°–1000°C using air and vitiated air samples containing 0–21 per cent O_2.

Weight loss increases as the reaction time decreases. This is due to the oxidation of the metal remaining in the sample after the fast initial combustion has occurred. The increased weight loss is therefore due to the formation of involatile metal oxides.

Carbon dioxide is the main product found. The higher the temperature and oxygen concentration the more CO_2 is formed. At 400°C carbon monoxide is produced during the early stages of burning, only if the O_2 concentration is greater than 10 per cent. At 600° and 1000° the formation of CO is independent of the O_2 concentration. Hydrogen chloride is a pyrolysis product at 400°–600°. At 1000° an additional source for HCl production is noted. Chlorine and hydrocarbons are found at the highest (1000°) temperature only. Phosgene is present throughout all the experiments with no particular trend.

The flow experiment performed here is a reasonable close approximation of actual conditions present during the early stages of a fire involving flame-retardant materials. The concentration of toxic gases appears to be most dangerous during the initial period of involvement of these halogenated substances.

Subject Heading: *Combustion products, analysis of.*

P. Breisacher

Countryman, C. M., Murray, J. R., and Philpot, C. W. (Pacific Southwest Forest and Range Experiment Station, U.S. Forest Service, Berkeley, California) "An Electronic Fire Weather Station," *U.S. Forest Service Research Note PSW-N17* (1963)

Continuous sampling of weather for extended periods over large areas is essential in conducting studies on the effect of weather variables on fire behavior. This has resulted in the development of an electronic fire weather station which is automatic and requires a minimum of human attention. A description of this fire weather station is presented in this paper.

The station consists essentially of three parts: the sensing elements, a programer, and a recorder. It can be housed permanently or be mobile, and is powered by 24-volts D.C.

A standard 3-cup Friez anemometer is used to measure wind speed with contact closures being accumulated in the programer and reset after each readout. This procedure results in an average wind velocity for the recording interval.

Wind direction is measured by a transmitter vane designed specifically for the fire station. It consists of a horizontal shaft fitted with a plastic vane and counterbalance and mounted on a vertical shaft to which a set of brushes are attached. The brushes move over a fixed printed circuit board and with each 45° clockwise rotation from north, increments of resistance are added, readout, and identified with wind direction. Eight directions are transmitted by the vane. Both the vane and the anemometer are mounted on opposite ends of a cross arm attached to a telescoping aluminum pole.

Measurements of net radiation are obtained with a radiometer designed to measure separately, with thermistors, temperatures of two flat, black aluminum plates oriented horizontally one above the other. Temperature differences of the plates are used to determine the net radiation. The complete unit is housed in a small aluminum case and attached to the anemometer pole with a short length of aluminum tubing.

A specially designed electronic psychrometer is used to measure wet and dry bulb temperatures. Thermistors, one of which is kept moist with wicking, are the sensing elements. Before temperatures are recorded, a fan draws air past the elements for 20 seconds.

An electronic fuel-moisture balance measures the fuel stick moisture. The unit consists of a counterweighted balance arm attached to a variable ultra low torque potentiometer. Changes in moisture in the standard fuel sticks pivots the arm and rotates the potentiometer, which then changes in resistance. The change is recorded in millivolts. In order to overcome friction a small dither motor vibrates the unit prior to reading.

Fine-fuel temperature is measured by a sensor consisting of three thermistors placed separately in three wood dowels and sealed in a styrene ring. The dowels are used to simulate the fine fuel. In use the sensor is inserted in the ground by means of a brass spike.

The programer, which is the central control unit of the station, receives data from all the sensing elements. The control unit contains:

1) A clock which controls the recording interval and provides a time check for the recorder.
2) A solid-state timer which controls the reading time of each sensor.
3) A sequence stepping switch which receives readings from sensors and transmits them to the recorder.
4) An anemometer stepping switch which accumulates anemometer closures.
5) A fail-safe timer which resets all instruments in case of any failure which may cause the recorder to remain on longer than one minute.

A number of switches on the control panel of the programer is described in the paper. One in particular enables the operator to select 6- or 30-minute recording intervals.

Data are accumulated on a balancing potentiometer recorder which utilizes standard chart line drive powered by a 24-volt motor. During recording, the chart paper moves continuously and stops during the interval. The supply of paper which lasts for one week is the limiting factor of maintenance.

The automatic station permits gathering large amounts of information on local weather patterns with a minimum of time and expense. Because of mobility it can be used to study weather effects on going fires. Possible uses with telemetering equipment are suggested by the authors.

Subject Headings: *Fire weather station, instrumentation of; Weather station, automatic instrumentation.*

W. Y. Pong

XIII. Fire-Fighting Techniques, Equipment

Langdon-Thomas, G. J. (Joint Fire Research Organization, Boreham Wood, England) "Roofs and Fire," *Joint Fire Research Organization Fire Note No. 3* (1963)

This note discusses the problems presented by both internal and external fires as they affect both the material and construction features of the roof.

It is pointed out that the manner in which a fire spreads in a one-story building is determined to a great extent by the material and structural characteristics of the roof. A great deal of attention is also given to the dangers inherent in combustible interior surfaces of the roof. It is stated that in considering the internal fire hazard of the roof, three factors should be taken into account: (1) assistance given by internal surfaces to the spread of fire, including any concealed spaces in the construction; (2) the resistance of the roof covering and any internal lining to penetration by fire from a fire inside the building; (3) the resistance of the roof and its supporting members to collapse.

It is rather surprising that no mention is made of the effect of automatic sprinklers on these features. It is apparent that the author decided to make his determinations without considering their impact on his conclusions.

This note goes on to discuss the surface flame spread characteristics of the internal surfaces and their effect on fire spread within the structure. In this discussion, the ratings of the "Surface Spread of Flame" test of British Standard 476—Part 1 is used. This will be of interest to American readers as they compare the ratings with those given by the "Steiner Tunnel Test." Considerable attention is given to the importance of reliable fastening of interior protective sheathing. This is a point worthy of further study in the United States. The importance of firestops in concealed spaces is also stressed.

Another section of this note is devoted to roof screens (draft curtains) and venting. This section treats these features somewhat superficially without the detail and quantitative results achieved in this country.

The final part of the first section is devoted to an analysis of those features bearing on roof collapse. In this discussion the differences between flat roofs, shell roofs, and trussed roofs insofar as collapse is concerned are analyzed.

The second part of this note is devoted to the roof problems presented by external fires. It is pointed out that fire may spread to a roof from an outside source by radiation, convection, direct contact with flame, or by flaming brands lodged upon the roof surface.

It is pointed out that the ability of a roof covering to resist penetration by fire depends upon the following: (1) the type of sub-structure; (2) the nature of the covering.

These two features are then analyzed in detail with major emphasis being placed upon the "External Fire Exposure Roof" test, British Standard 476—Part 3.

In summary, this note presents a good qualitative analysis of the fire problem presented by roofs. It can be strengthened by further investigation to develop quantitative data on venting, maximum undivided areas, and effects of sprinkler protection.

Subject Headings: *Roofs, fire spread; Fire spread, on roofs.*

J. J. Ahern

Malhotra, H. L. and Morris, W. A. (Joint Fire Research Organization, Boreham Wood, England) "Tests on Roof Constructions Subjected to External Fire," *Joint Fire Research Organization Fire Note No. 4* (1963)

This note outlines the development of the test, listed as British Standard 476—Part 3, which was issued in 1958. It also lists common types of roof construction which have been subjected to the test and indicates the test results.

It is pointed out that when a fire occurs outside a building, the roof can often be a vulnerable spot for penetration. An acceptable roof should reduce the risk of fire entering from a neighboring building and also should have an external covering which will not spread flame rapidly, thereby endangering adjoining roofs.

In the past, in the absence of a standard test, control was effected by prescribing roofs which had been found to be satisfactory in practice, but this, of course, tended to delay the use of new materials and constructions. This new test, in general, determines the ability of specimen roofs to withstand fire penetration and also measures their flame spread characteristics. Roofs are tested either sloping at an angle of 45° or flat, depending upon their intended use.

This note outlines test results on a wide range of roof constructions including timber decking, compressed-straw slabs, steel decking, aluminum decking, concrete slabs, and plastic.

This information will be of interest to architects, builders, and fire-protection authorities.

Subject Headings: ***Roofs, tests on, subjected to fire; Fire, effect, on roofs.***

J. J. Ahern

Stark, G. W. V. (Joint Fire Research Organization, Boreham Wood, England) "Control of Fires in Large Spaces with Inert Gas and Foam Produced by a Turbo-Jet Engine. Part 3. The Design and Operation of an Inert Gas Generator," *Joint Fire Research Organization Fire Research Note No. 512* (1963)

This note includes a description of an inert gas generator incorporating as the prime component a gas turbine. Also included are discussions of desired technical

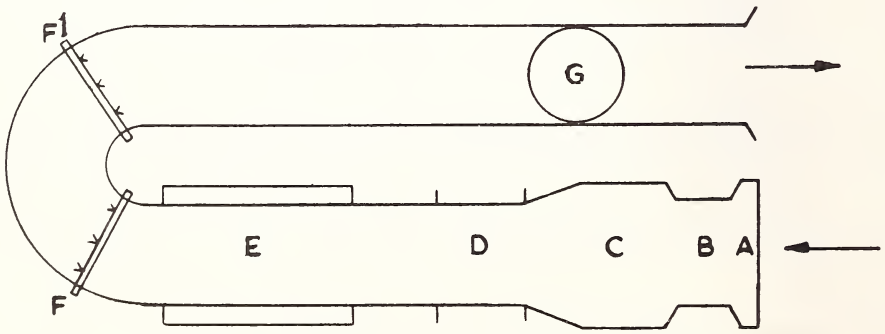

FIG. 1. General layout of experimental inert gas generator.

characteristics for consideration in further prototype development, and appendices giving the operating and maintenance procedures for the prototype which has been constructed and evaluated.

The inert gas generator consisted of a gas turbine unit consuming about $6\frac{2}{3}$ I.g.p.m. kerosene at full output, with accessory ducting, spray manifold, valves, and pumps; and the unit with accessories was mounted on a four-wheel, six-ton truck chassis. The inert gas generator schematic diagram is shown in Fig. 1.

Air enters at "A", and is compressed in a seven-stage compressor, "B". The main burners are located at "C". "D" denotes the reheat section. Section "E" is water-jacketed for cooling the exhaust. Water-spray injection manifolds are located at "F" and "F1" in the return bend duct, which is also provided with water-spray cooling. (About 90 per cent of the water input is vaporized, and the remaining is collected as a liquid from the duct.) "G" denotes a hydraulically operated bypass for diverting the gas stream from the selected point of injection.

Water at hydrant pressure is fed to the cooling jacket "E", then boosted to about 100 to 120 psig by four turbine-driven pumps powered by air bypassed from the turbine compressor, "B". This water is then fed to the spray manifold.

Salient suggested characteristics for further prototype development include:

a) Improving vaporization by augmenting the after-burner capacity, and adopting a linear exhaust duct configuration (the author discusses feasibility of using an articulated vehicle such that a system up to forty feet in length might be achieved).

b) Incorporating three hundred feet of duct to permit inert gas injection at a point of hazard to the generating equipment.

c) Providing for a gas volume capacity of two hundred and fifty thousand cubic feet.

d) Incorporating a form-generating capability, at a rate of ten thousand cubic feet per minute, for no less than ten minutes.

No test results were included in this note.

Subject Headings: *Fire, control of, by turbojet engine; Turbojet engine, use in controling fires; Foam, produced by turbojet engine.*

J. E. Malcolm

Eisner, H. S. and Smith, P. B. (Safety in Mines Research Establishment, Buxton, England) "Fire Fighting in Underground Roadways: Experiments with Foam Plugs," *Safety in Mines Research Establishment Research Report No. 130* (1956)

Mine fires are extremely difficult to extinguish. The fire, driven by the ventilation current, rapidly extends downwind and leaves behind it highly heated lengths of roadway, often filled with smoke and partially blocked by debris from the roof. The access to the fire through the burnt-out portion is dangerous while the fire races ahead faster than it can be quenched by conventional means. Even if the burning zone can be sealed off and ultimately recovered, new dangers arise by the influx of fresh air that may enhance explosion of combustible gas mixtures where none existed before. The method of fighting mine fires by foam plugs as described in this paper

meets, if properly applied, the need for getting the fire-quenching agent to the advancing front of the fire regardless of distance from the initial receding end.

The efficiency of the method depends chiefly, according to the inventors, on the dilution of oxygen by steam converted from foam moisture, and, of course, also on cooling by evaporation of water as well as on mechanical inhibition of air supply.

In applying the method, a hydrophilic fabric net is fitted across the gallery as near as possible to the outer end of the fire. Ventilation air passes through the interstices of the net, which is continuously sprayed with a dilute solution of foaming agent. Thus bubbles form and build up a foam plug that fills the roadway as it moves toward the fire. Already on approaching the conflagration through an elevated temperature zone of burned-out roadway, water contained in the foam evaporates; on further advance, the plug will arrest spreading of the fire, and, under favorable circumstances, cause its extinction. In any event, it appears that the foam will allow a close approach to the inner end of the fire and extinguishment of its smoldering remains by conventional procedures.

Experiments were carried out with a model gallery, a tube, 18 ft long, of 12 in. diameter, fitted with perspex windows at intervals and a suction fan at the exit. Near the entrance, various types of net could be attached to a frame and then sprayed with a dilute wetting agent from a 4-gallon storage cylinder under pressure. Different wetting agents and fabrics were tested, but no fire used in this setup. However fires could be successfully suppressed in a 230-yard long underground roadway of 56 sq ft cross section, ventilated by air speeds up to 1000 ft/min. The cotton net, fixed on a wooden frame near the entrance, was continuously wetted from a spraying nozzle, the solution being mixed in an aspirating-type proportioner. It is shown that foams of an expansion ratio of 1000/1, propagating at least 200 yards, can easily quench flaming combustion in high-intensity fires developed in cribs of 1000 lb dry timber and 125 lb conveyer belting.

Subject Headings: *Fire fighting, use of foam plugs; Foam plugs, use in fire fighting; Mines, fire fighting with foam plugs.*

H. M. Casse

Linacre, E. T. (Safety in Mines Research Establishment, Buxton, England) "Practical Aspects of the Foam-Plug Method of Fighting Large Mine-Airway Fires," *Safety in Mines Research Establishment Research Report No. 171* (1959)

Based on experiments in the laboratory in a ventilated tunnel including ten large fires, and on foam movement in six roadways, controlling factors, modifications of technique, and limitations of the foam-plug method of fighting mine fires[1] are discussed. Possible explosion hazards are considered.

Specific requirements for satisfactory operation are:

1) Water supply—a minimum of 1 gallon for each 300 cu ft ventilation air.
2) Ventilation—an optimum airspeed of about 100 ft/min.
3) Roadway shape and slope—it is difficult to fill a roadway higher than 10 ft or one that dips away from the net. The method fails where the roadway slopes down more than 1 in 5 and may fail, due to insufficient ventilation pressure, in roads rising steeper than 1 in 10.

4) Foam agent—most important is its water retaining capacity, measured by the "half-drainage-time" in minutes within which the foam loses half of its moisture. A foam-testing apparatus similar to the "model tunnel" of Eisner and Smith,[1] but only 9″ in diameter and 56″ long is described. The equipment requires a set of at least three bins, 2 ft high. Each bin is filled with foam, inverted on its lid and allowed to drain for a given time, then righted, and the residual foam is allowed to collapse in the bin. The collected liquid represents that retained by the foam at the chosen time. The thus determined "half-drainage-time" values depends on hardness and pH of the water. With 3% solution about 1 ton/hour of foam agent should be available.

5) Spraying nozzle—a special nozzle involving a ring of pairs of colliding jets was designed for spraying 100 gal/min of solution.

6) Net fabric and frame—cotton woven nets proved to be the best. A pore diameter of about 5 mm was satisfactory. The simplest frames were made of wood, erected vertically and sealed, except at the bottom, with cotton duck.

To avoid explosion hazards the method should not be applied in galleries exposing coal face or open goaf.

Reference

1. Eisner, H. S. and Smith, P. B.: "Fire Fighting in Underground Roadways: Experiments with Foam Plugs," *Safety in Mines Research Establishment Research Report No. 130* (1956).

Subject Headings: ***Fire fighting, use of foam plugs; Foam plugs, use in fire fighting; Mines, fire fighting with foam plugs.***

H. M. Cassel

Linacre, E. T. and Jones, D. H. (Safety in Mines Research Establishment, Buxton, England) "Materials and Equipment for the Foam-Plug Method of Mine Fire-fighting," *Safety in Mines Research Establishment Research Report No. 179* (1959)

The report gives further details regarding materials, equipment and techniques used in the foam-plug method[1,2]

1) Foam agents were of the alkyl-sulfate-type at a concentration of about 3 per cent. The water requires a pH between 7.1 and 8.6; its hardness should not exceed 700 ppm, its content of NaCl should be lower than 4000 ppm, if the "half-drainage-time"[2] is to be 2 min or more.[3] Laboratory determinations with the previously described foam tester[2] were confirmed on foam plugs in the gallery by inserting trays with lids that could be removed after different times. After complete collapse of the foam the liquid caught in the tray represented the moisture content of the foam at the chosen time.

The viscosity of the solution should not be greater than 50 centipoises, the surface tension below 40 dyn/cm. The foam bubbles formed should have a radius in the order of 0.5 inch with an expansion ratio of about 600. Properties of the agent should not change on storage at temperatures between 5° and 40°C.

2) The previously described spraying nozzle[2] was used with a set of exchangeable jet-rings. Drop diameters fell in the range from 0.5 to 2.0 mm.

Choice of net material is governed by the requirement of least obstruction to air

flow when wetted. A cotton net of 6.5 mm pores offered the minimum back-pressure of 0.12″ W.G. It is advantageous to stretch the net fully before using it.

Special attention was given to the leakage of air bypassing the foam plug. For plugs moving with a speed of 150 ft/min the "leak-factor", i.e., the ratio of volume air flow to foam volume produced per unit time, should not exceed 1.5 with air speeds from 250 to 330 ft/sec.

For introducing the foam agent, the previously described[2] inline proportioner was used under ground. An alternative arrangement, namely by forced injection into the water-supply pipe in the pit yard, is discussed.

References

1. Eisner, H. S. and Smith, P. B.: "Firefighting in Underground Roadways: Experiments with Foam Plugs," *Safety in Mines Research Establishment Research Report No. 130* (1956).
2. Linacre, E. T.: "Practical Aspects of the Foam-Plug Method of Fighting Large Mine-Airway Fires," *Safety in Mines Research Report No. 171* (1959).
3. Hartmann, I. Nagy J., Barnes, R. W., and Murphy, E. M.: "Studies with High-Expansion Foams for Controlling Experimental Coal-Mine Fires," *U. S. Bureau of Mines Report of Investigations 5419* (1958). In this work, water retention in foams could be more than doubled by the addition of 0.1% carbo methyl cellulose.

Subject Headings: *Fire fighting, use of foam plugs; Foam plugs, use in fire fighting; Mines, fire fighting with foam plugs.*

H. M. Cassel

Linacre, E. T. (Safety in Mines Research Establishment, Buxton, England) "The Formation and Movement of Foam Plugs for Mine Firefighters," *Safety in Mines Research Establishment Research Report No. 182* (1959)

The foam-plug method of fighting mine fires from a remote position[1–4] was the subject of further studies concerned with the rheology of the process without involving fires. Experiments in the laboratory, in a ventilated tunnel, and in six mine galleries served to clarify the factors controlling the proper filling of the roadway with foam. These are principally the back-pressures exerted on the ventilation current by the net and by the foam plug. On the assumption that a film of liquid splashed across the pores of the net through which air of velocity V is passing dislodges to form expanding bubbles of minimum radius r, the aerodynamic pressure, $\rho V^2/2$, must exceed that due to surface tension, $4S/r$, so that $V^2 \geq 8S/r\rho$, where ρ = density of air, S = surface tension. However, excessive airspeed prevents film formation, and enhances leakage. Hence, there exists an airspeed limit, for instance 300 ft/min for one net design. The optimum airspeed can well be estimated on the basis of capillary pressure, since it is also restricted by the requirement of moderate back-pressure of the foam plug which was found to be below 0.2″ W.G. for a plug 150 ft long, moving with a velocity of 150 ft/min. The spraying rate is shown to be of secondary importance in securing adequate filling, so long as the volume ratio of airflow and sprayed water is no more than a critical amount of the order of 2000. To minimize the "leak-factor" the "conversion efficiency", i.e., the fraction of

solution sprayed onto the net which is actually retained in the foam and the "half-drainage-time"[3] should be as great as possible.

References

1. Eisner, H. S. and Smith, F. B.: "Firefighting in Underground Roadways: Experiments with Foam Plugs" *Safety in Mines Research Establishment Research Report No. 130* (1956).
2. Hartman, I., Nagy, J., Barnes, R. W., and Murphy, E. M.: "Studies with High-Expansion Foams for Controlling Experimental Coal-Mine Fires," *U. S. Bureau of Mines Report of Investigations 5419* (1958).
3. Linacre, E. T.: "Practical Aspects of the Foam-Plug Method of Fighting Large Mine-Airway Fires," *Safety in Mines Research Establishment Research Report No. 171* (1959).
4. Linacre, E. T. and Jones, D. H.: "Materials and Equipment for the Foam-Plug Method of Mine Fire Fighting," *Safety in Mines Research Establishment Research Report No. 179* (1959).

Subject Headings: ***Fire fighting, use of foam plugs; Foam plugs, use in fire fighting; Mines, fire fighting with foam plugs.***

H. M. Cassel

Troutman, J. E. (Factory Insurance Association, Hartford, Connecticut) "Fire Protection for High-Piled Combustible Stock in Warehouses," *Quarterly of the National Fire Protection Association* **57,** 15–24 (1963)

The trend in warehousing to utilize the maximum practical building volume for storage purposes results in high piling of combustible stock which reduces the effectiveness of protective measures and increases the opportunity for fire to occur, as well as the over-all loss potential. This paper discusses the results of a fire test program aimed at determining what protection features would be necessary to (1) maintain the integrity of the building structure and (2) confine the fire to the pile of origin. The installation of automatic sprinkler protection is assumed. Piles of paper cartons were 11 to 21 feet high.

Conclusions as a result of the tests include the following:

1. If the contents burn in a manner similar to the paper cartons, variation in contents does not appear to change the initial fire characteristics, but does change the fire duration.
2. A stable pile resists control by automatic sprinklers to a much greater extent than an unstable pile. Pile collapse permits more water to reach the seat of the fire.
3. Ceiling temperatures can be controlled and serious structural collapse can be prevented by proper selection of the water spray application rate.
4. Fire in palletized cartons of stock 11 ft high can be controlled by a minimum application rate of 0.20 gpm/sq ft for ordinary hazard materials, with the opening of a large number of sprinklers. At this low density, the tendency for the fire to spread horizontally to the edges of the pile still exists.
5. Sprinkler discharge at any practical application rate cannot be expected to extinguish a fire that is well established in stock below the top two pallets of a pile.
6. When sprinklers are on a dry pipe system rather than a wet pipe system, a

fire can be expected to establish itself deeper in the pile and open a larger number of sprinklers.

7. Under conditions of slow fire development, combined with the generation of a large quantity of smoke and relatively slow sprinkler operation, a smoke detection system resulting in the early application of small hose streams would be of considerable value.

8. Fire can be expected to communicate from one pile to another when the aisle space between piles is less than 30 per cent of the height of the highest adjacent piles and may communicate when such clearance is less than 50 per cent of the height of the highest pile.

9. The vertical and horizontal rate of spread of fire increases as clearances between piles diminish. As thermal updraft increases, pressure develops between closely spaced stacks, and flame is pushed out in all directions.

Subject Heading: *Fire protection, in warehouses.*

W. G. Labes

Rhodes, J. M. (Factory Mutual Engineering Division, Norwood, Massachusetts) "Temperature Rating and Sprinkler Performance," *Quarterly of the National Fire Protection Association* **57**, 25–29 (1963)

When fire occurs in a sprinklered building, only those sprinklers directly above or very near the fire can act to control it. While control is taking place, hot gases can travel far beyond the flame envelope. Within these wide spreading gases, temperatures can be high enough to open sprinklers with "ordinary" operating temperature rating (135°–165°F), but not high enough to damage the structure or other exposed materials. As a result, sprinklers that are not needed operate. Quick operation of sprinklers—an advantage over a fire—may be a disadvantage elsewhere, wasting water and wetting down materials that might otherwise be unaffected.

This paper discusses the results of a program of 130 tests statistically designed to relate the variables of sprinkler temperature rating, ceiling temperature, number of sprinklers opened, opening time, and material burned. Two basic fire types were used, both sized to open more than five sprinklers of ordinary temperature rating: (1) a fire involving a stack of wood pallets 8 feet high, representative of the broad class of fires whose burning rate is greatly affected by sprinkler water; (2) a fire involving gasoline spray discharged at the rate of 1.5 gpm, representative of the class fire that is fixed in location and relatively unaffected by sprinkler water. Sprinklers used in the tests were of the solder type of various makes and temperature ratings ranging from ordinary (160°F), intermediate (212°F), high (286°F) and extra high (360°F). The full range of heat sensitivity and distribution effectiveness was covered.

The data show that, for the types of fires considered, there are advantages to be gained from more general use of sprinklers of higher operating temperature ratings, especially the intermediate rating. For fast, intense fires, the differences in opening

time among the various ratings are negligible. For slower fires where operating time differences are noticeable, the time delay is unimportant.

Subject Heading: *Sprinklers, performance tests.*

W. G. Labes

Bieberdorf, F. W. and Yuill, C. H. (Southwest Research Institute, San Antonio, Texas) "An Investigation of the Hazards of Combustion Products in Building Fires," *U.S. Public Health Service Contract No. PH86 62-208* (October 14, 1963)

This article is a survey of existing reports pertinent to the problems associated with the hazards of large structural fires. The report is concerned with those hazards to health that are directly attributable to the combustion process exclusive of intimate contact with the flames. The report is primarily concerned with evaluating such hazards associated with hospitals, with particular attention paid to the problem as it may affect the design, construction, and operation of such institutions.

It is generally recognized that many, if not a majority, of those who succumb to building fires are not seriously burned and that death or trauma must be due to other factors. It has been observed that better than 64 per cent of all fire fatalities can be directly attributed to smoke and fire gases. Toxic gases generated through pyrolysis of the various building interior finishes provides the greatest hazard. Materials such as wood, rubber, chlorinated methylacrylate, wool, silk, and other fabrics when thermally decomposed generate a variety of toxic gases such as ammonia, carbon dioxide, carbon monoxide, hydrogen chloride, hydrogen cyanide, hydrogen sulfide, sulfur dioxide, phosgene, and oxides of nitrogen. Smoke, although generally not considered to be toxic in the sense of the above gases, is a primary life hazard due to its effect on visibility and its irritating effect on the nose and eyes. A large number of full-scale burning tests were conducted and, in most, the hallways became intolerable because of smoke prior to the development of excessive heat; of course these results depend upon the location of the sampled area relative to the fire zone. The physiological effect of each of these toxic gases on the human respiratory system is discussed at great length.

With the development of new architectural materials, there arises a need for continued research into the burning characteristics of such materials. In the early stages of a fire located in a confined area the combustion process is essentially complete generating little carbon monoxide; however, as the oxygen is depleted the combustion process becomes more incomplete and the carbon monoxide concentration rises rapidly. Where ample oxygen is present a further problem arises since the air temperature within a burning structure may quickly exceed the thermal ignition temperatures of many of the combustible product gases, thereby generating the additional hazard of a gaseous explosion.

The amount of heat that develops during a building fire is a function of the caloric value, the amount of combustible material and the rapidity with which the reaction proceeds. Building burn-out experiments conducted by various investigators in Canada, Great Britain, France, Switzerland, and the United States on buildings that were to be demolished showed that air temperatures within the burning

structures rose to humanly intolerable levels in 2 to 10 minutes after fire onset. Further experiments showed that for ground floor fires the carbon monoxide concentration reached the danger level in second-floor rooms within about 12 minutes. Tests have shown that wood will not support combustion in atmospheres containing less than 14 per cent oxygen although the human body can function in atmospheres containing as little as 10 per cent oxygen. If we dissociate flame from heat, smoke, and combustion gases and consider it only as a visible evidence of fire, the primary hazard would appear to be the psychological one of panic. Many of our greatest fire disasters were a result of mass panic, the Coconut Grove fire of 1942 and the Winecoff and LaSalle Hotel fires of 1946 are two such examples.

The achievement of fire safety in hospitals and other buildings need not necessarily await a solution to the problems posed by combustion products. We already have the knowledge to attain a high degree of fire safety in buildings including hospitals. In addition, there are numerous methods that can be adopted to minimize the hazards of heat, smoke, and combustion gases. The means of assuring fire safety in buildings have been developed largely as a result of the study of actual building fires, including the manner in which the fires start and spread and evaluation of the success of corrective measures.

Subject Headings: *Fire hazards, due to combustion products; Combustion products, hazards of.*

H. E. Perlee

Davis, J. B., Dibble, D. L., and Steck, L. V. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) **and Phillips, C. B.** (California Department of Conservation, Sacramento, California) "Operational Tests of Two Viscous DAP Fire Retardants," *U.S. Forest Service Research Note PSW-N14* (1963)

This paper presents results of operational tests of sodium carboxymethylcellulose–diammonium phosphate (CMC–DAP) and ammonium pectate–diammonium phosphate (pectin-DAP) as fire retardants on 34 wildfires in California during the 1962 fire season. The mixing, handling, and storage of viscous DAP under actual airbase conditions, and its performance on wildfires burning under a wide variety of weather, topography, and fuel conditions were investigated.

Two air tanker bases, one in northern and another in southern California, were selected for testing these retardants. Evaluation of retardant effectiveness was based on reports from pilots, drop coordinators, ground control personnel, and research personnel.

During the five-month period of these tests no known case of a fire burning through a viscous DAP line was reported, although adjacent bentonite lines failed. Viscous DAP was found to retain its retardant effectiveness for long periods of time, have good penetration characteristics in heavy crown covers of hardwood and conifers, and was effective even when dropped at greater than 300 feet heights.

Good drop visibility of pectin-DAP was achieved by using paint-grade ferric oxide at a concentration of 10 pounds of pigment per 600 gallons of retardant

solution. For CMC–DAP a combination of one pound paint-grade ferric oxide plus 0.5 pound Rhoadamine B dye per 600 gallons of solution gave good visibility.

Both retardants were easily mixed in a side-entry batch mixer. Pectin–DAP reached its highest viscosity after 2 to 3 minutes of mixing; further mixing reduced the viscosity. The viscosity of CMC–DAP increased with mixing time reaching a maximum after 10 minutes with no apparent decrease with further mixing. Water temperature was also important in the viscosity of the solution. CMC–DAP increased in viscosity with a decrease in temperature. This became quite noticeable during the cooler months of the operations when a great increase in pump transfer time occurred. Pectin-DAP increased in viscosity with increasing water temperature up to 85°F, after which a drastic decrease occurred. Viscosities between 800 to 2000 centipoise gave good drop patterns and full coverage, and were easily pumped.

Corrosiveness of viscous DAP on aluminum, copper, and bronze was tested by attaching strips of these metals to three different places on the airplane. After several drops of retardant over a 5-week period, the strips were analyzed for weight loss and tensile strength. The use of sodium silicofluoride in the retardant mixture proved to be an effective inhibitor of corrosion for aluminum. No inhibitors were used for copper or bronze and weight loss due to corrosion was apparent. The authors state however, that corrosion of such metal parts can be minimized with protection and proper airplane maintenance. There was no detectable change in tensile strength of these metals.

The paper concludes that these operational tests confirm earlier laboratory and field studies indicating that viscous DAP solutions are superior to any other presently known fire retardant.

Subject Heading: ***Fire retardants, test of diammonium phosphate.***

W. Y. Pong

Dibble, D. L. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Roadside Hazard Reduction with Retardant Chemicals," *U.S. Forest Service Research Note PSW-N21* (1963)

The feasibility of using fire-retardant chemicals for season-long fireproofing of roadsides was studied in field experiments conducted in 1962 at two locations in California. The results of these experiments are presented in this paper.

Four retardant solutions were tested. These included: (1) diammonium phosphate (DAP), (2) algin–diammonium phosphate (viscous DAP), (3) sodium silicate–diammonium phosphate, and (4) a combination of algin, sodium silicate, and diammonium phosphate. Concentrations of DAP used varied from 15–30 per cent, algin 0.48 per cent, and sodium silicate 2 per cent.

The test sites were located in typical grass and brush fuel types. The first series of tests was conducted in late summer in fuel consisting of mixed annual grasses 12 to 24 inches high. This vegetation is common to the valleys and foothills of central California. The second test site was located in southern California in vegetation

typical of light to medium stands of chaparral consisting of annual grasses and brush. Tests on this second site were conducted in the fall.

At the first test site plots were sprayed with one of three concentrations of DAP, thickened (with algin) and unthickened. At the second test site plots were sprayed with one of two concentrations of either algin–DAP, sodium silicate–DAP, or sodium silicate–algin–DAP. Application rate at both sites was 2.0 gallons per 100 square feet.

The plans were to burn these plots at various intervals following treatment to determine the effectiveness of the retardant with time. Two series of tests were conducted at the first site, one 35 days after treatment and the other 79 days after treatment. Only one series of tests was made at the second site. This occurred six days after treatment.

Retardant effectiveness was evaluated on the basis of the degree of fire penetration into the retardant-treated area. Each test was classified according to whether the fire was: (1) completely stopped at the retardant edge, (2) stopped within the treated area, (3) slowed down but continued to burn through the treated area, and (4) not appreciably affected.

Unthickened DAP solutions in all three concentrations were found ineffective in stopping fires in grass. Thickened DAP, however, was very effective in stopping grass fires even after 79 days. The degree of fire penetration appeared to be dependent not only on the DAP concentration but also on the use of the thickener.

At the second test site viscous DAP again was found quite effective in grass. In heavier fuels, however, this retardant only temporarily slowed the fire, which, eventually stopped within the treated area or continued through it. The addition of sodium silicate to either thickened or unthickened solutions of DAP had no apparent affect.

Subject Headings: *Fire hazards, reduction on roadside; Fire retardants, use on roadside.*

W. Y. Pong

XIV. Miscellaneous

Safety in Mines Research Establishment (Sheffield, England) "Safety in Mines Research, 1962," *London: Her Majesty's Stationery Office*

The Safety in Mines Research Establishment in 1962 continued its research efforts directed towards reducing fire and explosion hazards in mines. A new high-speed camera has been installed to further fundamental studies of the ignition of methane by explosives. A technique has been developed by which a direct photograph and a shadowgraph of the detonation of an explosive and the resultant ignition of methane are taken simultaneously, each on one-half of a single photographic plate. As a result of these experiments, it is believed that the initial ignition of gas is caused by a shock wave from the explosive. However, the possibility still exists that "late reactions" that occur behind the detonation wave may also play a part, and experiments are being continued to resolve the question.

In the study of delay shot firing, studies of the transfer of detonation between two cartridges separated by either an air gap or solid matter was undertaken in view of the possibility that individual cartridges in a shothole may become separated from each other by an earlier shot in the round. This may prevent detonation from traveling along the whole length of the charge or even induce a deflagration.

To reduce the coal dust explosion hazard, a technique had previously been developed involving binding the dust with aerosols. Comprehensive trials of the process under mining conditions have confirmed the theoretical predictions of the transport, evaporation, and size distributions of aerosols up to fifty yards from the source; further work is required to prove the efficacy of binding at greater distances. The design of rock-dust barriers to arrest coal-dust explosions is being studied with a four-inch square shock tube. Dimensional analysis of the problem has been carried out which has indicated that a large number of dimensionless quantities must be accounted for. Since all cannot be simultaneously satisfied, further experiments are planned to determine which are the most important.

Further work on methanometry using "pellistor" elements in which a reaction causes a temperature change in a heating coil embedded in the element has led to encouraging results in field tests. Experiments with brine models of methane roof layers are described in which it was found that the relation between rate of mixing and layering number was in agreement with theory. A system providing a higher local ventilation velocity where needed without affecting the total quantity of air supplied to the heading has been successful in limiting methane concentrations even near a source. Work in progress to discover how flames propagate along the flammable fringe of a methane layer is described. Modeling techniques are used. It has been found that in the model study of flame acceleration the most important factors are the flame Reynolds number, the flame Mach number and the gallery roughness.

Studies of ignition hazard from friction between rocks and metals have lead to the conclusion that where speed cannot be reduced or water supplied continuously to the pick point, positive and adequate ventilation seems the only effective measure against the ignition of firedamp. Ignition of firedamp by electric discharge was studied by a break flash apparatus. One result was to show the inverse relationship between minimum igniting current and inductance. Much of the effort in this field is being directed towards unifying and reconciling the results which have been found to be apparatus-dependent.

Study of the thermal decomposition of wood has been conducted under the simplifying assumption that the rate at which volatile matter leaves the wood depends only on the rate at which it is being generated. It has been found that between about 270° and 350°C the course of decomposition is very sensitive to changes in temperature. Preheating of wood at temperatures less than 150°C for 24 hours appreciably slowed subsequent rates of decomposition.

