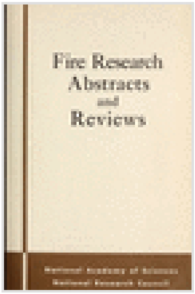

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National Academy of Sciences

National Research Council

FIRE RESEARCH ABSTRACTS AND REVIEWS

Robert M. Fristrom, Editor

The Committee on Fire Research

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

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FOREWORD

In these days of scientific belt-tightening, fire research continues to play the role of orphan. It is too problem-oriented for the academic community and too long-range to be welcomed by the community of applied technology. Beyond the budget squeeze common to most of us, the threat of complete phase-out faces some laboratories. One of these with direct impact on colleagues in the fire field is the scheduled closure this year of the Naval Radiological Defense Laboratory (NRDL) in San Francisco. The fate of the active fire research group at this laboratory is, at present, uncertain. The budgetary reasons behind the closure may have been overriding and the fire research group represents only a small part of this laboratory; but it does seem a pity that the work of an effective group such as this is put in jeopardy by a blanket shut off. Hopefully, as the situation develops, the past record of these fire research workers will be recognized and some method will be found to preserve the continuity of this productive group. Fire research needs a vocal, effective spokesman to point out that its problems do have scientific merit and that fire research programs with long-term, applied goals can be productive. The Committee on Fire Research has revised its *National Fire Research Program.* It is hoped that this will prove to be a persuasive document when it appears.

This issue begins with a penetrating analysis of the parameters important to mass fires and their scaling, by Professor Forman A. Williams of the University of California at San Diego, La Jolla.

Also carried in this issue are a series of authors' conclusions translated from the Russian journal, *Physics of Combustion and Explosion. Fire Research Abstracts and Reviews* will try to obtain abstracts of such articles where complete translations may become available only after several years' delay.

The alert reader will have already noticed several changes in our format. Subject Headings and Abstracter Credits have been advanced to the title block. It is hoped that this will assist the reader in deciding whether to scan or read a particular abstract. It will also aid one in following the work of his favorite abstracter. No index appears in this issue. A complete index will appear in the final issue of the year. The space thus saved will be used to expand the coverage.

Subject Headings, in the "key word" style used in government reports, are briefer. The first index term (in **bold face** type) is the "principal subject" term. This is the word or group of words in the title that most nearly describes the subject. In cases with multiple subjects of equal importance, it will be the term first mentioned in the title. Only this "principal subject" and terms not found in the title will be listed in the title block; but every substantive word in the title will appear in the index. An article can be retrieved from the index providing any term in the title is remembered. Alternate Section assignments will be listed where an article could logically be found in more than one Section.

To improve the selectivity of the projected index, each subject term and author listing will be identified by its principal subject term and section listing. To aid the searcher a Section Index will be added, listing titles for all three issues in order of appearance. Each title will be followed by the principal subject term in **bold face** type; additional subject headings will be listed in *italics* together with related terms and the author listings.

It is hoped that this format will allow a searcher to use the index to retrieve an article or group of articles through subject, section, author, or any word in the title. By reference to the Section Index, from the title and subject heading, the searcher can usually determine whether an article of interest has been located.

If this new format meets with the approval of the readers, we will consider revising the cumulative index.

R. M. Fristrom, *Editor*

REVIEWS

Scaling Mass Fires*

FORMAN A. WILLIAMS

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La Jolla, California

Related Sections: **N**, *G*, *I*

Subject Headings: **Mass fires**; *Dimensionless groups; Fire storms.*

Three possibilities are derived for partial scaling of mass fire phenomena, allowing for variability of atmospheric pressure, atmospheric temperature, atmospheric composition, fuel composition, and force of gravity. One possibility, which necessitates modifying only the atmospheric pressure, scales convection, turbulence, buoyancy, and convectively controlled burning rates, for practically achievable values of the ratio of the full-scale length to model length which may range up to slightly more than one order of magnitude. The most promising technique necessitates controlling both atmospheric pressure and centrifugal acceleration, and it scales convection, turbulence, buoyancy, convectively controlled burning rates, the scale height of the atmosphere, and radiation absorption and scattering lengths, up to practically achievable length ratios of nearly two orders of magnitude. The third technique entails adjusting every variable considered and scales convection, turbulence, buoyancy, radiation, all heat transfer and burning rates, up to a limiting length ratio slightly below one order of magnitude.

1. *Introduction*

Scaling denotes the process of deducing the behavior of a system, usually a large one, by designing and performing experiments on a different system, most often one which is appreciably smaller than the original system of interest. The original system is said to be "full-scale," and the system on which the experiments are performed is termed the model. Scaling is a useful technique in many branches of engineering, since it enables the engineer, by testing and perfecting a model, to develop a workable full-scale system without going to the expense of constructing one. Systems that are amenable to scaling can therefore be analyzed in detail at relatively low experimental cost.

The term "mass fire" as used herein, is intended to connote an otherwise nondescript fire whose size and complexity exceed certain ill-defined magnitudes. The

* This paper is based on Appendix C, "Scaling Mass Fires" (by F. A. Williams), pp. 91–144 of USNRDL-TR-67-150, "Urban Mass Fire Scaling Considerations," by W. J. Parker, OCD Work Unit No. 2536F, 19 Oct. 1967, Naval Radiological Defense Laboratory, San Francisco. Results of the work have been presented in "Three Unconventional Approaches to Scaling of Mass Fires," pp. 106–126 of "Proceedings: Tripartite Technical Cooperation Program Panel N-3 (Thermal Radiation) Mass Fire Research Symposium," DASIAC Special Rept. 59 (DASA 1949), October 1967, Defense Atomic Support Agency Information and Analysis Center, Santa Barbara. This work was supported by the Office of Civil Defense.

best way to attempt to make this vague definition comprehensible is perhaps to give specific examples of fires that do and do not fall in the category. A burning candle is not a mass fire. Neither is a single, small, burning, symmetrical pan of oil, nor a single, burning enclosure of a regular shape. A typical house afire might well be included in the present definition of mass fire. Burning cities and active forest fires would certainly represent mass fires. Stationary fire storms and propagating conflagrations will not be treated here on individual bases, but the mass fires discussed will not be prohibited from exhibiting fire-storm or conflagration characteristics. Thus, an attempt will be made to keep the definition of mass fire as general as possible.

The objective in scaling mass fires is to design small-scale experiments from which characteristics of mass fires can be deduced. This objective can be achieved only by developing *scaling laws* which relate the behavior of the small-scale model to the behavior of a mass fire. Some scaling laws may be precise, mathematical statements, while others may be qualitative observations. The intention of the present theoretical discussion is to investigate scaling techniques which experimentally are more ambitious than those employed in the past. Three unconventional scaling techniques emerge from the study; the three different associated sets of scaling laws will be derived.

It should be emphasized at the outset that all of the scaling laws presented here represent "partial" scaling, in which some of the phenomena that are known to occur are not properly scaled. In a readable review of the subject of scaling, Spalding[1] has emphasized that partial scaling is an art, not a science. Thus, the scaling laws presented herein *might not* properly relate the behavior of the full-scale system to that of the model. Experimental studies of a number of different models and of the degree to which they simulate the full-scale system might ultimately provide a reasonably good picture of the characteristics of the full-scale system that is of interest.