Temperature contours around small mine fires were determined and further confirmed the inapplicability of factory-type fire detectors in mines.

Further work of SMRE in mine ventilation, investigation of mining incidents, development of rescue apparatus, and many other activities are described. The report concludes with abstracts of recent publications and a bibliography.

Subject Heading: *Mines, research in.*

J. Grumer

Lawson, D. I. (Joint Fire Research Organization, Boreham Wood, England) "Fire Losses and Fire Research," *Institution of Fire Engineers Quarterly* **23,** 107–123 (1963)

A portion of the paper discusses estimated figures for fire losses issued by the *London Times*. Losses remained fairly steady up to 1958 only showing a slight increase, then a sudden jump occurred and from 1959 onwards the losses have remained at about twice the previous level. The general pattern that emerges is that the total number of fires in buildings attended by the brigades has increased by approximately 5 per cent per year until they now total about 70,000 per year; of these fires, about 0.35 per cent individually are estimated to cost more than 20,000 pounds. The author describes various attempts which have been made to explain the increasing cost of fires. Climatic effects such as mean daily temperature, rainfall, number of days of frost, showed no statistically significant correlation with fire loss. No significant correlation has been found between fluctuations of fire loss with the bank rate or with the gross national product. So far, in terms of monetary loss, no single factor has emerged that will explain the upward trend in fire loss. Generally speaking, the number of fires involving losses at various levels for different years appears to keep in step with the fire brigade attendances to fires in buildings, with the exception of the very large fires which appear to be increasing more rapidly.

The remainder of the paper is devoted to a discussion of remedial measures. In discussing the prevention of outbreaks of fire the author observes that the prevention of ignition is not so much a matter of obtaining new knowledge as applying the knowledge already available. The author concludes that fires due to carelessness will only be reduced when more is known about the influence of publicity which can only be determined by measurement under scientifically valid conditions. Fire prevention publicity should become a more effective weapon than it is at present.

He mentions well-known ways of preventing the spread of fire: adequate spacing of buildings; compartmenting of buildings; avoiding the use of flammable linings; good housekeeping; installing a fire-detection system; calling the fire brigade as soon as possible. The author believes that the problem facing the research worker is to find out how these measures can be achieved economically, which involves determining the part that each plays in reducing fire spread.

Although sprinklers and detectors have been in use for many years, the author states that much has yet to be found out about their performance in buildings. He cites British Standard 3116 as having done much to improve the reliability of detectors in buildings.

In discussing fire-extinction methods the author mentions the flooding of buildings with inert gas and the use of highly expanded foam. He describes tests which have shown that the foam will travel over long distances to reach the fire, while inert gas, being hot, rises to the ceiling and the building fills downwards. The foam on the other hand covers the ground first and this gives the operator the facility of directing the fire-fighting according to the location of the fire.

The author concludes with the warning that we are living in a changing world, new materials and new methods of construction are continually being produced and these have to be evaluated in terms of the risk they present. Unless fire protection

can keep pace with these changes the country will be continually faced with a rising toll of fire losses.

Subject Heading: *Fire, review of.*

E. C. Woodward, Jr.

Lindenmuth, A. W. (Rocky Mountain Forest and Range Experiment Station, U.S. Forest Service, Fort Collins, Colorado) "Effects on Fuels and Trees of a Large Intentional Burn in Ponderosa Pine," *Journal of Forestry* **60,** 804–810 (1962)

Approximately 27,000 acres of ponderosa-pine timber on the Fort Apache Indian Reservation were intentionally burned during the fall of 1956. The primary purpose of this burn was to test the feasibility of using controlled fire to reduce concentrations and accumulations of forest fuels and thereby reduce the chances for large destructive fires to occur. The burning plan called for low-intensity fire burning under near-minimum conditions for fire spread, to be set at the higher elevations to encourage the fire to burn downhill. Once the area was ignited it was allowed to burn freely within the established boundaries. Natural barriers were used to contain the fire. Little or no control action was necessary.

Burning was accomplished during the period November 5 to December 7, 1956. Some precipitation occurred during this period, interrupting the burning operations, but it was not until December 7 that a general storm occurred, ending the burning for the year.

During the fall of 1957, the results of the burning were surveyed. Two geographical areas were recognized for purposes of the survey; the McNary unit of approximately 15,000 acres and the Maverick unit of approximately 12,000 acres. About half the Maverick unit had been selectively cut between 1950 and 1956 prior to the burn. Data was kept separate for the Maverick cut and uncut units. The survey was limited to the influence of burning on fuels and timber stands and used as a basis, 6,666 sample points uniformly distributed over the area. For each plot, systematic notes were kept on potential fire intensity, actual fire intensity, reasons for crowning, stocking levels before and following the fire, and influence of the fire on existing or potential crop trees.

Some of the results are as follows:

One-fifth of the area did not burn at all, as compared to 55 per cent of the area that burned with a light surface fire, leaving much of the litter and practically all the coarse fuels; 17 per cent of the area burned with a hot surface fire; and 6 per cent of the area burned by crown fire, giving good surface fuel cleanup to 23 per cent of the area. Fuel reduction was proportional to fire intensity.

8 per cent of the total number of potential crop trees were damaged by fire.
11 per cent of the total number of potential crop trees were killed by fire.
6.9 per cent of the total number of sawtimber trees were damaged by fire.
0.8 per cent of the total number of sawtimber trees were killed by fire.

The author is the first to recognize the difficulties involved when attempting to apply fire to large areas under a variety of fuel, weather, and topographic conditions. He suggests that areas proposed for burning be subdivided into units that require the same general type of fire application so that fire intensity can be held more uniform, and the results be more in line with established burning objectives. There are many factors that can be manipulated to gain some control over fire intensity, particularly on smaller land units. This approach would increase the costs of doing the job but should also increase the proportion of benefits received to losses sustained. Eventually, economics will probably determine if an area can be burned and, if it can, when, where, and how to do it.

The author also suggests that more research is needed on how to manage fire to obtain the most efficient fire intensities for accomplishing specific land management objectives.

Subject Heading: *Fuel, forest, reduction by intentional burns.*

J. H. Dieterich

Dieterich, J. H. (Lake States Forest Experiment Station, U. S. Forest Service, St. Paul, Minnesota) "Litter Fuels in Red Pine Plantations," U. S. Forest Service Research Note LS-14 (1963)

This paper presents some detailed measurements of ground fuel weights under plantation stands of red pine. In all, 16 separate stand conditions were sampled, each with two 0.1-acre plots. Ten subsamples of forest floor material were collected from each plot. These subsamples were separated into two parts designated by the author as the L layer (litter) and the F layer (all material below the L layer to mineral soil). Ovendry weights were determined for each layer of each sample, and the total dry weight of fuel per acre was calculated. Depth measurements were also taken of both layers. These were used to determine the density of each layer.

The density value for the average forest floor was 9300 pounds per acre-inch. The L and F layers had densities which were 7000 pounds per acre-inch and 11,600 pounds per acre-inch, respectively. The author states that the density difference between the two layers clearly reflects why there are rapid changes in moisture in the less-dense litter layer while the heavier F layer has high moisture retention.

A good correlation between total weight of forest-floor fuels and basal area of the stands sampled was obtained in the study. Litter weight (L layer) was also found to be well correlated with basal area in stands 15 to 25 years in age. Graphs of these relations along with their prediction equations are given.

Subject Heading: *Fuel, forest, determination of.*

W. Y. Pong

Brown, J. K. (Lake States Forest Experiment Station, U. S. Forest Service, St. Paul, Minnesota) "Crown Weights in Red Pine Plantation," *U.S. Forest Service Research Note LS-19* (1963)

A source of large concentrations of fuel in red pine plantations is located in the live crowns. This study was made to determine the crown weights of red pine at different tree diameters, and to investigate the influence of site and density on the weight of individual crowns.

Trees ranging from 2 to 9 inches in diameter at breast height (d.b.h.) were selected for study from good and poor sites in high- and low-density stands. All live branches on each tree were removed and weighed. Estimates of needle weight per tree were made by sampling representative trees in each diameter class. Green weights were reduced to ovendry weights by using a moisture content of 110 per cent calculated from sample trees. Stand density varied from 690 to 1190 trees per acre in the high-density stands and from 440 to 550 trees per acre in the low-density stands.

Highly significant correlations between crown weight and d.b.h. were found for both sites and for the different density levels. For trees of the same d.b.h., individual crowns on good sites weighed more than crowns on poor sites, and crowns from low-density stands weighed more than crowns from high-density stands. A correlation between crown weight per cord and d.b.h. was also found to be highly significant. The use of these relations in estimating quantity of slash or fuel following a cutting operation is suggested.

The weight of needles per crown expressed as a per cent of total crown weight varied according to site and stand density. In good-site, high-density stands, needle weight was approximately 50 per cent of crown weight while in poor-site, low-density stands only 38 per cent of the crown weight was in needles. For all sites and densities a figure of approximately 43 per cent is suggested by the author.

Subject Heading: *Fuel, forest, crown weight.*

W. Y. Pong

Giere, A. C. and Sedillo, L. (U. S. Naval Weapons Evaluation Facility, Albuquerque, New Mexico) "A Method for Predicting the Temperature-Time History of a Solid Cylinder Immersed in an Open Fire," *NAVWEPS Report 7724 U.S. Naval Weapons Evaluation Facility, Albuquerque, New Mexico* (June 1, 1961)

The work described in this paper was carried out in order to provide a straightforward method for predicting the vulnerability of nuclear weapons to flame. Whereas, other standard methods of prediction require use of high-speed computers or modeling facilities, the procedure outlined here is analytical and requires only a knowledge of the body being heated and the flame temperature.

The weapon is treated as an infinitely long solid cylinder immersed in an open flame which is large enough to ensure uniform radial heating. Thus, all but radial coordinates are eliminated from the heat-conduction equation. Two different modes of heating are utilized. For an interval from the time of ignition to some arbitrarily established later time a constant flux is considered. From that arbitrarily established time to the end of heating a flux is used which is proportional to the difference be-

tween the flame and surface temperature. The authors point out that such flux models imply essentially radiative heating in both intervals with the surface temperature becoming significant and reradiating appreciably in the second interval.

The actual case considered dealt with a 15-inch long, 3-inch diameter steel cylinder immersed in a JP–4 fuel fire approximately 20 feet in diameter. The cylinder was instrumented with twelve thermocouples on a plane perpendicular to it axis at its midpoint spaced at three distances from the axis. Both ends of the cylinder were insulated with 1.5 inches of sauereisen to minimize axial heat conduction. In carrying out the test, the cylinder was supported horizontally about 2 feet above the fuel surface. Flame temperature was approximately 1000°C. Run time was 600 sec.

A major portion of the paper deals with the derivation of the equations for the temperatures determined by the constant flux model and then the varying flux model. Comparison was made between the experimental data and each of the models for what the authors consider reasonable ranges of heat flux. It was shown that the constant flux model gave excellent agreement early in the run but, as expected, predicted temperatures which were too high by the end of the run. The varying flux model failed to give reasonable agreement according to the authors although this reviewer found the agreement satisfactory for all but the temperature of the surface. The authors concluded that a combination of the two models gave the best agreement. By judicious choices of a constant flux for the first portion of the run, a time at which to change to the varying flux model, and an effective heat transfer coefficient for the latter portion of the run, excellent agreement was achieved between the experimental and calculated temperatures for all but the cylinder surface.

To account for the variation in calculated and measured surface temperatures, the authors postulated a thin insulating oxide layer. The thickness of this layer was calculated from this variation and from an estimate of the oxide's conductivity to be 0.015 cm.

A number of significant points occur to this reviewer. First, the heat flux of 3.35 cal cm^{-2} sec^{-1} chosen for the constant flux portion, if totally due to radiation, necessitates an emissivity of unity from the 1000°C flame which the authors indicate existed. Second, the postulate of the thin insulating oxide layer which was necessary to explain the peculiarities of the surface temperature might have fit just as well with other models to give equally good agreement. Finally, the procedure outlined can be useful in predicting warhead temperatures in flames only in those cases where the flame temperature is constant in time and space, and is known, and all heat transmitted is known to be by radiation. Where significant variations in flame temperature or convection exists, serious errors will result.

Subject Heading: *Fire, prediction, of solid cylinder immersed in.*

F. Falk

Cundiff, R. and Gordon, W. (U. S. Naval Weapons Evaluation Facility, Albuquerque, New Mexico) "A Method for Predicting the Temperature-Time History of an Object Engulfed by an Aircraft-Fuel Fire," *NAVWEPS Report 8004 U.S. Naval Weapons Evaluation Facility, Albuquerque, New Mexico* (September 1963)

This paper presents an analytical method for predicting the temperature–time history of a simulated nuclear weapon engulfed in a large open aircraft–fuel fire.

The method consists of the solution of the Fourier conduction equation for two simple modes of heat transfer to the surface of the cylindrical weapon. In effect, it is an extension of the work of A. C. Giere and L. Sedillo[1] in which the original analytic solution was presented.

In both methods the heating is assumed to take place via two different modes. While the surface temperature of the cylinder is low, the heat flux is assumed to be constant and independent of surface temperature. As the temperature rises, the heat flux is assumed to be directly proportional to the difference between the flame temperature and the surface temperature. It is pointed out by the authors that such dependency implies that radiation is the predominant means of heat transfer. In the present paper the time to change from the nonsurface temperature dependent mode of heat transfer to the dependent mode is chosen when the heat radiated away from the surface is one-tenth of that incident on it.

To test the analytical method, data were obtained for comparison by heating a well-instrumented 60-inch long, 3-inch diameter, stainless-steel cylinder by placing it 3 feet above a 24-foot square pan of burning gasoline. In addition to 36 thermocouples embedded at various radii and locations in the cylinder, the instrumentation included 20 meters of various types placed in the flame to measure flame temperature and heat output. The period of heating continued for 25 min with water being pumped into the pan to maintain the initial level of the gasoline.

In the earlier work by Giere and Sedillo a generally similar test had been run without the measurement of flame temperature or heat output. The analysis, therefore, assumed a constant flame temperature throughout the test. With the benefit of the more detailed instrumentation in this later test it was shown that significant variations in flame temperature could exist both in time and space. For example, in one general area the temperature varied from 800°C during the first 7 min of burning to 700°C during the next 11 min, and finally to 830°C during the last 7 min. Similar variations were experienced in space.

In the analysis of the data the authors first considered an average flame temperature throughout the 25-min period. Using a reasonable value, approximately 800°C, they were able to stay within 50° to 100°C of the experimental temperatures throughout the test period. To obtain better agreement, the authors used the experimentally determined flame temperatures for the periods for which they were measured. The analytical technique was similar in both cases with care being taken to begin each heating interval with the temperature distribution in the cylinder obtained from the previous interval. The resultant agreement between calculated and measured temperatures was excellent. For the data shown, the agreement was generally considerably better than ± 15°C.

As is pointed out by the authors, this paper demonstrates that, with an accurate knowledge of a fire temperature and its variations, excellent agreement can be obtained between predicted and measured temperatures. Of more significance in practical usage, in the opinion of this reviewer, is the fact shown early in the paper that with only an approximation of the flame temperature, very good temperature predictions can be made. In practice, the designer who must consider the possibility of heating of this type will have to estimate the possible flame temperature. He can, as shown here, safely use calculated temperatures based on this estimate with a high degree of confidence as long as he can assure himself that heat transfer by convection is insignificant with respect to that transferred by radiation.

Reference

1. GIERE, A. C. AND SEDILLO, L.: "A Method for Predicting the Temperature-Time History of a Solid Cylinder Immersed in an Open Flame," *NAVWEPS Report 7724 U. S. Naval Weapons Evaluation Facility, Albuquerque, New Mexico.* (June 1, 1961).

Subject Headings: ***Fire, prediction, of time–temperature in aircraft; Aircraft, fire, prediction of time–temperature.***

F. Falk

COMMENTS AND DISCUSSIONS

On Electric Leakage Fires

T. KINBARA
Sophia University, Tokyo, Japan

The electric-leakage fire is defined, in Japan, as a fire caused by the heat due to electric leakage through building materials. Thus, the fire, which starts, for instance, from inside a radio set due to an electric short circuit, does not belong to this category. Leakage fires occur in Japan 200–300 times a year and have been studied extensively. A detailed report was issued from the Fire Prevention Society of Japan[1] and the following is a summary of this report.

If power transmission wires of some thousand volts contact wet wooden materials, the current flows through them, and at the moment the materials are dried and the current begins to stop, electric sparks which appear inside the material make it catch fire.[2] Even if the voltage is 100–200 volts, similar phenomena are seen if the material is drenched with water containing salt.[3]

Most of the leakage fires are caused, however, by an electric current of 100–200 volts which flows through metallic building materials such as zinc roofs, aqueducts, etc., among which wire laths are predominant.[1] The wire lath is a wire netting used for suspending the mortar in walls. The mechanism by which wooden boards catch fire by the heat from lath wire has been studied by K. Tsukamoto, *et al.* and it has been found that the leakage current must exceed 10 amperes to cause fire.[1] In the actual survey, however, there have been some fires in which the leak currents were believed (from several points of view) to be less than 5 amperes. Thus, it was necessary to seek some other mechanism to explain leakage fires of this kind. In this connection, Kinbara and Iwazaki made laboratory studies as well as actual surveys[4] and came to the following conclusions.

Solid carbon has three states of aggregation: amorphous, graphite, and diamond, among which graphite is electrically conducting whereas the others are nonconducting. When a wooden sample is heated, it turns, at first, to amorphous carbon, and if it is continually heated for a long time, it is gradually converted into graphite. The higher the temperature, the shorter the time needed for the conversion. Thus, the resistance of an amorphous carbon rod heated at temperature T for a given period of time is roughly expressed in the following equation:

$$R = a \exp(-bT),$$

where a and b are constants depending on the size and shape of the rod as well as the heating time.

A lath wire of 0.9 mm diameter was nailed onto a wooden board to make close contact with the board and then the wire was cut at a point. The two wires were adjusted so that the both ends just met, and then were charged with current of about 5 amperes. A spark which appeared at this junction, by displacing one of the ends slightly, graphitizes the board surface because of its extremely high temperature. If the current is repeatedly passed and broken, it was found that the surface was completely graphitized and the current flowed through it, keeping it white hot.

The high temperature turned the inner layer to graphite again, and this graphitization spread out, layer by layer, until at last the board burst into flame.

Some leakage fires were caused by this mechanism. The evidence for this is that the carbon at the point where the fire is considered to have started is conductive, and that the iron nails used for nailing lath wires onto the wooden board are melted. Ordinary combustion can neither graphitize boards, nor melt iron nails.

Since this mechanism was clarified, many cases have been classified under this category. Thus the ebonite in a switch was graphitized by repeated small sparks, and the gum of covered wire was graphitized by heated wires which carried excessively heavy current.

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ABSTRACTERS

THOMAS C. ADAMSON, JR.
University of Michigan

GEORGE A. AGOSTON
Stanford Research Institute

JOHN J. AHERN
General Motors Corporation

THOMAS P. ANDERSON
Northwestern University

LOREN E. BOLLINGER
The Ohio State University

PETER BREISACHER
Aerospace Corporation

FREDERICK L. BROWNE
Madison, Wisconsin

GEORGE M. BYRAM
Southern Forest Fire Laboratory
U. S. Forest Service

HANS M. CASSEL
Silver Spring, Maryland

WELBY G. COURTNEY
Reactions Motors Division
Thiokol Chemical Corporation

OWEN P. CRAMER
Pacific Northwest Forest and Range
Experiment Station
U. S. Forest Service

GLADYS S. CUFF
Royal Oak, Michigan

DANIEL DEMBROW
National Aeronautics and Space Administration

J. H. DIETERICH
Lake State Forest Experiment Station
U. S. Forest Service

G. DIXON-LEWIS
The University, Leeds (England)

R. H. ESSENHIGH
The Pennsylvania State University

GEORGE R. FAHNESTOCK
Southern Forest Experiment Station
U. S. Forest Service

FELIX FALK
Applied Physics Laboratory
The Johns Hopkins University

K. M. FOREMAN
Republic Aviation Corporation

ALLEN E. FUHS
Aerospace Corporation

ARTHUR L. GOLDSTEIN
Ionics, Incorporated

ROBERT A. GORSKI
E. I. duPont de Nemours & Company

BERNARD GREIFER
Atlantic Research Corporation

L. R. GRIFFITH
California Research Corporation

GEOFFREY L. ISLES
The University, Leeds (England)

OLIVER W. JOHNSON
Johnson-Williams, Inc.

WILLIAM C. JOHNSTON
Westinghouse Research Laboratories

IRVING R. KING
Texaco Experiment, Incorporated

SHELBY C. KURZIUS
AeroChem Research Laboratories, Inc.

WILLIS G. LABES
Illinois Institute of Technology

JOSEPH B. LEVY
Atlantic Research Corporation

RONALD LONG
University of Birmingham (England)

A. S. C. MA
City & Guilds College (England)

JAMES E. MALCOLM
Office of Chief Engineers
U. S. Army

D. G. MARTIN
Imperial College (England)

HOWARD N. McMANUS, JR.
Cornell University

ALAN W. McMASTERS
Pacific Southwest Forest and Range
Experiment Station
U. S. Forest Service

C. C. MIESSE
General Electric Co.

WILLIAM G. MORRIS
Pacific Northwest Forest and Range
Experiment Station
U. S. Forest Service

A. E. NOREEN
Boeing Airplane Company

CLEVELAND O'NEAL, JR.
National Aeronautics and Space Administration

HENRY EDGAR PERLEE
U. S. Bureau of Mines

M. G. PERRY
University of Sheffield (England)

WEE YUEY PONG
Pacific Southwest Forest and Range
Experiment Station
U. S. Forest Service

LOUIS A. POVINELLI
National Aeronautics and Space Administration

J. KENNETH RICHMOND
Boeing Airplane Company

DANIEL E. ROSNER
AeroChem Research Laboratories, Inc.

WILLIS A. ROSSER, JR.
Stanford Research Institute

P. R. RYASON
California Research Corporation

R. H. SABERSKY
California Institute of Technology

R. G. SIDDALL
University of Sheffield (England)

JOSEPH M. SINGER
U. S. Bureau of Mines

PHILIP L. START
University of Sheffield (England)

ALEXANDER STRASSER
U. S. Bureau of Mines

K. SUMI
National Research Council (Canada)

CLAUDE P. TALLEY
Texaco Experiment, Incorporated

DONALD L. TURCOTTE
Cornell University

FORMAN A. WILLIAMS
University of California, La Jolla

HENRY WISE
Stanford Research Institute

E. C. WOODWARD
University of South Carolina

RICHARD W. ZIEMER
Electro-Optical Systems, Inc.

E. E. ZUKOSKI
California Institute of Technology

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FOREWORD

Beginning with the next issue, a new editor will bear the responsibility for Fire Research Abstracts and Reviews. Dr. R. M. Fristrom, APL/The Johns Hopkins University, has accepted Professor H. C. Hottel's invitation to undertake this task. He will bring to it an experience based on many far-reaching contributions to combustion research. It is in this and related areas that much additional effort is needed in order to supply the technology of fire prevention and extinguishment with an understanding of basic principles. Without it, progress will be wholly empirical, fitful, expensive and, often, inadequate.

Fires are more destructive in their consequences but receive far less attention than air and water pollution. The annual death toll of 12,000 persons and property damage of two billion dollars in the United States alone is appalling. The recent near disaster of the Santa Barbara (California) fire underscores the gravity of the situation. It indicates inadequacies in prevention methods, difficulties of mounting an adequate counter-offensive, limitations in analyzing what occurred and what lessons can be learned. The support that is available to groups attempting to bring about improvements is simply inadequate.

The antiquity and the seeming complexity of the problem has discouraged a well-planned attack. The assistance and skills of the most competent individuals and organizations have not yet been fully marshalled. Responsibilities for protection against fires are scattered among groups with such restricted goals that sight is often lost of the over-all needs.

On almost every important front—development of new techniques, understanding of fundamental principles, education and training, exchange of ideas—a larger effort would be beneficial. Much technological experience in the prevention and prosecution of warfare could readily be transferred to the fire field. As with many other problems of long standing, the "bits-and-pieces" approach is painfully slow and inefficient. It barely keeps pace with current needs.

It is a pleasure to report that, at the recent Tenth International Symposium on Combustion (co-sponsored, in part, by the Committee on Fire Research, National Academy of Sciences—National Research Council), fourteen papers were submitted on Fire Research topics. This was the first time that so many substantial contributions were presented to and discussed by a large scientific audience. The Proceedings of the Symposium, which will include the comments on each paper, will be published by The Combustion Institute, Pittsburgh, Pennsylvania early in 1965.

W. G. BERL
Editor

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REVIEWS

Research into Fire Protection

D. I. LAWSON
Director, Joint Fire Research Organization, Boreham Wood, England

[The following article is based on a lecture to the Royal Society of Arts, November 20, 1963. It is reprinted by permission of the Editorial Board of The Institution of Fire Engineers
Editor]

There are three main objectives in fire protection, rather like lines of defense.

1. To eliminate all outbreaks of fire.
2. To ensure that all outbreaks are localized.
3. To ensure that the brigades are able to extinguish all outbreaks quickly and efficiently, even the few that become large fires.

Eliminating Outbreaks

No one would expect to succeed in eliminating all fires, but this in no way detracts from the importance of the objective. In spite of all efforts, our statistical records show that the number of fires attended by the brigades, excluding trivial chimney fires, has risen from 72,000 in 1950 to 167,000 in 1962 (Fig. 1). About half of these occur out-of-doors and their number depends markedly on the weather, the warm dry summers of 1947, 1949, 1952, 1955, and, above all, 1959, showing pronounced peaks.

Fires in buildings are more important than those in the open, by virtue of both the greater potential risk to life and the loss of the building including the goods stored in it. The number of fires in buildings attended by the local authority brigades has risen steadily from 44,000 in 1950 to 73,500 in 1962. It is unlikely that this is due to an increasing willingness to call the fire brigades, because the proportion of fires found to have been extinguished on arrival has not varied during these years (Fig. 2).

Fires are produced as a result of human activity; this may be measured by the gross national product, a term embracing the value of goods, buildings, and fuels produced. The number of fire calls may be compared with the gross national product or rather the product normalized to take into account the changing value of the pound. The number of fires per annum rises more rapidly than the normalized gross national product (Fig. 3) which may be explained by the fact that some goods are consumed as they are produced, while others are durable and accumulate over a number of years.

There is no evidence to suggest that over the last decade new hazards have arisen; generally speaking, the causes are the same and about three fires out of every four are due to a failure to apply information already known. Fires due to the usage of fuels, cigarette smoking, and children with matches figure prominently. It is difficult

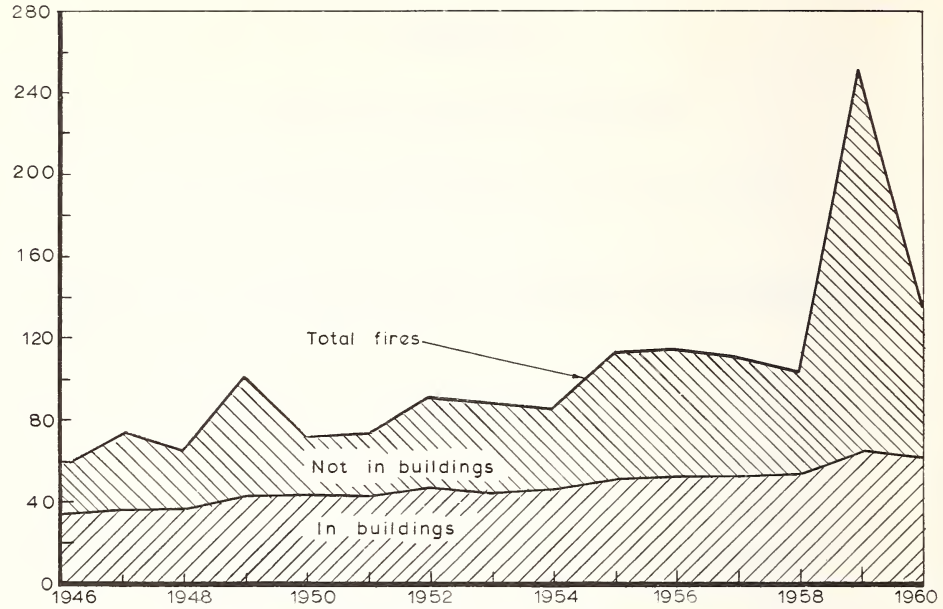


FIG. 1. Annual incidence of fires—United Kingdom, 1946–1962.

to believe that the very rapid increase in the number of fires in the period 1950 to 1962 is a reflection of a change in our national behavior, and yet, recently, the number of fires attributed to smoking materials, electricity, and gas has risen more rapidly than our consumption of these products (Fig. 4). This would indicate that either the apparatus consuming the fuel is becoming less safe or the user is paying

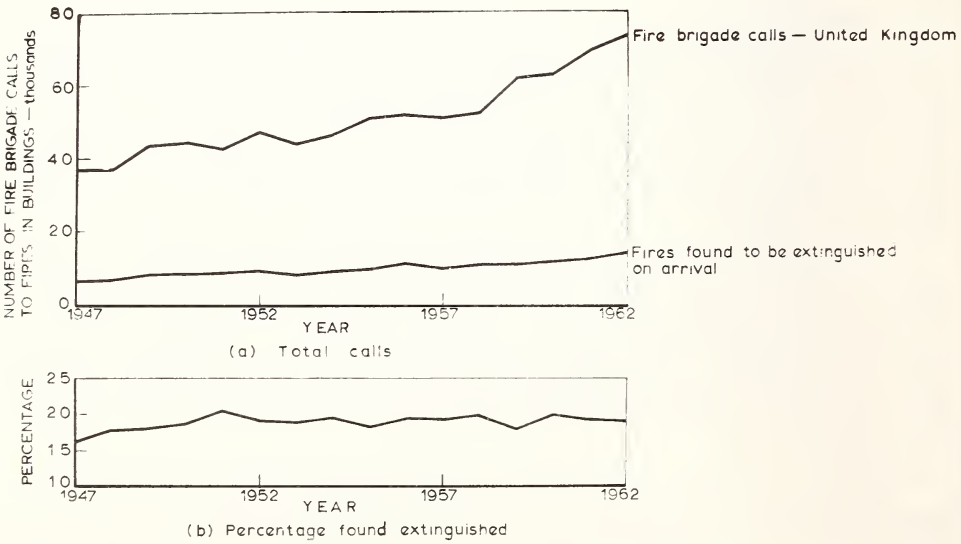


FIG. 2. Fires found to be extinguished on arrival of fire brigade.

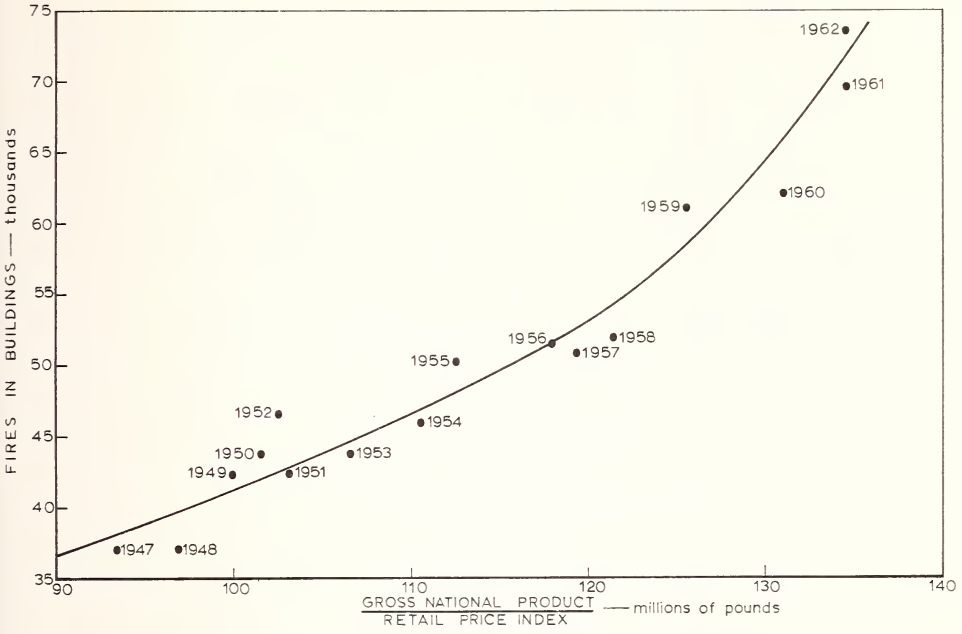


Fig. 3. Fires in buildings and the annual production of goods.

less attention to the hazards. As the trend is similar for different igniting sources, it may be that the user is at fault. It is likely that the increase in the production of both igniting sources and flammable materials explains the rapid upward swing in the fire curve; certainly this seems to be true for fires attributed to smoking materials (Fig. 5). Whatever the explanation, the conclusion is the same, that our awareness of the hazards of fire is not matching our increasing production.

It seems that the growth in the number of fires is influenced largely by the increasing responsibilities placed on the community by the expanding national economy. It is too facile to charge the public with increasing carelessness. The production of a favorable public response to the prevention of fire ought to be studied. A failure to respond may be due to a genuine lack of knowledge; this could be found by sample surveys so that propaganda could be directed to the areas of ignorance. Of course, the mere possession of knowledge will not influence all individuals, so it will also be necessary to measure the influence of propaganda on the behavior of sample populations with a view to devising more effective ways of conveying fire prevention information.

Fatalities. Every year approximately 600–700 people lose their lives because of burning accidents, the numbers showing no significant trend with time. The same is true for deaths in conflagrations which account for just over 100 of these fatalities (Fig. 6). However, the number of deaths due to clothing becoming ignited by gas or electric fires has shown a downward trend with time (Fig. 7). This must be due to the influence of the Heating Appliances (Fireguards) Act, 1952, which requires gas, electric, and oil-burning appliances to be fitted with fireguards before sale, rather than to the influence of newer clothing materials, for the number of deaths resulting from clothing becoming ignited by other sources of heat has not decreased.

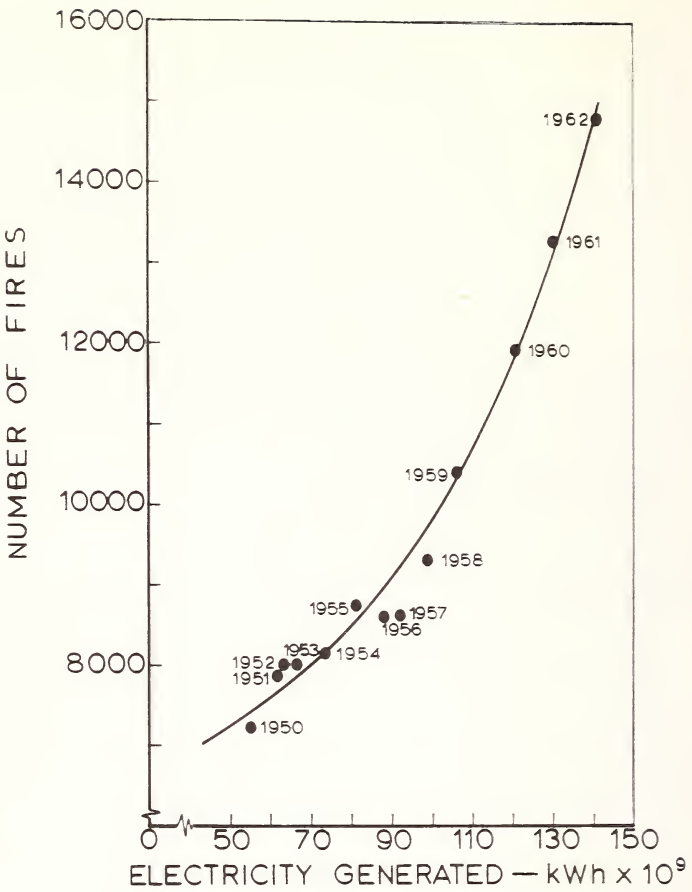


FIG. 4(a). Fires due to electricity.

With electric and gas fires alone (the figures for oil fires are not available) the Act is at present responsible for the saving of 40 lives per year, compared with the 1952 figures, despite the increased usage of fuels. No similar trend is apparent for the domestic fire, which does not automatically carry a fitted fireguard.

Despite considerable work carried out by the Joint Fire Research Organization to devise standard for fabrics of low flammability, and of the efforts of manufacturers to produce materials conforming to these standards, deaths due to clothing becoming ignited still account for about one-half of all deaths by fire.

Localizing Fires

The prevention of outbreaks of fire is in the main a problem of human science, while that of preventing fire spread depends on the material sciences, the results of research into the latter being applied through administration rather than through the general public. Much of our work is concerned with fires in buildings, since these are economically more important than those out-of-doors.

Although the number of fires in buildings has increased rapidly in recent years, it is gratifying to note that the fire spread for each fire is less. Generally speaking,

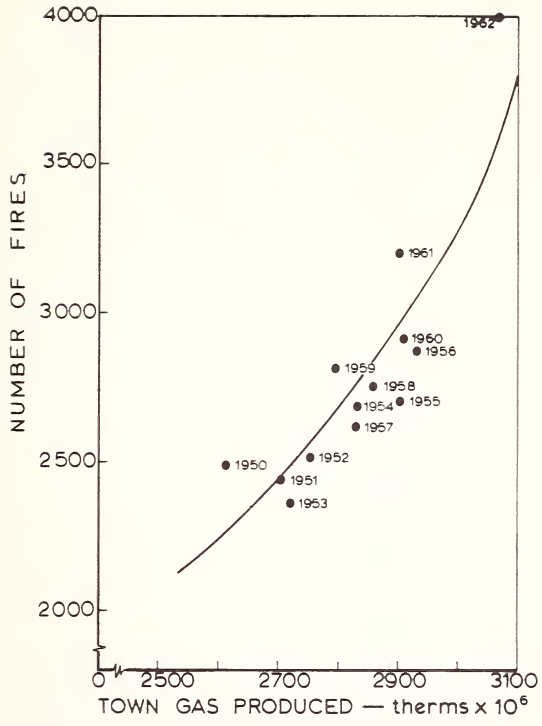


FIG. 4(b). Fires due to gas.

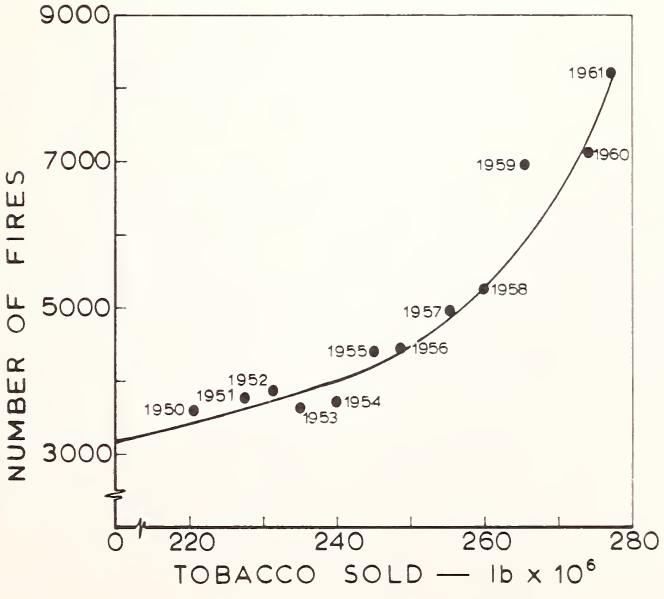


FIG. 4(c). Fires due to smoking materials.

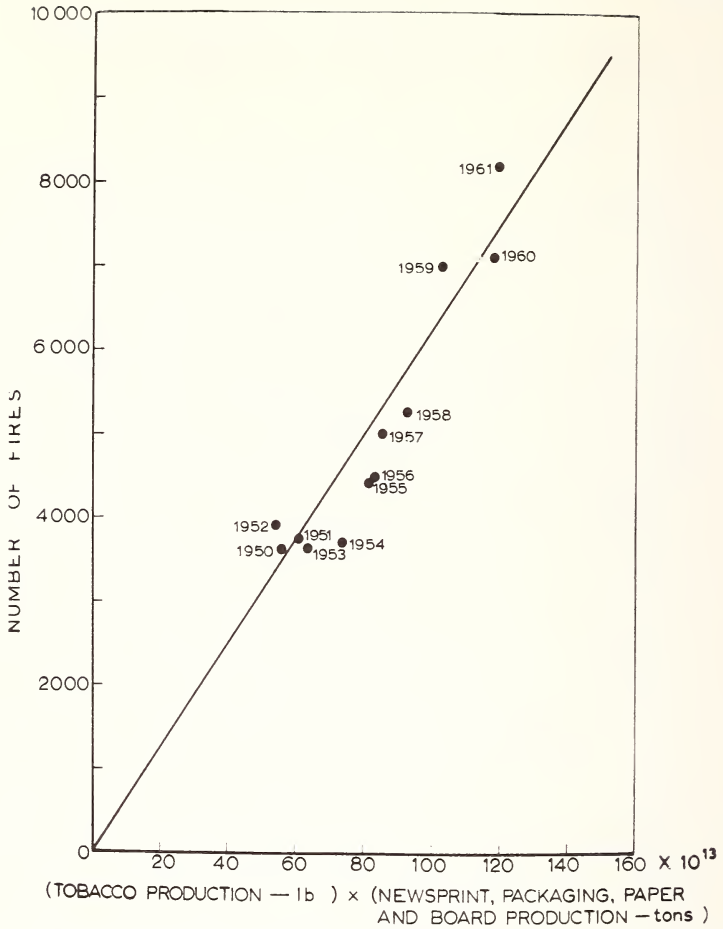


Fig. 5. Fires in buildings due to smoking in relation to tobacco and paper production.

it is the number of smaller fires that has increased rather than the larger fires (Fig. 8). This must be a result of the combined efforts of the Fire Service, the building legislators, insurance, and, we like to think, research, including as it does the continual devising of standards of safety; the testing of materials has played its part, too. This reduction of fire spread is reflected in the cost of fires, for the current average cost of fires, after making due allowance for inflation, is about 20 per cent less than it was in 1947 (Fig. 9). Had these factors not operated, the current loss resulting from fire might well have been some £10 million per annum more than it is today.

Modern buildings are built as a series of fire compartments, the walls, floors, and columns serving as barriers to flame and heat while still continuing to perform their load-bearing functions, the aim being to confine a fire to the compartment of origin. An important part of fire research, therefore, must be the study of the growth of fire in compartments and their ability to contain fires. It would be quite impracticable to study a subject of such complexity with full-scale fires, so recourse to modeling must be made. It is essential that the physical principles of the developing

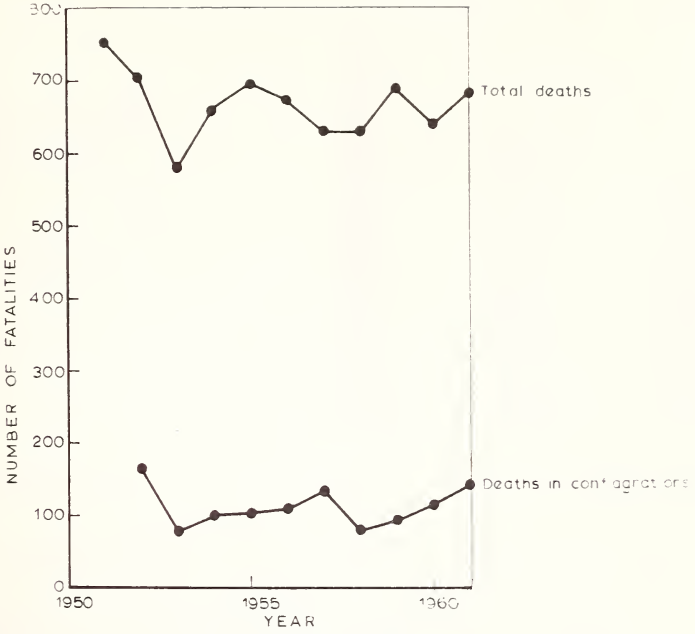


FIG. 6. Deaths due to fire.

fire be understood before the results from models can be applied with confidence to the large compartments encountered in everyday life. All fires left to themselves have a similar history; after ignition, a fire spreads initially much as it would do in the open, but later the restriction of the enclosure is felt as the air supply be-

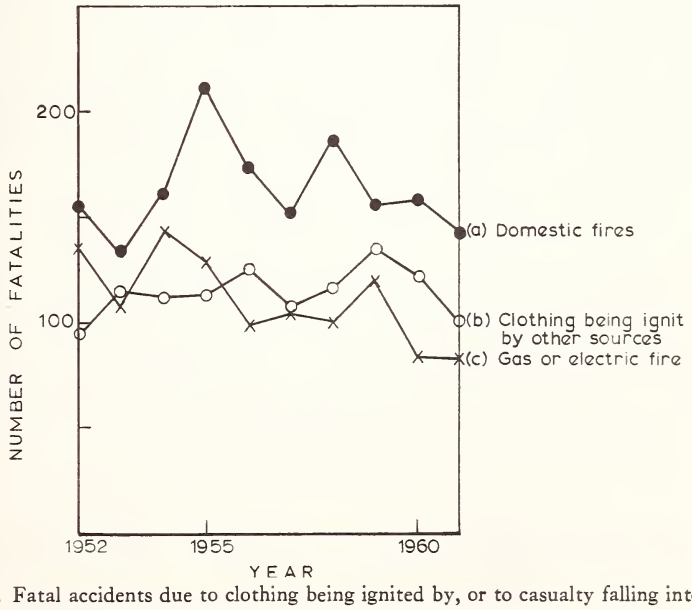


FIG. 7. Fatal accidents due to clothing being ignited by, or to casualty falling into fire.

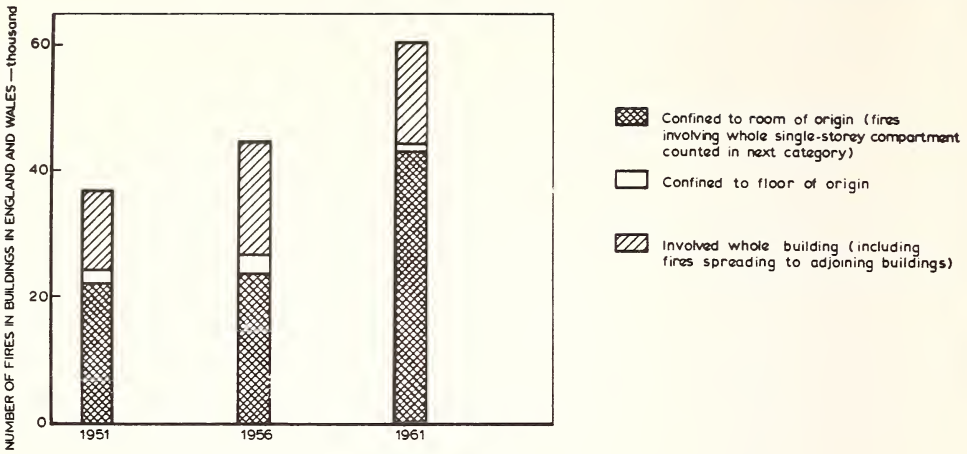


FIG. 8. The smaller fires attended by fire brigades are tending to increase rather than the larger ones.

comes limited. The combustion at this stage is incomplete within the compartment and flames appear from the windows. The heat radiated from the flames and the window apertures falls on nearby buildings and these become ignited if the separation is insufficient. Fire spread involves the study of ignition, size of flames, rate of burning and radiation to other buildings.

Ignition. If cellulosic materials are heated sufficiently, the flammable gases evolved will ignite, the more rapid the rate of heating, the more rapid the ignition. In most everyday fires we are concerned with ignition at times between 1 and about 2000 seconds. While the detailed process of ignition is very complicated, it is relatively easy to predict when a material will ignite, by making the assumption that ignition will take place when the surface has been brought to a given temperature.[1] This works fairly well in practice and enables a wide range of experiments to be expressed on a single curve (Fig. 10). A study of ignition is necessary to understand the spread of fire which is a continuous process bringing the unburned material ahead of the flame front to the point of ignition. (A knowledge of ignition is also used in deciding how far buildings should be separated.)

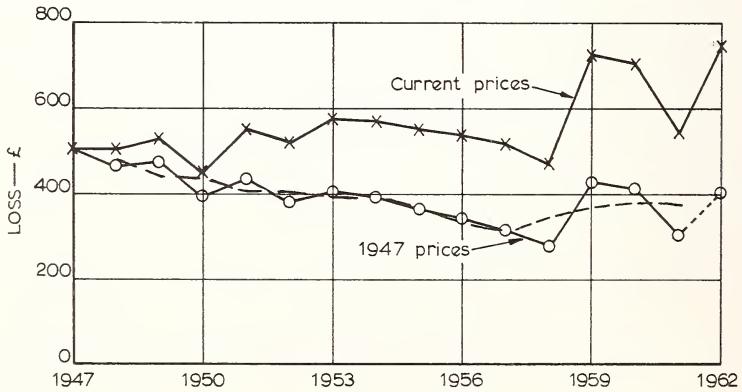


FIG. 9. Average direct loss/fire (assuming all loss in buildings).

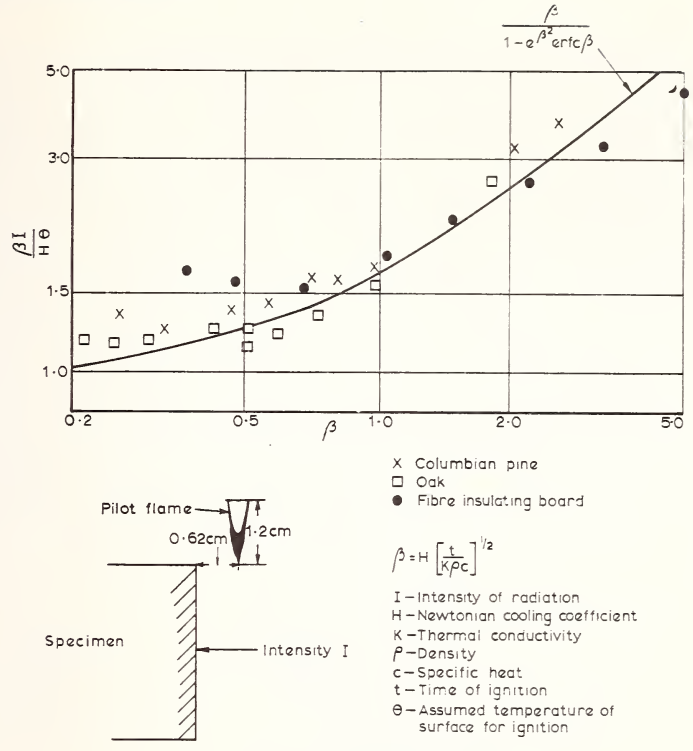


FIG. 10. Ignition of wood.

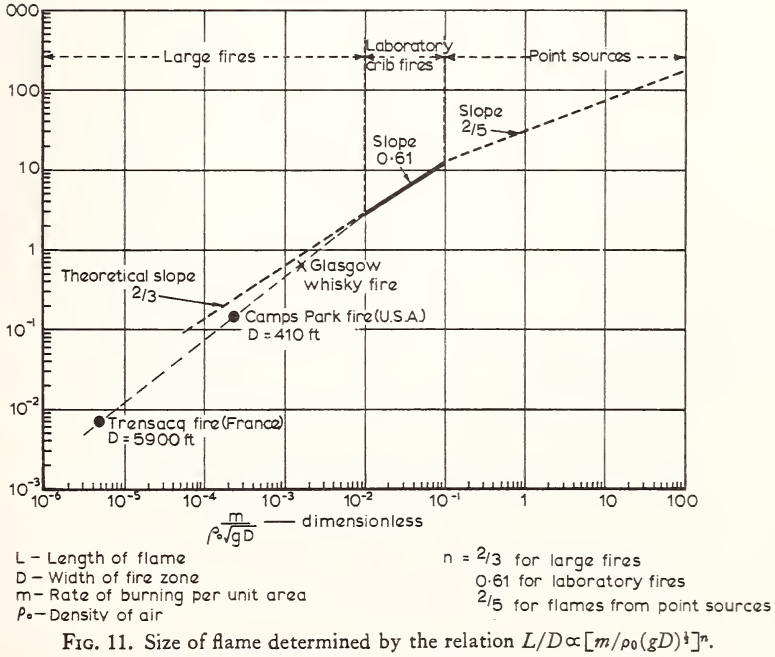
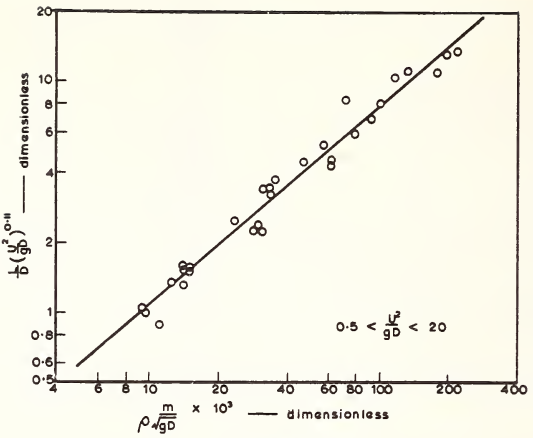
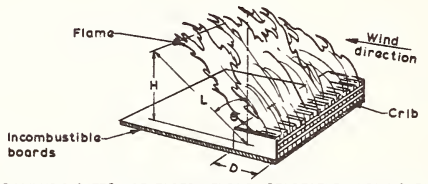


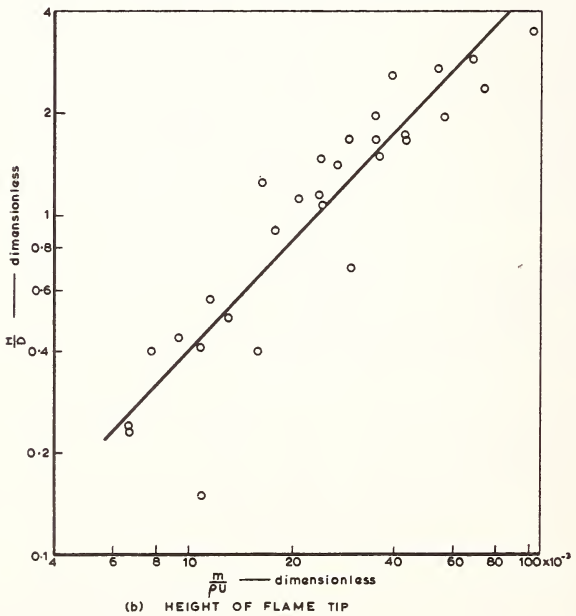
FIG. 11. Size of flame determined by the relation $L/D \propto [m/\rho_0(gD)^{\frac{1}{2}}]^n$.



(a) FLAME LENGTH



DIAGRAMMATIC SKETCH OF EXPERIMENTS TO REPRESENT BURNING ZONE



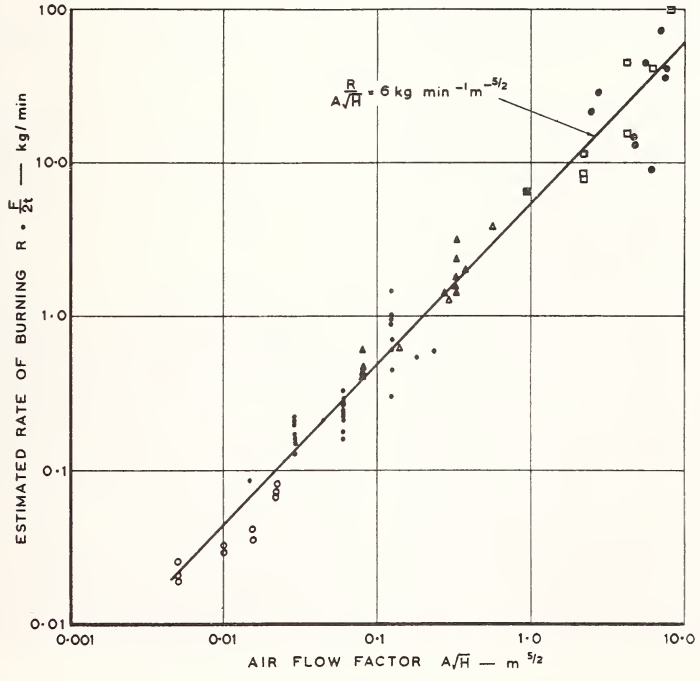
(b) HEIGHT OF FLAME TIP

FIG. 12. Effect of wind speed and burning rate on flames.

The simple treatment just outlined is equivalent to assuming that at these rates of heating, the chemical heat generated by the material itself may be neglected. This ceases to be true for ignition periods in excess of 2000 seconds when the analytical approach becomes much more complex and is important in studying the self-heating and storage of materials.[2]

At the other end of the scale (ignition in less than 1 second, which involves a high rate of heating) ignition is likely to be determined by the mechanical behavior of the surface under thermal shock and by the aerodynamics of the issuing combustible gases. The extreme rates of heating required for ignition in such times lie in the province of nuclear explosions.

Size of flames. During its early stages, a fire in a building burns as though it were in the open. The size of its flames governs the level of radiation to surrounding materials, which affects the rate of spread of the fire. A flame is continually entraining air so that combustion can take place, the flame length being just sufficient for combustion to be complete. By studying the entrainment of air into flames it has been possible to predict, for a wide range of fires, their size in terms of the rate of burning and the linear dimension of the fire area[3] (Fig. 11). The same theory is



Experiment	Floor area ft²	Floor area m²	Symbol
J.F.R.O.	1 4 9	0·093 0·37 0·83	○ • ▲
J.F.R.O.	34	3·2	■
J.F.R.O.	100	9·0	●
Kawagoe	11 100approx.	1·0 9approx.	△ □

FIG. 13. Rate of burning at restricted air flow in room fires.

also being applied to flames from windows, treating the window aperture as the fire area and the burning compartment as a producer of gaseous fuel. A further development bringing together, in terms of dimensionless variables, all the results for the length and vertical height of flames in winds should be important in the study of forest fires (Fig. 12).

So far, we have been concerned with the very early stages of a fire when it can be considered as being unrestricted by any enclosure. It is within this period that detectors should operate. When the flames reach the ceiling of a compartment, the hot layer of flaming gases mixes with difficulty with the cool air beneath and, consequently, the flame length increases rapidly. The layer of flame at ceiling height irradiates combustible materials stored on the floor and the fire develops rapidly. This breakpoint in the development of a fire has been called "flash-over" and is an important stage for it marks the division between a small and a large loss.

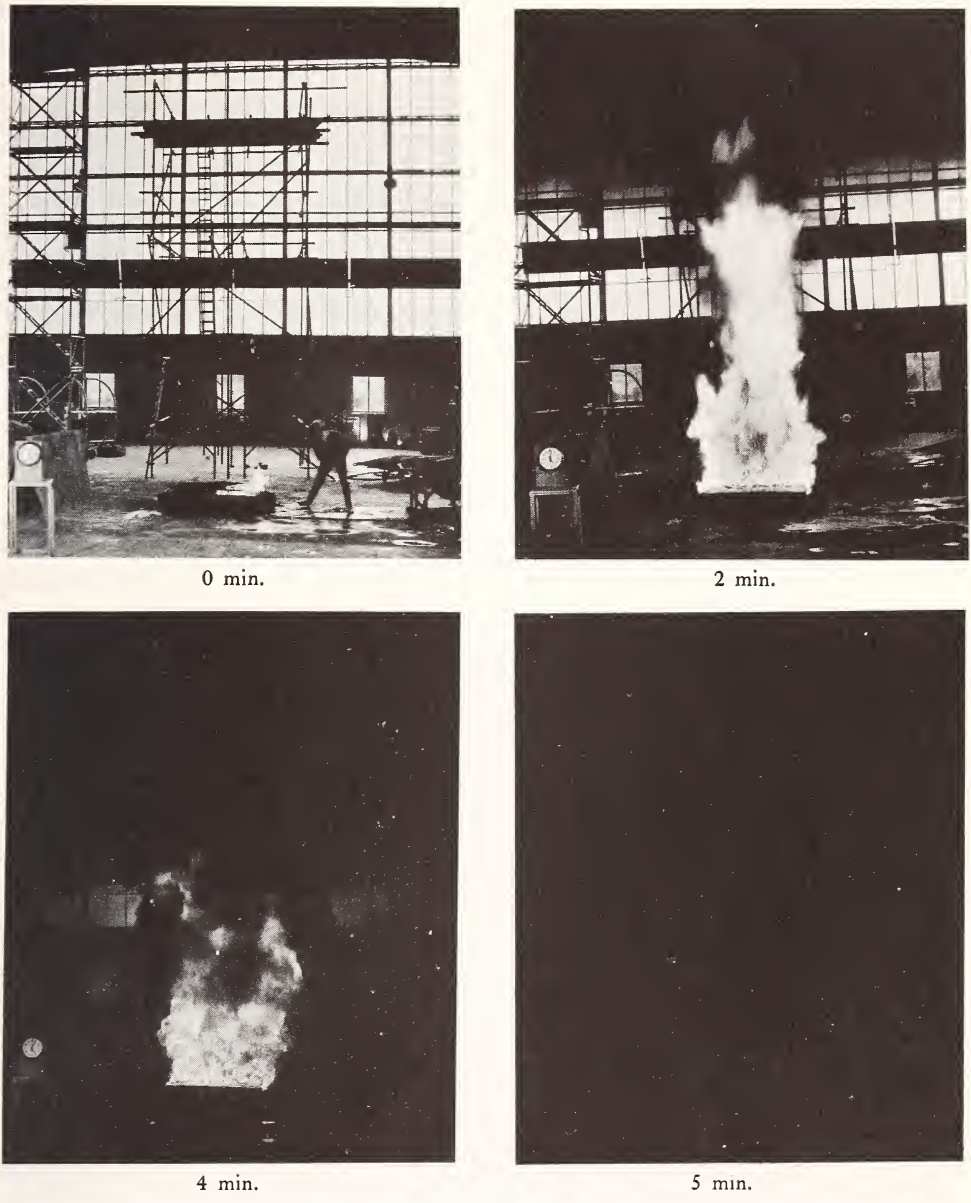
I have avoided mentioning one difficulty; the size of flames depends on the rate of burning but the rate of burning depends on the heat supplied to the fuel which, in turn, depends on the size of the flames. To make progress, the two latter factors are now being studied separately so that the points of equilibrium can be derived.

Fires involving whole compartments. When a fire has involved a whole compartment, the question arises as to whether it can be contained by the walls, floors, and columns remaining integral. Structural damage to these is a matter more of the duration of the fire than its temperature. The duration depends on the quantity of stored fuel and its rate of burning, which, in turn, varies with the air supply. From simple buoyancy considerations,[4,5] the air supply depends on the area of the window openings and the square root of their dimensional height (Fig. 13). While this is roughly true, it is not sufficiently accurate for predicting how long a structure will have to withstand a fire, for it can give errors involving a factor of two in the rate of burning and, hence, in the duration of the fire. This has led to a more detailed study of steadily burning fires in model compartments, in which the heat transfer from the flames to the fuel is being considered.

It is only by understanding the different kinds of fire and why they occur that it will be possible in the future to lay down rational standards for the fire performance of structural elements in buildings. It has not yet been possible to model their performance in fire, so fire tests are carried out on structural elements of approximately full size in large column, wall, and floor furnaces to determine whether they will withstand the action of fire while continuing to act as a barrier to flame and heat under normal load conditions.

Roof venting. Although the compartmenting of buildings is the best method of preventing fire spread throughout a building, the compartments themselves have sometimes to be very large to accommodate manufacturing processes. It is therefore important to see what can be done to minimize the fire spread in a large single compartment.

A small fire can completely black out the whole of the interior of a compartment, e.g., a petrol fire of area only 20 square feet will be completely hidden in a compartment, having a volume of 250,000 cubic feet, in 5 minutes (Fig. 14); the fire can then burn unchecked. One remedy is to arrange for sections of the roof to open automatically by fusible links as soon as possible after the fire starts. This prevents the building becoming smoke-logged and helps to reduce the temperature of the load-bearing roof trusses, thereby preventing the collapse of the roof in the fire area. If the roof space is divided by screens, the hot gases from the fire fill up one section,



0 min. 2 min.

4 min. 5 min.

FIG. 14. Blacking out of 250,000 cubic foot compartment by a petrol fire 20 square feet in area.

rather like an inverted bath, and open the roof vents in that section. This has the dual function of increasing the exhausting action of the vents and of preventing the spread of fire at roof level. Model-scale experiments have provided design data for the size and disposition of the vents and for the subdivision of the roof.[6]

Recently, the value of this work has been demonstrated by a fire in the upholstery and trim store of a motor manufacturer. Due to the operation of the roof-venting

system, the brigade could fight the fire, 13,200 square feet in area, in clear conditions, which undoubtedly proved one of the important factors in reducing fire spread.

Multi-storied buildings. A multi-storied building consists of a series of fire compartments stacked vertically. These are connected by staircases and lifts which are themselves enclosed by fire-resisting walls, so that escape routes are always kept open. If a fire occurs in one storey, the built-in fire resistance of the ceiling will prevent its spread upwards, unless the flames from a window can ignite the contents of the compartment above, thus leap-frogging the built-in fire protection of the ceiling. To avoid this, depending on the occupancy, under-window panels are required to resist fire for 1, 2, or 4 hours. If the building is faced with curtain walling, brick or block walls of appropriate fire-resistance have to be provided on the floor slabs behind the curtain walling and this has been so far an onerous restriction. Recent experiments on a large-scale tower building have shown that curtain walling can be constructed to have the necessary fire resistance, provided that attention is paid to the design of the panels, to the method of fixing, and to fire-stopping between adjacent storeys.

It is clearly important that, in a fire, staircases should remain clear of smoke and toxic products of combustion. Experiments are now in progress to see to what extent smoke-stop doors leading onto staircases are able to perform this function.

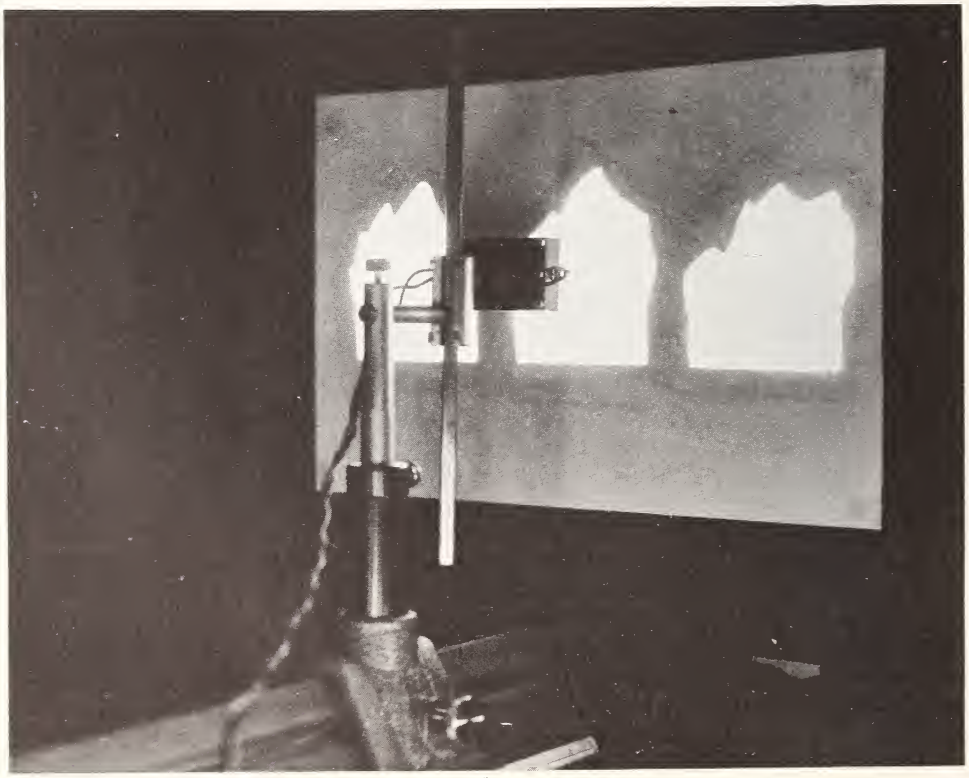


FIG. 15. Measuring radiation from windows using an optical model.

In parallel, a statistical survey is being made on the habits of the public in using smoke-stop doors, as it is essential that they should remain closed.

So far, the rate of outbreaks of fire in multi-storied buildings has been about the same as in traditional dwellings, through the pattern of causes has differed. Fortunately, the rate of fires spreading beyond the room of origin seems to be much lower, but the consequences are potentially more serious.

Spread between buildings. Buildings have to be separated to prevent rapid fire spread between them, leading to a conflagration. To find the required separation, it is necessary to know the radiation from a burning building and how this decreases as the distance increases, then, knowing the radiation necessary to ignite combustible materials, the required distance to prevent ignition can be found. The calculation of this distance is complicated, but, fortunately, the fact that light travels in the same way as heat can be exploited and it is only necessary to make an optical model of the burning facade of a building and measure the light intensity[7] to work out the necessary distances (Fig. 15). Tables of required distances of sepa-

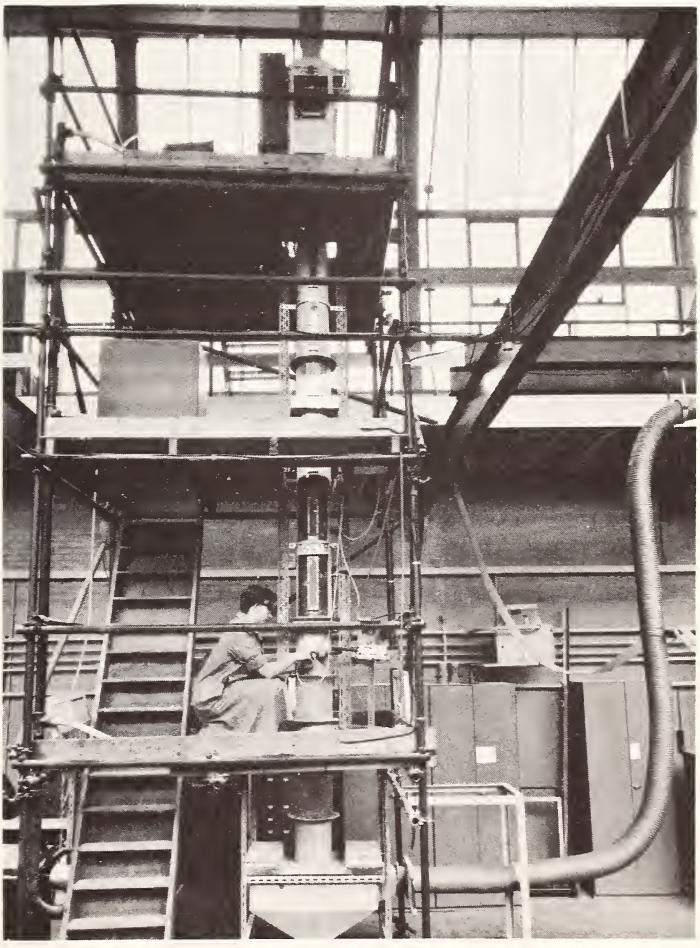
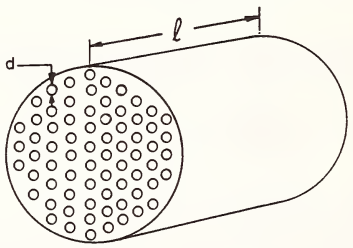


FIG. 16. Dust explosion: a large-scale vertical explosion tube apparatus.

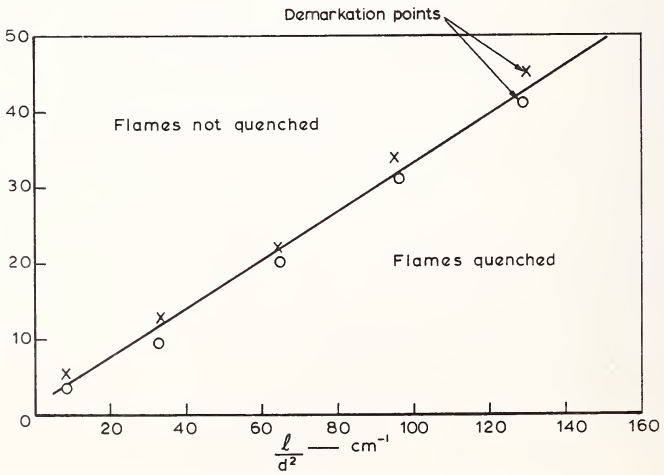
ration, based on these calculations, appear in the Draft Building Standards (Scotland) Regulations, 1961.

Explosion hazards. We have been considering flaming combustion over materials in bulk; special problems arise, however, when combustible materials are produced as dusts as in the industrial processes of cutting, grinding, crushing, etc. Due to the increase in surface area of these materials when they are dispersed, flames are propagated at speeds of tens of meters per second. It is clearly important that dangerous dusts should be recognized so that appropriate safety measures can be taken. As these will increase the cost of the process, the tests for hazardous dusts should be realistic. At present, many dusts that seem to have had a good industrial record are classed as dangerous. Experiments are therefore being carried out on the propagation of flames through mixtures of combustible dusts and inert powders, dispersed at various concentrations, to find the flammable limits (Fig. 16).

Explosion hazards also exist when flammable mixtures of air and vapors are being



PERFORATED BLOCK ARRESTER



(d< quenching diameter for flammable mixture)

Fig. 17. Flame-arrester efficiency.

conveyed along ducts from drying processes. The propagation of flame in such gases may be stopped by using a flame arrester. This consists of a heat exchanger for cooling flames, so that combustion can no longer take place. Rapidly moving flames are more difficult to stop than flames moving slowly, and experiments have now shown how arresters may be designed to stop flames in gases[8] (Fig. 17).

Occasionally, it is not possible to fit a flame arrester and then precautions have to be taken to ensure that an explosion may be vented before the pressure rises to such a level that the duct is disrupted. This may be achieved by fitting weak links which open up as the flame is propagated. The results of one series of experiments are shown in Fig. 18.