The present study does not address itself either to questions of what to measure in the experimental model or to questions of how to solve theoretical equations that describe the behavior of the model. Attention is restricted to the problem of constructing a model that simulates the full-scale system. Indeed, for a phenomenon so complex as a mass fire, it may be more profitable to isolate parts of the system, such as fire whirls, and to study theoretically and experimentally the dynamics of each part separately, under well-controlled conditions, and perhaps only at full scale. This alternative avenue to modeling is excluded here explicitly; it is for this reason that the participle "scaling" is used instead of "modeling." Since questions of what to investigate in the model are ignored, the present study is essentially incomplete. However, it is so difficult to observe accurately a full-scale mass fire, that the ability to construct a laboratory modeling facility in which a reasonably complete simulation of the entire full-scale phenomenon can be established and observed repeatedly may in itself constitute a profitable advance. Although many specific desirable measurements are already evident to the expert, it may be best to postpone asking in detail what to measure and what to analyze, until after repeated qualitative observations of controlled model fires in a laboratory modeling facility have been accomplished.

2. *Literature*

A very small portion of the massive literature on scaling is concerned with the scaling of mass fires. One reason for this de-emphasis is surely that mass fires are extremely complex phenomena and are therefore likely to present quite formidable scaling problems. Another reason may be that because of the complexity of mass fires, scientifically oriented investigators are likely to believe that more progress toward the understanding of fire phenomena in general, can be achieved by studying simpler fire configurations. Thus, there exists a considerably larger body of experimental research that is related to the scaling of specific, simple types of fires.

Among the experimental studies of simple fires which may have a bearing on the scaling of mass fires are a series of investigations on the mechanisms and rates of burning of liquid pools.[2–11] Spalding[12] has shown that the observed rate of regression of the liquid surface for the largest pools can be explained by assuming that the burning rate is controlled by natural convective heat transfer, even though radiative heat transfer has often been assumed to be dominant in this large-scale, turbulent regime. Spalding's result may provide some physical support for assigning radiation a subordinant role to convection in models of mass fires, as is done in most of the models described herein.

Experimental studies on the burning of cellulosic fuels have in general, been considerably less conclusive than those on liquid-pool burning. Of the very large number of such studies which exist, only those that appear to be most closely related to the scaling of mass fires will be referenced here.[10,13–22] Thus, the large body of information on the ignition of cellulosic materials and on the detailed mechanism of combustion of small cellulosic elements is not cited, except for studies which give special consideration to scaling problems.[13–14] It may be remarked in this regard that if proper scaling laws were known, then the usual technique[14] of decreasing surface areas and keeping thicknesses constant in order to maintain constant burning time might be less desirable than maintaining complete geometrical similarity and accepting changes in burning time as dictated by scaling.

Work on models of propagating fires[15–18] should certainly be relevant to scaling of various aspects of mass fires. However, this work has not yet been able to remove uncertainties concerning conditions under which radiative or convective heat transfer control flame-spread rates in continuous beds of cellulosic fuels, nor are full-scale field data on rates of fire spread sufficiently accurate for use in scaling studies.[23] Therefore there is little experimental basis for initiating studies of the scaling of flame-spread aspects of mass fires.

On the other hand, the experimental data on flame heights, obtained from the model experiments on flame propagation, exhibit a close correspondence with data obtained from stationary fires. There have, in fact, been many laboratory measurements on flame heights for stationary fires in cellulosic fuels.[10,19] Most of these experimental results can be correlated well by various reasonable modifications of buoyant-plume theories.[19] Buoyancy phenomena also influence fire-whirl behavior[20] and large-scale fire behavior;[21] one objective of a current, extensive study[22] of large (up to 50 acres) stationary fires and fire storms is to ascertain the dependence of buoyant plume properties as well as of temperature and velocity fields on fuel-bed size and geometry. These observations of the importance of buoyant plumes in mass fires point up the relevance of theoretical and experimental (e.g., Ref. 24) plume studies on systems that do not necessarily utilize cellulosic fuels.

The importance of plume phenomena has led Byram,[25] in what appears to be the only previous discussion of scaling mass fires, to base his scaling laws entirely on buoyant plume theory. Byram's work appears to provide a useful beginning for the present study, and it will be employed as a point of departure. However, to consider *only* buoyant plumes is certainly a gross oversimplification, as may be inferred from the discussion on scaling given by Hottel.[26] The character of the present work is perhaps more closely related to that of the approach of Hottel than to any other published work on fire.

Neither Byram[25] nor any of the work cited in Refs. 2 to 24 consider adjusting atmospheric conditions in the development of scaling techniques for fires. It has often been suggested informally that better scaling might be achieved by using, for example, a different atmospheric pressure in the model than in the full-scale system. Although such approaches are well-known in attempts to scale other combustion systems,[27] Hottel's paper[26] appears to be the only published reference to procedures of this type for fires. The primary intention of the present work is to explore the possibilities of these scaling techniques and of others that are more sophisticated but also more complex and more expensive.

3. *Dimensionless Groups*

Any approach to the development of mathematical scaling laws entails identifying relevant dimensionless groups constructed from the physical quantities that describe the system. The relative advantages of various means for identifying dimensionless groups have been discussed in the original report on which this paper is based and will not be considered here. The specific approach adopted in the present work was to postulate a set of equations and boundary conditions that are believed to describe the system, with reasonable accuracy, to nondimensionalize these equations and to take note of the dimensionless groups that arise in the nondimensionalization.

Although processes such as heat conduction and finite-rate chemical kinetics occur in condensed phases in mass fires, it was decided that processes occurring in the gas phase are of paramount importance and that therefore the most relevant equations are those of gas dynamics. Condensed-phase processes were included only through boundary conditions. Buoyancy, finite-rate chemical kinetics and radiative transport were included in the gas-phase conservation equations. Since it would be overly ambitious to make the entire set of gas-phase equations statistical, turbulence was included only in an heuristic manner by introducing effective turbulent transport fluxes into the species, momentum and energy conservation equations with the intention that each turbulent flux term encompass all turbulent phenomena that affect the corresponding equation. Equations governing multiphase flows[29] were not introduced, since it was felt that undue complications would be caused by the additional parameters such as particle-size distributions which would arise; the view was taken that there may exist a critical particle size below which the presence of condensed phases can be neglected in the conservation equations and above which it is reasonable to account for the presence of condensed materials through boundary conditions. Instead of writing explicitly the boundary conditions for the conservation equations, use was made of physical arguments to infer what parameters would enter through boundary conditions. Certainly not all potentially relevant boundary conditions were taken into account. Nevertheless, a set of 29 types of dimensionless groups was identified, thereby providing a much more thorough description of mass fires than has been sought previously.

In Table 1 is listed the set of nondimensional integrodifferential conservation equations that was obtained. Nomenclature is defined in the List of Symbols, and the dimensionless π groups that appear are defined in Table 2. In the order in which they appear, the equations given in Table 1 express conservation of mass, conservation of momentum, conservation of energy, conservation of chemical species,

TABLE 1.
Nondimensional Equations.

$$\pi_0(\partial\hat{\rho}/\partial\hat{t})+\hat{\nabla}\cdot(\hat{\rho}\hat{\mathbf{v}})=0$$

$$\pi_0(\partial\hat{\mathbf{v}}/\partial\hat{t})+\hat{\mathbf{v}}\cdot\hat{\nabla}\hat{\mathbf{v}}=-(\pi_1/\pi_3)(\hat{\nabla}\hat{p}/\hat{\rho})+(1/\hat{\rho})\hat{\nabla}\cdot\hat{\tau}+\pi_2\hat{\mathbf{g}}$$

$$\pi_0(\partial/\partial\hat{t})[\hat{h}+\pi_3(\hat{v}^2/2)]+\hat{\mathbf{v}}\cdot\hat{\nabla}[\hat{h}+\pi_3(\hat{v}^2/2)]=\pi_1(1/\hat{\rho})(\partial\hat{p}/\partial\hat{t})-(1/\hat{\rho})\hat{\nabla}\cdot\hat{\mathbf{q}}$$
$$+\pi_3(1/\hat{\rho})\hat{\nabla}\cdot(\hat{v}\cdot\hat{\tau})+\pi_3\pi_2\hat{\mathbf{v}}\cdot\hat{\mathbf{g}}+\pi_3\pi_2\sum_{i=1}^{N}Y_i\hat{\mathbf{V}}_i\cdot\hat{\mathbf{g}}$$