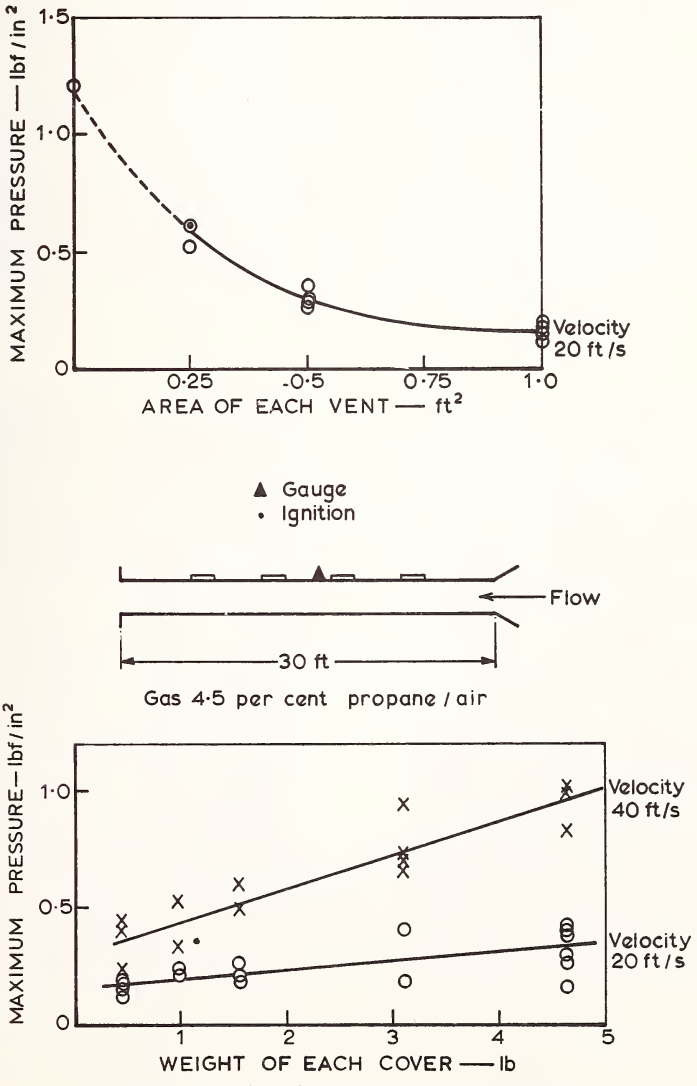


Fig. 18. Venting of ducts carrying flammable gases.

Extinction

Sprinklers and fire detectors. Since many industrial fires occur outside working hours, sprinklers form a valuable means of combating them; not only do they detect fires and give the alarm but they also start to extinguish them. Ideally, a sprinkler should extinguish the fire that has caused it to open and so, both the fires necessary to open sprinklers and the extinction of such fires must be studied separately.

A program of work in which a study is being made of the opening of sprinklers, both directly above and to one side of various sizes of fire in compartments of various heights (Fig. 19) is now nearing completion at the Joint Fire Research Organization. It has been found that the area of fire necessary to open a sprinkler varies with the height of the compartment raised to the power 5/2. Similar considerations apply to all fire detectors which are thermally operated.[10] Information from these experiments, in addition to that on the growth of fire in compartments, should help to decide at which stage in a developing fire sprinklers can be expected to open.

The next phase of the work will be to find the rate of application of water necessary to extinguish fires that open sprinklers; it should then be possible to state for the first time in quantitative terms what can be expected of a sprinker system.

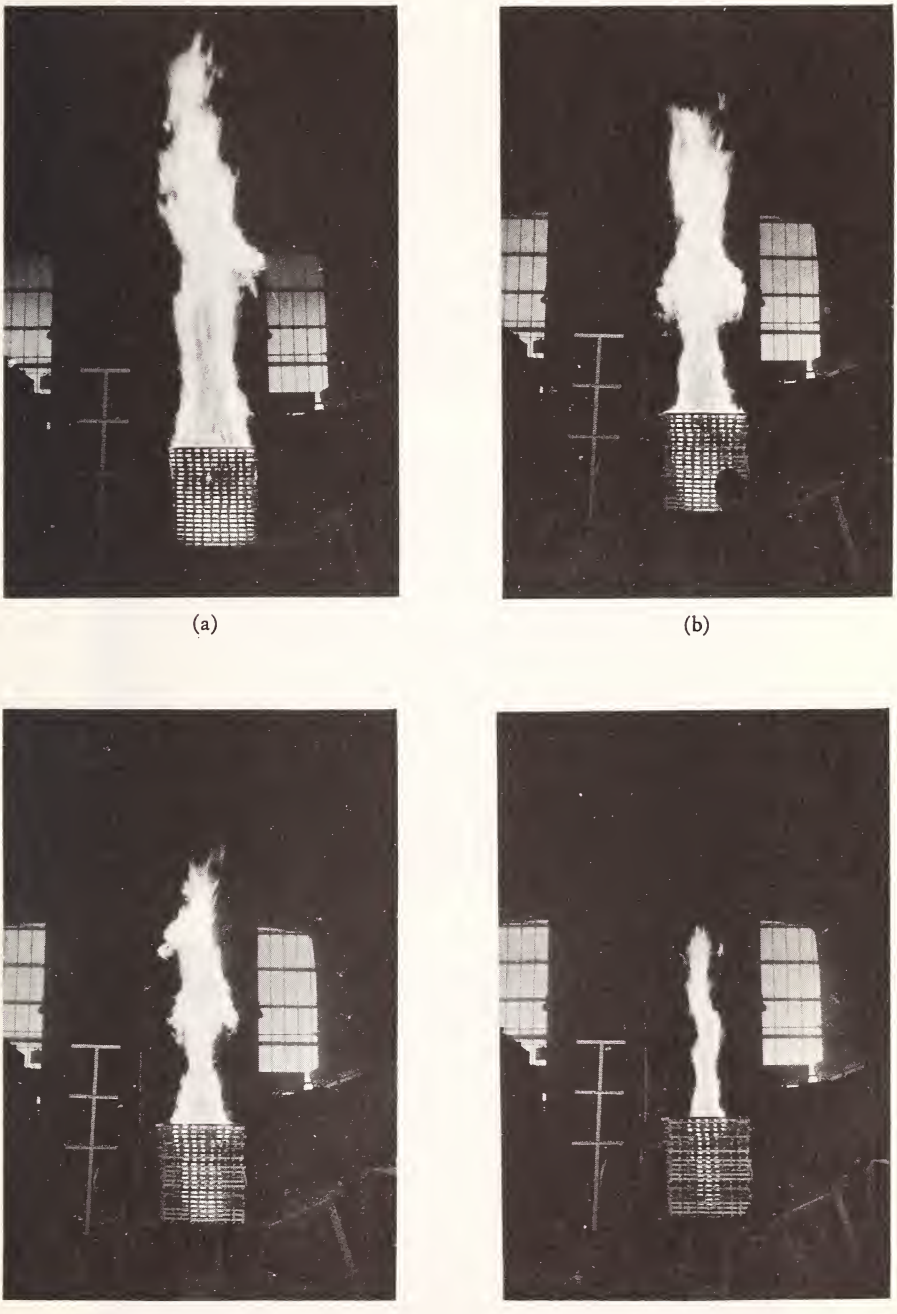
The present tests for thermal fire detectors, based on work carried out by the Joint Fire Research Organization, ensure that detectors operate quickly in building fires without giving false alarms as a result of vibration and ambient changes in temperature. A corrosion test measures their ability to withstand industrial atmospheres. In consequence of these tests, nearly every commercial detector of the thermal type has been modified to improve its performance.

Jet engine. Flaming combustion from extensive fires ceases when the oxygen content of the atmosphere falls to about 14 per cent. In order to extinguish fires altogether, i.e., to prevent smoldering combustion, the oxygen content has to be reduced to a low percentage. Flaming combustion in buildings may be controlled by the injection of large quantities of inert gas; however, because of leaks which are likely to occur, particularly under fire conditions, it is not practicable to extinguish fires completely without auxiliary fire fighting.

A modified jet engine has been constructed which will produce about 45,000 cubic feet of gas per minute, having the following composition[11]:

Nitrogen	46 per cent
Oxygen	7 per cent
Carbon dioxide	3 per cent
Water vapor	44 per cent.

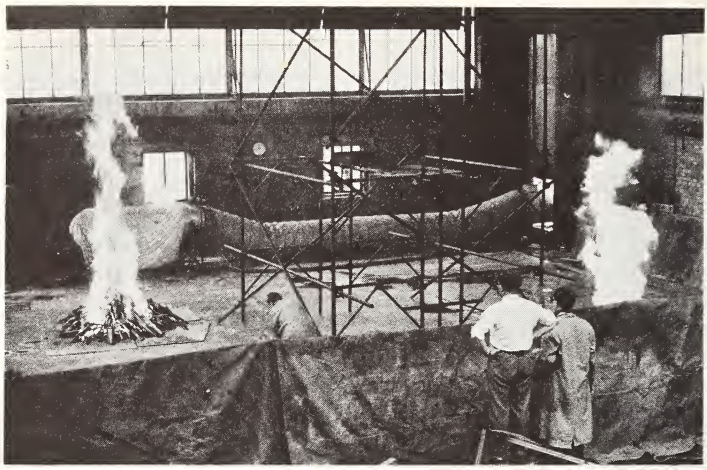
This inert gas will extinguish flaming combustion in a compartment of volume 250,000 cubic feet in about 20 minutes. The injected gases, being hot, rise to the roof and the compartment fills downwards, so that roof fires are extinguished first. Visibility is good and firemen can enter to extinguish the smoldering combustion, which will give rise to flaming combustion again if the injection of inert gas is stopped. While it has been found possible to extinguish fires in complicated basements about 100 yards from the point of injection, the visibility was not good, and further fire tests are necessary in this type of risk to investigate the clearing of the mist so that firemen may enter under relatively clear conditions.



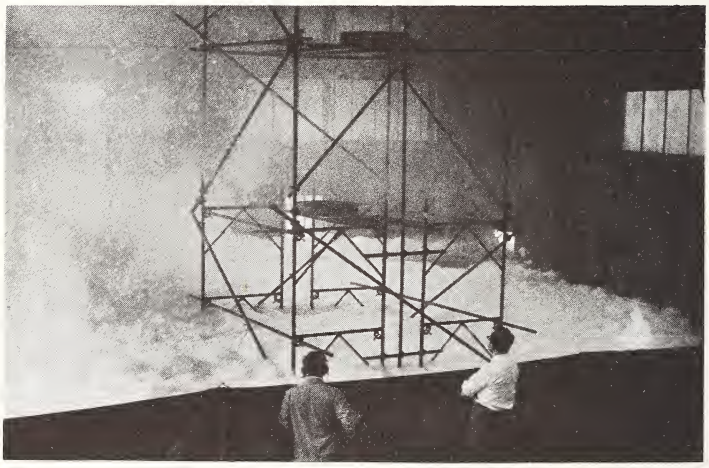
(a) (b)

(c) (d)

FIG. 19. Sizes of fire required to operate sprinklers in compartments having heights (a) 36 ft, (b) 28 ft, (c) 20 ft, (d) 12 ft.



0 min.



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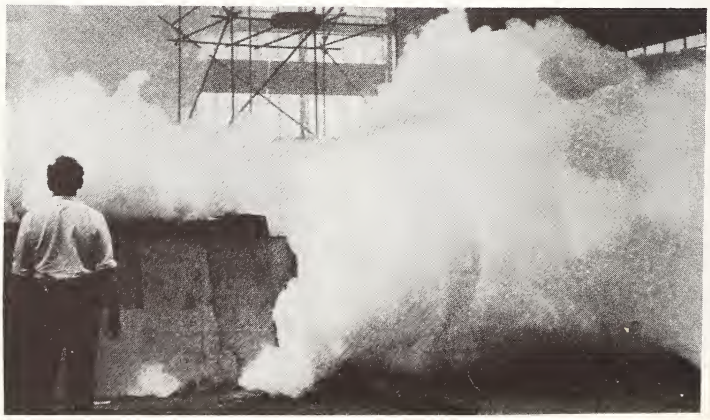

5 min.

FIG. 20. Fire extinction by the massive application of highly expanded foam.

The jet engine can also be used to produce large volumes of highly expanded foam at about 80,000 gallons per minute. This has the advantage of conveying both inert gas and water to the fire (Fig. 20). The foam contains from 1/500 to 1/1000 of its volume of water which improves the extinguishing power of the inert gas by a factor of 2. Difficulties have been found in preventing the water from draining from the foam before reaching a fire, but a foam compound has now been found which is much more effective than those previously used. The water in the foam makes it heavier than air despite the buoyancy of the inert gas, so that the foam flows first over the floor and the building fills upwards.

Times of attendance at fires. During 1956, the local authority brigades in country boroughs were attending 80 per cent of the fires within 5 minutes of being called. Since then, however, the traffic has increased in density and a new survey, taking into account time of day, is being made for various cities. The increase in traffic has brought about an increase in noise level and there has been some doubt as to whether the present fire bell would be audible to drivers of heavy lorries. Randomized experiments have been made with various warning sounds and, as a result, it has been found that the type of sound is not so important as its volume. A fire engine with the present bell can be directly behind a lorry and be inaudible to the driver. The most audible equipment available is a group of four horns which can be heard 140 feet away. The performance of the present fire bell can be improved by amplification so that it can be heard at 70 feet.

Economic Considerations

Finally, it is necessary to look at the economics of fire protection, for any investment in fire protection should be matched by a reduction in fire loss. The direct loss attributable to fire is published by *The Times*, and this has risen throughout

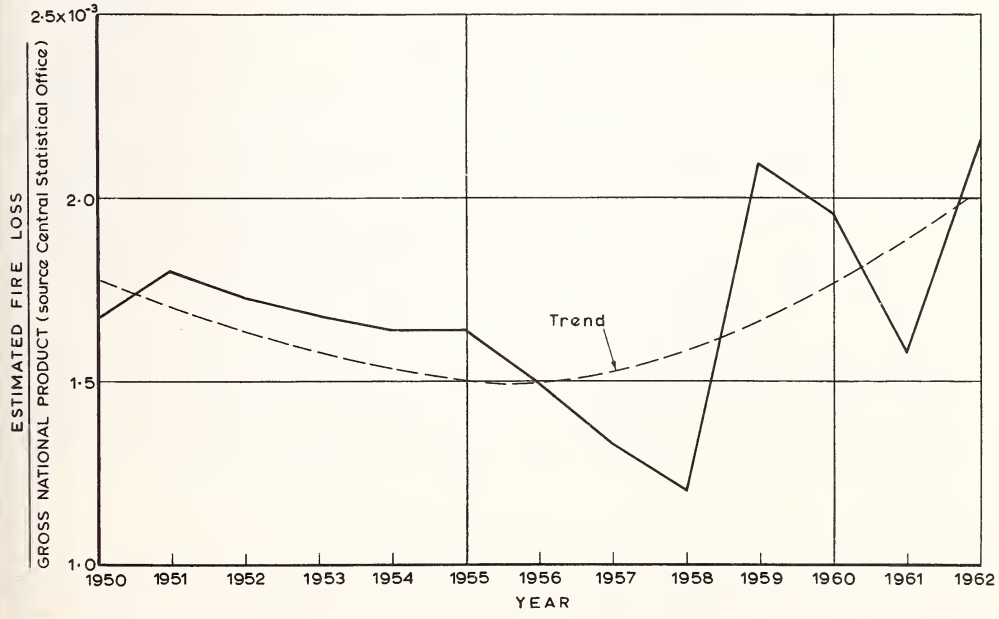

Fig. 21. Fire loss and gross national product.

the last twelve years, and particularly since 1959. The direct loss can be compared with the national activity in terms of the gross national product and it is found that about 1/500 of the national effort is destroyed by fire—about four times that consequent upon industrial disputes in 1960 (Fig. 21). While this fraction decreased during the early 1950's, it now seems to be rising again,[12] though it is difficult to say why until further information is available.

The nation makes an investment to prevent or diminish this loss, in designing buildings to prevent the rapid spread of fire, in information services, in local authority and industrial fire services, in hospital treatment for the injured, and in research and development. It also makes an investment in insurance administration. Although the primary purpose of insurance is to redistribute the burden of loss when it occurs, insurance costs include a considerable proportion of technical, survey, and other servicing expenses to promote improvement in fire protection and to diminish fire risk. From all these investments, exclusing direct fire loss, the nation receives real benefit. The total amounts to between £200 million and £300 million per annum made up as follows:—

Estimated Annual Investment in Fire

Item	Cost (£ million)
Direct loss (1962)	56.0
Structural protection in buildings	30.0–150.0
Local authority fire brigades	30.0
Industrial fire fighting	20.0
Treatment of injury	0.3
Insurance administration (including technical survey and other servicing expenses)	50.0
Research and development (government and industry)	0.3
Total	186.6–306.6

It is an unsatisfactory state of affairs when the most uncertain item is the cost of fire protection in buildings, which is much greater than the current direct fire loss of £56 million. To approach the problem of balancing fire protection with building costs, much more is required to be known about the current expenditure on fire protection and the ends to which it is being directed. Clearly, it would not be worth making a further investment of £56 million per annum unless the Utopian situation could be reached in which all monetary fire loss had been abolished.

Putting the cost of fire at its lowest figure of £200 million and the national investment in research and development by both government and industry at about £300,000 per annum, the investment in research and development amounts to about 0.15 per cent of the annual turnover in fire expenditure. This is a very modest figure and yet our own nation is among the more enlightened where fire research is concerned.

Conclusion

I have tried to give you a picture of the current problems we are facing in research and I hope that you will have seen in it lines of development which should

have an important bearing on our understanding of the kinds of fire which occur in buildings, how they develop, and how they may be extinguished. New materials and new forms of construction are continuously being evolved, but it is only by understanding the problems in this basic way that progress will be made.

From what has been said you will see that, as a country, our efforts in preventing the growth of fire are meeting with success. You will remember that at the research level it was the application of material sciences that would be likely to make its impact on reducing fire spread, and this side of our work appears to be having its effect. The reduction of fire loss is a matter of reducing the number of outbreaks and, in these days of materialism when the importance of individuals is apt to be overlooked, it is probably comforting to the humanist to find that responsibility for reducing fire losses rests with the citizen. This view, however, must be tempered by the thought that it is difficult to bring about a favorable response of the population to a negative subject like fire protection. People do not want to think about fire; this is something that always happens to the other fellow.

The ever rising number of outbreaks and the rising cost of fires seem to be a consequences of living in an affluent society which has new responsibilities and new distractions. Unless new ways of enlisting public cooperation are found, it is difficult to see any way of halting the increasing inroads that fire is making into our economy.

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Forest Fire Research in the Forest Service—USDA

A. A. BROWN

[This review of the activities of the Forest Service—USDA in the area of forest fire research was written by the former director of the Forest Fire Research Division. On the occasion of his recent retirement the following brief, but heartfelt, letter was sent to add to a collection of similar sentiments from his friends:

Dear Arthur:
Too bad that your August 25 party kept you from coming to Cambridge to listen to the Fire Research discussions at the Tenth Combustion Symposium. I know you would have been pleased that the seeds planted by you years ago are now prospering. It's never easy to break new ground, but it must be good to know that the effort was worthwhile.
With warmest wishes for the future,

Sincerely,

(S) W. G. BERL

Editor]

Introduction

Forest fires of conflagration proportions are a part of the North American history of development. In part they are a legacy of the past, in part they are a product of the modern day environment. In the virgin coniferous forest, periodic fires set by lightning were a part of the natural environment. This contributed to an acceptance of forest fires as natural phenomena about which man could do little as were storms and floods. This acceptance prevailed with some notable exceptions for the first 100 years of settlement and agricultural development in the United States. But uncontrolled use of fire for many purposes and extensive timber cutting which created great areas of hazardous fuels, so increased the frequency and destructiveness of such fires that public demand to protect forest resources and man's activities from the threat of wild fires found increasing expression in both state and federal legislation.

The creation of the National Forests in 1905 was a part of this change in public policy. The Forest Service created in the U. S. Department of Agriculture was charged with the protection, development and use of the resources of these vast public properties. There was little experience and no precedent to guide the development of systematic protection. At the start, fighting wild fires in the West was often a David and Goliath affair with Goliath too often winning. Under these circumstances the Forest Service had to become first of all a successful fire fighting organization. Most of its early leaders devoted their talents to meeting the exacting requirements imposed by the erratic and emergency nature of the forest fire problem and the whole organization participated in an activity loosely known as Fire Control Planning. This was the present day equivalent of Operations Research, though the methods and mathematics lacked the elegance that now dignifies this approach. This activity provided the base and created the demand for a more formal research program.

Historical Development

Actually Forest Research was the first forestry activity in the Department of Agriculture and some research on forest fires was conducted sporadically in and out of the Department long before the creation of the National Forests. In 1881 the Meteorological Branch of the Army Signal Service (later to become the U. S. Weather Bureau) conducted studies on "the mechanisms governing the ignition, spread, and intensity of forest fires." But the creation of the U. S. Forest Service and the establishment of its Branch of Research in 1915 gave a new focus and continuity to forest research in the United States. For some time fire research was incidental to other forestry research and it was not until 1923 that the first full-time fire research position was created. Mr. H. T. Gisborne was assigned to this position and began his pioneering studies at Priest River, Idaho. He began active field study of the effect of weather on the start and subsequent behavior of forest fires. Shortly after this the analysis of fire records and the development of fire control systems became recognized as a fire research activity in California and a small but active fire research unit was established there. At the start it was headed up by Show and Kotok who were respectively Regional Forester and Experiment Station Director of the California Region. They had initiated such studies in 1919. Research in the effect of weather on forest fires was initiated at the Pacific Northwest Station at Portland, Oregon in 1922 through field work at the Wind River Experimental Forest by Hoffman and Osborne. Pioneering work particularly on fire damage, such as by Adams in the Ozarks was also under way in the East. This early work was carried on by a few widely scattered individuals, some of them on a part-time basis. Nevertheless much productive research was accomplished because of close teamwork between research men and forest administrators. The development of meaningful forest fire statistics, and of guide lines which set the pattern for systematic control of forest fires on an area-wide basis took place before 1930. The McNary-McSweeney Act of 1928 gave this work new impetus. The subsequent Civilian Conservation Corps and other emergency conservation programs of the 1930's had the effect of promptly converting planning concepts developed by research into fire control systems with supporting structures and hardware. This was particularly true of planned systems of fire lookouts, of small systematically placed fire fighting crew units located for fast attack on fires, and of supporting communication and transportation systems.

Perhaps the outstanding advance of the period was the inauguration of systematic rating of fire danger. This grew out of the micrometeorological research by Gisborne in the Northern Rocky Mountain Region. It culminated in 1934 in a system for taking account of both cumulative and daily fluctuations in the factors that affect the inception and spread of fires in forest environments. Though the rating of fire danger was hightly empirical, it met a long felt need and was eagerly adopted by forest fire agencies. By 1940 all National Forest organizations and several state agencies were operating systems of fire danger rating.

In the World War II period the forest fire research program was a casualty of the drive for economy in civilian activities. It was cut drastically in both funds and personnel and remained at a low ebb from 1941 to 1948. In 1948 with a modest increase in funds a new Division of Forest Fire Research was created to head up this activity in the Chief's office of the Forest Service. This was the first step toward recovery.

In 1950 the new Division entered into a research contract with the Operations Research Office, The Johns Hopkins University, to study the effects of nuclear explosions on forests and other forms of natural cover. This included both thermal and blast effects. This work was expanded in 1951. In 1952 its sponsorship was transferred to the Armed Forces Special Weapons Project. Research in this field for Civil Defense and National Defense has continued on an intermittent basis to date. It is reported through some eighty publications. This activity gave timely stimulus to the program of the Division. In 1953 a strong and productive fire research staff was functioning, though funds had recovered only to near the 1932 level. In the subsequent ten years, growth in both funds and personnel has been rapid. With growth, more basic research is being undertaken and a much more balanced program is progressively being realized.

The Committee on Fire Research and the Fire Research Conference of the National Academy of Sciences—National Research Council created in 1955 have exerted a strong influence in the development of depth in the current program. This has come about through (1) the creation of a climate favorable to basic research on free burning fires, (2) the development of a suggested key program of basic fire research for attention by all agencies, (3) continuing stimulation of interest and coordination of effort in fire research between agencies through contract research and various devices, and perhaps most important of all, (4) publication of "Fire Research Abstracts and Reviews" providing a common medium of publication, exchange, and reference.

Of great importance too has been the development of major forest fire laboratories at Macon, Georgia; Missoula, Montana and Riverside, California. The laboratory at Macon was built by the state of Georgia. It is equipped and staffed by the Forest Service under a special cooperative agreement with the Georgia Research Council. The laboratories at Missoula, Montana and Riverside, California are federally financed.

Current Programs

The current program consists of long term and short term studies in twenty-eight active projects. These studies range from a basic or highly theoretical approach to that of developing simple and practical guide lines from research findings for operational use. Most of the basic research is carried on at the three forest fire laboratories especially designated for this purpose. Additional field programs are conducted at seven regional experiment stations (Juneau, Alaska; Berkeley, California; Fort Collins, Colorado; New Orleans, Louisiana; St. Paul, Minnesota; Columbus, Ohio; Upper Darby, Pennsylvania). The professional staff engaged in these programs consists of 75 scientists with necessary clerical and subprofessional support. Seven scientific disciplines are represented including foresters, meteorologists, engineers, physicists and chemists in descending order of numbers. Several sociologists and a plant physiologist are also working on current projects. Work on economic aspects of forest fires and their control is planned.

The program may be described as largely "in-house" since very little research by private contractors is involved. Nevertheless broad authority for cooperation exists and cooperative projects with universities and other research agencies on one hand and forest fire control and other operating agencies on the other are typical features of the program in each region.

In addition, as discussed in the preceding section, the Fire Research Division of the Forest Service has often acted as contractor for fire research needed by agencies of the Department of Defense. The place of this activity in the current program will be described briefly in a later section.

To permit a more definitive review of the current national program in forest fire research it is broken down into the following six fields of effort.

(1) Fire behavior
(2) Fire prevention
(3) Fire control
(4) Fire damage
(5) Fire use
(6) Fire research and National Defense

Fire behavior. - The objective of this research is to develop a complete understanding of the free burning fire and how it responds to the variables in its environment. The variables introduced by fuels, weather, and topography are regarded as the controlling factors by workers in forest fire research. Included in the objective is the establishment of quantitative correlations of ignitions and subsequent behavior, with the controlling physical factors in the environment. This is for the purpose of developing valid means of prediction of the probability of ignition; the rate and manner of spread; the rate of energy release and its distribution; height, depth, and character of flaming; time histories of thermal and convective forces; tendency to spot ahead and to propagate through tree crowns. These objectives are ambitious since the relationships are extremely complex and are compounded by the effects that fire itself exerts on its environment. It is not expected that they will be realized within the time span of existing plans. Nevertheless, much of this information is so important to the success of fire fighting that approximations based on the best available information must be constantly employed. Progress through research will no doubt consist of successive improvement in the accuracy of these approximations for field use.

The present status of work in this area may be described as at the point where the "what" and much of the "why" of fire behavior are known, but only a start has been made on the "how much"—the quantitative descriptions of fire behavior. Progress has been in two stages. At first heavy dependence was placed on individual personal experience gained through observing and fighting fires. Next a systematic program of recording detailed information on each fire was undertaken. This included the action taken to control it and the degree of success attained. By this means mass statistics became available which permitted objective evaluation of observed relationships and personal experience of thousands of men on many thousands of fires. This statistical approach continues to be highly productive for fire control planning and many other purposes. But it has severe limitations in supplying complete information on fire behavior, since the information it provides is limited for the most part to frequency, probability, or distribution.

The second stage of development has come about through experimental methods with test fires. Until recently these were small outdoor test fires under selected weather conditions. Because of the large number of variables that always enter in even under carefully selected conditions, these methods too have had limitations. They have revealed trends and have contributed much new insight but the data obtained have not been adequate to provide the quantitative descriptions needed.

In the last few years, the use of models in the new laboratories has begun to produce new quantitative information on the energy budget, on rate of forward spread of a flame front as influenced by the fuel and its arrangement, the moisture content of the fuel, and the amount of air movement. A fire whirl model is also providing new information on the vortex formations that so often characterize the convective activity of wildfires.

In this program, mathematical description of fire behavior is not an end in itself, but only a step toward better prevention and control of fires. Relationships established for fire models must be tested in the field. Similarly, field case studies of wildfires reveal unexplained phenomena that can best be explored under controlled laboratory conditions.

Both field and laboratory studies of fire behavior may be termed fire physics since they focus on the dynamic physical relationships of a fire.

Since combustion is a chemical process, the chemical relationships must also be taken into account. The very excellent work on flame inhibitors and on the chemistry of intermediate products of combustion which has been in progress by universities and by private research institutions, has been taken into consideration in fixing the level of similar work in the Forest Fire Research program. To date the effect of trace chemicals on the combustion of cellulose fuels has been investigated and a start has been made in the chemistry of retardants

Long range plans for research in fire behavior assume that this work will not be completed in the foreseeable future, and that it will depend on many agencies and institutions. Nevertheless active and continuing research aimed at complete understanding of the free burning fire is regarded as an essential corner stone of the future Forest Fire Research Program.

Fire prevention. - The prevention of fires in practice consists of two means of approach. One is aimed at controlling the source of ignition, the second is aimed at controlling the fuels in which ignition occurs. Research in support of fire prevention varies similarly in its objectives, and draws on a variety of disciplines.

Perhaps the most ambitious objective in this field is that of reducing the number or severity of fire-setting lightning strikes through use of cloud-seeding methods. This is one of the objectives of "Project Skyfire," the lightning storm study at Missoula, Montana. This project also involves basic research in electrification of the atmosphere and is supported by the National Science Foundation. Two research projects aimed at reducing the number of man-caused fires have as their objective a more complete understanding of the human habits, attitudes, and motives that lead to preventable man-caused fires. These projects use the sociological approach. Both are in cooperation with universities. One is with the University of Southern California, the second is with the University of Mississippi. This research is expected to improve discrimination in choice of media and methods in behalf of fire prevention. It should result too in more insight generally into the human aspects of the forest fire prevention problem. Hopefully it will provide for the first time a numerical basis for evaluating fire prevention measures. It may also provide a new tool for determining the optimum combination of measures for each local situation.

The need of research in other aspects of fire prevention has been obscured in part by the apparently forthright nature of much of the task of keeping firebrands from coming in contact with forest fuels. But to do so completely in a large wildland unit would require either complete control of people or their total exclusion.

Such drastic measures are not available to the forest land manager. The objective must be attained by less direct means. Under many circumstances it is more practical to control the quantity and nature of forest fuels than to prevent their exposure to firebrands. This principle may take many forms. A familiar form is the cleared railroad right-of-way and firebreaks of a variety of specifications. These have a dual purpose. If they function as intended they prevent ignition on the cleared strip which in turn acts also as a barrier to the rapid spread of small fires which may ignite nearby. In the past, firebreaks that would serve this purpose only have been regarded as uneconomic except in special situations. However, planning that can combine such functions with other needed functions has many possibilities. Research is underway in California to explore this field.

A second form of fire prevention through hazard reduction is aimed more specifically at preventing the runaway fire than at reducing the number of ignitions. This, in general, consists of the controlled or prescribed burning of hazardous fuels over considerable areas. Research in this field has been confined for the most part to that of techniques of burning by which the fire can be closely controlled in both area and intensity. The science and art of "prescribed" burning depend for continuing progress on research in forest fire behavior.

In the Southern States prescribed burning in wintertime to reduce the fuel hazards that build up through natural processes has had considerable attention. Prescribed burning in this case is applied to green timber stands and must be carried out in such a way that minimum damage is done to living crop trees. Such burning is employed also to prepare seedbeds for natural or artificial re-seeding, to control competing unwanted vegetation, and as a sanitary measure to control brown spot disease on longleaf pine seedlings.

In the West, broadcast burning is practiced following clear cutting operations in old growth timber. In such instances very heavy fuels are involved, particularly in the Douglas fir forests of the Northwest. Fuels up to 100 tons per acre on areas of 10 to 60 acres are surrounded by green forests. To reduce fuels effectively an intense fire is required. Complete control of such fires with no damage to the surrounding green timber is very exacting. It requires continuing research to develop guidelines sufficiently precise to avoid disaster by the uninitiated. Research on this is also in progress.

In forest land management for varied purposes, particularly in the maintenance of favorable habitat for small game, some use of fire appears to be indicated. This too requires exacting research to determine how maximum net benefits without unacceptable damage can be achieved.

In addition to elimination or reduction of fuel by burning there is a potential for reducing ignitions and for setting up barriers to free spread of fire by treatment of fuels to reduce their flammability. At present the most effective chemicals are quite soluble and are removed by rain. Even so such use is practical in intensively used areas in California. Research to develop more persistent "flame proof" treatment of grass and other flashy fuels is underway.

A further method of limiting the extent of runaway fires is through cultural methods. Serious thought is being given to the establishment of irrigated green belts to break up the continuity of flammable brush cover in California. Similarly coniferous plantations can be separated by strips of broadleaf trees or by cultivated fields or pastures. Such principles can be applied in management of lands to avoid disastrous continuity of forest fuels under regimes of intensive land management.

This might be regarded as "built-in" fire prevention. As such it deserves high priority in future investigations.

Fire control. - The over-all objective in Forest Fire Control is to devise optimum systems for reducing forest fire losses to the point where the sum of costs plus losses are at a minimum. Fire control systems in turn depend on 3 lines of defense. The first is prevention of as many fires as possible from starting, the second is quick control of the fires that do start while they are still small, the third is holding to a minimum the damage and costs of runaway fires that develop in spite of these provisions. Even routine operation of these three lines of defense requires good organization, training, and administrative management. But progress in each, depends on a high level of continuing research.

Research in prevention of fires has been separately discussed. The early research referred to as "fire control planning" has been briefly described in the preceding. Two concepts featured this latter work. The first was that in forest fire fighting as in all fire fighting, "time is of the essence." This concept grew out of studies of fire fighting experience. It was applied to the fire organization in the form of time standards for each action leading up to attack on a fire. These time standards were given emphasis by the slogan "get them small." They were referred to in early studies as "hour control" standards. They were varied to reflect fire fighting experience in each fuel type. In natural fuels where fires spread most rapidly, elapsed time standards from first discovery of a fire to attack on it were set at a half hour or less. This was the minimum. Protected areas were zoned accordingly up to a maximum allowable attack time of four hours.

To meet these time standards the concept of "coverage" of area within specified time limits was developed. In detection, this consisted of visible area from a forest fire lookout. In planning for first attack it consisted of area that could be reached by the available means of travel and travel routes from existing or proposed fire crew locations. "Coverage" on a map gave a graphic picture of the degree to which standards were being met. It also provided a systematic basis for improving the system. The objective toward which the system was being designed is simple in concept. It is to attack every fire soon enough to control it with locally available forces before much damage is done. Dependable means of quick detection of fires is the first essential; an expandable system of communications that can be quickly extended to any part of the protected area is likewise essential. The third requirement is a system of transportation and of equipment that will enable fire fighting forces to reach any fire that starts in any part of the protected unit within specified time limits. These are exacting requirements.

Communication networks and transportation systems each introduced additional parameters. Yet plans for both utilized a similar model approach. Together a rather complete set of specifications for orderly development and placement of all elements of fire control systems emerged from research carried out during the 1930 to 1940 period.

Fire danger rating provided the guidelines for operating these systems.

In each sub-climate of the United States there are only certain times of year when weather and the condition of forest fuels combine to create danger of forest fires. The periods when such conditions normally occur are known as the fire season and are defined for purposes of budgeting and financing. In northern regions the fire season is short, in the south it is nearly year long but intermittent. The length of the season affects the proportion of the fire fighting force that can be offered

yearlong employment, etc. From day to day during the fire season, the danger of fire fluctuates with wind, rain, and sun. Following heavy rains it is very low but climbs steadily in drought periods and may build up rapidly to an extreme point when strong, very dry winds persist. These changes determine the size of the potential fire fighting job. It may vary by a factor of five in a few days.

Systems of fire danger rating have been developed to reflect these changes. Though quite imperfect, they have become such valuable guides to the management of fire control activities that they are in general use. Eight such systems have been employed in the various forest regions. A special project aimed at substituting a single national system is under way. The development of a national system requires new research to fully substitute measured relationships for empirical estimates. This may require continuing work over a good many years.

Even a perfect system of rating fire danger gives information only on existing or past conditions. The forest manager needs also to anticipate the changes ahead. For that reason, the forecasting of changes in weather that will affect fire danger is also of critical importance in keeping the fire control organization geared to the job. Fire-weather forecasting needs to be localized and to be within rather exacting limits of accuracy. Much research is necessary to attain the standards needed. In the meantime, like the rating of fire danger, fire-weather forecasts are depended on for making emergency decisions and for projecting today's fire danger to tomorrow.

The standards for developing fire control systems and the principles that apply in planning and managing such systems are now in need of reanalysis. Former "rule-of-thumb" applications need to be replaced by more carefully computed relationships and objectives of long-standing need to be critically reexamined in the light of economic and technological change. This is a promising field for application of the techniques and methods of Operations Research. Such work is planned but has not yet made much progress.

Small fires that end small are controlled by offensive attack. But it takes surprisingly little increase in the fires' output of heat energy to drive an attack force back into defensive positions. While some fires are held, in such situations, it is here that most fires escape control. Better ways to increase the striking force of fire fighting units to enable them to maintain the offensive against small hot fires is badly needed. This problem has high priority for research. It is the special objective of current research on fire retardants and suppressants. It is also the principal purpose of aerial attack on fires to provide close support to fire fighting operations on the ground. This has proved most effective in holding small hot fires in check long enough for ground fire fighting crews to complete the job.

The runaway fire cannot be entirely prevented. It continues to be an unsolved problem. There are no known ways for example for successfully making a direct attack on the head of a fast running large fire. Control is usually possible only when the run has stopped or sufficient outside additional area has been backfired out to contain the fire's head.

Finding new ways to increase the effective output of forest fire fighting units can greatly strengthen this third line of defense as well as the second.

Because of the magnitude of the job of planning, directing and carrying out the suppression on large fires, there are many other problems that presently contribute to excessive costs and losses. Most of these are operating problems susceptible to approach through operations research techniques. A start has been made on these through a current cooperative project with the University of California.

Better knowledge of fire behavior is an urgent underlying need. Until the behavior of a fire can be reliably predicted far enough ahead to plan and execute its control, high efficiency can not be attained. The model studies already discussed have special significance to progress in this area.

Fire damage. - Complete devastation following conflagration type forest fires is mute evidence that forest fires can be extremely damaging. Not all fires are so spectacular, nor their effects so readily apparent. Even when the destruction is complete, the problem of assessing the actual damage is extremely complex because damage occurs in numerous forms and may be both immediate and long-term in nature.

The research objective is to explore the kinds of damage done by forest fires and develop systems for appraising damage after any fire event and for estimating expected damages from possible fires in the future. In the beginnings of organized fire control, it was sufficient to consider only the dollar value losses to currently merchantable timber. But with the growing population and its expanding economy, other forms of damage, as well, have taken on greatly added significance.

Much of the past effort has been devoted to the economic evaluation of damage by fire to the timber resource, including the effects on merchantable trees, young growth, the problem of regeneration, and the growing potential of the site. Where kill is complete, evaluation of the fire impact on the tree crop is often reasonably clear. In many instances, however, outright killing may be light or entirely absent. In hardwood forests, particularly, this is the usual case, and one that has been particularly difficult to resolve.

Fires in our hardwood forests are always surface fires. Typically they burn only the leaf and twig litter on the ground surface. Flames are often only two to four feet high. Following such a fire, recovery soon appears to be complete, yet considerable damage may have been done. The flames may have been hot enough to kill a small section of bark and the cambium beneath it, perhaps no larger than the palm of one's hand on a high proportion of the rapidly growing trees. Within a year or two this piece of bark cracks and may drop off. This opens the way for important heart rot fungi. Eventually, the wound may appear to heal, but because fungi have gained entrance, each tree is doomed to become a hollow shell, even though continuing to grow and to appear normal. Repeated fires in this way convert hardwood forests into unproductive stands of decadent trees.

Part of the current research is to find ways to identify immediately after a fire, trees that have been permanently damaged by bark wounds to they can be removed from the stand in an orderly salvage operation. Studies in the East and South have correlated the probability of damage occurrence with the fire danger index at the time of the fire. This is a useful device for land managers but still does not identify the particular trees that may have been permanently damaged.

To date the most intensive study concerned with damage to other than timber was devoted to expected damage from runoff and erosion following fire on Southern California chaparral covered watersheds. When chaparral burns, virtually everything is consumed but the larger green stems and stumps, completely exposing the soil.

Damage results when subsequent rains produce accelerated surface runoff and debris-laden floods downstream. This treasured water is lost to human use and both upstream improvements and those in the floodplains below are susceptible to physical damage from the combined flooding and erosion.

This study surveyed the soil and geologic characteristics of more than 250 drainage units covering the area. It then analyzed thousands of rainfall, stream gage, reservoir inflow and debris basin records. This established for each drainage the probable increases in runoff, erosion, and flood stage for all future expected rainfall events during a prolonged period of watershed recovery after fire.

The next step was to inventory all upstream and downstream improvements susceptible to damage and estimate the cost of repair or replacement required for different sizes of storm runoff events. The cost of removing debris and reshaping downstream channels was also included. A system based on the probability of occurrence of different storm events permitted the summation of all expected damage and its conversion to expected losses in dollars per acre burned. These ranged from a few cents per acre on desert-facing slopes up to $1,000 per acre in the most critical areas.

The planned program provides for the development of systematic methods for estimating watershed fire damages for broad-scale application. Methodology must differ somewhat from that in the California study because nowhere else are such intensive networks of watershed performance records available covering a long time period. Several preliminary approaches have been made.

One particularly difficult problem is that of evaluating in any useful quantitative sense some recognized forms of damage to which no way has been found to attach a meaningful dollar value. There are several of these, but the ones most prominent in current land management programs are concerned with fire damage to recreation and to wildlife.

Forest recreation is increasing very rapidly and in many areas already competes very strongly with other forest uses. But burned areas lose their attractiveness, at least temporarily, and often for the foreseeable future. Attempts to establish any quantitative measures of the importance of preventing their burning have not thus far been successful.

The situation is much the same with respect to fire effects on wildlife. Few birds and animals are actually burned by forest fires. Often though, the effects on habitat are drastic, sometimes adversely and in some cases beneficially. But how to evaluate either in terms other than changes in resident populations has not been determined.

There is precedent in other fields for assessing as part of damage certain associated indirect losses. The planned program includes definition of those that may be identified as insurable damage for possible recovery by private forest owners and for establishing as well, the total losses suffered by the community. Various indirect losses in this category include loss of profit from the processing and sale of forest products, lost wages, interrupted rail and highway traffic, disrupted power transmission, air and water pollution, lost revenue from recreationists and loss of use or occupancy during rehabilitation. There are many others.

Fire use. - The history of fire use in the woods in the United States has been continuous since the country was first settled. Fire was first used to clear the land for agricultural crops and otherwise open up the country for settlement. It was later used extensively in many parts of the country to keep the forests open and favor the growth of palatable forage for livestock, but without any particular effort to limit the area burned. This practice is still prevalent in parts of the Midwest and South.

In later years, controlled fire has been used in a more systematic fashion for various forest management purposes. "Controlled burning" implies the applica-

tion and confinement of fire to a planned area. The principal emphasis is on confinement of the fire, not on what it burns. It therefore does not have much place in the managed forest, but where it is applicable, it is the most economical method for eliminating large quantities of flammable material.

More recently, systems of "prescribed burning" have been developing through research in use of fire for hazard reduction and silvicultural treatments in growing forest stands as well as for other purposes.

Prescribed burning is controlled burning with the additional requirement that the fire have a specified rate of spread and intensity. This is a tremendously more exacting requirement than for controlled burning alone, but when met it permits fire to be used as a low-cost treatment for hazard reduction, preparation of seed bed for natural reproduction, control of hardwood competition in pine stands, and other uses that require selection and control of what burns.

The research objective is to perfect appropriate techniques for prescribed burning that under the widest possible range of weather and fuel conditions will accomplish desired results. The research includes study of the heat tolerance of local tree and shrub species and their parts and of different age and size classes; the temperature rise in plant parts in relation to different combinations of rate of fire spread and fire intensity; and ways to make fire burn with acceptable combinations of these characteristics under different fuel and weather conditions.

The research in techniques of burning includes mechanical and chemical pretreatments as well as variations in firing patterns. A major objective is to develop methods that can be varied as needed to maximize the number of days per year that can be utilized for prescribed burning purposes. Without this diversity in techniques, prescribed burning in many localities and for many purposes must be confined to too few days to be operationally practical.

Fire research and national defense. - The Division of Fire Research has been active in the field of nuclear weapons effects for over 14 years. In May, 1950 the Operations Research Office, The Johns Hopkins University, under the direction of the Department of the Army, invited a research contract with the Forest Service to study the effect of fire and blast in forest areas. A five-man research team under this contract, at Berkeley, California, surveyed the status of knowledge and published ORO Technical Manual 108 in December 1950.

In 1951, the Forest Service program at Berkeley was expanded to include laboratory and field experimentation to solve some of the unknown factors that TM 108 indicated were important to the accurate prediction of the effects of nuclear attack. During 1951 static and dynamic loading stress tests were conducted on coniferous tree species, a field study was made of the probable effects of atomic weapons on the forests of western Europe, blast and ignition studies were conducted in connection with atomic weapons tests in Nevada, and static and dynamic loading tests were tried on yucca trees in the Mojave desert to correlate with the data obtained from the field tests. The 1951 operations produced the first measurements of critical ignition energies for common forest fuels and gave some indications of the effect of fuel moisture on ignition energy.

The Forest Service also participated with Associated Universities, Inc. in Project EAST RIVER to evaluate the destructive threat of atomic weapons and recommend nonmilitary defense measures.

1952 was spent preparing for and conducting a more refined series of blast effects and fuel ignition studies at the second series of atomic weapons tests in Nevada.

Results of these tests emphasized the low ignition energies at which glowing ignition takes place in punkey wood. The tests also raised some fundamental questions regarding the behavior of materials of high moisture content, the effect of angle of incidence and shape of the thermal pulse, the possibility of fire extinguishment by blast wave winds, and the effectiveness of glass and window screens in shielding interior fuels from ignition. During the remainder of the year, work was concentrated on static loading tests of hardwood trees of the eastern United States, theoretical work on the thermal properties of forest fuels, a survey of the number and size of openings in forest canopies, and the construction of a thermal source.

This square wave, flat plate carbon source, developed by the Forest Service and Department of Engineering, University of California, Los Angeles, was the first to successfully duplicate bomb intensities and spectral distributions with an effective irradiation area of one square foot. Analysis of the thermal properties of forest fuels resulted in clearly defining the "kindling fuel" concept and in testing the properties of materials that make them kindling fuels.

An elaborate series of ignition and blast studies were again carried out at the Nevada proving grounds. These included effects tests on the "imported forest" created by pine trees up to 60 feet in height which were trucked in about 65 miles from Mt. Charleston and set in concrete in a preplanned pattern. They also included a test so designed that one house was massively ignited, one ignited from secondary sources and one did not ignite, due to the presence or absence of kindling fuels. During the test series, less spectacular but perhaps more fundamental studies were made on the effect of angle of incidence, various types of screens, and blast wave phenomena on the probability of persistent ignition. Theoretical studies of fire convection and convection columns were also undertaken to provide a better understanding of "fire storm" initiation and behavior.

The question of "blowout" of incipient fires by blast winds was not satisfactorily settled during the field operation. Consequently, a shock tube was designed and incorporated into the thermal source so that the effect of blast on fire could be studied in the laboratory. An extensive series of surveys was conducted during 1953 to determine the number of ignitions to be expected in various types of occupancy in the major cities of the United States. Blast loading tests were continued on a variety of hardwood and conifer trees.

In 1954 the program was centered in the Pacific Forest Service Experiment Station where tree breakage measurements were made in connection with current weapons tests. During the year the Forest Service also developed a fire danger rating system for urban areas so that probability of ignition in cities could be correlated with weather conditions in much the same way as in forests.

With the end of the weapons test program in the continental United States, fire research activities were oriented around the problems of mass fire prediction and control rather than the prediction of thermal effects from nuclear weapons.

In the early summer of 1954 the Federal Civil Defense Administration, together with military agencies and various regional and national fire agencies sponsored a one-year field study known as Operation FIRESTOP. This program, conducted at Camp Pendleton Marine Base in California, was designed to test methods of combatting mass fires such as those to be expected following nuclear attack. This cooperative effort was headed largely by personnel from the fire program at Berkeley. Although feasibility studies were conducted in a large number of fields, perhaps the best known results of Operation FIRESTOP were the introduction of aerial attack

on fires using free-falling liquids, and the development of practical fire-retardant chemicals for large-scale use.

Under FCDA sponsorship some of the Forest Service group worked on Operation CIVIL in 1956 in cooperation with the University of California at Berkeley. The Forest Service assignment was to assess the effect of mass fires on fallout patterns and to study the possibilities of radiological decontamination through the use of fire. These studies showed conclusively that post attack fires will have a significant effect on fallout patterns.

In 1957 the Office of Defense Mobilization requested the Forest Service to devise a rural fire damage assessment system to be used in conjunction with the other components of the National Damage Assessment System in the various exercises of the Operation ALERT series. Working jointly with ODM and the Office of Civil and Defense Mobilization, the Forest Service prepared a series of maps and tables predicting the area of rural burnout to be expected following nuclear attack under various weather conditions.

In 1958 the Forest Service concluded its defense contracts. Defense oriented fire research was confined to theoretical and laboratory studies of fire spread and no work was undertaken directly concerned with the effects of nuclear weapons.

In 1962, the Forest Service again became directly involved in fire research for national defense and began a series of four studies for the Office of Civil Defense.

The first, to compile data on rate of fire spread for use in mathematical modeling studies, was completed in 1963. Reports from nearly 2000 urban and wildland conflagrations were studied to obtain the data contained in the final report.

Another study, to determine the frequency and severity of critical fire weather patterns of the United States will be completed within the next year.

A third project to study the feasibility of airborne infrared equipment for detecting and mapping fires through dense smoke has proved highly successful. Fire mapping feasibility has been demonstrated and the present work is aimed at developing operational guidelines and improving equipment capabilities.

The fourth OCD contract with the Forest Service is a long-term study of the interactions between mass fires and their environment. Work during the first two years has been largely spent in developing instrumentation capable of obtaining accurate measurements under the extreme environmental conditions associated with mass fires.

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ABSTRACTS

I. Ignition Phenomena

Vanpée, M. and Bruszak, A. E. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "The Ignition of Combustible Mixtures by Laminar Jets of Hot Gases," *Bureau of Mines Report of Investigation 6293* (1963)

This is the final report on the study of the ignition of explosive atmosphere by steady laminar jets of hot gas, carried out since 1957 at the Explosive Research Laboratory of the Bureau of Mines. Another part of the project on the ignition by turbulent jets was summarized earlier. At the beginning, the work was centered on the possibility of the ignition of firedamp atmosphere by explosions in the mines, but later the model was extended to include the problems of bluff body flame stabilization and of the oxidation kinetics in the temperature range 600° to 1400°C.

The basic experimental arrangement included an ignition source, which was a steady jet of hot gas heated in an electric furnace before entering a large vertical cylinder through which a cold explosive medium flowed very slowly. The temperature of the jet was gradually raised to the value at which ignition took place further downstream in the cylinder, and this temperature was defined as the ignition temperature of the explosive medium. Preignition reactions were studied by placing a water-cooled quenching plate in the mixing zone.

The compositions of both cold explosive mediums and hot jets were varied to provide conditions such as: mixture of fuel (pure or mixed) and air to be ignited by inert jet; fuel (with or without diluent) by oxidizing jet, etc. Therefore, the model facilitates the study of both premixed and diffusion flames. Furthermore, in spite of its complicated physical conditions, which lead to difficulties of deducing chemical factors, this flow model was still considered to be more advantageous and fundamental for kinetic studies than the isothermal processes taking place in a closed vessel, due to the fact that reactions are free from the interference of the reaction products and from the wall effects.

The investigation covered two parts. In the first part, ignition temperatures were measured under variable conditions of jet diameters, flow velocities, contact times, ambient pressures, and compositions. The complete program was carried out for methane, ethane, propane, ethylene, propylene, isobutylene, and carbon monoxide. Some fuels, such as hydrogen, formaldehyde, benzene, etc., were submitted to part of the test program. The second part involved a detailed analysis of the ignition process by taking temperature, composition, and velocity profiles in the mixing zone before ignition. Two typical fuels, carbon monoxide and methane, representing two well-defined types of ignition processes were chosen for this program.

The first type of ignition process was characterized by the presence of a luminous preignition zone, in which heat generated by reactions played a critical role in the ignition process. The method of analysis was based on the application of heat balance at each point in the jet, which permitted the deduction of the heat generated by and the specific rate of the chemical reactions. The ignition data provided a good relative measurement of the reactivity of different fuels, but were not helpful

in deducing frequency factors and activation energies of the reactions, owing to the fact that the present theory of ignition processes considers only a reaction of first order and is restricted to semi-infinite parallel flows.

In the second type of ignition process, preignition reactions were practically absent. For methane, a typical fuel of this type, the limit of the reaction zone was very sharp and the onset of fast reactions occurred over distances of a fraction of a millimeter. It has been proposed that such a reaction was chain-branching, and its limits may provide a direct method for establishing its mechanism of ignition.

In this publication, the experimental arrangement, procedure, and results were described and discussed in full detail, and results of earlier publication on ignition temperatures were also included. Readers will appreciate that it is a thorough and comprehensive report of a worthy project.

Subject Heading: ***Ignition, by hot gas jet.***

A. S. C. Ma

Bruszak, A. E., Burgess, D., and Wijnen, M. H. J. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Reaction Kinetics in Hot-Gas Ignition of Ethane-Air," *Combustion and Flame* **7**, 245–251 (1963)

This paper reports on the application of a technique suggested by Vanpée and Wolfhard[1] for the study of the preignition reactions occurring in flammable mixtures. The technique consists of passing hot jets of inert gases into the cool flammable mixtures and measuring the temperature profile inside the hot jet at various points upstream of the point where ignition occurs. The heat balance equation is given as

$$\rho U C_p(-\partial T/\partial x) - \rho V C_p(-\partial T/\partial r) - (\partial/\partial r)[-\lambda r(\partial T/\partial r)] + \mathcal{Q} = 0,$$

where ρ is the density, t the absolute temperature, C_p the specific heat, λ the thermal conductivity, U the velocity in the direction of flow x, and V the velocity in the radial direction r. The terms represent, from left to right, axial convection, radial convection, radial conduction and chemical heat production. The application consists in solving the above equation for $\mathcal{Q}$ as a function of the fuel and oxygen concentration and temperature.

In the present study the inert gas was nitrogen and the flammable mixture was ethane–air. Jet temperatures varied from 800° to 875°C.

The treatment of the heat balance equation is simplified by neglecting the radial convection term. This has been proposed on the basis of particle track photographs.[1] In the present work it was found that for jets flowing into air, i.e., $\mathcal{Q} = 0$, the axial convection term agreed well with computed radial conduction terms for low heights in the jet and for a narrow range of initial jet temperatures. For these same restrictions it was found that the radial conduction term was essentially independent of temperature and flammable mixture composition. The heat production rates could therefore be determined from the axial temperature profiles which were measured by means of fine thermocouples. The initial jet temperatures and the flammable mixture compositions were varied.

From the effect of the mixture composition on the axial temperature profiles

the formula for $\mathcal{Q} = k(C_2H_2)(O_2)^{0.25}$ was determined. The temperature dependence of $\mathcal{Q}$ was found to be expressible by

$$\mathcal{Q} = 4.5 \times 10^{11} \exp(-49{,}000/RT)(C_2H_6)(O_2)^{0.25} \text{ cal/cm}^3 \text{ sec}$$

By means of this expression the points on the ignition diagram were calculated for 850° to 975°C jet temperature and were in agreement with the observed values.

It is concluded that the method is a useful tool for studying preflame reaction.

Reference

1. Vanpée, M. and Wolfhard, H. G.: ARS J. *29*, 517 (1959); *Fire Research Abstracts and Reviews 2*, 108 (1960).

Subject Heading: ***Ignition, of ethane, by hot gas jet.***

J. Levy

Klinkenberg, A. (Royal Dutch/Shell-Gruppel, The Hague, Holland) "Electric Charging of Poorly Conducting Liquids in Turbulent Flow," *Chemie Ingenieur Technik* **36**, 283–290 (1964)

The usual Helmholtz–Gouy theory of electrokinetics is compared with the theory of the charging of poorly conducting liquids in turbulent pipe flow. For poorly conducting liquids the free charge is distributed over the entire tube cross section and is caused by a diffusion mechanism of the ions through the boundary layer. The corresponding mathematical development given in this article is a simplification of that given by Kozman and Gavis. The problem of interest here is not the actual mechanism of charge generation within the turbulent fluid but only the mechanism of charge distribution. In the classical solution of this problem the electrostatic and fluid dynamic problems are treated separately and then superimposed to obtain the final solution. In the present theory there is no such separation of the two processes. The steady-state equation for the ion concentration of a monovalent electrolyte in the classical problem is obtained by equating the diffusion and electrical migration of the ions,

$$-D_i(dC_i/dy) + \mu_i C_i E = 0,$$

where

$$E = -dV/dy$$

and

$$S = F(C_+ - C_-) = \varepsilon\varepsilon_0(dE/dy);$$

further, according to the Einstein equation,

$$D_i = \mu_i(RT/F).$$

The subscript i refers to either the cation or anion, D is the diffusive coefficient, μ the electrical mobility, E the electric field strength, C the ion concentration, y the radial distance measured from the pipe wall, V the electric potential, S the total space charge, F the Faraday constant, R and T the gas constant and absolute

temperature, and ε and ε_0 the dielectric constants of the liquid and free space, respectively. These equations in conjunction with the two boundary conditions

$$y = \infty; \qquad E = 0$$

and

$$y = 0; \qquad (C_+)_0 = \alpha^2 C_\infty$$

completely describe the classical problem. The quantity α is defined by the latter boundary condition. Introducing the dimensionless quantities

$$\gamma = C_+/C_\infty$$

and

$$\mu = y/(RT/2F^2C_\infty)^{1/2}$$

into the above equations, the following solution to the differential equation results,

$$\gamma = \cot^2 \{\tfrac{1}{2}(\eta + \ln [(\alpha + 1)/(\alpha - 1)]\}.$$

The quantity $(RT\varepsilon\varepsilon_0/2F^2C_\infty)^{1/2} \equiv \delta$, known as the characteristic length, is, according to Debye, the thickness of the electrical double layer near the wall. If this layer is thin and can be considered as flat, then the product of the space charge and fluid velocity can be integrated over the tube cross section to give current strength for the flowing liquid:

$$i = -\pi d\tau\varepsilon\varepsilon_0\rho/\eta,$$

where τ is the shearing stress at the wall, $\rho = V_{y=0} - V_{y=\infty}$, and d the tube diameter. From this relation one can show that for laminar flow the current strength is proportional to fluid velocity whereas for turbulent flow the proportionality is to the 7/4 power of the velocity.

Although these expressions have been confirmed for aqueous solutions, they do not appear to apply for hydrocarbons. The authors conclude that due to the smallness of τ in aqueous solutions, the electrical double layer lies entirely within the laminar boundary layer, whereas for poorly conducting liquids this is not true. Further, for the same reason the electrical streaming effect in water is undetectable, whereas for hydrocarbons this is not the case. For poorly conducting liquids in turbulent flow, it is assumed that the space charging takes place exclusively within the turbulent nucleus and therefore the electric field strength in the boundary layer is constant. It can further be shown that the current strength is given by the relation,

$$i = i_\infty[1 - \exp(-Z/\bar{V}\tau)],$$

where $\bar{V}$ is the average fluid velocity and Z the axial coordinate measured from the tube entrance. For turbulent flow, the steady-state equation for ion concentration now becomes,

$$\int \frac{dc_i}{C_i} = \frac{EF}{RT} \int \frac{dy}{1 + D/D_i},$$

where D_i is the turbulent diffusion coefficient. The integral on the right hand side of this expression is the boundary layer thickness δ_1. After some further mathematical manipulation, the authors obtain the following expression for the limiting current strength associated with turbulent pipe flow of poorly conducting liquids:

$$i_\infty = 0.070\varepsilon\varepsilon_0(RT/F)\,\mathrm{Sc}^{0.25}\,\mathrm{Re}^{0.875}\bar{V}[1 - (C_0/C_\infty)].$$

This expression can be compared with those obtained previously, where

$$i_\infty = C\mathcal{E}\mathcal{E}_0\rho\bar{V}.$$

Flow	*Electric boundary layer*	*Authors*	*C*
Laminar	—	Helmholtz	$\delta\tau$
Turbulent	Thin	Reichardt	$0.124\ Re^{0.75}$
Turbulent	Thick	Present author	$0.070\ Re^{0.875}\ Sc^{0.25}$

Although it is not possible to distinguish between the various theories with the experimental data obtained to date, several observations can be made: (1) the experimental values of i_∞ are always higher than the theoretical by factors of about 5 to 15 for various electrolytes in kerosine, (2) the differences between kerosine and naphtha (the two liquids principally investigated) are contrary to theory for rubber and steel tubes of 0.05 m diameter, and (3) the same tubes with different electrolytes give different strengths of charge.

Subject Heading: ***Electrostatic charge, of liquid.***

H. E. Perlee

Robertson, A. F. (National Bureau of Standards, Washington, D. C.) "Surface Flammability Measurements by the Radiant-Panel Method," *American Society for Testing and Materials Special Technical Publication No. 344*, 33–46 (1962)

The author reviews the development of the radiant-panel flammability test method and some pertinent early research studies. He also presents some of the more recent findings made with this technique.

The need for a simple laboratory-scale method of measuring the surface flammability of materials triggered the development of the radiant-panel test method about ten years ago. The method was based on the concept that the flammability of solids is a function of the ratio of heat-release rate to critical ignition energy of the material studied. The test was designed to measure these two factors. Because the flammable behavior of materials during practical use is influenced by size, geometry, orientation, etc., it was deemed unprofitable to try to make the test exact. Accordingly, flammability was expressed in the form of an empirical index that ignores feedback factors.

Method

The specimen is mounted to face the heat source and is inclined at a 30° angle to it. The radiant heat source operates with a controlled heat-flux rate at its surface similar to that of a black body at 1238°F. A stack and associated thermocouples placed above the sample serve as a heat-flux meter for measuring the rate of heat release.

The actual measurements made are $\Delta\theta$, the maximum stack thermocouple temperature rise in degrees Celsius above the maximum determined when an asbestos

cement board is exposed, and t_n, the time after exposure, in seconds, for arrival of the flame front at distance n, in inches, from the upper end of the specimen. The index first used included time measurements only at three and at twelve inches. It was soon obvious that a more refined index was needed, however, because values of the index could fluctuate greatly depending on whether the flame just reached or failed to reach the twelve-inch mark. A more direct measurement of the maximum rate of heat release was also needed so the new index was defined as

$$I_s = (0.1\Delta\theta/\beta)[1 + t_3^{-1} + (t_6 - t_3)^{-1} + (t_9 - t_6)^{-1} + (t_{12} - t_9)^{-1} + (t_{15} - t_{12})^{-1}]$$

where β is a calibration constant for the stack and thermocouple assembly obtained by substituting an auxiliary calibrating burner for the flammable specimen and the t's are now time elapsed at three inch intervals along the specimen. The constant 0.1 was chosen to bring this index into closer conformity with that of the ASTM tunnel test method E84. The two methods cannot be expected to give identical results but limited data indicate that there is similarity of results over the range of flame-spread indices of about 10 to 150 for these two methods and for the eight-foot tunnel method developed by the Forest Products Laboratory, as well.

Previous Research

The author cites some pertinent results of earlier research with this method. One interesting study showed how a variety of finishes reduced the flammability of a cellulose fiberboard insulation material.[1] Part of another study indicated the importance of surface finish thickness in determining flammability.[2] Flammability data were also obtained for twelve different plastic materials in this same study. Recently, cellular-foamed plastics were tested. The effectiveness of fire-retardant treatments again varied widely but the flammability of untreated polyurethanes seemed to exceed that of polystyrenes by a factor of ten or more. A final interesting work investigated the effectiveness of paints in reducing the flammability of wall panels.[3] Conventional paints seemed as effective as many of the fire-retardant coatings.

Recent Findings

Early work had established that the minimum specimen thickness for which the flame-spread index would not differ greatly from that of thicker specimens was about 0.25 inch. Recently, however, the I_s for 0.25 inch Douglas fir plywood was found to be about twice that for 0.75 inch solid Douglas fir boards. Consequently, this study was renewed for a variety of materials. The earlier conclusion was more or less substantiated but Douglas fir was definitely an exception, possibly because of the wide variation in density, and thus the thermal properties, of the annual rings.

Since thinner specimens showed a tendency to bow out, some tests were made with a change in the standard mounting procedure. They indicated that the character of the thermal contact with the backing material as well as the specimen thickness is very important.

Another factor studied recently was the effect of the humidity of the atmosphere in which specimens were conditioned. Data for unfinished materials, i.e., spruce, hardboard and fiberboard from which the finish had been stripped, suggest that

flammability is an inverse power function of the moisture content of the specimen on an ovendry weight basis. A good finish on fiberboard almost eliminated this moisture influence as well as significantly reducing flammability.

Conclusion

The author concludes that the radiant-panel test method has increased our understanding of the flammable behavior of solids but he stresses the vital need to determine the pertinence of the flammability classification systems now used to the hazard presented by building materials during actual fires. He also stresses the unlikelihood that any one test method will be able to predict the surface flammability hazard of all materials in all situations.

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Subject Heading: ***Flammability, measurement of, by radiant-panel method.***

G. S. Cuff

Eickner, H. W. and Peters, C. C. (Forest Products Laboratory, U. S. Forest Service, Madison, Wisconsin) "Surface Flammability of Wood Coatings," *Quarterly of the National Fire Protection Association* **57**, 320–330 (1964)

The 8-foot tunnel test method for measuring the surface flammability of finish materials, first described by Bruce & Miniutti,[1] has been used to measure the flame-spread behavior of 32 finish treatments applied to $\frac{3}{8}$-in. exterior-type grade A-C Douglas fir plywood. The resulting flame-spread index is assumed to be directly related to the rate of spread of fire on the interior finish during a building fire. Thus, a material showing a high index represents a more flammable material than that showing a low index. The finishes studied involved interior and exterior oil-base paitns, semi-gloss and gloss enamels, interior and exterior latex paints, varnish, lacquer, and shellac as well as 19 commercial and experimental fire-retardant paints.

The experimental results showed that shellac and lacquer finishes increased the flammability of the specimen by 11 to 23 per cent above that of the uncoated plywood, while with one exception other decorative coatings had little or modest influence, 2 to 23 per cent, in reducing surface flammability. Only about half of the fire-retardant paints tested showed ability to provide significantly lower flame-spread index numbers than the best of the more conventional paints studied. The flammability of the surfaces coated with the fire-retardant paints were significantly higher than that reportedly obtained by use of the ASTM E–84 test method.

Smoke density values measured by the use of the 8-foot tunnel apparatus on fire-retardant paint coatings were greater by a factor of three to six times more the values observed for the uncoated Douglas fir plywood. These high smoke indications for fire-retardant paints differ from reported results by the ASTM Method E–84, where lower smoke production behavior was observed. It is suggested that this disparity of results between the two test methods is probably due to

differences in the draft conditions involved and that the results by use of the 8-foot tunnel method may be more indicative of behavior during building fires.

Reference

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Subject Headings: ***Flammability, of wood coatings; Wood, flammability of.***

A. F. Robertson

II. Thermal Decomposition

Eickner, H. W. (Forest Products Laboratory, U. S. Forest Service, Madison, Wisconsin) "Basic Research on the Pyrolysis and Combustion of Wood," *Forest Products Journal* **12**, 194–199 (1962)

This review outlines a program of basic research at the Forest Products Laboratory, U. S. Forest Service, Madison, Wisconsin, on the pyrolysis, combustion, and action of fire retardants on wood and its components. After surveying the pertinent literature,[1] a program was proposed and received a two-year grant of funds from the National Science Foundation. The review is illustrated with data from the original authors' reports most of which were not published until later or have not yet been published.[2–9] The experimental apparatus is described briefly.[2] Five of the proposed methods of study are sketched: (i) static thermogravimetric analysis (weight loss in vacuum or nitrogen at successive fixed temperatures) to study activation energies,[3] (ii) dynamic thermogravimetric analysis (weight loss in vacuum, inert gas, or oxygen at linearly rising temperature) to study temperatures at which active pyrolysis (weight loss) begins and the temperature range within which it is completed,[3,4] (iii) differential thermal analysis in vacuum, inert gas, or oxygen to determine temperatures at which thermally significant processes or reactions set in and their thermal character and relative importance,[3,5,6] (iv) heat of combustion of the volatile products of pyrolysis taken as the difference between the heat of combustion (oxygen bomb) of wood and of char remaining after pyrolysis to different extents of weight loss,[7] and (v) proximate analysis of products of pyrolysis (fixed gases, water, tar, and char).[8,9]

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Subject Headings: *Wood, combustion and pyrolysis; Pyrolysis, of wood.*

F. L. Browne

III. Heat and Material Transfer

Jeschke, P., Karsch, K. H., and Schwiete, H. E. (Institute for Mining Mineralogy of the Aachen Institute of Technology, Aachen, Germany) "Thermal Conductivity of Refractory Materials," *Chemie Ingenieur Technik* **35,** 583–586 (1963)

It is emphasized that while the Fourier equation of heat conduction is usually applied to both homogeneous and porous refractory materials, the mechanism of heat flow in the two material types is considered to be quite different. Radiant heat transmission assumes an important part of the heat flow mechanism for opaque but porous materials. However, convection phenomena are usually of minor importance. The paper considers three properties influencing heat flow through porous refractory materials:

1. Temperature of material,
2. Internal texture and porosity, and
3. Thermal conductivity of individual mineralogical components.

Data are presented on the conductivity as a function of temperature for various porosities of corundum, mullite, magnesite brick, and fire clay bricks. It is found that above room temperature, the conductivity of homogeneous, nonporous, dielectric material, impermeable to radiation, decreases with increase of temperature. However, radiant transmission increases with temperature and, for porous materials, a significant portion of heat may be transferred through pores by this mechanism. These two mechanisms result in conductivity temperature curves, for these materials, which frequently show a minimum at some intermediate temperature.

It is suggested that for fire clay bricks radiant transmission is possible not only through pore spaces but in the vitrified volume of the material. It is stated that radiant transfer is of controlling importance in determining heat transfer for fire clay bricks at porosities of about 40 per cent. (We assume that this statement is made for temperatures above 750°C.)

Data are presented for conductivity of corundum, and a variety of clay bricks as a function of porosity. These show that for a given temperature there is a linear decrease of conductivity with increasing porosity. It is concluded that the "total porosity" is the property most suitable for defining the influence of texture on conductivity of refractory materials.

The shape of the pores in bricks are usually not spheroidal in form but distorted as a result of the forming process. Usually the axis of symmetry of the ellipsoidal or tubular voids formed are parallel. This can be shown by permeability studies of thin wafers cut in different directions. Experimental work on dry formed fire clay

bricks shows that conductivity in the direction of the void axis is 15 per cent greater than at right angles to them, where the corresponding permeability ratio may be on the order of 2:1. However, with other methods of forming the bricks, much greater differences in conductivity, 40 per cent in some cases, were observed for specimens showing the same permeability ratio.

The mineral components including vitrified portions of the brick were also found to significantly affect conductivity. Thus, the thermal gaseous and other exposure conditions during use of the refractory may modify the character of the components and, likewise, the conductivity. Tables are included to show the influence of atmospheres of air, smoke with CO_2, and smoke with CO on the "mullite," cristobalite and Roentgen-amorphous contents of the bricks. It is shown that the mullite content is independent of furnace atmosphere, while the cristobalite content is reduced when air is replaced by smoke with CO and increased when smoke and CO_2 forms the furnace atmosphere. The Roentgen-amorphous portion is reduced for atmospheres of smoke with CO_2 and increased for an atmosphere of smoke and CO. There is no discussion of the duration or temperature of firing conditions causing these changes.

Subject Headings: *Thermal conduction, of refractory materials; Refractories, thermal conduction of.*

A. F. Robertson

Schetz, J. A. (General Applied Science Laboratories, Inc., Westbury, New York) and **Eichhorn, R.** (Princeton University, Princeton, New Jersey) "Natural Convection with Discontinuous Wall-Temperature Variations," *Journal of Fluid Mechanics* **18**, 167–176 (1964)

An experimental investigation was carried out to study the natural convection from a vertical flat plate. The plate was 16.75 in. wide and 20 in. high and was so designed that the lower portion could be maintained at a uniform temperature T_1 and the upper portion at a temperature T_2. The over-all height of the plate is designated by L and that of the lower portion by x_0. The temperature of the surrounding air was given the symbol T_∞. The experimental conditions included values of the ratio $(T_1-T_\infty)/(T_2-T_\infty)$ above and below unity. The Grashof number based on the height of the first portion of the plate was about 3×10^7 in all but one experiment, in which it was reduced to about one tenth of this value. The installation was arranged so that the boundary layer could be examined by an interferometer and the temperature distribution in the fluid was determined from an interferogram. The local heat transfer rate at the plate was computed from the slope of the temperature distribution at the wall. Temperature profiles are presented in the form of graphs of $(T-T_\infty)/(T_2-T_\infty)$ vs $(y/2x)\,\mathrm{Gr}^{1/4}$. Each graph corresponds to a different value of the ratio $(T_1-T_\infty)/(T_2-T_\infty)$ and the several curves on each graph refer to different levels of elevation.