$$\pi_0(\partial Y_i/\partial\hat{t})+\hat{\mathbf{v}}\cdot\hat{\nabla}Y_i=(\hat{w}_i/\hat{\rho})-(1/\hat{\rho})\hat{\nabla}\cdot(\hat{\rho}Y_i\hat{\mathbf{V}}_i),\qquad i=1,\cdots,N$$

$$\mathbf{\Omega}\cdot\hat{\nabla}\hat{I}_\nu=\pi_4\hat{\rho}\hat{\kappa}_\nu(\hat{B}_\nu-\hat{I}_\nu)+\pi_5\hat{\rho}\oiint\hat{\sigma}_\nu(\hat{I}_\nu'-\hat{I}_\nu)\,d\Omega'$$

$$\hat{\tau}=\pi_6\hat{\mu}[(\hat{\nabla}\hat{\mathbf{v}})+(\hat{\nabla}\hat{\mathbf{v}})^T-\tfrac{2}{3}\hat{\nabla}\cdot\hat{\mathbf{v}}U]+\pi_7\hat{\tau}_T$$

$$\hat{\mathbf{q}}=-\pi_6\pi_8\hat{\lambda}\hat{\nabla}\hat{T}+\hat{\rho}\sum_{i=1}^{N}\hat{h}_iY_i\hat{\mathbf{V}}_i+\pi_9\hat{\mathbf{q}}_T+\hat{\mathbf{q}}_R$$

$$\hat{\mathbf{q}}_R=\pi_{18}\int_0^\infty\oiint\hat{I}_\nu\mathbf{\Omega}\,d\Omega\,d\hat{\nu}$$

$$\hat{\nabla}X_i=\pi_6\sum_{j=1}^{N}\pi_{10ij}(X_iX_j/\hat{D}_{ij})(\hat{\mathbf{V}}_j-\hat{\mathbf{V}}_i-\pi_{11j}\hat{\mathbf{V}}_{jT}+\pi_{11i}\hat{\mathbf{V}}_{iT}),\qquad i=1,\cdots,N$$

$$\hat{w}_i=\pi_{12i}\sum_{k=1}^{M}(\nu_{ik}''-\nu_{ik}')\pi_{13k}\hat{A}_k\exp(-\pi_{14k}/\hat{T})[\prod_{j=1}^{N}(X_j\hat{p}/\hat{T})^{\nu_{jk}'}$$
$$-\pi_{15k}\hat{K}_{ck}\prod_{j=1}^{N}(X_j\hat{p}/\hat{T})^{\nu_{jk}''}],\qquad i=1,\cdots,N$$

$$\hat{p}=\hat{\rho}\hat{T}\sum_{i=1}^{N}(Y_i/\pi_{12i})$$

$$\hat{h}=\sum_{i=1}^{N}\hat{h}_iY_i$$

$$\hat{h}_i=\pi_{16i}+\pi_{17i}\int_{\hat{T}^0}^{\hat{T}}\hat{c}_{pi}\,d\hat{T}$$

$$X_i=(Y_i/\pi_{12i})/\sum_{j=1}^{N}(Y_j/\pi_{12j})$$

$$\hat{B}_\nu=(15/\pi^5)[\exp(\hat{\nu}/\hat{T})-1]^{-1}\hat{\nu}^3$$

TABLE 2.
Dimensionless Groups Relevant to Scaling of Mass Fires.

Dimensionless Group	Physical Meaning
$\pi_0 = L/Vt_b$	A measure of the flow-field unsteadiness caused by factors other than turbulence.
$\pi_1 = p_a/\rho_a c_{pa} T_a$	A measure of the ratio of specific heats, γ.
$\pi_2 = gL/V^2$	A buoyancy quantity related to reciprocal Froude number, Fr (and therefore related to Grashof number, Gr, through Reynolds number).
$\pi_3 = V^2/c_{pa}T_a$	A quantity proportional to the square of the Mach number, M, and related to the scale height of the atmosphere through π_1 and π_2.
$\pi_4 = L\rho_a \bar{\kappa}_\nu$	Ratio of characteristic dimension to radiation absorption length.*
$\pi_5 = L\rho_a \bar{\sigma}_\nu$	Ratio of characteristic dimension to radiation scattering length.*
$\pi_6 = \mu_a/\rho_a VL$	Reciprocal of the Reynolds number, Re.
$\pi_7 = \bar{\tau}_T/\rho_a V^2$	Ratio of effective turbulent stress to dynamic pressure.
$\pi_8 = \lambda_a/\mu_a c_{pa}$	Reciprocal of the Prandtl number, Pr.
$\pi_9 = \bar{q}_T/\rho_a V c_{pa} T_a$	Ratio of effective turbulent heat flux to rate of convection of enthalpy.
$\pi_{10ij} = \mu_a/\rho_a D_{ija}$	Schmidt number, Sc_{ij}, for species pair i, j.
$\pi_{11i} = \bar{V}_{iT}/V$	Ratio of effective turbulent diffusion velocity to characteristic velocity.
$\pi_{12i} = m_i p_a/\rho_a R' T_a$	Ratio of molecular weight of species i to molecular weight of ambient air.
$\pi_{13k} = (LA_{ka}/V)(R'T_a/p_a)^{\left(\sum_{i=1}^{N} \nu_{ik}' - 1\right)}$	Ratio of flow time to chemical time for reaction k; reciprocal of Damkohler's first similarity group D_I for reaction k.
$\pi_{14k} = (E_k/R'T_a)$	Dimensionless activation energy for kth reaction.

TABLE 2. (Cont'd)

Dimensionless Group	Physical Meaning
$\pi_{15k}=K_{cka}(p_a/R'T_a)^{\left[\sum_{i=1}^{N}(\nu_{ik}''-\nu_{ik}')\right]}$	Dimensionless equilibrium constant for kth reaction.
$\pi_{16}=Q/c_{pa}T_a$	Dimensionless gas-phase heat of combustion; a simplification of π_{16i}.
$\pi_{16i}=h_i^0/c_{pa}T_a$	Ratio of enthalpy of formation of species i to ambient thermal enthalpy.
$\pi_{17i}=c_{pia}/c_{pa}$	Ratio of specific heat of species i to specific heat of ambient atmosphere.
$\pi_{18}=\sigma' T_a^3/\rho_a V c_{pa}$	Ratio of blackbody radiation flux to rate of convection of enthalpy.
$\pi_{19\alpha}=L_\alpha/L$	Ratios of lengths specifying terrain, fuel size and location (e.g., building density, firebreaks, etc.) to characteristic length.
$\pi_{20}=W/\rho_a V t_b$	Ratio of time-average mass burning rate per unit ground area to convective mass flux (fuel loading–burning time group).
$\pi_{21l}=Y_l$	Dimensionless fuel composition parameters reflecting fuel type, moisture content, building construction, building contents, etc.
$\pi_{22l}=c_l/c_{pa}$	Dimensionless heat capacities for fuel constituents.
$\pi_{23l}=T_l/T_a$	Dimensionless gasification temperatures for fuel constituents.
$\pi_{24l}=\Delta h_l/c_{pa}T_a$	Dimensionless heats of gasification for fuel constituents.
$\pi_{24'}=[c_l(T_l-T_a)+\Delta h_l]/c_{pa}T_a$	Effective dimensionless total heat required to gasify a unit mass of fuel; a simplification of π_{22l}, π_{23l} and π_{24l}.
$\pi_{25i}=Y_{ia}$	Dimensionless ambient atmospheric composition parameters (e.g., humidity).

TABLE 2. (Cont'd)

Dimensionless Group	Physical Meaning
$\pi_{26}=\mathrm{v}_w/V$	Dimensionless ambient wind velocity.**
$\pi_{27}=\Gamma L/V$	Dimensionless ambient atmospheric circulation.**
$\pi_{28}=T_a'/T_{ad}'$	Dimensionless ambient atmospheric lapse rate parameter determining atmospheric stability.**

* For each of these quantities it is better to specify a distribution (over radiation frequency) than to specify merely a single number.

** For each of these quantities it is better to specify a distribution (over position in the ambient atmosphere) than to specify merely a single number.

radiation transport, viscous stress formula, total heat flux formula, radiative heat flux formula, diffusion law, chemical reaction rate law, equation of state, caloric equation of state, relationships between mass fractions and mole fractions, and Planck formula. Among the specific and reasonable assumptions that have been introduced in these equations are the steady-state and local thermodynamic equilibrium approximations for radiative transfer and neglect of bulk viscosity, thermal diffusion, pressure-gradient diffusion, radiation pressure, radiation energy density, induced emission, and Compton scattering. The equations, with relevant boundary conditions, are presumed to determine the $\hat{\mathrm{x}}$ and $\hat{t}$ dependences of $\hat{p}$, $\hat{\rho}$, $\hat{\mathrm{v}}$, $\hat{T}$, $\hat{h}$, $\hat{h}_i$, X_i, Y_i, $\hat{I}_\nu$, $\hat{B}_\nu$, $\hat{\tau}$, $\hat{\mathrm{q}}$, $\hat{\mathrm{q}}_R$, $\hat{\mathrm{V}}_i$ and $\hat{w}_i$, when the constant π's, the vector $\hat{\mathrm{g}}$ and the functions $\hat{\kappa}_\nu(\hat{T}, X_i)$, $\hat{\sigma}_\nu(\hat{T}, X_i)$, $\hat{\mu}(\hat{T}, X_i)$, $\hat{\lambda}(\hat{T}, X_i)$, $[\hat{\rho}\hat{D}_{ij}](\hat{T})$, $\hat{c}_{pi}(\hat{T})$, $\hat{K}_{ck}(\hat{T})$, $\hat{A}_k(\hat{T})$, $\hat{\tau}_T$, $\hat{\mathrm{q}}_T$ and $\hat{V}_{iT}$ are known. The proper functional dependences are indicated here for all gas properties except the last three; functional dependences are not known for the turbulent fluxes. It was deemed undesirable to introduce additional π parameters describing the functional dependences of the eleven types of gas properties.

The dimensionless groups π_0 through π_{18} arise from the equations themselves, while the groups π_{19} through π_{28} are introduced through boundary conditions. Groups π_{19} through π_{24} are associated with fuel elements, while π_{25} through π_{28} are associated with the ambient atmosphere. The groups π_{19}, π_{20} and π_{21} may affect boundary conditions for all conservation equations; π_{22}, π_{23} and π_{24} primarily affect boundary conditions for the energy conservation equations. Possible influences of such secondary properties as condensed-phase thermal conductivities and surface emissivities have been ignored. Atmospheric parameters, particularly π_{28}, are discussed in Appendix A.

4. *Selection of Basic and Core Groups*

Clearly it would be a formidable task for an experimenter to construct a model in which the 29 types of dimensionless groups that we have defined possess the same values as in a full-scale mass fire. Therefore there exists an incentive to identify a subset of these groups which seems to be most important. A reasonable subset appears to be

$$\pi_2,\ \pi_4,\ \pi_6,\ \pi_{16},\ \pi_{18},\ \pi_{19\alpha},\ \pi_{20},\ \pi_{24'},\ \pi_{26},\ \pi_{27},\ \pi_{28}, \tag{1}$$

which will be termed the basic set of groups. The basic set contains geometrical similarity groups ($\pi_{19\alpha}$), a buoyancy group (π_2), a Reynolds number (convection) group (π_6), two radiation groups (π_4 and π_{18}), a gas-phase heat release group (π_{16}), a fuel gasification energy group ($\pi_{24'}$), a fuel loading or burning rate group (π_{20}), and finally three ambient atmosphere parameter groups (π_{26}, π_{27}, π_{28}) which are not likely to introduce severe scaling problems because the experimenter can vary v_w, Γ, and T_a'. The seven groups π_2, π_4, π_6, π_{16}, π_{18}, π_{20}, and $\pi_{24'}$ all appear to be of such critical importance that they should not be ignored; they form a core subset of the basic set and (since V and t_b are "determined" by the physics) provide the experimenter with five scaling instructions that are exceedingly difficult to follow simultaneously.

The motivation for adopting the basic set (1) involves a detailed study of Table 2 and can be accorded lengthy discussion:

The unsteadiness group π_0 has been omitted because the equations in Table 1 imply that terms involving π_0 are small if π_0 is small and because numerical estimates ($t_b \geq 20$ min, $V \gtrsim 20$ ft/sec) indicate that $\pi_0 \ll 1$ unless L is very large ($L \gtrsim 5$ miles). Physically, to neglect π_0 is equivalent to treating the fluid dynamics as being quasi-steady and is likely to be a better approximation for stationary fires than for propagating crown fires or blowup fires.

The thermodynamic groups π_1, π_{12} and π_{17} as well as the molecular transport property groups π_8 and π_{10} have been omitted on the grounds that it is difficult to change their values very greatly, so that scaling techniques are not likely to introduce significant variations in these groups even if they are ignored.

The Mach number group π_3 has been omitted with the realization that the scale height of the atmosphere then will not be modeled properly (see Appendix A). However, the second and perhaps the most promising scaling technique that we shall describe fortuitously maintains π_3 constant.

The radiation scattering group π_5 has been omitted through the observation that the scattering coefficient is roughly the same kind of parameter as a radiation absorption coefficient and that therefore only one group of this type, π_4, need be retained. We shall in fact associate only one number with π_4 and shall therefore neglect the frequency dependences of the absorption and scattering coefficients. This stringent approximation may not be too poor when absorption and scattering are produced principally by small solid particles.

The turbulence groups π_7, π_9 and π_{11} have been omitted on the assumption that they are determined by other groups (π_2 and π_6) that have been retained and therefore automatically should remain approximately constant.

In omitting the chemical kinetic groups π_{13} and π_{14} we have introduced a significant simplification that tends to make the fire scaling problem easier than other combustion scaling problems. The mathematical justification for neglecting these groups in mass fires is that as L increases π_{13} increases and eventually causes the quantity in square brackets in the equation for $\hat{w}_i$ of Table 1 to approach zero in order to prevent $\hat{w}_i/\hat{\rho}$ from becoming much larger than any other term in the species conservation equation. Physically, in large fires there is enough time for the reactive gases to reach chemical equilibrium, so that simple diffusion-flame approximations can be employed and mixing processes control heat release rates. It should be emphasized that this approximation can be true only in an average sense since kinetics will be important in the burning of smaller fuel elements.

The group π_{15} has been omitted on the assumption that it will not change significantly in scaling because chemical equilibria will always favor reaction products (e.g., CO_2 and H_2O) in the gas. However, scaling techniques that involve large changes in pressure, for example, will eventually violate this assumption.

The single group related to heats of formation π_{16} is retained in place of π_{16i} on the assumption that only one representative type of gaseous fuel need be considered. The value of Q in π_{16} is an average upper heat of combustion that may differ somewhat from handbook values since it pertains to initially existing fuel and atmospheric conditions (e.g., water content).