In a first experiment the two wall temperatures were maintained at the same value $(T_1=T_2)$ and the resulting temperature distribution was compared with an analytical solution. The agreement was very satisfactory. Other temperature profiles (all taken at levels greater than x_0) clearly showed the influence of the heat transfer in the lower portion. For example, when the temperature of the lower

portion significantly exceeded that of the upper one, heat was transferred from the air to the first part of the upper portion. At heights greater than $2x_0$, the temperature profiles as well as the heat transfer rates were largely similar to those for a plate of uniform temperature T_2.

To obtain some estimate of the prevailing flow patterns, observations were made with a separate installation consisting of a vertical cylinder in a water tank. The cylinder was made of two segments which could be heated separately. The flow was made visible with the tellurium dye technique. When the temperatures of the lower and the upper portion of the cylinder exceeded the water bulk temperature, the resulting flow pattern was similar to that obtained for a uniform surface temperature. When the temperature of the upper portion was below and that of the lower portion above the ambient temperature, two currents flowing toward each other developed. At the level at which two streams met they formed a jet-like flow normal to the surface. For the larger temperature differences this jet became unsteady.

Subject Heading: ***Convection, natural, with discontinuous temperature variations.***

R. H. Sabersky

Weiss, N. O. (U.K.A.E.A., Culham Laboratory, Abingdon, Berks., England) "Convection in the Presence of Restraints," *Philosophical Transactions of the Royal Society of London* **A256,** 99–147 (1964)

The paper consists of a broad treatment of free convection. Special emphasis is given to the effects of rotation and magnetic fields. The general equations governing such flow have been developed in linearized form by Boussinesq and these equations have been taken as the basis of the analysis. Attempting a solution in terms of normal modes, the time dependence of each mode may be expressed by a factor e^{st}, where t is the time, and the coefficient s is determined by a characteristic equation of the form

$$s^3+As^2+Bs+C=0.$$

The coefficients A, B, and C depend on the wave number of the mode, the Rayleigh number, the Taylor number, the Prandtl number and the ratios ν/η and $\mu H^2d^2/4\pi\rho\eta\nu$, which are of importance in the presence of a magnetic field. ($\nu=$ kinematic viscosity, $\eta=$ resistivity, $\mu=$ permeability, $H=$ magnetic field, $d=$ typical dimension, $\rho=$ density.) The last named parameter is given the name "Chandrasekhar number." For background and detail, frequent reference is made to: Chandrasekhar, S. "Hydrodynamic and hydromagnetic stability," Oxford, Clarendon Press, 1961.

By analyzing the characteristic equation purely from a mathematical point of view, regions may be defined in which s is real and positive, real and negative, complex with a positive real part, and complex with a negative real part. The effect of the parameters on these regions is then examined and the significance of the boundaries between regions is discussed. Special attention is drawn to the effect of rotation on the transition from oscillatory motion to nonoscillatory unstable motion ($s=$ real). The distinction between these two types of unstable motion is believed

to be important for heat transfer as the oscillatory mode is considered less effective for this purpose.

Subsequent to the analysis of the characteristic equation, the equations of motion themselves are being examined. In linearized form these equations may be written as follows:

$$\partial\theta/\partial t = w\beta + \kappa\nabla^2\theta$$

$$\partial\zeta/\partial t = 2\Omega\left(\frac{\partial w}{\partial z}\right) + \nu\nabla^2\zeta$$

$$(\partial/\partial t)(\nabla^2 w) = -2\Omega\frac{\partial\zeta}{\partial z} + g\alpha\nabla_1^2\theta + \nu\nabla^4 w$$

Each term is now interpreted as to its physical meaning and stability limits are described as the condition for which the pertinent force terms are in balance. In the absence of rotation and magnetism, the forces in question are those due to buoyancy and viscosity. The stability limits for this case are examined first and the modifications introduced by rotation and magnetism are then estimated. The results of the discussion are, of course, qualitative only, but it is shown that the conclusions agree with those of the foregoing mathematical analysis.

Having gained confidence in the qualitative approach by this agreement, an attempt is made to extend this approach for the purpose of making estimates of the heat transfer rate in the nonlinear flow regime. A plane layer of fluid with a cellular flow pattern is postulated for this discussion. The qualitative arguments lead to the conclusion that, when the Rayleigh number (Ra) is much smaller than unity, the heat transfer rates are proportional to Ra^2, whereas they are proportional to $Ra^{\frac{1}{2}}$ for high Rayleigh numbers. It is further concluded that oscillatory motion is not likely to be efficient in transporting heat and a significant improvement ought to occur when the oscillatory motion changes to non-oscillating unstable flow.

It is hoped that the concepts developed in this paper will be useful in the design of future experiments in the field of free convection.

Subject Headings: ***Convection, in presence of rotation; Rotation, effect on free convection.***

R. H. Sabersky

Howard, L. N. (Massachusetts Institute of Technology, Cambridge, Massachusetts) "Heat Transport by Turbulent Convection," *Journal of Fluid Mechanics* **17,** 405–432 (1963)

This paper is about the transport of heat by turbulent convection from a surface to a horizontally infinite layer of superimposed fluid. The treatment is mathematical and is based on the model embodied in the equations of the Boussinesq approximation.

Below the critical Rayleigh number the only solution of the Boussinesq equations satisfying all the boundary conditions and the requirements of homogeneity is the purely conductive one with no fluid motion. Above the critical Rayleigh number this solution still exists, but it is no longer stable, and other solutions are possible. Experimentally, provided the Rayleigh number is not too much above critical, a steady cellular convection occurs. Solutions of the Boussinesq equations have been found which correspond to this behavior. Experimentally, again, if the

Rayleigh number is increased to a value well in excess of critical, this steady cellular convection is replaced by an unsteady motion which at high Rayleigh numbers can only be described as turbulence. It seems likely, therefore, that all steady solutions of the Boussinesq equations become unstable if the Rayleigh number is large enough, so that even if all the solutions were known, there would be a considerable lack of uniqueness. The problem of which of these solutions is experimentally realized has not been solved.

Malkus[1] has suggested that the solution which is actually realized is that which, for a given temperature difference, gives the largest heat flux. Unfortunately, our inability to find all the solutions prohibits the use of this approach, and Malkus suggested a strengthened form of his hypothesis, to the effect that the heat transport which actually occurs for large Rayleigh number is not only the maximum among all solutions of the Boussinesq equations but may be almost as large as the maximum obtainable when fields of velocity and temperature are admitted which no longer satisfy the Boussinesq equations but are restricted only by the continuity equation, the boundary conditions, the requirements of homogeneity and the two simplest integral consequences of the Boussinesq equations, known as the "Power Integrals." Whether or not these hypotheses are correct, they do yield an upper bound to the heat transport which is of some interest in itself. It is with the determination of this upper bound to the heat flux with which this paper is concerned.

The determination of an upper bound to the heat transport is viewed as a process of successive approximation in which the problem of maximum heat transport is subjected to an increasing number of constraints by the imposition of more and more integral consequences of the Boussinesq equations, tending in the limit to the determination of the maximum heat transport subject to the full Boussinesq equations. The cases considered are as follows:

1. Maximum heat transport consistent with continuity, homogeneity, boundary conditions, and one of the power integrals.
2. Maximum heat transport consistent with boundary conditions, homogeneity, and both power integrals.
3. Maximum heat transport consistent with continuity, homogeneity, boundary conditions, and both power integrals.

Rigorous upper bounds on the heat transport are obtained for these cases, and, although it would not be reasonable to suppose that the maximizing fields of temperature and velocity would necessarily resemble those which really occur, comparisons are made between the average properties of the maximizing fields with the experimental derivations of Townsend.[2] Similarities are obtained which lend some support to the view that the actual motion which occurs approximates a solution of the Boussinesq equations which maximize heat transport.

The paper is written in a scholarly style which makes reading it a considerable pleasure.

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Subject Headings: ***Convection, turbulent, heat transfer by; Heat transfer, by turbulent convection.***

D. G. Martin

Shukla, R. N., Kulkarni, S. B., Gharpurey, M. K., and Biswas, A. B. (National Chemical Laboratory, Poona, India) "Some Observations on the Water Evaporation Reduction Due to Monolayers of *n*-Fatty Alcohols, *n*-Alkoxy Ethanols & Their Mixtures," *Indian Journal of Technology* **1**, 141–142 (1963)

Evaporation reduction R as a function of temperature T was measured for *n*-fatty alcohols (identified as A_n in subsequent discussion), *n*-alkoxy ethanols (identified as E_n) and their mixtures. For A_{22} and E_{22}, R had a positive slope and for A_{16} and E_{16} the slope of R as a function of T was negative. Equimolar mixtures $E_{16}E_{22}$, $E_{16}A_{22}$, $A_{16}E_{22}$, $A_{16}A_{22}$, listed in order of efficacy of the film, gave intermediate values of R in the range 0.65 to 0.75. Mixtures give R larger than the arithmetic mean of the two components. Mixtures $E_{16}A_{22}$ and $A_{16}A_{22}$ exhibit maximum R at about 28°C. A negative slope or a maximum in R is indicative of spreading difficulty.

Mixtures in the ratio 1:9 were also investigated. It was found that addition of a small quantity a lower homologue to a compound with spreading difficulty has a beneficial effect on the resulting monolayer.

There is continuous loss of the molecules from the monolayer and to be effective in reducing evaporation it is necessary to replace the retardant, e.g., from floating solid specks. Hence the spreading ability of a compound is an important feature of evaporation reduction.

Subject Headings: *Water, evaporation, reduction by monolayers; Evaporation, of water; Monolyers, reduction of water evaporation by.*

A. E. Fuhs

LaMer, V. K., Aylmore, L. A. G., and Healy, T. W. (Chemistry Department, Columbia University, New York, New York) "The Ideal Surface Behavior of Mixed Monolayers of Long-Chain *n*-Paraffinic Alcohols," *The Journal of Physical Chemistry* **67**, 2793–2799 (1963)

Ideal surface layers obey a mixture law

$$\ln r_{12} = x_1 \ln r_1 + x_2 \ln r_2,$$

where r_{12} is the specific evaporation resistance of the mixture, r_1 the resistance of pure 1, and x_1 the mole fraction of 1. On semilog paper the preceding equation plots as a straight line; deviations from ideal behavior are readily apparent as deviations from linearity.

It was found that close members of a homologous series behave as ideal surface mixtures. However, at low surface pressures ($\pi < 15$ dyne/cm) it is essential to purify the reagents and the subphase. Impurities, undetectable by gas chromatography, can cause departure from the mixture law. It was demonstrated experimentally that a binary mixture of 1-octadecanol and 1-hexadecanol exhibits ideal behavior to surface pressures as low as 5 dyne/cm.

There are two other types of surfaces from mixed monolayers that can be identified. These are nonideal surface solutions, an example being 1-octadecanol and stearic acid, and ideal or nonideal behavior with complex formation or rearrangement at specific compositions. An example of the latter is a mixture of 1-hexadecanol and 1-hexadecyl sulfate. The pressure-area isotherms show a progressive discontinuity.

At low surface pressures the behavior of mixed monolayers is extremely sensitive to impurities or contamination.

Subject Heading: *Monolayers, behavior of mixed.*

A. E. Fuhs

IV. Diffusion Flames

Choulis, D. and Wilson, M. J. G. (Imperial College, London, England) "The Stability of a Diffusion Flame Burning in Products of Combustion," *Combustion and Flame* **7**, 369–374 (1963)

It is established that radicals and atoms, especially OH, O, and H, are important in combustion. A possibility that has received little attention is that of transferring radicals from one flame to another with the object of detecting and estimating any effects on the second flame. This is interesting because flames are often stabilized by the recirculation of products of combustion and if these products have burned recently enough they may provide not only heat but also a supply of short-lived atoms and radicals. Such a supply is provided in the experiment by a lean hydrogen–air flame burning on a porous disc. This produces a column of hot products in which the concentration of radicals decreases with time and hence with height above the burner while the temperature, velocity, and molecular composition vary much less until diluted by the surrounding atmosphere.

A tiny methane diffusion flame burning on a water-cooled tube was introduced into this main flame as the test flame. On increasing the methane flow, the dead space increased slightly and the test flame suddenly blew off. The rate of flow of methane, *Vb*, to produce blowoff was measured at various positions above the burner, *Vb* decreasing with increasing height above the burner. Measurements of temperature and velocity distribution in the main flame were made by a thermocouple and a quartz fiber anemometer.

Possible causes for the change in *Vb* are variation in temperature, velocity, and radical concentration.

The temperature and velocity profiles show that these could only have a minor effect on *Vb*. It has been shown that the OH concentration in a lean hydrogen–air flame is many times the calculated value and also that OH reaction with methane is important. Since Kogarko[1] has shown that the addition of radicals reduces ignition delay, a tentative explanation of the variation of *Vb* with height is offered based on the velocity distribution which occurs at the mouth of the test burner, i.e., the velocity of the methane boundary layer increasing on moving away from the burner.

It seems that combustion can be stable only if any delay which precedes ignition can be completed before the gas velocity exceeds the burning velocity of the mixture. Thus a reduction of ignition delay, by the addition of radicals, would make it possible for the flame to move upstream to a region of lower velocity, where it could be blown off only by a correspondingly greater flow of methane. Difficulties with the present apparatus are that measurements cannot be made where the radical concentration falls to its equilibrium value and that it is not known how many radicals recombine on the surface of the test burner.

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Subject Headings: ***Diffusion flame, stability of; Flame, diffusion, stability of.***

G. L. Isles

V. Combustion Principles

Maguire, B. A., Slack, C., and Williams, A. J. (Safety in Mines Research Establishment, Buxton, England) "The Concentration Limits for Coal Dust–Air Mixtures for Upward Propagation of Flame in a Vertical Tube," *Combustion and Flame* **6**, 287–294 (1962)

The authors report experimental results obtained with a vertical tube flame propagation apparatus for the determination of flame propagation limits in coal dust clouds. The combustion tube described was 14.2 cm in diameter and 468 cm in height. Coal dust was fed to a vibrating sieve at the top of the combustion tube, by means of a series train of a belt conveyer, and screw feeder. Near the bottom of the combustion tube (about 460 cm from the upper end) was incorporated a photocell system to determine, by means of the coal dust suspension opacity, the coal dust concentration. To ignite the coal dust, a system was used embodying an electric-spark gap, and a methane-pulse flame, about 5 cm in height during the ignition pulse. The flame front was photographed by a drum camera, and time-scale calibration was made by a neon lamp flashing at 100 cycles per second at 10 cm intervals along the combustion tube, from 190 to 350 cm from the ignition system. Line markings were provided to facilitate photographic analysis.

The coal dust used had a mean particle size of 30 microns determined on a weight basis, with a volatile matter content of 36 per cent on an ash-free basis. The coal dust concentration in the air investigated ranged from 0 to 2.6 grams per liter. Prior to test trials, the coal dust was stored at constant temperature in airtight cans. In a given trial, the dust concentration was continuously recorded up to the time of ignition. In trials resulting in successful ignition, the distance of flame front travel through the dust suspension was recorded.

Specific experimental observations reported by the authors include:

1. For the concentrations studied, the dust particle sedimentation velocity is constant, and is dependent on the dust-size distribution. For example, the velocity of fall for the "plug" of particles at a concentration of 0.4 grams per liter was noted to be about 15 times the Stokes free-fall velocity for the mean particle size of the dust used (30 microns on a weight basis).
2. With upward flame front propagation, the "steady state" or static system coal dust concentration measured, is lower than the actual dust concentration in the flame front.
3. The upper concentration limit for flammability is critically dependent on the length up the combustion tube from the point of ignition, which is specified as the requisite distance to define successful ignition, where as the lower concentration limit for flammability is virtually independent of this specified distance.

Flammable limits were defined in this study as those concentrations (upper or lower limit concentrations) giving a 0.5 probability for propagating or not propagating a flame up specified distances in the combustion tube. Distances of 0.4, 0.5, 1.0, and 1.5 meters, respectively, were used.

A total of 238 trials were made and the results analyzed.

Probit techniques[1] were used in the analysis. Since the individual trial results indicated either 0 or 100 per cent propagation, results of a set of consecutive concentrations were grouped such that percentage propagations in ten or more individual trials were obtained, and probits of these were plotted against concentration. A regression line was then drawn through the points plotted. From this stage of the analysis the normal probit technique was followed. It was found that a log concentration probit scale gave no significant improvement in the computed data, thus the computations were made on a straight concentration basis.

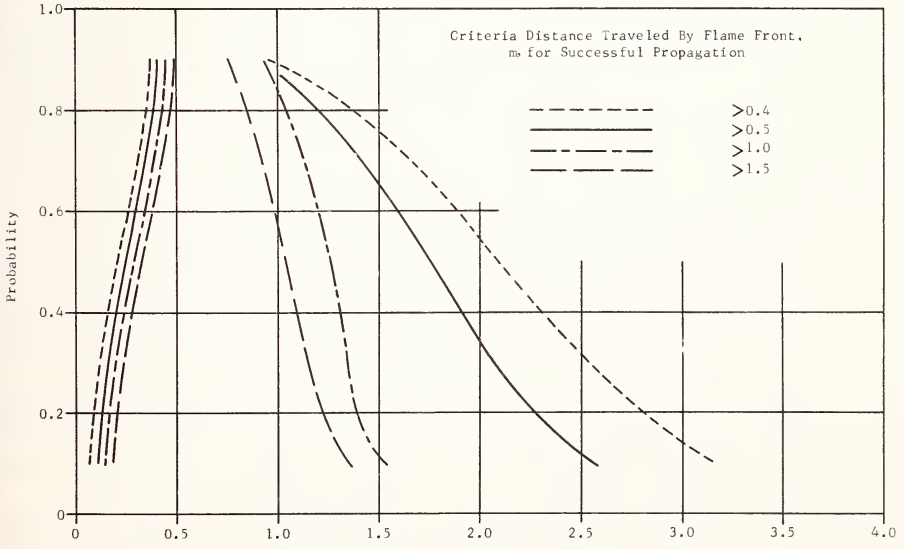
The techniques considered satisfactory were the probability of propagation P; at concentration, X is given by

$$P = (2\pi\sigma^2)^{-\frac{1}{2}} \int_{-\infty}^{x} \exp[-(x-\bar{x})^2/2\sigma^2]\, dx,$$

where $\sigma^2 =$ the variance of x and $\bar{x} =$ the mean of the distribution of x.

It was pointed out that the upper-limit mechanism and lower-limit mechanism interfered in the high probability of propagation region. The lower mechanism was cited as what might be defined as an energy transfer phenomenon from the ignited to unignited particles, whereas the upper limit was described as a manifestation of an insufficiency of energy in the propagation flame front to activate ignition of the upstream particles; hence, the energy imparted by the ignition source could enable propagation over a limited distance, i.e., until consumed in making up the deficit between combustion energy (in a regime of only partial combustion of the fuel) and ignition activation energy. Thus, the upper-limit mechanism affords an explanation of the dependency of the upper limit upon the distance of propagation up the combustion tube selected to define successful propagation.

The results of experimental trials and analyses are presented in 3 tables, and 3 figures such as the one presented here.



Variation of the probability of propagation with average concentration for various criteria definition distances expressed in meters, for successful propagation.

The techniques of experiment design and analysis are discussed, and 14 references are cited, four of which concerned the statistical techniques applied.

Reference

1. Bliss, C. I.: Quart. J. Pharm. *11*, 192 (1938).

Subject Headings: ***Coal dust, propagation limits; Dust, propagation limits.***

J. E. Malcolm

Field, M. A. (The British Coal Utilization Research Association, Leatherhead, England) "Predicting the Burning Time of the Coke Residue of Pulverised Fuel," *The British Coal Utilisation Research Association Bulletin* **28,** 61–75 (1964)

The paper under review is itself a review; anyone reasonably conversant with the literature of combustion of pulverized coal will, therefore, be familiar with most of the papers covered.

The author centers his review around the standard theory of reaction control by diffusion through a boundary layer, originally developed by Nusselt. He then discusses in turn the influence of: a temperature gradient in the boundary layer; the effect of changing CO/CO_2 ratio; the effect of volume change (that he develops by extension from an analysis by Van der Held); and the double-film extension in which the surface reaction is reduction of CO_2. This part of the review shows reasonable agreement on the theoretical principles between the authors quoted. The integrated burning rate leads to an equation for the burning-out time t_b that has the recommended form

$$t_b = \lambda \sigma d_0^2 / 6 D_0 \rho_0 f_g (T/T_0)^{0.75},$$

where σ is the particle density; d_0 its initial diameter; D_0 the s.t.p. diffusion coefficient; ρ_0 the s.t.p. gas density; f_g the fractional oxygen concentration; and T the absolute temperature. λ is a coefficient lying between 1.0 and 2.0 to allow for either CO or CO_2 formation that should tend to 1.0 at high temperatures. The reviewer would suggest that, in practical cases, a correction for volatile loss must also be made.

The influence of the surface reaction, when this is not fast, is also discussed. The effect is to split the total burning time into the sum of two others: one for the chemical process and one for the diffusional process. Whether the additional (chemical) term is, in fact, significant is indeterminate. In the author's view the evidence is contradictory, so no decision on its importance can at present be made; the present reviewer would agree with this, subject only to the qualification of the last paragraph (below).

Numerical comparisons with experimental data are also made. These seem to be in broad agreement with prediction.

Other factors discussed include: the influence of finite excess air; relative motion of gas and particle; effect of ash; and effect of other reactions.

Of the subject matter covered, there are no surprises to those conversant with the literature; it is, however, a useful summary and a most convenient introduction for those less familiar with the field. Two omissions, however, of considerable rele-

vance to the importance of chemical control are the papers by Beér and Thring[1] and by Lee, Thring and Beér.[2] In the present reviewer's opinion these would seem to establish the dominance of *chemical* factors over diffusional in reaction control of small particles (less than 100 microns) at flame temperatures (1000° to 2000°K), in clear support of the same conclusion by Hottel and Stewart.[3]

References

1. Beér, J. M. and Thring, M. W.: Proc. Anthracite Conf., Nov. 1960, Pennsylvania State University M.I. Expt. Stu. Bull. No. 75, Sept. 1961.
2. Lee, K. B., Thring, M. W., and Beér, J. M.: Combustion and Flame *6*, 137 (1962).
3. Hottel, H. C. and Stewart, I. M.: Ind. Eng. Chem. *32*, 719 (1940).

Subject Headings: ***Coat dust, burning time; Powders, burning time.***

R. H. Essenhigh

Cramer, F. B. (Rocketdyne, Canoga Park, California) "The Onset of Detonation in a Droplet Combustion Field," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 482–487 (1963)

The ability of liquid sprays of low volatile fuels to support detonation waves is a phenomenon established by earlier work by Webber,[1] which was the starting point of the review by Cramer. The sprays were formed in 2×96 in. vertical tubes, one steel, and the other transparent for photographic studies. The fuel, diethocyclohexane (DECH), was sprayed into the tube through a set of 5 injectors. The tube already contained oxygen at one atmosphere, and the reportedly uniform dispersion was then subjected to a gas-driven shock from an electrically-sparked H_2/O_2 mixture before it could settle. Methods of investigation and measurement of the resulting phenomena in the tube included: pressure variations with time at 7 stations (3, 6, 12, 24, 48, 72, and 96 inches from the driver section); photographic studies, particularly of the drop dispersion; and drop-size distribution determinations, which showed, typically, 20 per cent less than 100 microns, 50 per cent less than 200 microns, and 80 per cent less than 300 microns.

The results showed that explosion was mostly initiated between 1 and 2 feet from the driver section (about 1 to 2 milliseconds after ignition of the driver gas); but, significantly, this was only obtained in fuel rich mixtures, with 50 per cent failures around 50 per cent fuel rich, and needing nearly twice stoichiometric for zero failures. The data presented graphically showed the initial forward pressure perturbations turning into a shock front, with these being followed by the burning zone and contact surface. At some moment in time, flame flashed from the burning zone to the shock front, and detonation commenced.

Interpretation of these data followed from analysis of the drop behavior in the gas stream. Calculation of drop trajectories based on reasonable drag assumptions suggested the following picture. In the first stage of gas motion, separation of fine from coarse drops occurred, so the burning front *initially* traveled into a coarse spray that was deficient in fine drops, these having been moved downstream into the region following. In this next region, these fine drops were subsequently overtaken by the combustion wave, the combustion wave accelerating in consequence as the second stage. In this region, which had lost its own fine drops, there was

estimated to be roughly a one-to-one replacement, so the drop size distribution was restored approximately to the original. Meanwhile, ahead of this again, in a third region, the shock front now established was shattering the larger drops, evidently by shearing off surface layers before the drop inertia could allow the drops to deform or accelerate in response to the loading. In this third region, a microspray was therefore developed with great rapidity by this shattering, having a surface area that was estimated to be an order of magnitude greater than in the initial spray. Fast reaction in this microspray was then able to drive the combustion zone to the shock front and subsequently to maintain the now-developed detonation wave.

The authors make no comment on the high fuel-rich mixture required for successful propagation. This is only a minor point but has some interest. The reviewer would hazard the opinion that it is likely to be due to either: (i) an ignition or initiation failure by reduction of the surface and volume requirements in the initial zone to a low combustion limit by loss of fine drops; or to (ii) a propagation failure due to the need to establish at least a low limit concentration of the microspray in the detonation zone if the reaction of the coarse drops is then too slow to contribute usefully to the heat release. It would be interesting to know which is the case.

Reference

1. Webber, W. T.: *Eighth Symposium (International) on Combustion.* Williams and Wilkins, 1962.

Subject Headings: ***Drops, onset of detonation; Detonation, of drops.***

R. H. Essenhigh

VI. Radiation

Mavrodineanu, R. (Philips Laboratories, North American Philips Company, Inc. Irvington-on-Hudson, New York) "Flame Characteristics and Emission," *Spectrochimica Acta* **17**, 1016–1042 (1961)

The paper under review is itself a review of 26 pages, 18 figures, 4 tables, and 155 references. Three of the references cited (Nos. 55, 102, and 101) provide a bibliography of the subject running to over 1600 further references covering the 111 years from 1848 to 1959.

The review is divided into six sections as follows:

Introduction. A flame and the coarse structure of a bunsen flame are described and defined in simple qualitative terms.

Combustion mixtures, limits of flammability or explosion, ignition temperatures, burning velocity, detonation velocity and pressure. The listed phenomena are defined and described.

Flame structure and radiation. A description and brief discussion of the existence of the bunsen burner cones and the separators used for their investigation; some of the species found by spectral examination, and by mass spectrometer analysis; and phase discrimination methods of measuring flame emission intensities.

Flame temperature. The problems of temperature measurement when the energies in the various degrees of freedom are and are not in equilibrium are mentioned. The temperature pattern in premixed bunsen-type flames and the degree of disequilibrium, or otherwise, at different points in the flame are described.

Brief considerations on some reactions and ionization in flames. The effect on the flame of atomized metal solutions is discussed.

Droplet size in an atomized solution. Methods of creating drops, and of changing droplet size, and instances where the droplet size influenced the emission characteristics of the flame are described.

The review is almost entirely qualitative. The approach is phenomenological, flame behavior being described, with references cited, followed by a statement of the results obtained by the investigators in the work quoted. In a few instances, suggested interpretations of the stated behavior are also given.

The experienced worker in the field is unlikely to find any surprises in the review; its principal value to him will probably be as a source of references. It is more likely to be of use to the newcomer to the field of combustion and flame spectra as an easily read and assimilated review before embarking on the more solid quantitative material in the major reference books on the subject.

References

55. Gilbert, P. T., Jr.: *Analytical flame photometry: New developments.* ASTM Special Technical Publication 269, 1960.
102. Mavrodineanu, R.: *Considerations on analytical flame spectroscopy* (in French). VIII Colloquium Spectroscopicum Internationale, Lucerne, Sept. 14–18, 1959, pp. 15–29. Sauerländer, Aarau, 1960.
101. Mavrodineanu, R.: *Bibliography on analytical flame spectroscopy*, Appl. Spectroscopy *10*, 54, 137 (1956); *13*, 132, 150 (1959); *14*, 17 (1960). (Available through Beckman Instruments, Inc., Scientific Instruments Division, 2500 Fullerton Road, Fullerton, Calif.)

Subject Heading: ***Flame spectroscopy, review of.***

R. H. Essenhigh

VII. Suppression of Combustion

Ibiricu, M. M. and Gaydon, A. G. (Imperial College, London, England) "Spectroscopic Studies of the Effect of Inhibitors on Counterflow Diffusion Flames," *Combustion and Flame* **8**, 51–62 (1964)

A counterflow diffusion flame burner was used for studying the inhibiting effects of methyl bromide, bromine, carbon tetrachloride, chlorine, and phosphorous oxychloride on flames of hydrogen, methane, or ethylene burning with air. Use of the opposed flow burner is believed to be a closer approximation to actual fires, which are most frequently of the diffusional-type. A quantitative study was made of changes in the flame spectra when small quantities of inhibitors were added to either the air or the fuel side of the burner. The OH emission at 3064 Å, the C_2 bands at 5165 Å and 4737 Å and the continuous background radiation alongside the band heads, the CH at 4315 Å and the continuous emission due to carbon (measured at 5700 Å) were detected using two spectograph-photomultiplier combinations. A platinum/platinum–rhodium thermocouple was used to measure the flame temperature midway between the flame center and the edge of the flame; the height of the thermocouple was adjusted for maximum reading. All flames were studied with either stoichiometric air/fuel ratio or with excess air.

Generally, the results show a decrease of the OH intensity ratio (ratio of radiation intensity with additive to intensity without additive) with increasing additive

concentration followed by flame extinction in some cases. The decrease in intensity ratio showed some dependence on whether the inhibitor was added from the fuel or air side as well as the velocity of the fuel and air. In some cases a small initial increase in OH intensity was detected prior to its decay. Phosphorus oxychloride showed the most marked reduction in OH intensity and also the strongest inhibiting action. Temperature variations (plotted as maximum temperature with inhibitor to maximum temperature without inhibitor) showed curves closely resembling the OH emission curves with changing inhibitor concentration. The relative emission intensities for CH, C_2 and solid carbon show that CH attains a very moderate peak, then falls slowly. Emission of the C_2 bands and solid carbon increased rapidly at low inhibitor concentration values, attaining a sharp maximum of several times the initial intensity followed by a decay. Marked variations existed between the effects of the various additives (fuel versus air side) on the hydrogen-air flames and methane-air flames.

The results appear to be consistent with the following processes: (1) removal of OH radicals, most likely by reaction $HBr+OH=H_2O+Br$ or $HCl+OH=H_2O+Cl$; (2) a decrease in the exothermic oxidation processes; (3) an increase in the pyrolysis or polymerization processes, due partly to less competition with oxidation processes and partly to direct catalysis of these processes by the halogens; (4) an increase in soot formation following polymerization and pyrolysis; (5) a fall in temperature at the flame center due to the arrest of the exothermic oxidation and radiative heat loss from soot particles. (6) flame extinction as the temperature falls to the limiting ignition temperature.

Many individual effects, peculiar to a particular fuel or additive, remain unexplained. However, $POCl_3$ is the most effective inhibitor, usually producing the strongest effects on the spectrum. Methane flames are the most easily extinguished, probably because of their high ignition temperature. The additives usually produced the strongest inhibition when introduced on the fuel side.

Subject Headings: *Inhibitors, spectroscopy of, in diffusion flames; Diffusion flame, inhibitors; Flame, spectroscopy of inhibition.*

L. A. Povinelli

Cullis, C. F., Fish, A., and Ward, R. B. (Imperial College, London, England) "The Influence of Bromine Compounds on Combustion Processes," *Proceedings of the Royal Society* **A276**, 527–541 (1963)

This paper is a very careful study of the effect of hydrogen bromide and four bromomethanes on slow combustion and spontaneous ignition of several organic fuels. The experiments were performed in a static vacuum system consisting of a silica reaction vessel suspended in an electric furnace. To facilitate rapid introduction of a second reactant, the silica vessel was connected through a wide-bore tap to a premixing vessel. When the desired amount of second reactant entered the reaction vessel ignition was denoted by a sudden pressure pulse very often accompanied by a bright flash of light. A very mild pressure pulse indicated slow combustion (cool flame passage). Ignition delay (time between introduction of second reactant and occurrence of ignition) was the criterion used most often to measure and compare the effects of the various additives. The slow combustion studies were performed by following the progress of reaction manometrically, periodic

analysis of unchanged fuel, and analysis of certain specific products. The results of this work are reported in terms of changes produced in two criteria by the five additives. One criterion is the time taken for a given small pressure change to occur (a measure of initial reaction rate); the other is the maximum rate of pressure change which the authors interpret as reaction rate development. Gas chromatography was used to analyze residual fuels and most condensible products.

Because the effects of the different additives depended on the fuel undergoing combustion, the results are presented for each fuel graphically and in tables. In order of increasing minimum ignition temperature, the fuels employed were acetaldehyde, diethyl ether, isopentane, formaldehyde, isopropyl alcohol, ethane, methane, benzene, and cumene. The five additives were CH_3Br, CH_2Br_2, CH_2ClBr, CF_2Br_2, and HBr. Throughout the course of these experiments, no brominated organic compounds other than the additives themselves were detected.

The well organized "Discussion" section of this paper is a tribute to the authors' ability to simplify complicated phenomena. They first identify the species responsible for the action of bromine compounds on fuels. While HBr exerts a marked influence on slow combustion and ignition of the fuels studied, the bromomethanes have a well-defined effect only when the temperature is above 250°C. Further, when they do show an appreciable influence their effect is qualitatively similar to that of HBr. The dibromo compounds were in general more effective than the monobromo compounds. These findings suggest that the bromomethanes are *not* responsible for any appreciable effect on slow combustion or spontaneous ignition processes. The oxidation or pyrolysis products (presumably Br or HBr) of these additives do cause an appreciable effect. To support this view, the authors point to the 280°C temperature where bromomethane begins to react with O_2 and this agrees with present experiments where no appreciable effect was recorded below about 280°C. Dibromomethane is a less effective promoter than hydrogen bromide at 416°C but the reverse is true at 510°C; where essentially, complete destruction of the organic compound gives rise to twice the molar amount of HBr.

Now, the authors discuss the promoting influence of hydrogen bromide after having clearly labeled the species responsible for affecting the processes being considered. Using an argument based on activation energies, it is shown that HBr reacts with oxygen much easier than does methane and therefore provides an extra mode of chain initiation. Ethane and benzene when reacting with O_2 have high activation energies and the presence of HBr should lead to enhanced chain initiation. With other fuels, where the activation energy of their reaction with oxygen is lower than $HBr+O_2$, another explanation is offered for the promoting effect. In the main HBr accelerates the later stages of these compounds (rather than the initial phase as with CH_4), and its effect can be ascribed to reaction with intermediate peroxides to give rise to enhanced chain branching. A table showing a decrease in the concentration of peroxyacetic acid when HBr is added to acetaldehyde serves to support this mode of action.

Finally, a discussion of the retarding influence of hydrogen bromide is presented. Methane and formaldehyde are the only fuels studied where certain stages of their oxidation were retarded by HBr. This effect is much more in evidence with CH_4 and is observed only when small amounts of the additive are present. Retardation must be attributed to the replacement of reactive chain-carriers by less active species. The principal chain-carriers involved in the slow combustion of methane are CH_3, OH, HO_2, and CHO.

Several reactions are written showing the production of these radicals and their

subsequent reaction. Through this scheme the authors show that the initial rate of CH_4+O_2 reaction is increased at the expense of the maximum rate, which is what they observed experimentally. They conclude that in the later stages of the reaction, retardation is largely brought about by removal of OH radicals by HBr.

Perhaps the significant contribution of this paper can be given in the following statements:

(1) The inability of bromine compounds to retard the oxidation of any of the other fuels studied implies that the mechanism of inhibition is in some way peculiar to the reactions occurring during the slow combustion of methane.

(2) The fact that bromine compounds exert (through the agency of HBr) an exclusively retarding influence on the reactions occurring in oxygen-supported *flames* suggests that the processes inhibited bear a close relation to the reactions retarded during the slow combustion of methane.

Subject Heading: ***Bromine compounds, influence on combustion.***

C. O'Neal, Jr.

Fenimore, C. P. and Jones, G. W. (General Electric Research Laboratory, Schenectady, New York) "Flame Inhibition by Methyl Bromide," *Combustion and Flame* **7**, 323–329 (1963)

This paper is another valiant effort to deduce the kinetic mechanism of methyl bromide inhibition of hydrogen flames. To begin, the authors carefully make note of much of the previous work performed in this area. In particular, they were interested in the flammability limit work of M. C. Burdon *et al.* These workers determined the amount of CH_3Br necessary to render various H_2–air mixtures nonflammable. Their results showed that the amount of inhibitor required was related to the oxygen in the initial mixture and to the calculated adiabatic flame temperature.

For purposes of easier discussion, we write the following equations:

$$H+O_2 \xrightarrow{k_1} OH+O \tag{1}$$

$$H+CH_3Br \xrightarrow{k_2} CH_3+HBr \tag{2}$$

$$H+N_2O \xrightarrow{k_3} N_2+OH \tag{3}$$

$$H+CH_4 \xrightarrow{k_4} CH_3+H_2 \tag{4}$$

Burdon and co-workers suggested that Eq. (1) was opposed by a terminating process represented in Eq. (2). The stated purpose of the present paper is to obtain an independent value of k_2 and check the validity of Burdon's interpretation. Secondly, they present some limited data on inhibition of nonadiabatic flames by methyl bromide; and finally, an appendix is presented giving some information on the rate of reaction of CH_3 radicals with nitric oxide.