The groups π_{21l} are omitted on the grounds that the fuel composition is directly relevant only insofar as it affects other parameters and on the assumption that the fuel is sufficiently homogeneous for other parameters that have been retained (π_{16}, π_{19}, π_{20}, $\pi_{24'}$) to suffice in describing the fuel. This same argument is used for replacing the fuel-property groups π_{22}, π_{23} and π_{24} by the single group $\pi_{24'}$; thus, it is assumed that such fuel parameters as the surface temperature per se are less important than the total energy that must be transferred to the fuel to cause gasification. The atmospheric composition groups π_{25i} are also omitted on the assumption that they are pertinent only insofar as they influence retained groups such as π_{16}.

The primary objective of the preceding discussion has been to demonstrate that numerous approximations are involved in arriving at a simplified set of five scaling instructions that are most reasonable physically but that still are considerably more demanding than the scaling techniques that have been investigated previously.

5. *Standard Scaling Technique*

The approach to model design is to select some groups from the core subset and to keep these groups constant in scaling. The less control an experimenter has over his model, the fewer groups he will be able to select. Since selection of different sets of groups leads to different scaling laws, it is clear that many widely differing scaling experiments can be designed by experimenters with limited model control. The recognized importance of buoyancy has usually led to the selection of π_2 and, in order to maintain a constant buoyancy strength, π_{20}. When model experiments are performed in normal sea level air under standard gravitational acceleration (the "standard" technique), this approach causes values of the core groups π_4, π_6 and π_{18} and of the geometrical groups $\pi_{19\alpha}$ in the model to differ from those in the full-scale system, thereby violating proper scaling of radiation, convection, turbulence characteristics, fuel-bed geometry, and heat transfer rates. It might be said that in this approximation one is studying only a buoyant plume, and it is not clear that the fire or its behavior is of any significance other than acting as a buoyancy source. In order to improve upon this state of affairs, it is necessary to provide greater control over the model.

6. *Scaling Technique Involving Pressure Adjustment*

One approach to achieving greater control is to carry out the model tests inside a pressure chamber. If conditions inside such a chamber are to correspond to free-burning fire conditions, then the chamber volume must be much larger (typically by a factor of 10^4) than the total volume of the fuel that is to be burned. Therefore a large chamber would be required.

The ability to vary the ambient pressure provides the experimenter with one additional controlled variable. Changes in pressure are not expected to affect the groups π_{16} or $\pi_{24'}$ appreciably; thus, the advantage of constancy of these two groups is shared by the standard technique and by techniques using pressure variation. Furthermore, pressure changes alone do not affect π_1, π_8, π_{10ij}, π_{12i}, π_{14k}, π_{16i}, π_{17i}, π_{22l}, π_{23l}, π_{24l} and π_{25i}; the only type of group that is maintained constant by the standard technique but not when pressure varies is π_{15k}. Thus, the experimenter does not pay much of a penalty in the background similarity groups by varying p_a. On the other hand, he can use this variability in many different ways to provide better scaling of groups in the core set. We shall discuss one of the possibilities after pointing out certain general properties of three members of the core set, π_4, π_6 and π_{18}.

First, one can see that simultaneous scaling of both of the radiation groups π_4 and π_{18} requires* that $p_a \sim L^{-1}$ and can be achieved only if it is possible to make $V \sim L$. Since it appears that this last condition would be difficult to achieve, we may conclude that complete radiation scaling is likely to be unattainable through size and pressure adjustments alone (except possibly for highly opaque flames in which the parameter π_4 may be unimportant). Furthermore, simultaneous radiation and convection scaling cannot be obtained through the technique under discussion. One can, in fact, see quite directly that π_6 (the parameter that is probably most closely related to turbulence characteristics and to convective heat transfer) and the radiation parameter π_{18} cannot both remain constant unless a highly sophisticated approach to the scaling problem is adopted. If π_6 and π_{18} are constant, then their ratio

$$\pi_{18}/\pi_6 = L(\sigma' T_a^3/\mu_a c_{pa}) \tag{2}$$

will also be constant, but since the factor multiplying L depends only on temperature and on physical properties of the system, any change in L necessitates a change in either T_a or physical properties, in order to keep the ratio constant. Thus, simultaneous scaling of radiation and convection will not be achievable in either of the two simpler approaches that we shall discuss.

Let us assume that complete geometrical similarity is imposed ($\pi_{19\alpha}$ constant). The variability of pressure can then be used to maintain the buoyancy group π_2 constant. This produces the standard scaling law $V \sim L^{1/2}$, and it implies that $\pi_4 \sim L p_a$, $\pi_6 \sim L^{-3/2} p_a^{-1}$, $\pi_{18} \sim L^{-1/2} p_a^{-1}$ (π_{16}, $\pi_{24'}$ constant). In general, it is not clear how p_a should be varied in order to keep π_2 constant. One can argue, as suggested earlier, that constancy of π_2 is to be achieved by making a buoyancy source strength group constant, which in turn is achieved by making a burning-rate group (π_{20}) constant. Since π_{20} is expected to depend on the groups related to heat transfer, π_4, π_6, π_{18} (and $\pi_{19\alpha}$, which is constant here), one may then infer that in general some

* The result cited here relies on the hypothesis that $\bar{\kappa}_\nu$ is unaffected by pressure, an assumption which is difficult to verify from fundamentals because a very large number of parameters like $\bar{\kappa}_\nu$ would appear in a proper formulation. The rough manner in which $\bar{\kappa}_\nu$ was introduced imparts a pressure and temperature dependence to this quantity and makes both of these dependences exceedingly difficult to estimate. The pressure exponent of $\bar{\kappa}_\nu$ is not apt to be large, and we assume throughout the scaling discussion that it is zero.

combination of π_4, π_6 and π_{18} would have to be kept constant in order to maintain π_2 constant. Physically, a decrease in the convective heat transfer caused by a change in π_6, can be offset by an increase in the radiative transfer caused by changes in π_4 and π_{18}.

If the burning rate π_{20} is controlled entirely by convective effects, then in order to keep π_2 constant, it should be sufficient to maintain π_6 constant. This would lead to the scaling instruction $p_a \sim L^{-3/2}$ and would imply that the only varying core groups behave as $\pi_4 \sim L^{-1/2}$ and $\pi_{18} \sim L^{1/2}$, a result which might conceivably lead to little change in overall radiative heat-transfer rates over a limited range of opacity. On the other hand, if π_{20} is controlled entirely by radiative effects, then one might want to keep either π_4 or π_{18} constant. It is not clear which of these two radiation groups is of greatest importance; Spalding[1] introduces only π_{18}, but Hottel[26] stresses the importance of π_4. If π_4 is selected, we obtain the instruction $p_a \sim L^{-1}$ and produce the variations $\pi_6 \sim L^{-1/2}$, $\pi_{18} \sim L^{1/2}$; if π_{18} is selected, we obtain the instruction $p_a \sim L^{-1/2}$ and produce the variations $\pi_4 \sim L^{1/2}$, $\pi_6 \sim L^{-1}$. Perhaps an intermediate power variation $p_a \sim L^{-n}$ $(0.5 \leq n \leq 1)$ would scale the overall radiative heat-transfer phenomena that contribute to π_{20}; at any rate, we are not able to achieve truly correct radiation scaling by the present technique.