Three H_2—N_2O—NO—CH_3Br—A flames were burned on a water-cooled, flat flame burner at reduced pressure. Temperature traverses were obtained with a quartz coated thermocouple. Composition traverses were made by mass spectroscopic analyses of samples taken through a quartz probe. Methyl bromide was the only bromine compound that appeared on the mass spectrograms. The disappear-

ance of the inhibitor was followed, but not the rate of appearance of bromine or hydrogen bromide. The detection of HBr in the presence of water cannot be accomplished with the instrument used in this work. However, analyses for methyl bromide were not so affected.

Composition profiles were converted to reaction rates by standard procedure. An expression for the mass fraction of flow carried by the species in question is presented; and it involves the linear velocity of the gas, the species molecular weight, and the linear velocity of the species. This latter term involves in its equation a distance of the flame from the porous plate, a constant mass velocity, and a diffusion coefficient for the species considered. Diffusion coefficients are usually calculated or obtained from other systems. In this paper, the authors deduced their coefficients from the composition traverses.

In Fig. 1 traverses through a flame of the following composition are shown: $H_2+1.20\ N_2O+0.96\ NO+0.24\ CH_3Br+1.32$ A. The flame had a mass flow of 3.77×10^{-3} g cm^{-2} sec^{-1}, and was burned at 10 cm of mercury pressure. The reaction rate constant for the decomposition of methyl bromide [Eq. (2)] was found to be 1.4×10^{13} cm^3 mole^{-1} sec^{-1} at 1900°K for the flame described above. Two other flames were studied; one had the same pressure but only half the mass flow, the other twice the pressure and the same mass flow. For both flames at 1600° and 1700°K, k_2 was 1.2×10^{13} when [H] was one-fifth and one-half of that in the first flame at 1900°K. The reaction rate constant so determined was twice as large at 1900°K and 1.7 times as large at 1600° to 1700°K as those expected from the interpretation of Burdon. The authors point out that despite their own errors, the uncertainties in the ratio k_2/k_1 as inferred from flammability limits might well exceed a factor of two for the following reasons: (1) a flammability limit need not reflect a breakdown in the usual burning reactions; (2) the ratio of reactants in the flame was probably not the ratio in the initial mixture; and (3) T (adiabatic) was not the reaction temperature.

The hydrogen atom concentration deduced at 1900°K was close to the equilibrium concentration appropriate to $H_2=2H$. It was probably not affected very strongly by the additive, because [H] developed in fuel-rich H_2–NO–N_2O–A flames without CH_3Br is also of the order of the equilibrium concentration. If an inhibitor is thought of as decreasing concentrations of radicals which would otherwise be many times equilibrium, the flame studied at 1900°K could not be called inhibited—nor perhaps could any oxidation which did not involve branching reactions.

To insure chain branching as in Eq. (1), the authors studied flames of H_2, O_2, NO, A with additions of CH_3Br, CH_4, or neither. All three flames were slightly lean in fuel. The decrease in NO was too small to observe reliably and only a trace of HCN was formed. In obtaining the disappearance of oxygen, an excellent graph of temperature and composition traverses through the three flames is shown (temperature and mole fraction versus distance from burner). From the profiles and calculated reaction rate curves, one sees that the CH_3Br flame stood farthest from the burner and lost least heat to it. As a result the O_2 reacted at temperatures about 100° hotter than in the methane flame. Since the consumption of oxygen is equal to $k_2[H][O_2]$ very early in these flames, the higher reaction temperature implies a smaller [H] in the CH_3Br reaction. At 1300°K, the methane flame had $[H]=1.7\times10^{-9}$ mole cm^{-3} while the methyl bromide flame had a composition only 74 per cent as large. The three lean flames (CH_3Br added, CH_4 added, neither added) consumed different amounts of oxygen and, therefore, generated different quantities of free radicals. The oxygen consumed, however, was the same within

10 per cent in the methane and methyl bromide flames. To eliminate O_2 consumption as a variable, three fuel-rich flames were studied. The oxygen profiles of these flames were translated into reaction rates by the usual method. From a plot of the reaction rate versus temperature, one observes clearly that oxygen consumption occurred at a higher temperature with CH_4, and even higher when CH_3Br was the additive.

In the discussion, the authors state that the Burdon *et al.* interpretation of the inhibited flammability limit experiments is essentially correct. The agreement of their independent estimate of k_2 is the basis for this conclusion. They also conclude that methyl radicals, no matter what their origin, are powerful inhibitors.

In the oxygen flames where hydrogen atom concentration is considerably larger than equilibrium, the methyl bromide flame had a much lower [H] than an equivalent methane flame. The authors believe that the CH_3 radicals formed from CH_3Br are effective inhibitors, but infer that the HBr must be important also. The methyl radicals formed in Eqs. (2) and (4) consume some of the free radicals, but probably no more in the CH_4 than in the CH_3Br flame. The higher reaction temperature of the latter is attributed to more complete recombination of active radicals (H, OH, and O) in the presence of the halogen. To support this halogen catalyst viewpoint, the work of many researchers is cited.

Finally, in an appendix a convincing argument is presented on methyl radical reaction with nitric oxide.

Subject Headings: *Methyl bromide, effect on flame inhibition; Inhibition, of flame, by methyl bromide; Flame, inhibition, by methyl bromide.*

C. O'Neal, Jr.

Abrams, M. C. (General Dynamics/Pomona, Pomona, California) "Chemical Flame Quenching Theory," *Pyrodynamics* **1**, 131–141 (1964)

In this paper the author discusses the extinguishment of flames by chemical agents and suggests that "when the inhibitor interferes with the principal reaction by interacting with the fuel or oxidizer constituents, it is actually diverting these constituents into noncombustion type reactions until either the fuel-rich or fuel-lean concentration ratio has been exceeded." The consequence of this view is that for fuel-rich flames, an agent that interacts with the oxidizer would be more effective while in fuel-lean systems an agent that interacts with the fuel would be more effective. The author then suggests that the alkyl halides, which constitute one type of flame inhibitor would be expected to react with fuels such as hydrogen and hydrocarbons while the alkali metal salts would tend to react with oxidizers.

Experimental evidence to support the above view is presented based on the amounts of CH_3Br, CH_3I, aqueous potassium carbonate and aqueous sodium carbonate required to extinguish stoichiometric, fuel-rich and fuel-lean methane–air and hydrogen–air flames. The alkyl halides were found to extinguish fuel-lean flames more readily than stoichiometric or fuel-rich flames while the opposite was true for the alkali–metal salts. Results with carbon monoxide-air flames were anomalous.

Subject Headings: *Flame, extinguishment, theory of; Extinguishment, of flames, theory of.*

J. B. Levy

Tuve, R. L., Peterson, H. B., Jablonski, E. J., and Neill, R. R. (U. S. Naval Research Laboratory, Washington, D. C.) "A New Vapor-Securing Agent for Flammable-Liquid Fire Extinguishment," *NRL Report 6057* (March 13, 1964)

Of all fuels involved in fire hazards, gasoline and similar flammable liquids are most demanding in the requirements for extinguishing methods. The teamwork described in this report succeeded in developing a new method and new apparatus, using new materials to cope with this problem, i.e., by the application of dry chemical powder ($KHCO_3$) immediately followed by foam blanketing.

In search for improved surfactants to replace the hitherto used protein products, synthetic perfluorosulfonic acid derivatives[1] (mixture FX–183, Minnesota Mining and Manufacturing Co.) proved to be excellent for vapor-securing, regenerative, aqueous foam coverage. These agents in aqueous solution reduce the surface tension to less than 20 dynes/cm.

The selection of optimum concentrations was based on the following foam characteristics: 1) *Expansion*, i.e., initial gas volume in ft^3/liquid volume in cm^3; 2) *Quarter Drainage Time* which is required to collect 25 per cent of original liquid; 3) *Burnback Time*, a measure of foam resistance to flame exposure. This is determined in a 2 in. deep, 8 in. diameter brass pan divided into halves by a barrier whose top edge is flush with the rim, but whose lower edge terminates $\frac{1}{8}$ in. above the bottom. After covering one segment with foam, the free fuel surface of the other is ignited. The time for complete disappearance of foam when fuel burns freely in both segments is taken as burnback time.

Since air or CO_2 produced unsatisfactory foams, following the example of "aerosol shaving cream" refrigerant gas, dichlorodifluoromethane, as foam-expanding agent was emulsified as liquid under pressure in the surfactant solution. Foam generated by injecting air turbulently through the solution was applied from a spray nozzle.

Nevertheless, it was necessary to increase the viscosity of the solution by the addition of ethylene oxide polymer, 3 per cent of which raised the drainage time from 2.5 to 18 min.

The superiority of fluorocarbon over protein surfactants derives chiefly from the capability of film formation at the air-fuel interface.[2] From the foam boundary of a partially foam-covered gasoline surface, protrude almost invisible streamers of a film whose existence manifests itself by the emergence of "secondary," vapor-filled bubbles, larger than those of the primary foam. This film is, of course, an extension of one existing at the foam-fuel interface from the very beginning, and replenished by drainage while it expands. The spreading of this film continues to the rim of the receptacle, thus sealing off the whole fuel area. Data are given for the time requirement of complete fuel-area sealing as function of application density. The film spreading velocities are of the order of only 1.5 cm/min at 70°F, while oleic acid spreads on water with a velocity of about 20 cm/sec. As the surface tension decreases with rising temperature the efficiency of the vapor-securing film reduces correspondingly; it practically ceases above 100°F.

In intermediate scale (about 100 ft^2 area) flame exposure tests, ignition by means of a small torch took place after foam application only where the covering was disrupted, but the fire would be extinguished as the foam and film barrier flowed in to close the opening, within seconds. Holes up to one square foot could be readily sealed by fresh foam application.

When the ignition of "secondary" foam causes a flame to travel across the surface the bubbles collapse from the approaching heat and their vapor content burns off,

but the fire is stopped even though the gasoline surface is freely exposed. From the same primary foam a new secondary vapor-securing film forms that can again be flashed off without igniting the bulk of the fuel. This process can be repeated for many cycles before, finally, the film becomes vulnerable when the hydraulic head of the remaining foam is insufficient to close ruptures.

From experiments of that nature the following specifications for the most favorable application were obtained:

Foam expansion 8; quarter drainage time 6 min; quantity of surfactant solution close to 0.05 gal/ft²; ethylene oxide polymer 0.5 per cent; refrigerant 1 gal per 15 gal solution; solution application rate 0.4 gal/ft²/min during 5 to 6 min. The proportion of dry chemical powder and securing agent solution used was 5 lb per gal.

For large scale operation (400 ft² area) a mobile pressurized dual-agent extinguishing machine was constructed, equipped with double rubber hose for independent application of the dry and liquid component through suitable nozzles. Tests were run with gasoline, JP–4 and JP–5 fires. The efficiency of the device is illustrated by the failure of extinguishing a gasoline fire by applying 0.3 lb/ft² of dry chemical, whereas a little more than half that quantity sufficed in conjunction with vapor-securing foam for complete extinguishment.

The authors are well aware of the need for further research to elucidate the phenomena of film formation on surfaces of hydrophobic liquids.

References

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2. Ellison, A. H. and Zisman, W. A.: J. Phys. Chem. *60*, 416 (1956).

Subject Headings: *Foam, use of, perfluorosulfonic acids; Surface tension, reduction by perfluorosulfonic acids.*

H. M. Cassel

Mitchell, D. W. and Murphy, E. M. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Flammability of Rigid Urethane Foam," *Foamed Plastics—Proceedings of a Conference Sponsored by U. S. Army Natick Laboratories and National Academy of Sciences—National Research Council Committee on Foamed Plastics* (April 22–23, 1963)

This paper summarizes research conducted under the auspices of the U. S. Bureau of Mines on methods for controlling the burning of urethane foam and determining its flame penetration and spread. Optimum resistance to flame penetration was obtained from a formulation containing a reactive phosphorus polyol, a halide, a highly functional low equivalent weight sucrose polyether polyol, and a highly aromatic polyisocyanate. When such foam is exposed to flame or heat, a nonmelting intumescent char develops that insulates the substrate of foam. The phosphorus increases the char strength and raises the autoignition temperature of the solid foam components; the halide inhibits burning, presumably by disrupting the chain reaction for sustained combustion; the aromatic polyisocyanate chars without melting, and the low equivalent weight sucrose polyether polyol swells and develops an intumescence which inhibits flame penetration.

In mining applications, however, the prevention of flame spread is equally important as resistance to flame penetration. An improved criterion for assessment

of foamed plastics for use in mines was suggested. A flammability index number which combines the flame spread index of ASTM E 162–60T with the flame penetration time from a newly developed and highly reproducible Bureau of Mines test was recommended. The authors found that flame spread could be prevented by coating urethane foam of low flammability index with either sodium silicate, latex, or alkyd paint.

To verify the adequacy of the Flame Penetration Test, the authors conducted large-scale tests in the Bureau of Mines Experimental Coal Mine. Coal without a foam covering was ignited and the flame penetration and burning rates were determined and compared with coal covered with foam of various flame penetration times. It was found that foam formulated to resist flame penetration may entail several added hazards. First, a secondary flame of short duration and low flame temperature may spread rapidly across the foam surface. Secondly, while an intumescent char is essential to reduce flame penetration, if the foam chars without swelling, flame may penetrate the foam and produce hot, burning pieces which fall from the coated surface. Finally, noxious fumes may be released from the heated foam. Heat from a typical mine fire will cause the fluorocarbons used as the blowing agent in the urethane foam to expand and rupture the membranes covering the foam cells, releasing bromides which act as a flame reaction suppressant. The bromide in turn inhibits the oxidation of carbon monoxide to carbon dioxide, and in addition, isocyanate is present, released from the char promoting agent.

The conclusion was reached that for mine applications, rigid urethane foam must (1) resist flame penetration to the combustible substrate, (2) prevent flame spread through foam covered areas, and (3) retain desirable properties when exposed to hot air currents.

Subject Headings: *Flammability, of polyurethane foam; Foam, urethane, flammability of.*

D. Dembrow

VIII. Model Studies and Scaling Laws

Sweeney, J. R. and Biswell, H. H. (University of California, Berkeley, California) "Quantitative Studies of the Removal of Litter and Duff by Fire under Controlled Conditions," *Ecology* **42**, 572–575 (1961)

On each of four experimentally burned plots the weights of 30 forest floor samples, 2 × 2 feet in size, were determined before and after burning. Twenty-four samples were reconstituted so as to be one-third litter and two-thirds duff, with six samples each of four weights: 1362, 2724, 4086, and 5448 grams (approximately equivalent to 16.3, 32.5, 49.0, and 65.3 tons per acre). The control samples, six in each plot, ranged in weight from 198.8 to 1589 gr. (2.4 to 19.0 tons per acre). Plots were burned in late winter; air temperature was 50°–64°F, relative humidity 24 to 40 per cent, litter moisture content 9.7 to 24.1 per cent, and duff moisture content 18.2 to 44.3 per cent. Two fires were on level ground, one ran up a 10 per cent slope, and one backed down the same slope.

Average loss of litter per plot ranged from 61 to 85 per cent, of duff 17 to 32 per cent. For the three plots with the lowest fuel moisture contents, per cent of fuel consumed increased with total weight present. The wettest plot showed an opposite

tendency. Amount of organic material consumed varied greatly among samples; always, enough was left to cover the mineral soil.

The stated conclusion, "that fire can be used under controlled conditions in forest management . . . without destroying all the litter and duff and exposing the soil," may unduly extrapolate from the findings of this small-scale study. It is one thing to show that small fires can burn without doing unacceptable damage, quite another to conclude that therefore fire can be used in forest management on an operational scale.

Subject Headings: ***Fire, removal of litter and duff; Duff, removal by fire; Burns, prescribed, for duff removal.***

G. R. Fahnestock

McArthur, A. G. (Fire and Timber Bureau, Commonwealth of Australia, Canberra, Australia) "Control Burning in Eucalypt Forests," *Forestry and Timber Bureau, Commonwealth of Australia Leaflet No. 80* (1962)

Fires started by aborigines and lightning have burned dry Australian eucalypt forests frequently enough to keep ground fuels to around 2 or 3 tons per acre. Greater amounts have accumulated in wet forests. Dry-site eucalypts are quite fire-resistant because of thick bark, dormant buds, and lignotubers; wet-site species are less resistant. About 3 per cent of the commercial eucalypt forest burns annually. Fuel-reduction burning would be a feasible and economic means of reducing area burned and damage.

"Control burning" is defined as "the planned application and confinement of fire to the vegetation of a preselected area"; it is synonymous with "prescribed burning," the accepted term in the United States. In the narrow sense, control burning refers to burning small strips or areas to protect high values or to guard against known high risks. In a broader sense, which is the concern of this paper, control burning can reduce fuel accumulations over wide areas, thereby reducing rate of fire spread, fire intensity, difficulty of control, and likelihood of fire incidence. Additional beneficial effects of control burning can include improved grazing, killing unwanted vegetation, reduced populations of harmful insects and animals, improved access and visibility, reduced soil moisture competition, and increased penetration of the soil by rainfall. Burning according to rather precise prescription can provide the desired benefits with negligible damage to timber, soil, and other values.

Many complex forces govern fire behavior and make it difficult to predict, but it is relatively easy to forecast the behavior of low-intensity fires and determine limits within which control burning can be done safely. The key is fire intensity, which may be expressed by the equation

$$I = Hwr,$$

where $I =$ fire intensity in Btu/sec/ft of fire front, $w =$ weight of available fuel in tons per acre, $r =$ rate of spread in ft/sec. Optimum intensity is 13 to 50 Btu/sec/ft, giving a flame height of 1 to 3 ft, and a scorch height of 6 to 15 ft. Fires are unlikely to cross control lines and will require little if any patrol. Lower-intensity fires do not spread well; higher intensities are more risky and damaging but can be used in

some situations up to a maximum of 100 Btu/sec/ft. With the tables and charts given one can estimate available fuel, rate of spread, flame height, and scorch height from observed weather, topography, and forest-stand characteristics. A chart shows the limits of poor, optimum, and risky burning on the basis of rate of spread and flame height, making use of the equation unnecessary.

Area that can be burned at one time ranges from 100 to 900 acres depending on difficulty of the chance and number of men available. Production rates cited range from 8 to 63 acres per man hour. The optimum burning crew consists of probably 4 men and a supervisor, preferably a forester. Lighting is accomplished by means of a grid of spot fires set in rows perpendicular to the prevailing wind and progressing into the wind. The wider the spacing of spot fires, the cheaper the operation and the less damage to standing timber. Supervision by a person experienced in fire behavior is necessary to vary techniques to meet changing conditions. As a safety precaution, burning should start during or after the severest burning period of the day. If meteorological and fuel conditions are suitable, successful burns can be made at any time of the year.

This bulletin is a significant contribution to the literature on controlled use of fire. The guidelines for determining suitability of conditions for burning are far more complete than any other this reviewer has seen. They appear quite useful and sound in principle, although not literally applicable to every situation. The charts for estimating fire behavior should be tested for applicability to prescribed burns in the southeastern United States. In comparison with the treatment of fire behavior, the section dealing with techniques of burning is surprisingly unsophisticated. Only quite general descriptions are given of burn layout, exterior and interior lines, types of fire (back, head, flank) for different purposes and situations, and lighting patterns. Little cognizance is taken of the important fact that selection of the appropriate type of fire and firing pattern can to a large extent control fire intensity, hence can broaden the range of conditions under which burning is feasible. Fortunately these minor limitations of the presentation are readily apparent to an experienced prescribed burner and therefore detract little from the value of the publication.

Subject Headings: *Burns, prescribed, in eucalypt forest.*

G. R. Fahnestock

IX. Atomization of Liquids

Browning, J. A. (Browning Engineering Corporation, Hanover, New Hampshire) "High Energy Atomizer for Fire Extinguishment," *U. S. Patent Office*, (Patented May 8, 1962) 3,033,292

The fire-quenching effects of cooling and oxygen exclusion, which are provided by a finely atomized "fog" spray, inspired the invention of an internal burner atomizer. As demonstrated by Fig. 1, the burner provides high-temperature, high-pressure combustion products which exhaust through a converging nozzle at sonic velocity. Water is injected radially into the exhaust jet, and is atomized pneumatically by the sonic stream, as reported previously by Bitron.[1] Since droplet

HIGH ENERGY ATOMIZER FOR FIRE EXTINGUISHMENT
Filed Jan. 27, 1960

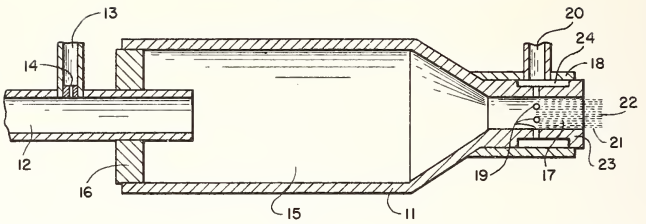

FIG. 1

formation occurs by the process of secondary atomization, drop size is determined by the Weber number criterion.[2]

$$W_c = V_a^2 \rho_a D/\sigma = \text{constant}$$

or

$$D = W_c \sigma/\rho_a V_a^2, \tag{1}$$

where the higher velocities (V) and higher gas densities (ρ_g) in the nozzle throat result in extremely fine atomization.

Water flow rates are sufficiently high to prevent the rapid conversion to steam, at the same time reducing the exhaust gas temperature to a few degrees above the water supply temperature. High gas velocity (2500 fps) and density, and moderate exhaust gas temperature (hence, low vaporization rates) provide the additional advantage of deep penetration (100 ft) as predicted by Miesse.[3]

$$L = VD^2/\lambda, \tag{2}$$

where λ is the evaporation rate.

References

1. BITRON, M. D.: Ind. Eng. Chem. *47*, 23 (1955).
2. MIESSE, C. C.: Appl. Mech. Rev. *9*, 321 (1956).
3. MIESSE, C. C.: "Ballistics of an Evaporating Droplet," Jet Propulsion, *24*, 237 (1954).

Subject Headings: ***Fire, extinguishment, by high-energy atomizer; Atomizer, for fire extinguishment; Extinguishment, by high-energy atomizer.***

C. C. Miesse

X. Meteorological Interactions

Turner, J. S. (Division of Radiophysics, CSIRO, Sydney, Australia) "The Flow into an Expanding Spherical Vortex," *Journal of Fluid Mechanics* **18,** 195–208 (1964)

Several investigators have made experimental studies of the mean motion in and around isolated elements of buoyant fluid released into a uniform fluid at rest. They have found a vortex-like circulation superimposed on the upward motion with the shape and mean velocity distributions remaining similar with height. A buoyant

element expands and spreads out as it travels upward due to the incorporation of fluid from the environment; the observed distribution of velocity in and around a buoyant 'thermal' is very close to that in the spherical vortex of constant size described by Hill (see Lamb 1932)[1] whose solution of the equations of motion represents a vortex moving with constant velocity and size.

The present paper concerns the explanation of past detailed experimental results in terms of an expanding spherical vortex. In this model it is assumed that the motion of a particle near an expanding sphere is instantaneously the same as for a sphere of constant radius of the same size. The expansion is proportional to the distance traveled, and the sphere radius a at time t in a coordinate system of rest relative to the center of the sphere is

$$a = \alpha t U = \alpha t,$$

where α is the tangent of the half angle of spread and U the upward velocity of the sphere which is taken as unity. In order to treat the expanding sphere as fixed in size, a dimensionless coordinate ρ is introduced such that

$$\rho = r/\alpha t U = r/\alpha t,$$

where r is distance of a particle from the sphere center. Outside the sphere where $\rho > 1$, the equations of motion in spherical coordinates are

$$d\rho/dt = -(\alpha t)^{-1}\{\alpha\rho + (1 - 1/\rho^3)\cos\theta\}$$

$$d\theta/dt = (\sin\theta/\rho\alpha t)(1 + \tfrac{1}{2}\rho^3),$$

where θ is the angle measured from the direction of the approaching stream. Inside the sphere where $\rho < 1$, the equations become

$$d\rho/dt = (\alpha t)^{-1}\{-\alpha\rho + \tfrac{3}{2}(1 - \rho^2)\cos\theta\}$$

$$d\theta/dt = \tfrac{3}{2}(\sin\theta/\rho\alpha t)(2\rho^2 - 1),$$

with the initial conditions provided by the final values obtained from the preceding pair of equations.

The main features of the solutions (with $\alpha = \frac{1}{4}$) are presented in a diagram which gives particle paths with particle positions separated by equal time intervals. Shown also are the successive shapes into which a horizontal plane of fluid is distorted by the passage of the expanding spherical vortex. Particles near the vertical axis above the approaching sphere are incorporated into the front of the sphere and swept sideways in the outer layers away from the upper axial stagnation point. Particles some distance from the axis enter the sphere through its lower surface. More distant particles may fail to enter. Unlike the sphere of constant size, the expanding sphere does not have a total drift function; particles in the wake of an expanding sphere continue to move upward after the sphere has passed.

Experimental thermals are slightly more flattened than the calculated streamlines indicate. Also, the mean velocity distributions so far measured do not show the discontinuity of velocity gradient implied by the model. Otherwise the main features of the motion in and around a buoyant thermal can be explained very well by the expanding spherical vortex model.

Reference

1. Lamb, H.: Hydrodynamics, Cambridge University Press, 1932.

Subject Headings: *Vortex, flow into expanding sphere.*

G. M. Byram

Broido A. and McMasters, A. W. (California Forest and Range Experiment Station, Berkeley, California) "The Influence of a Fire-Induced Convection Column on Radiological Fallout Patterns," *California Forest and Range Experiment Station Technical Paper Number 32* (March 1959)

The purpose of this investigation was to determine whether fire-induced convection columns could significantly affect radiological fallout patterns. An idealized theoretical analysis is presented which shows that the updraft velocity associated with a convective column can be expected to modify a fallout pattern.

In order to verify this prediction a set of experiments was carried out in a 6 ft by 6 ft wind tunnel. Flow velocities of 2, 4, and 6 miles per hour were used. A two foot square convective column was generated using two 12 in. by 0.25 in. ribbon burners with propane as the fuel. The ribbon burners were 10 in. apart and parallel to the direction of flow near the floor of the tunnel. It was estimated that the updraft in the convective column was 2.5 miles per hour. The fallout was simulated with soil in the particle size range 74 to 210 microns. The particles were injected with a Binks Model No. 171 Flock Gun. A reasonably uniform distribution was obtained over a 2 to 3 foot width and a 10 foot length. The particles were injected near the ceiling of the wind tunnel and from 3.5 to 11 feet upstream of the burners. It was found that the effect of the convection column was to increase the lateral dispersion and downwind movement of the fallout, giving a more disperse, less concentrated pattern. The convective column moved the point of maximum concentration downstream by as much as a factor of two and the maximum concentration of particles was decreased by as much as a factor of ten.

As the authors point out, since the experiments are not sealed it is dangerous to extrapolate the results to full-scale conditions. However, it does seem fair to predict that similar effects could be observed in the vicinity of a large-scale, free-burning fire.

Subject Headings: *Convection column, effect on fallout pattern; Fallout pattern, influence by convection column; Fire, convection column, influence on fallout.*

D. S. Turcotte

Fosberg, M. A. (Pacific Southwest Forest and Range Experiment Station, Berkeley, California) and **Schroeder, M. J.** (U. S. Weather Bureau, Berkeley, California) "A Warm Sea Breeze?" *U. S. Forest Service Research Note PSW–N18* (1963)

This is a nontechnical account of a type of sea-breeze front that continues inland as a "warm" wind shift line after the temperature discontinuity becomes stationary. The winds described flow through two 25-mile-wide gaps in the coastal mountains

of California—over San Francisco Bay and through Petaluma Gap east of Bodega Bay, 45 miles north. These streams of air merge and continue inland toward Stockton in the Sacramento Valley. The authors observed 11 occurrences of the "warm sea breeze" during 49 days of study in July and August of 1961 and 1962.

The sea-breeze front acquired these distinctive characteristics when the offshore layer of cool marine air was a comparatively shallow 2000 feet beneath a deep inversion. The east Pacific high extended into Oregon and Washington producing a slightly offshore geostrophic flow from the north along the northern California coast.

With vertical cross section and surface streamline analyses, the authors describe a typical example that occurred August 15, 1962. The sea breeze started inland, crossing the coast at 0800 PST. As the shallow layer of marine air moved inland, it was rapidly warmed, and by 1000 PST the temperature discontinuity began to lag behind the wind shift. By 1100 PST and 20 miles inland, the temperature discontinuity became stationary. The wind shift continued inland at an average speed of 10 mph for another 80 miles accompanied only by a change in direction and speed and no appreciable change in temperature or humidity.

In the example described, offshore temperatures in the marine air were 55° to 60°F and increased in 20 miles overland to 90° to 95°F where the temperature discontinuity became stationary. The authors suggest that the wind-shift line represents the sea-breeze front.

This report contributes to knowledge of mesostructures important in fire weather and other types of forecasting where local weather structures are important.

Subject Heading: *Wind, analysis of warm sea breeze.*

O. P. Cramer

XI. Operational Research Principles Applied to Fire Research

Turner, J. A. (British Columbia Forest Service, Victoria, British Columbia) "The Uses of Evaporation Data and Theory in Forest Management," *Proceedings of Hydrology Symposium No. 2*, Toronto, Canada, 200–211 (1 & 2 March 1961)

This paper briefly cites a number of ways, mostly quite familiar to forest fire control specialists, of using direct and indirect measures of evaporation to indicate severity of burning conditions. Technical details of the methods are not given, and no data, equations, formulas, or tables are included.

In the estimation of forest fire danger, measurement of evaporation has been explicitly considered as a factor over most of Canada. Direct determination of the moisture content of standardized indicator fuels has been used in British Columbia and most of the United States. Recent indications that "effectively the same accuracy could be achieved by the use of temperature, relative humidity, and wind speed data" permit reduction of instrumentation and interpretation of routine weather forecasts in terms of fire danger. Some success has been reported for a Russian moisture-balance technique employing estimation of evaporation losses based on solar radiation multiplied by a coefficient representing effects of cover type and residual moisture.

Measuring the build-up of fire danger resulting from long rainless periods (1) indicates amount of moisture remaining in slow-drying fuels and, to some extent,

in living vegetation, and (2) provides an estimate of the depth of the water table, which is important where surface water is used for fire fighting. In Manitoba swamps during dry weather, the daily drop in water level was correlated best with air temperature, an easy-to-measure indicator of evapotranspiration. Potential fire danger is estimated in Germany through calculating the state of soil moisture by means of a water budget using daily rainfall and 1400 LST saturation deficit adjusted for local seasonal conditions. Nelson[1] developed a soil-moisture-budget type of drought index for the southeastern United States for which he "was unable to show any direct relationship with any measurable index of fire season severity," although years when fire control was most difficult were the years of greatest water loss.

Direct relation of fire-season length and severity to computed moisture budget has not been particularly successful, but in parts of British Columbia the number of fires per month has correlated rather well with the monthly hours of sunshine. No such correlation was found in Georgia after the effects of relative humidity and wind were eliminated. Monthly moisture (rainfall?) deficiency also was correlated moderately well with number of forest fires in certain British Columbia districts, but not so well as with hours of sunshine. In New South Wales all major fires occurred in years when a synthetic soil moisture index reached zero, except once when rainfall was too light to support a good enough growth of grass to carry the fire.

A precipitation/evaporation ratio of 1.2 or less for the preceding 30 days was found to be necessary for successful prescribed burning in Queensland. A chart has been developed to show the amount of evaporation necessary to give satisfactory burns after 30-day rainfall of any given amount.

Discussion of the paper deals with various points regarding rate of drying in relation to difference between current and equilibrium moisture content, size and ventilation of fuel particles, and vapor pressure difference.

Reference

1. Nelson, R. M.: *Drought Estimation in Southern Forest Fire Control*, U. S. Forest Service Southeastern Forest Experiment Station Paper 99, 1959.

Subject Headings: ***Forest management, use of evaporation; Evaporation, effect on burning conditions; Burning condition, of forest, effect of evaporation.***

G. R. Fahnestock

XII. Instrumentation

Alvares, N. J. (U. S. Naval Radiological Defense Laboratory, San Francisco, California) "Measurement of the Temperature of the Thermally Irradiated Surface of Alpha Cellulose," *USNRDL–TR–735 Defense Atomic Support Agency Contract MIPR 526–64* (24 March 1964)

This reports a continuation of the study of the ignition of pure alpha cellulose by thermal radiation. The material used is in the form of thin sheets (0.01 to 0.03 in.) blackened by the addition of about 2.0 per cent by weight of carbon black to the initial pulp mix. The samples are irradiated in a carbon arc image furnace which

employs two opposing 36 in. paraboloidal reflectors to concentrate the energy from the arc onto a spot 0.375 in. in diameter with an irradiance of 100 cal cm^{-2} sec^{-1}. The time of exposure is controlled by an air driven shutter. The carbon arc radiation of wavelengths longer than 2.4 μ is filtered out by a 0.75 in. slab of Plexiglas which is placed in the parallel beam next to an aluminum grid attenuator. In this way the irradiance of the spot on the alpha cellulose is reduced to about 7 cal cm^{-2} sec^{-1}. The energy radiated normally from the surface of the sample is directed through a 4 in. hole in the 36 in. reflector to the radiation detector. This is a liquid nitrogen-cooled lead sulfide photoconductive cell in front of which there is a 3.41 μ narrow band pass interference filter. The lead sulfide cell is located in a permanently evacuated Dewar behind a sapphire window. The signal from the detector is fed into the differential amplifier of an oscilloscope and the display is photographed by a Polaroid Land Camera. The over-all time of response of this system is 30 milliseconds.

The wavelength region 3.41 ± 0.02 μ selected by the filter is practically free from H_2O and CO_2 absorption bands and is close to the peak wavelength sensitivity of the lead sulfide cell; it does not include any of the arc radiation which is limited to wavelengths shorter than 2.4 μ by the Plexiglas filter.

Calibration is effected by placing a standard black-body source, having an orifice 0.2 in. diameter, at the position normally occupied by the specimens of alpha cellulose. The temperature of this source is varied from 200° to 1000°C in 100°C increments. The signal from the lead sulfide cell caused by the transient temperature rise of the surface of the cellulose is fed into the oscilloscope and the deflection of the measurement pulse is photographed. This can be compared to the temperature calibration and the resulting temperature readings plotted as a function of time. Since the sensitivity of the cell changes from day to day, the calibration procedure has to be repeated for each set of samples exposed to the arc.

A separate determination of the total normal emittance of the alpha cellulose at a wavelength of 3.41 μ indicates that this is unity at 207°C and it is assumed that this remains unchanged over the temperature range of the ignition experiments.

Typical temperature versus time traces, as recorded by the Polaroid Land Camera for 0.02 and 0.03 in. samples, respectively, are similar in shape. Each shows a definite change in slope at about one-half the amplitude and also a very sudden increase in slope near the top of the curve. It is at this point that the alpha cellulose ignites, as is confirmed by the presence of a voltage pulse on an accompanying flame detector trace. The change in slope near the middle of the trace could be caused by either a change in thermal conductivity, by the transpiration of gases, or by endothermic reactions. The enhancement of the trace after the ignition point is reached is probably due to emission from incandescent soot particles in the flame.

For irradiances of approximately 7 and 14 cal cm^{-2} sec^{-1}, the temperature of the surface at the instant of ignition is 600°C for samples thicker than 0.02 in. However, due to the possibility of small errors in the emittance and to a small but finite radiating depth over which a temperature gradient exists, the surface temperature at ignition may be somewhat greater than the 600°C (approximately) recorded but not over 650°C.

Subject Headings: *Temperature, of irradiated cellulose; Cellulose, surface temperature.*

R. Long

MacHattie, L. E. (Defence Research Medical Laboratories, Toronto, Canada) "Temperature Measurement of Textile Fabrics under Intense Thermal Irradiation," *British Journal of Applied Physics* **14,** 267–270 (1963)

A method for subjecting fabrics to intense thermal radiation and measuring the resulting surface temperature rise is described. Conditions simulating the flash radiation from nuclear explosions were studied with intensities up to 18.6 cal/cm² sec.

The illuminating source was a tungsten filament lamp and the blurred image of the filament was projected onto the test fabric, yielding an illuminated area of 1 cm². Wavelengths above 3.5 microns were filtered out. The fabric "surface" temperature was measured during exposure with an infrared detector. All wavelengths below 3.5 microns of the radiation entering the detector were filtered so that reflected source radiation would not be observed. Since fabrics have some transparency, the temperature determined by this method is some mean temperature of all the fibers visible to the pyrometer.

The system was calibrated by moistening the fabric prior to exposure with liquids of various boiling temperatures. The sample was exposed and the detector output observed. The output level at which the rise is temporarily arrested by the boiling of the liquid from the fabric corresponds to the liquid boiling point temperature. Calibrations were made for temperatures between 100° and 302°C.