From these various considerations, it appears that

$$L_a \sim L, \qquad p_a \sim L^{-3/2} \tag{3}$$

may well be physically the most desirable set of scaling instructions for techniques in which the pressure is permitted to change. This variation cannot scale detailed radiative phenomena and can scale overall radiative phenomena only fortuitously, at best. However, for systems in which the burning rate is convectively controlled, this variation is expected to produce proper scaling for the burning rate group (π_{20}), for the buoyancy group (π_2), for the Reynolds number (convective heat transfer) group (π_6), and therefore probably also for the various turbulence phenomena. So many of the complete set of dimensionless groups are expected to be kept constant in this way that it is shorter to list those which are not: π_0, π_3, π_4, π_5, π_{13k}, π_{15k}, π_{18}. Various scaling laws and instructions that would apply are:

$$\begin{array}{lll} V \sim L^{1/2}, & W \sim L, & \text{burning rate} = W/t_b \sim L^{-1}, \\ t_b \sim L^2, & H \sim L, & v_w \sim L^{1/2}, \\ \Gamma \sim L^{-1/2}, & T_a' \sim \text{const}, & T_a \sim \text{const}, \\ \rho_a \sim L^{-3/2}, & Y_{ia} \sim \text{const}, & Y_l \sim \text{const}, \\ T_l \sim \text{const}, & Pr \sim \text{const}, & Sc_{ij} \sim \text{const}, \\ \bar{\tau}_T \sim L^{-1/2}, & \bar{q}_T \sim L^{-1}, & \bar{V}_{iT} \sim L^{1/2}. \end{array} \tag{4}$$

Unfortunately, Eq. (3) calls for sizable pressure increases in going to small models. For example, to scale a fire one mile in diameter down to one 50 ft in diameter by this rule would require use of 1000 atm pressure in the model experiment.* Aside from expense, pressures this high would produce deterioration of scaling by bringing in effects that have not been discussed here (e.g., condensation, shifts in gas-phase

* The pressure requirements for the partial radiation scaling discussed in this section are considerably less severe.

chemical equilibria). Nevertheless, scaling of a 50-ft fire to one 5 ft in diameter by going to 30 atm pressure in the model, may be an example of a reasonable undertaking based on this technique.

7. *Scaling Technique Involving Pressure and Body-Force Adjustments*

The magnitude of the acceleration vector **g**, operative during burning, can be increased in the model by placing the model fire at the end of an arm of a spinning centrifuge. To avoid unwanted convective currents it would still be necessary to enclose the fire in a chamber whose dimensions are large compared with the size of the fuel bed. Provision may be made to adjust the pressure in the chamber. The chamber must subtend a small azimuthal angle from the center of rotation to assure that the **g** vector will be parallel throughout the chamber. A long centrifuge arm and a low angular velocity are desirable for minimizing spurious Coriolis effects; specifically, the angular velocity of the centrifuge must be small compared with representative gradients of the components of gas velocity perpendicular to **g** in the chamber.

The quantities π_2 and π_{28} are the only members of the complete set of dimensionless groups which are affected by the value of g. The group π_{28} can be made invariant by adjusting T_a'. Consequently, the logical way to use a variable g in scaling is first to perform scaling by completely disregarding π_{28} and the buoyancy effects, then to adjust g in such a way that buoyancy scales correctly, and finally to adjust T_a' for proper scaling of the lapse rate. The first step is complicated; the second and third are conceptually simple. It is clear from the discussion in the preceding section that neither simultaneous scaling of convection and radiation nor complete radiation scaling can be achieved here.

Among the many scaling approaches that can be discussed, let us enforce complete geometrical similarity and assume that the burning rate is controlled by convection. At constant pressure, constancy of π_6 requires that $V \sim L^{-1}$, and consequent constancy of π_{20} implies that the burning rate, $W/t_b \sim L^{-1}$. The requirement on g dictated by constancy of π_2 is the scaling instruction

$$g \sim L^{-3}, \tag{5}$$

and the requirement on T_a' for constancy of π_{28} can be shown to be the instruction

$$T_a' \sim L^{-3},$$

since T_{ad}' is proportional to g. The result shown in Eq. (5) indicates that a severely limited range of scaling of this type is achievable in practice; 1000-g acceleration is required to scale a 50-ft fire to a fire 5 ft in diameter.

Permitting controllable ambient pressure enables us to keep the radiation group π_4 constant as well. This technique would lead to the scaling laws $V \sim$constant and $W/t_b \sim L^{-1}$ and to the scaling instructions

$$p_a \sim L^{-1}, \quad g \sim L^{-1}, \quad v_w \sim \text{const},$$
$$\Gamma \sim L^{-1}, \quad T_a \sim \text{const}, \quad T_a' \sim L^{-1}. \tag{6}$$

The result is a substantial reduction in the severity of the acceleration requirement (e.g., only 10 g's are needed for scaling a 50-ft fire to 5 ft) and also a reduction in the severity of the pressure requirement discussed in the preceding section (e.g., only 10 atm pressure are needed in the model for scaling from 50 ft to 5 ft). Since this approach produces invariance of π_3, π_4 and π_5* in addition to invariance of the many parameters indicated at the end of the preceding section, the technique seems to be quite appealing. The only members of the complete set of groups which are not properly scaled by this technique are π_0, π_{13k}, π_{15k} and π_{18} (viz., transient fluid dynamics, chemical reaction rates, chemical equilibria, and the radiative energy flux). The only unscaled member of the core set is $\pi_{18}(\sim L)$.

8. *Scaling Technique Involving Adjustment of the Composition and Temperature of the Ambient Atmosphere*

The technique to be discussed here cannot produce as complete scaling, in terms of total number of groups properly scaled, as does the technique described at the end of the preceding section. The atmospheric properties and fuel properties whose variations will be discussed affect many members of the complete set of dimensionless groups that have been defined. The reason for investigating property variations is that they might provide greater control over the core set of groups.

Variation of atmospheric composition by oxygen enrichment or by addition of inerts affects π_{16} substantially and also affects the core groups π_4, π_6, π_{18} and $\pi_{24'}$. It is not desirable to change π_{16} because many aspects of fire behavior depend on the amount of gas-phase heat release.† Therefore changes in atmospheric composition should be accompanied by changes in atmospheric temperature that are adjusted to keep π_{16} fixed. Conversely, any change in T_a should be accompanied by an atmospheric composition change which serves to maintain π_{16} constant. Thus, oxygen enrichment should accompany an increase in T_a, and oxygen depletion should accompany a decrease in T_a.

If T_a is changed, then some modification in fuel properties probably is desirable in order to maintain $\pi_{24'}$ fixed. This complication raises doubt concerning the utility of any variations of atmospheric properties other than pressure. Nevertheless, it may be worthwhile to consider adjusting T_a, because Eq. (2) implies that this is probably the only way that simultaneous scaling of radiation and convection can be achieved.

Let us consider first the possibilities for "complete" radiation scaling, under the assumption that radiative heat transfer controls the burning rate. By looking at the product $\pi_4\pi_{18}$, we see that radiation scaling requires $\sigma' T_a^3 \bar{\kappa}_\nu / c_{pa} V \sim L^{-1}$, i.e., $T_a^{3+m}/V \sim L^{-1}$, where m is essentially the temperature exponent of $\bar{\kappa}_\nu$. Complete radiation scaling also requires constancy of π_4, which implies that $T_a^m \rho_a \sim L^{-1}$. To

* We assume that $\bar{\kappa}_\nu$ and $\bar{\sigma}_\nu$ are independent of p_a.

† It is conceivable that the atmospheric composition can be changed in such a way that the total amount of gas-phase heat release per unit mass of fuel consumed is constant. One way to do this is to change the fuel from oxygen to something else, but such a replacement is likely to produce many similarity-destroying chemical effects (changes in K_{ck}, $\bar{\kappa}_\nu$, etc.). A simpler way is to replace some or all of the nitrogen by another inert and perhaps to change the inert/oxygen ratio slightly in order to compensate for any influence of change in heat capacity on effective heat release. The only appreciable influences of the inert substitution appear to be changes in the transport coefficients and in the mean molecular weight. Effects that are largest in magnitude are obtained by substituting light gases such as He, which decrease ρ_a and increase μ_a and λ_a. These variations appear to be in the wrong direction to be beneficial in scaling. The simple procedure of varying only the oxygen/nitrogen ratio, as considered in the main text, exerts negligibly small effects on the density, transport properties, and heat capacity of the atmosphere.

proceed further, we must consider what process controls V. The most reasonable V-controlling process is buoyancy, and therefore, at constant g, $V \sim L^{1/2}$. This yields $T_a^{3+m} \sim L^{-1/2}$. This dependence is consistent with the simultaneous constancy of π_{18} and π_{20} only if $W/t_b \sim \sigma' T_a^3/c_{pa} \sim T_a^3 \sim L^{-3/(6+2m)}$, which is the resulting scaling law for the burning rate. It is also consistent with the constancy of π_4 only if $\rho_a \sim T_a^{6+m}$, which is not apt to be consistent with an assumption of constant atmospheric pressure. Thus, in order to achieve complete radiation scaling at constant g, one must adjust the pressure and the temperature in the manner

$$p_a \sim L^{-(7+m)/(6+2m)}, \qquad T_a \sim L^{-1/(6+2m)}. \tag{7}$$

Since it is very difficult to estimate m, it is not clear whether this requires p_a and T_a to increase or decrease in scaling. If $m=0$, we find $p_a \sim L^{-7/6}$ and $T_a \sim L^{-1/6}$, the last of which is a relatively weak variation. The procedure cited here (including appropriate adjustment of atmospheric and fuel compositions) produces constancy of all core groups except π_6, which varies as $L^{-(n+3+2m)/(6+2m)}$, where n (which lies in the vicinity of unity) is defined as the temperature exponent of μ_a.

To achieve simultaneous scaling of radiation and convection, it follows from Eq. (2) that a requirement is $T_a^{n-3} \sim L$. If the requirements of convection and buoyancy scaling and constancy of g are superimposed on this requirement, then the condition $p_a \sim L^{-(11-n)/2(3-n)}$ is obtained. These results imply that T_a must be increased somewhat for the model (typically $T_a \sim L^{-1/2}$) and that p_a must be increased greatly for the model (typically $p_a \sim L^{-5/2}$). The procedure would assure constancy of all members of the core set except π_4, but the pressure requirements would severely limit the size range over which scaling could be performed.* The severity of the pressure requirement can be alleviated by permitting g to vary; it can be shown from the constancy of π_2 and π_6 that $p_a^2 g \sim L^{-(11-n)/(6-2n)}$ is the more general scaling requirement. For $n=1$, the partition of p_a and g scaling that produces the widest L range obtainable in the laboratory is approximately $p_a \sim L^{-3/2}$, $g \sim L^{-2}$ and is probably capable of allowing the characteristic model dimension to differ from that of the full-scale system by one order of magnitude at most.

It should be clear by now that *all* members of the core set can be kept invariant by allowing g to vary in addition to p_a and T_a. The relevant set of scaling instructions can easily be shown to be

$$\begin{aligned} &L_\alpha \sim L, && p_a \sim L^{(m+n-4)/(3-n)}, \\ &T_a \sim L^{-1/(3-n)}, && g \sim L^{-(2m+n+3)/(3-n)}, \\ &Q \sim L^{-1/(3-n)}, && T_l \sim L^{-1/(3-n)}, \\ &\Delta h_l \sim L^{-1/(3-n)}, && v_w \sim L^{-(m+n)/(3-n)}, \\ &\Gamma \sim L^{-(m+3)/(3-n)}, && T_a' \sim L^{(2m+n+3)/(3-n)}. \end{aligned} \tag{8}$$

The instructions for Q, T_l and Δh_l refer to how the atmospheric and fuel compositions are to be varied. Associated scaling laws can be inferred directly [e.g., flame height $H \sim L$, burning rate $W/t_b \sim L^{-3/(3-n)}$, burning time $t_b \sim L^{(6-n)/(3-n)}$, etc.]. For $n=1$ and $m=0$ the p_a, T_a and g instructions in Eq. (8) reduce to $p_a \sim L^{-3/2}$, $T_a \sim L^{-1/2}$

* There is an upper limit for Q (corresponding to a pure oxygen atmosphere) which establishes an upper limit on T_a, above which π_{16} can no longer be kept constant. But the practical pressure limit would be encountered before this intrinsic temperature limit is reached, for the scaling instructions cited here.

and $g \sim L^{-2}$, all of which appear to be about equally severe in limiting the full-scale-to-model-length ratio to a maximum factor of 10. The scaling requirements cited in Eq. (8) appear to be considerably more difficult to achieve than those cited in Eq. (6).

9. *Additional Remarks on Adjustment of the Fuel Composition*

Some adjustment in fuel properties was required in the preceding section [Eq. (8)] in order to keep $\pi_{24'}$ constant. Specifically, it was implied that the surface gasification temperature and the heat of gasification should be increased by a factor lying between 1 and 4. To maintain $\pi_{24'}$ constant, it is necessary only that $c_l T_l + \Delta h_l$ vary appropriately, and this may be achieved by adding nonvolatile, noncombustible inerts to the fuel. However, for improved radiation scaling (and perhaps to a lesser extent, for improved scaling of convective heat transfer) it is desirable to increase T_l and Δh_l proportionally, a task which may prove to be more difficult. A survey of properties of known natural and modified cellulosic fuels would be needed to ascertain how well the desired adjustments can be made.

A different possible use of adjustments in fuel composition is to aid in scaling the troublesome radiation parameters $\bar{\kappa}_\nu$ and $\bar{\sigma}_\nu$ (groups π_4 and π_5). It may be reasonable to assume that in flames from cellulosic fuels, small carbon particles dominate the absorption and scattering of radiation. If this assumption is true, then $\bar{\kappa}_\nu$ and $\bar{\sigma}_\nu$ can be tailored by selecting fuels with appropriate (carbon) smoke output, measured in terms of particle-size distributions and particle-number densities. If desired smoke variations cannot be achieved with available fuels, it may be possible to modify smoke properties of the fuels by adding appropriate quantities of inert particles (e.g., Al_2O_3) which have the proper size distributions. The particles should be placed at locations in the fuel where they will be swept into the flames by the gas flows. Some degree of trial and error may be needed in developing tailored smoke, but since radiative absorption and scattering properties of small solid particles are relatively well-known, the task may be eased through some theoretical aid.

If fuel composition could be used to adjust $\bar{\kappa}_\nu$ and $\bar{\sigma}_\nu$ at will, then the groups π_4 and π_5 could be kept constant independently of other variations, and one additional parameter would be liberated for use elsewhere in the scaling process. It has been indicated in the previous section that for reasonable values of the temperature exponent n of the viscosity coefficient, the value of the temperature exponent m of the absorption coefficient should be approximately equal to zero in order to produce the widest range of scaling lengths for complete scaling of the core set. The ability to adjust $\bar{\kappa}_\nu$ and $\bar{\sigma}_\nu$ through fuel composition would enable one to specify $m=0$ arbitrarily in the scaling rules, to produce constancy of π_4 through changes in fuel composition, and thereby to achieve the maximum scaling range. For the simpler approach defined in Eq. (6), the ability to adjust π_4 and π_5 by changing fuel composition may again prove to be useful, provided that the pressure dependences of $\bar{\kappa}_\nu$ and $\bar{\sigma}_\nu$ are not negligible; in this case the fuel composition would be changed so as to offset any variations in π_4 and π_5 produced by errors in their assumed pressure dependence.

10. *Conclusions*

Very few of the multifarious partial scaling possibilities for mass fires have been exploited. Untried techniques are available which necessitate construction of a chamber that is large in comparison with the model fuel bed (chamber volume $>10^3$ ft^3) and in some cases construction of a large centrifuge that is capable of accelerating the chamber to 10 or 100 g's. The chamber must be equipped with a means for maintaining its internal pressure at levels above 10 atm and for some purposes, also with a means for raising the oxygen content and temperature of the gases within it.