Temperature-time curves were obtained for a number of common fabrics as a function of exposure intensity. Irregularities in the rate of rise were observed and can be attributed to various phenomena such as vaporization of moisture from the fiber, change of emissivity of the fabric due to bleaching of the pigment from heating, or melting of the fiber, as in the case of synthetic materials. Curves are given for the radiation of unbleached and black cottons, fortison, wool, nylon, Terylene, and Orlon, up to temperatures of about 300°C.

Subject Heading: ***Temperature, measurement, on textiles.***

R. W. Ziemer

Lincoln, K. A. (U. S. Naval Radiological Defense Laboratory, San Francisco, California) "Flash Vaporization of Solid Materials for Mass Spectrometry by Intense Thermal Radiation," *USNRDL–TR–735 Defense Atomic Support Agency Contract MIPR 526–64* (24 March 1964)

An apparatus is described where the rapid vaporization of cellulosic materials inside the vacuum chamber of a mass spectrometer permit the detection of both short-lived and stable products of the reaction.

The materials are heated to a high temperature utilizing intense pulsed thermal radiation generated from a xenon flashtube. The vaporized products of the reaction are immediately passed into the ion source of a Bendix time-of-flight mass spectrometer where spectra are quickly obtained.

The sample is held on a quartz rod placed within a pyrex vessel. The latter is attached to the bottom flange of a 2 in. gate valve which serves as a vacuum lock when samples are reloaded. A helical flash tube surrounds the vessel. The thermal radiation will heat only the sample; all surrounding parts remain relatively cool. This eliminates the problem of long outgassing times of the sample vessel. The

temperatures attained are not measurable but some upper limit can be obtained. The variation of total incident energy can be varied by controlling the power input to the GE FT–625 flash tube. The thermal pulse is on for about half a millisecond. If small (10 μg) quantities of cellulose are used, then no observable pressure rise occurs within the mass spectrometer. Since the product gases are present only for a short time, it is necessary to display the spectrum on an oscilloscope. The spectrum is photographically recorded when the camera shutter is actuated, which in turn triggers the flash tube power supply, thus activating the xenon flash tube. The spectrum obtained is actually a time-integrated superposition of many thousands of spectra. This is perfectly adequate for most applications. Relative peak heights can be obtained within a few per cent accuracy.

The samples tested must possess a high optical absorbancy in the visible and infrared and also have a large surface to volume ratio. To further refine this technique it is suggested that a pulsed laser beam be impinged upon a very small area (such as a definite crystal face) of the sample. This will alleviate the problems associated with optical absorbancy, size, or shape of sample. Even greater sensitivity could be obtained by placing the sample between the first two grids of the ion source. Here all of the sample would be vaporized into the adjacent electron beam. This method would also greatly eliminate the detection of ions generated from all collisions prior to entry into the electron beam.

The flash vaporization technique is adaptable to any high-melting, low-vapor pressure material including refractories and heavy metals. Slow low-temperature pyrolysis reactions can also be conducted in this apparatus by simply placing the material in the bottom of the test tube and warming the whole vessel to the temperature desired.

Subject Headings: ***Cellulose, flash vaporization; Vaporization, flash, of cellulose.***

P. Breisacher

Dixon-Lewis, G. and Isles, G. L. (The University, Leeds, England) "Sharp-Focusing Schlieren Systems for Studies of Flat Flames," *Journal of Scientific Instruments* **39,** 148–151 (1962)

The composition and temperature profiles of various flame systems have been investigated extensively by spectroscopic and direct sampling techniques. The former method is often beset by problems of resolution and rather extensive errors in temperature determination due to inability to predict all products present in the complex reaction system. The direct sampling of these flames using small quartz microprobes lends more certainty to the identity of most of the species present. The use of small (1 mil) thermocouples for temperature recording when combined with appropriate radiation corrections gives reasonably good results as compared to sodium line-reversal spectroscopic measurements.

One of the problems associated with the insertion of microprobes and thermocouples into flat flames is the possible disturbing effect they can have on the "local" position of the flame front in relation to the probe tip. A wide aperture optical system has been successfully employed using direct photographic methods to pinpoint the local probe positions in the analysis of self-luminous flames. When non-

luminous flames are to be studied, a schlieren system is devised to find the necessary reference plane. In order to focus attention upon the disturbed area around the probe tip, it is necessary to obliterate the images generated outside of this region. In essence the apparatus consists of a double slit source with vertical deflections occurring obliquely to the optical axis. Images produced in the transverse movement across the flame will be out of focus at the photographic screen. The principal part of the optical system is the wide angle aperture in the vertical or disturbing direction. A cutoff plate is placed ahead of the last of three lenses used to coincide with the focal plane of the middle lens. This is the image selector for extremely fine detail which is focused by the third and final lens on the photographic plate.

The application of this system to the study of flat flame systems is described. The location of the schlieren maximum is the reefrence plane needed to determine accurately the position of the gases sampled by the probe or thermocouple. Schlieren gradients are determined with the disturbing element inserted and absent. Lateral movement of the localized schlieren maximum will then indicate the degree of disturbance in the essentially flat flame contour. Several photographs of both wide and narrow aperture schlieren images with a disturbing wire in and out of focus are shown.

Subject Heading: ***Flame, focusing schlieren system.***

P. Breisacher

National Fire Protection Association "A Method of Measuring Smoke Density," *Quarterly of the National Fire Protection Association* **57,** 276–287 (1964)

A self-contained Smoke Density Chamber is described for measuring the burning characteristics of small samples of building materials. The chamber is patterned after the ASTM D–568–61 apparatus (Standard test method for flammability of plastics 0.050 in. and under, in thickness) and rates combustible materials according to the quantity of smoke produced and the rate of smoke evolution, when standard sizes of specimens are ignited and kept burning with a propane burner.

The smoke is measured by the proportion of a light beam that penetrates a 12-in. path through the chamber. Photometer readings are made at 15-second intervals over the 4-minute duration of the tests. By plotting the light absorption data versus time, the smoke production rate (slope of the curve) and total smoke produced (area under the curve) can be determined. Maximum smoke density can be read directly from the curve.

The effects of test variables such as burner propane pressure, specimen size, humidity conditioning, supporting screen mesh size on the maximum smoke density (per cent), and the maximum smoke production rate (per cent/minute) were studied.

Standard test conditions were defined as 1x1x0.25 in. specimen size; 40 psi propane pressure to burner; 2.5-in. square of 4 mesh 0.035 gage stainless-steel wire cloth sample holder; and sample conditioning by Procedure A of ASTM D618–61 (Standard methods of conditioning plastics and electrical insulating materials for testing).

Typical test results for various materials under these conditions are given, in terms of maximum smoke density (per cent) and maximum smoke production rate

(per cent/minute). These were: red oak (2, 1); ponderosa pine (48, 44); acrylic (2, 4); self-extinguishing acrylic (97, 114); polystyrene (100, 296); polyvinyl chloride (100, 240); flame-retardant coated plywoods (15, 54) and (56, 23); flame-resistant polyester (99, 151); glass fiber acoustical tile (2, 8); gypsum wallboard (1, 0.5); glass fiber sound control blanket (13, 52); asbestos millboard (0, 0).

Ten figures show plots of per cent light absorption as a function of time, and photographs of the apparatus taken during the tests.

Subject Heading: ***Smoke, density measurement.***

B. Greifer

Cucchiara, O., Donaghue, T., and Chleck, D. (Parametrics Incorporated, Waltham, Massachusetts) "Detection of Hydrogen Aboard Aerospace Flight Vehicles," *Technical Documentary Report No. APL TDR 64–51 Contract AF 33(657)–8916, Air Force Systems Command, Wright–Patterson Air Force Base*, Ohio (April 1964)

Gaseous hydrogen is widely used in industry and will be employed on an increasingly larger scale in future aerospace activities. Its explosive characteristics in reacting with air or halogens warrants a detection device of versatility, reliability, and simplicity; present techniques have severe limitations.

This report describes the investigation leading to construction of a laboratory model of a device for detecting hydrogen by direct means, in concentrations up to one per cent for primarily sub-atmospheric pressure environments. The technique makes use of the reduction reaction of hydrogen and a kryptonated metal oxide containing radioactive Kr^{85}. The liberated krypton gas is proportional to the reacting hydrogen and reduces the radiation of the radioactive source. This measured rate of decrease of source activity can be related to hydrogen concentration.

A mixture, of equal proportions, of kryptonated platinum dioxide and aluminum oxide is considered the optimum source based on sensitivity and response to hydrogen in an oxygen-free environment.

The device consists of a flow-through quartz sampling chamber containing the radioactive source. The kryptonate mixture is deployed as a coating on a nichrome heating wire; the temperature variation of sensitivity can be conveniently exploited. Radiation activity is monitored by a direct-viewing Geiger counter and displayed on a ratemeter which has an interlocking audible alarm for alerting to critical concentrations.

The observed increase in sensitivity with source temperature allows two operating ranges. For the normal "hazard" setting, response to 1 per cent hydrogen concentration is less than 7 seconds and the sensor life is about two weeks. A "high hazard" setting produces a response time of less than one-half second, for one per cent hydrogen, while the source operating life diminishes to one day.

The kryptonate detector displays insensitivity to contaminants such as water vapor, carbon dioxide, and sulfur dioxide. The observed sensitivity to hydrocarbon vapors, such as methane, xylene, and methyl alcohol indicates its potential capability of detecting these equally hazardous gases. In mixtures of hydrogen and nitrogen, for the pressure interval between 50 and 380 mm Hg the technique is sensitive only to hydrogen volumetric fraction (not to partial pressure). In applica-

tions such as aerospace vehicles this pressure insensitivity presents a certain convenience.

In summary, the detection technique employing kryptonates has been found to have a high specificity to hydrogen, is simple to operate and maintain, and when used with standard radiation-counting instruments exhibits reliable read-out and display with low over-all electrical power and small spatial demands.

Subject Heading: ***Hydrogen, detection of.***

K. M. Foreman

XIII. Fire-Fighting Techniques, Equipment

Price, H. E., Crain, C. L., and Siciliani, F. A. (Serendipity Associates, Sherman Oaks, California) "A Survey of Human Factors Engineering Problems in Fire-fighting Equipment," *Office of Civil Defense, Department of Defense Contract OCD–PS–64–3* (February 1964)

The authors report the findings of an investigation of human-operator compatibility of fire-fighting equipment currently used in the State of California. The study comprised personnel interviews, questionnaires, a review of suggestions submitted by personnel of the Los Angeles City Fire Department under a departmental suggestion program, and attendance at drills and actual fires. (The report does not include a specimen of the questionnaires, since these were designed during the investigation.)

One observation noted is the great variety of vehicular equipment, with some items remaining in service for as long as 30 years. Certain human-factors engineering problems are cited to be generally common to all models of the types considered, such as

1. Lack of safety devices
   a. On brush trucks, where it is common for nozzle men to ride front fenders, no pressure limiting valve is provided to protect them and safety belts are not provided,
   b. On structural trucks, safety belts are not provided for fire fighters riding the rear steps,
   c. On aerial ladders, safety harnesses are not provided.
2. Lack of consistency and rationale in instrument readout, control panel arrangement, shape-coding of control levers, and control panel illumination. (The authors strongly recommend demarcation of instrument and control panels, arrangement consistent with function, and shape-coding of levers for blind sensing, use of nonreflecting gage glasses, and red colored lighting for compatibility with night-dark adaptation.)
3. Lack of facility for communication between personnel in situations such as
   a. Between vehicle operators and nozzle men on brush fire trucks,
   b. Between personnel wearing breathing apparatus and personnel located outside the immediate hazard area (such as involved building),
   c. Between personnel on aerial ladders and ground personnel,
   d. Between vehicles of various emergency services (e.g., police, fire,

electricity, etc.) including fire services from different municipalities. The authors cite the hazard for all emergency services to use the siren as a mobile warning device, i.e., hazard of collision by two vehicles using siren warnings. However, the device used by the French fire services was not cited as an alternate.

4. Gross inconvenience in design of hose line equipment storage spaces on vehicles. In some vehicles, equipment mounted externally must be removed to gain access to internal storage, and in other configurations, personnel must crawl inside storage space to obtain needed equipment.

The authors were not charged with the mission to search out all deficiencies, or to propose remedial action in each instance. The purpose of the study was to determine if there is a need to apply human-factors engineering techniques in fire-fighting equipment design and use. The authors feel that the examples cited justify the statement of need. They recognize that training of personnel is a key factor in building an effective man-machine team, and that man is capable of circumventing many machine inconveniences; however, they point out that after onset of fatigue, and under stress man will be less effective in those instances where inconveniences and ambiguities are introduced by the poor design of the machine from the standpoint of human factors.

Several suggestions are presented for correcting current problem areas:

1. Modify existing equipment in so far as feasible in fire department shops to correct deficiencies such as illogical instrument readout, glare from gage glasses, etc.
2. Fire department procurement activities should apply human-factors requirements in developing procurement specifications.
3. A national organization should be developed to provide leadership, so that complete design of equipment with human-factors requirements can be undertaken, and studies can be conducted leading to preparation of model specifications supporting human-factors requirements.
4. A human-factors guide manual should be prepared, specifically for fire apparatus.

Pending the availability of a specific manual, or guidance specifications for human factors in fire apparatus, the authors suggest use of one or more of the following references:

a. Human Engineering Design Criteria for Aerospace Systems and Equipment. Part 1—Aerospace System Ground Equipment. NIL–STD–803A (USAF), 1964.
b. Manual of Standard Practice for Human Factors in Military Vehicle Design. T. M. 21–62, Human Engineering Laboratories, Aberdeen Proving Ground, U. S. Army, 1962.
c. Human Engineering Guide to Equipment Design. Edited by Clifford T. Morgan *et al.* New York: McGraw Hill, 1963.

The authors recommend that the Office of Civil Defense coordinate with other national organizations in more extensive application of human-factors requirements in fire-fighting equipment design.

Subject Heading: ***Fire fighting, equipment design.***

J. E. Malcolm

Rasbash, D. J. (Joint Fire Research Organization, Boreham Wood, England) "Control of Fires in Large Spaces with Inert Gas and Foam Produced by a Turbo-Jet Engine. Part 1. Introduction and Properties of Inert Gas and Foam," *Joint Fire Research Organization F. R. Note No. 507* (September 1962)

A number of studies have been made during the past two decades with the objective of developing new methods of removing the dense smoke which often makes fire fighting difficult or impossible. The techniques studied have included artificial ventilation, water sprays for washing down smoke, devices for location of objects and sources of heat through smoke, and injection of inert gases to suppress the burning rate. Artificial ventilation, water sprays, and heat source techniques proved impractical except under certain conditions. The use of inert gases did not proceed until 1954 when it was suggested that inert gases with flow rates up to 100,000 cubic feet per minute could be obtained by vaporizing the appropriate quantity of water vapor into the exhaust of a jet engine.

In 1960, Great Britain's Joint Fire Research Organization, with the cooperation of the National Gas Turbine Establishment, constructed a prototype inert gas generator capable of producing 50,000 cubic feet of gas per minute. About the same time, the Safety in Mines Research Establishment developed a method of controlling mine fires through the use of high-expansion foam prepared from detergent solution. It was clear that the jet engine approach could be used to produce high-expansion foam as well as inert gas. It was shown that the use of the inert gas-foam generator could have significantly reduced losses in 32 out of 36 fires about which enough information was known to allow an assessment of the generator's usefulness.

Tests were then run with the jet engine to determine the properties of the inert gas and foam produced. The unit was designed to allow the introduction of air into the generator at a maximum rate of 25 pounds per second. Fuel can be introduced at a maximum rate of 0.83 pound per second. Water at 15°C was sprayed onto the combusted products to reduce the temperature of the exhaust to 120°C. At the maximum fuel–air ratio of 0.033 pound of fuel per pound of air, the inert gas produced by the generator contains 47.5 per cent water vapor, 42.5 per cent N_2, 6 per cent O_2 and 4 per cent CO_2. If the fuel to air ratio entering the generator could be increased to 0.067, the concentration of oxygen in the inert gas would be close to zero. Although the oxygen content of the jet engine exhaust is the most important variable to control, the temperature of the gas, the proportion of CO_2 and water vapor, and the temperature of the combustion zone also have effects on the inerting properties. It has been shown for premixed stoichiometric flames for gases containing water vapor, that a temperature of 1590°K is the minimum required for flame propagation. At this temperature, the maximum allowable oxygen concentration for suppression of combustion is 12.5 per cent. This limitation provides a large safety margin since diffusion flames normally extinguish at higher oxygen concentrations than premixed flames and because many gases have limiting flame temperatures in excess of 1590°K. At a fuel–air ratio of 0.033, which is the maximum that can be introduced into the generator, the product contains 6 per cent oxygen. This would indicate that the inert gas from the generator could be diluted with approximately 70 per cent of its volume of air and still be able to suppress combustion.

The extinction of smouldering combustion depends on both the thickness of the smouldering layer and the nature of the smouldering material. Prolonged exposure to the inert atmosphere may be necessary in many cases to reduce smouldering in

layers 10 to 15 centimeters deep and to reduce the temperature below the point where rapid reignition is possible once the inert atmosphere is removed.

Foam and inert gas have complementary uses. Foam tends to fill buildings from the floor upwards while inert gas tends to fill the building from the ceiling downward. The bubbles inside the foam produced by the inert gas generator have lower oxygen concentrations than foam produced by other methods. Should the water drain out of the foam before it reaches the fire, the gas itself would be sufficiently inert to extinguish combustion in most instances.

A series of tests were made under field conditions to evaluate the operating characteristics of the inert gas generator. These tests are described in later papers.

Subject Headings: ***Fire, control of, by turbojet-produced gas and foam; Foam, generation by turbojet engine; Turbojet engine, foam production by.***

A. L. Goldstein

Rasbash, D. J. (Joint Fire Research Organization, Boreham Wood, England) "Inert Gas Generator for Control of Fires in Large Buildings," *The Engineer* **215,** 978–984 (1963)

In 1960, an inert gas generator based on the Viper jet engine was designed and built by the National Gas Turbine Establishment for Great Britain's Joint Fire Research Organization. The generator produces inert gas, containing as little as 7 per cent oxygen, from raw materials consisting of fuel, air, and water.

Tests were undertaken to determine the ability of the inert gas generator to extinguish fires in barn-like single story buildings and in basement buildings. The jet engine gas generator was mounted on a six-ton truck which carried sufficient kerosene fuel to produce the maximum output of inert gas for 30 minutes. The gas was conveyed to the building using ducting made of synthetic fiber. For a duct of 2.5 ft diam, the velocity of the gas stream produced was 150 ft/sec. Depending on the fire conditions encountered, the inert gas was applied directly to the fire or was converted to high expansion foam by the use of a foaming agent. The generator was able to produce inert gas at rates of 30,000 ft^3/min to 50,000 ft^3/min and foam at rates up to 20,000 ft^3/min.

The inert gas, injected at 110°C into the barn-like building, contained 7 per cent oxygen, 44 per cent water vapor, 46 per cent nitrogen and 3 per cent CO_2. Since the gas was lighter than air, combustion was extinguished first at the roof of the building and then progressively downwards to a plane 4 feet above floor level. At this level the oxygen concentration was too high to permit complete extinguishment. No significant change in the control of the combustion was noted even with dilution of the inert gas with up to 50 per cent of its own volume of air. Ambient temperatures ranged from 60°C at floor level to 95°C near the roof, making it difficult for firemen to enter the building for purposes of extinguishing smouldering combustion.

Tests performed in basements showed that both gas and foam could move easily through a series of rooms and doors to extinguish combustion. Visibility in the basements tended to be poor due to the nature of the foam and to condensation of the water vapor in the inert gas. Inert gas atmospheres containing less than 10 per cent

oxygen proved too hot to allow immediate entry of firemen to extinguish smouldering combustion. However, in areas where foam was applied, firemen utilizing air-breathing apparatus were able to walk on the foam without difficulty.

The tests described above indicate that the use of an inert gas generator can help to bring about more rapid fire control than is attainable with present conventional methods in cases where the fire has not advanced to the point where walls and roof have collapsed. If the appliance were to be put into use in the early stages of a fire, it would prevent both the spread of the fire to other areas as well as further damage to areas already attacked. It could allow more time to get a fire-fighting force together to effect complete fire suppression. In advanced fires where smoke is a problem and the fire-fighting force is already assembled, the generator could be used to eliminate the dense smoke which prevents firemen from reaching the fire, as well as suppressing further combustion.

Several improvements were suggested that may be applied to future efforts on the gas generator apparatus. Work still remains to produce a more transparent gas in which fire fighters can remain for prolonged periods. Further field tests with firemen must also be carried out to gain the experience which can lead to improved definition of the combustion situations where the inert gas generator technique may have application.

Subject Headings: *Gas, generation by turbojet engine; Turbojet engine, gas generation by; Extinguishment, by turbojet-generated gas.*

A. L. Goldstein

Davis, J. B. (Pacific Southwest Forest and Range Experiment Station, Berkeley, California) "Dropping Fire Retardants by Helicopter," *U. S. Forest Service Research Note PSW–27* (1963)

Area covered by a tank load and weight retained per unit area of a standard fuel were tested for four retardants dropped from the following tanks:

Los Angeles County Fire Department — Flat, metal, with interior baffles, variable-width discharge gate, electrical and mechanical controls; capacity 105 gal; attached to landing gear by clamps; cost, $1200.

Meade — Open-topped, metal, rear-end dump; capacity 800 lb; attached to fuselage by struts; cost, $600.

Irvin Air Chute — Vinyl sleeve 7 ft long by 3 ft in diameter; lower end retracted inside itself to form 100-gal bag; discharge by release of retracted end; snapped to bomb shackle; cost, $330, for tank plus release mechanism.

The retardants were plain water and water thickened with CMC (sodium carboxymethylcellulose–7 HSP), algin gel (sodium alginate-Keltex FF plus calcium chloride) and Gel-Guard (synthetic polymer, Dow Chemical Company).

Effective coverage (2 gal or more per 100 ft^2) was greater for 100-gal helitanker drops made from 50–60 ft at 25–40 mph than for 180-gal airplane drops made from 90–100 ft at 100 mph. (Only comparisons with Los Angeles tank are given.) Helitanker coverage patterns were similar in shape to those made by fixed-wing aircraft but were somewhat smaller. Drop accuracy and control of the ground pattern

were best with the Los Angeles tank, somewhat poorer with the Irvin, and poorest with the Meade.

Retention of plain water was best by 30 to 50 per cent for drops made with the Meade tank. However, viscosity agents increased retention up to 9 times for the Los Angeles tank and 16 times with the Irvin, as against only doubling with the Meade.

Helitankers, based close to the fire and serviced by Mobile Equipment such as fire trucks and the Arcadia batch mixer, can fit the operation to the current need. In general, retardant viscosity should be increased and flying speed decreased with increasing coarseness and quantity of fuel. Short flying time, high accuracy, and good ground coverage tend to make cost per effective gallon of retardant lower for helitankers than for fixed-wing air tankers.

Subject Headings: ***Fire retardants, application by helicopter; Helicopter, application of fire retardants.***

G. R. Fahnestock

XIV. Miscellaneous

Perlee, H. E., Liebman, I., and Zabetakis, M. G. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Review of Fire and Explosion Hazards of Flight Vehicle Combustibles," *Aeronautical Systems Division, Wright–Patterson Air Force Base, Ohio ASD Technical Report 61–278, Supplement 2* (April 1963)

This review is the third annual report on the fire and explosion hazards associated with combustibles and other gases likely to be found in aircraft and missile systems. The data on mixing, explosion pressure, venting, and auto-ignition obtained during the past year is summarized.

Homogeneous Mixtures

The ignition of homogeneous mixtures in vented and unvented enclosures is considered. Pressure records for explosions of vented hydrogen–air mixtures show two pressure peaks. The first peak appears to be dependent on the rupturing pressure and vent diaphragm inertia, and the second larger peak on the vent opening size.

Heterogeneous Mixtures

A brief study was made of flames propagating through quiescent heterogeneous combustible–air mixtures. The results indicate that burning velocities at any point depend only on the composition of the gas mixture at that point and are not dependent on the previous history of the flame. It was also found that these velocities are equal to the velocities associated with homogeneous mixtures of corresponding concentrations.

Concentration profiles obtained when methane–air mixtures are permitted to diffuse downward into air were calculated with the aid of an analog computer. A similar calculation was made for pentane–air mixtures diffusing upward into air. Combining this information with explosion limit data, calculated upper and lower limit-of-flammability curves were obtained as a function of diffusion time. Com-

parison of experimental results with calculated data indicate that flammable gas mixture zones resulting from the molecular diffusion of a combustible into air exhibiting large concentration gradients cannot, in general, be predicted *a priori* from diffusion theory. Although the position of flame extinguishment at the lean limit is in general predictable from diffusion theory, the position of extinguishment at the rich limit is not predictable.

The turbulent mixing of two moving fluids was studied and an approximation of the Richardson number was evaluated. The Richardson number represents a ratio of the work done against gravity to that done by the turbulent stresses. If the turbulent stresses are large enough (low Ri number), mixing of the two fluids will occur; otherwise, (large Ri number) a stable layer results. Richardson's number appears to be a valid criterion for mixing processes in flowing stratified systems of natural gas and air, and carbon dioxide and air. Flames associated with flowing stratified systems were found to propagate at speeds considerably greater than those associated with corresponding homogeneous mixtures.

Experiments were conducted on pool fires of gasoline, JP–6 and unsymmetrical dimethylhydrazine (UDMH) in air atmospheres, to determine if such combustion processes could be extinguished by venting to a low pressure environment. Venting a liquid pool fire to a low pressure environment was found to increase the liquid regression rate and the flame size. The more volatile the liquid, the more pronounced the effect. Since a fire in an aerospace vehicle compartment consumes oxygen, generates toxic products, and develops heat and pressure, it was concluded that, to the extent practicable, all flammable fluid storage tanks and lines should be located and routed so as to preclude any possibility of leakage into crew compartments.

Preliminary experiments were conducted to determine the type and magnitude of the effects of a gravitational field on the auto-ignition characteristics of fuel–air systems. Auto-ignition studies of fuel vapor–air mixtures were conducted in spherical heated vessels subjected to radial acceleration fields of 1g and 10g magnitude. Although further work is required to verify these findings, the results do indicate a possible dependence of the auto-ignition on the acceleration field strength.

Subject Headings: *Fire hazards, in flight vehicles; Explosion hazards, in flight vehicles; Hazards in flight vehicles, fire; Hazards in flight vehicles, explosion.*

W. G. Labes

Zabetakis, M. G. and Perlee, H. E. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Compressor and Related Explosions," *Bureau of Mines Information Circular 8187* (1963)

This paper presents a literature survey and an evaluation of current experimental programs pertaining to air-compressor explosions and other high-pressure explosions that result from the ignition of flammable mixtures. Explosions caused by mechanical failure resulting in equipment rupture were not considered.

The survey contains information on the nature of the combustible involved in compressor explosions, possible methods of ignition, and the preventive measures that could be used to eliminate such explosions.

Air-compressor explosions cannot be explained by a single reaction mechanism or sequence of events. Explosion mixtures may be produced in many ways; for example, by the sudden release of large quantities of lubricating oil (as by failure of an oil seal), by rapid vaporization of oil that has accumulated slowly in high-pressure piping, or by the production of decomposition products from carbonaceous products on the inner wall of the discharge piping. The ignition source may be heat-produced in a catalytic reaction (as by iron oxide-rust), heat-produced in a compression process, or a shock wave that propagates through a combustible vapor-air mixture. Several examples of ignition and explosion under various conditions are given to illustrate the above findings.

To determine whether ignition will occur in a specific case, in addition to the properties of the oil, the following factors should be considered.

1. Initial pressure
2. Initial gas temperature
3. Rate of pressure rise
4. Heat-transfer characteristics
   a. Pipe dimension, geometry, and material
   b. Environmental temperature
   c. Gas transport properties
5. Compression ratio

Ignition-pressure curves, calculated from autoignition temperature tests at the Bureau of Mines, for two commercial lubricants are compared with compression-ignition data reported by other investigators. The experimental ignition pressures are found to be higher than those calculated from the autoignition studies. The difference is attributed to heat losses encountered in the compression-ignition studies. The autoignition curves apparently represent the limiting results for compression ignition in very large containers.

To better assess hazards at specific installations, the authors recommend development of analytical expressions that will correlate various factors involved in compression ignition. For this purpose, autoignition temperatures of lubricants should be obtained at operating pressures and then combined with appropriate heat-transfer expressions.

Frequency of ignition can be minimized by establishing proper maintenance and cleaning schedules, by using less flammable lubricants, and possibly by eliminating lubricants from the high-pressure system in a filter or oxidizing by a catalyst.

Subject Heading: ***Explosion, in compressors.***

J. M. Singer

Smith, J. B., Cousins, E. W., and Newman, R. M. (Factory Mutual Research Corporation, Norwood, Massachusetts) "Fire Hazard to Fallout Shelter Occupants: A Classification Guide," *Final Report FMRC No. 15328 for Office of Civil Defense Contract No. OCD–PS–64–40* (April 3, 1964)

A number of buildings in this country have been evaluated by architects and engineers as community shelters against nuclear radiation fallout. The authors

have prepared a Classification Guide for similar use by architects and egnineers to identify the relative safety of fallout shelters from fire.

A very good job has been done in selecting factors for evaluation. The guide was field tested by several architects and a consulting engineer. Trial surveys were made at existing designated shelters in buildings of varied construction, occupancy, and age, in relatively congested areas. Consistent results were obtained.

While the proposed method attempts to make it possible for architects and engineers without particular fire protection engineering background to classify shelters, the contractors properly warn that, for design and improvement of protection, dependence cannot be placed on written general standards. Each situation must be viewed as it exists and specifications worked out for each particular case.

Use of the guide enables classification of shelter areas into four general categories: Class A, B, C, and D. Classes A and B represent reasonably satisfactory safety from fire for the occupants. Classes C and D identify the less desirable locations.

The general approach was to consider the exposure by fire to the people in a shelter from the conditions existing in three areas.

The first of these areas is the space of the shelter structure that is actually occupied by people. The contractors report that the exposure to people from a fire in these spaces was ignored on the grounds that it would be difficult to acquaint an analyst making the survey with all the variables which might need to be considered. The Office of Civil Defense requested that this part of the shelter space not be evaluated specifically on the grounds that it would be continuously occupied and under constant surveillance, and that any fire would be quickly discovered and could be handled by the occupants using manual fire-fighting equipment. This is probably an overly optimistic assumption, but the contractors' point is valid.

For the second area, the shelter structure itself, a method is presented for evaluating the fire conditions found. Analysis of the building is based on accepted fire protection practices. Where the occupancy or construction is combustible, automatic sprinkler protection is indicated as necessary. However, a shelter building which has a combustible roof-deck with a combustible roof covering is an unacceptable situation regardless of whether sprinkler protection is provided or not. A reliable system of water supplies to the automatic sprinkler system and the presence of enclosures for stairways and elevator shafts can be considered to make shelters of combustible construction or occupancy acceptable.

A vacant building, or an occupied building of ordinary hazard, the products, process, packaging or storage of which is noncombustible, with metal furniture and enclosed stairways, would classify Class A.

An occupied building of extra-hazard occupancy would be Class D. So would an occupied building of ordinary hazard with combustible products, process, packaging or storage with no automatic sprinkler protection. The latter building would be Class B if sprinklered with a water supply available in event of public water supply failure and Class C if the water supply is from the public system.

Analyses, similar in general intent, are presented for basements and to evaluate the building construction.

All of this is realistic fire protection engineering, but architects and engineers may have some difficulty adjusting to the extent to which automatic sprinkler protection affects the final classification. Circulation of this Classification Guide will do much to educate engineers and architects who are normally inclined to ignore combustible features of construction and occupancy.

The third area considered is the property external to the shelter building which could expose the shelter building. In normal practice, this factor is handled by fire protection engineers as a matter of judgment. The contractors in this case have provided a guide to evaluating the primary factors which might enter into this outside exposure. Very few papers have been written on the mechanics of exposure, so that this particular part of the report is a useful contribution in this field.

The method requires determining whether the fire load of the exposure is high or low, identifying the exposing building construction, counting the number of stories in the exposing buildings, determining separation distances and the wall lengths of the exposing buildings, lumber piles, or other exposure. Scale diagrams are provided from which the architect or engineer can put these figures together and come up with a rating factor.

The contractors point out that they have not attempted to determine the relative safety of shelters which might be located in a "fire-storm" area. In a great many cases, however, the factors considered in rating exposure will identify the factors present in a fire-storm area.

Subject Heading: ***Fire hazards, in fallout shelters.***

H. Bond

Broido, A. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Some Problems in Fire Research," *Pyrodynamics* **1,** 27–40 (1964)

This paper, based on a lecture presented to the American Institute of Chemical Engineers, 28 November 1962, highlights a number of problems of large-scale fires for which only the most rudimentary and, often, contradictory explanations are possible at this time.

After summarizing some statistics on recent fires in which the energy release exceeds that of several megaton nuclear bombs, attention is drawn to the following problems: the possible modes of air entrainment into a burning city; the meteorological conditions that might lead to "blow-up fires" in forests; the details of trace constituents affecting the burning behavior of common fuels.

The article gives an intriguing glimpse into numerous problems of considerable complexity that deserve the attention of experienced fluid dynamicists and combustion scientists. Only when quantitative relationships can be cited will one feel satisfied that the fire problem is "under control."

Subject Heading: ***Fire research, problems.***

W. G. Berl

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ABSTRACTERS

THOMAS C. ADAMSON, JR.
University of Michigan

GEORGE A. AGOSTON
Stanford Research Institute

JOHN J. AHERN
General Motors Corporation

THOMAS P. ANDERSON
Northwestern University

LOREN E. BOLLINGER
The Ohio State University

PETER BREISACHER
Aerospace Corporation

FREDERICK L. BROWNE
Madison, Wisconsin

GEORGE M. BYRAM
Southern Forest Fire Laboratory
U. S. Forest Service

HANS M. CASSEL
Silver Spring, Maryland

WELBY G. COURTNEY
Reaction Motors Division,
Thiokol Chemical Corporation

OWEN P. CRAMER
Pacific Northwest Forest and Range
Experiment Station
U. S. Forest Service

GLADYS S. CUFF
Royal Oak, Michigan

DANIEL DEMBROW
National Aeronautics and Space Administration

J. H. DIETERICH
Lake State Forest Experiment Station
U. S. Forest Service

G. DIXON-LEWIS
The University, Leeds (England)

R. H. ESSENHIGH
The Pennsylvania State University

GEORGE R. FAHNESTOCK
Southern Forest Experiment Station
U. S. Forest Service

FELIX FALK
Applied Physics Laboratory
The Johns Hopkins University

K. M. FOREMAN
Republic Aviation Corporation

ALLEN E. FUHS
Joint Institute of Laboratory Astrophysics

ARTHUR L. GOLDSTEIN
Ionics, Incorporated

ROBERT A. GORSKI
E. I. duPont de Nemours & Company

BERNARD GREIFER
Atlantic Research Corporation

L. R. GRIFFITH
California Research Corporation

GEOFFREY L. ISLES
The University, Leeds (England)

OLIVER W. JOHNSON
Johnson-Williams, Inc.

WILLIAM C. JOHNSTON
Westinghouse Research Laboratories

IRVING R. KING
Texaco Experiment, Incorporated

WILLIS G. LABES
Illinois Institute of Technology

JOSEPH B. LEVY
Atlantic Research Corporation

RONALD LONG
University of Birmingham (England)

A. S. C. MA
City and Guilds College (England)

JAMES E. MALCOLM
Office of Chief Engineers
U. S. Army

D. G. MARTIN
City and Guilds College (England)

HOWARD N. McMANUS, JR.
Cornell University

ALAN W. McMASTERS
Pacific Southwest Forest and Range Experiment Station
U. S. Forest Service

C. C. MIESSE
General Electric Co.

WILLIAM G. MORRIS
Pacific Northwest Forest and Range Experiment Station
U. S. Forest Service

A. E. NOREEN
Boeing Airplane Company

CLEVELAND O'NEAL, JR.
National Aeronautics and Space Administration

HENRY EDGAR PERLEE
U. S. Bureau of Mines

M. G. PERRY
University of Sheffield (England)

WEE YUEY PONG
Pacific Southwest Forest and Range Experiment Station
U. S. Forest Service

LOUIS A. POVINELLI
National Aeronautics and Space Administration

J. KENNETH RICHMOND
Boeing Airplane Company

DANIEL E. ROSNER
AeroChem Research Laboratories, Inc.

WILLIS A. ROSSER, JR.
Stanford Research Institute

P. R. RYASON
California Research Corporation

R. H. SABERSKY
California Institute of Technology

R. G. SIDDALL
University of Sheffield (England)

JOSEPH M. SINGER
U. S. Bureau of Mines

PHILIP L. START
United Steel Companies Limited (England)

ALEXANDER STRASSER
U. S. Bureau of Mines

K. SUMI
National Research Council (Canada)

CLAUDE P. TALLEY
Texaco Experiment, Incorporated

DONALD L. TURCOTTE
Cornell University

FORMAN A. WILLIAMS
University of California, La Jolla

HENRY WISE
Stanford Research Institute

E. C. WOODWARD
University of South Carolina

RICHARD W. ZIEMER
Electro-Optical Systems, Inc.

E. E. ZUKOSKI
California Institute of Technology