One of the three partial scaling techniques that were discussed essentially requires only elevation of the ambient pressure. Its scaling instructions are

$$L_\alpha \sim L, \qquad p_a \sim L^{-3/2}, \qquad v_w \sim L^{1/2}, \qquad \Gamma \sim L^{-1/2}, \tag{9}$$

i.e., geometrical similarity, atmospheric pressure varying as the $-3/2$ power of the characteristic length, wind speed proportional to the square root of the characteristic length, and atmospheric circulation inversely proportional to the square root of the characteristic length. This technique successfully scales the burning rate, buoyancy phenomena, convective effects, and probably turbulence, provided that the burning rate is controlled by convective (or conductive) heat transfer. In general, it does not scale transient fluid-flow, radiative or chemical kinetic phenomena properly. Practical limitations on pressure levels in the model appear to limit the length ratio over which scaling can be achieved by this technique to a value slightly in excess of a factor of 10.

Perhaps the most promising technique requires both pressure elevation and application of a centrifugal acceleration. Its scaling instructions are

$$L_\alpha \sim L, \qquad p_a \sim L^{-1}, \qquad g \sim L^{-1}, \qquad v_w \sim \text{const}, \qquad \Gamma \sim L^{-1}, \qquad T_a' \sim L^{-1}, \tag{10}$$

which differ from those of the previous approach in the length-scale exponents of $p_a(-1)$, $v_w(0)$ and $\Gamma(-1)$, in the fact that the acceleration must vary inversely with the characteristic length, and in the fact that the temperature lapse rate of the atmosphere must now be made to vary (inversely with L). This technique successfully scales the burning rate, buoyancy phenomena, the scale height of the atmosphere (equivalent to Mach number scaling), radiation absorption and scattering lengths (in some degree of approximation), convective effects, and probably turbulence, provided that the burning rate is not appreciably affected by changes in the radiant energy flux. The closeness of the approximation to proper scaling of radiation absorption and scattering lengths may be improved by adjusting the cellulosic fuel properties in an effort to tailor smoke characteristics. The technique does not scale transient fluid dynamics, chemical kinetics, or the radiant energy flux parameter properly. It lessens the severity of pressurization requirements for the model and thereby extends the practically achievable scaling-length ratio, perhaps nearly to two orders of magnitude with sophisticated equipment.

The third and most complex of the interesting techniques entails application of centrifugal acceleration, pressure elevation, temperature elevation, oxygen enrichment of the atmosphere, and adjustment of fuel properties. Its scaling instructions are given in Eq. (8). The technique correctly scales the burning rate, buoyancy phenomena, radiation absorption and scattering lengths (in a certain approximation), radiant energy flux, convective effects, and probably turbulence. In general, it scales neither transient fluid dynamics nor chemical kinetics. Restrictions on oxygen enrichment, centrifugal acceleration and pressure level limit the length ratio over which scaling can be achieved by this technique to slightly less than one order of magnitude.

The technique whose scaling instructions are given by Eq. (10) and are discussed more fully in Section 7, appears to offer so many potential scaling advantages that experiments based on this technique should be initiated.

NOMENCLATURE (see also Table 2)

A_k	preexponential frequency factor for kth reaction
$\hat{A}_k$	$\equiv A_k/A_k(T_a)$
B_ν	Planck blackbody source function
$\hat{B}_\nu$	$\equiv B_\nu(k'T_a/h')/\sigma'T_a^4$
c'	velocity of light
c_l	heat capacity per unit mass for fuel l
c_p	specific heat at constant pressure for gas mixture
c_{pi}	specific heat at constant pressure for species i in the gas
$\hat{c}_{pi}$	$\equiv c_{pi}/c_{pi}(T_a)$
D_{ij}	binary diffusion coefficient for species i and j
$\hat{D}_{ij}$	$\equiv D_{ij}/D_{ij}(T_a)$
E_k	activation energy for kth reaction
g	magnitude of body force per unit mass
$\mathbf{g}$	acceleration vector (body force per unit mass)
$\hat{\mathbf{g}}$	$\equiv \mathbf{g}/g$, unit vector in direction of body force
h	enthalpy per unit mass for the gas mixture
$\hat{h}$	$\equiv h/c_{pa}T_a$
h'	Planck's constant
h_i	enthalpy per unit mass for species i
$\hat{h}_i$	$\equiv h_i/c_{pa}T_a$
h_i^0	standard enthalpy of formation per unit mass for species i at temperature T^0
H	flame height
I_ν	radiation intensity (energy per unit area per unit solid angle per unit frequency per second) in direction $\mathbf{\Omega}$
$\hat{I}_\nu$	$\equiv I_\nu 15h'^2c'^2/2\pi^5k'^3T_a^3 = I_\nu(k'T_a/h')/\sigma'T_a^4$
I_ν'	radiation intensity in direction $\mathbf{\Omega}'$
k'	Boltzmann's constant
K_{ck}	equilibrium constant for concentrations, for kth reaction

$\hat{K}_{ck}$	$\equiv K_{ck}/K_{ck}(T_a)$
L	characteristic length such as fire ground diameter
L_α	other geometrical lengths, $\alpha=1, 2, \cdots$
m_i	molecular weight of species i
M	total number of chemical reactions occurring
N	total number of chemical species present
p	hydrostatic pressure
$\hat{p}$	$\equiv p/p_a$
$\mathbf{q}$	heat flux vector
$\hat{\mathbf{q}}$	$\equiv \mathbf{q}/\rho_a V c_{pa} T_a$
$\mathbf{q}_R$	radiative heat flux vector
$\hat{\mathbf{q}}_R$	$\equiv \mathbf{q}_R/\rho_a V c_{pa} T_a$
$\bar{q}_T$	representative turbulent heat flux
$\mathbf{q}_T$	turbulent heat flux vector
$\hat{\mathbf{q}}_T$	$\equiv \mathbf{q}_T/\bar{q}_T$
Q	gas-phase heat released per unit mass of fuel gases consumed
R'	universal gas constant
t	time
$\hat{t}$	$\equiv t/t_b$
t_b	burning time
T	temperature
$\hat{T}$	$\equiv T/T_a$
T'	vertical temperature gradient
T^0	a fixed standard reference temperature
T_l	gasification temperature for fuel l
U	unit tensor
v	absolute value of $\mathbf{v}$
$\mathbf{v}$	mass-average velocity of the gas mixture
$\hat{\mathbf{v}}$	$\equiv \mathbf{v}/V$
$\mathbf{v}_w$	wind velocity
V	characteristic mass average velocity of the gas mixture
$\mathbf{V}_i$	diffusion velocity of species i

$\hat{\mathbf{V}}_i$	$\equiv \mathbf{V}_i/V$
$\bar{V}_{iT}$	representative turbulent diffusion velocity of species i
$\mathbf{V}_{iT}$	turbulent diffusion velocity of species i
$\hat{\mathbf{V}}_{iT}$	$\equiv \mathbf{V}_{iT}/\bar{V}_{iT}$
w_i	mass rate of production of species i by chemical reactions
$\hat{w}_i$	$\equiv w_i L/\rho_a V$
W	fuel loading (weight of fuel per unit ground area)
$\mathbf{x}$	position coordinate
$\hat{\mathbf{x}}$	$\equiv \mathbf{x}/L$
X_i	mole fraction of species i
Y_i	mass fraction of chemical species i in gas
Y_l	mass fraction of chemical constituent l in fuel, also other pertinent dimensionless fuel-type and fuel-density parameters not easily included in either W or L_α
Γ	vertical component of vorticity vector in the ambient atmosphere
Δh_l	heat of gasification per unit mass for fuel l
κ_ν	absorption coefficient per unit mass, for radiation of frequency ν
$\bar{\kappa}_\nu$	average absorption coefficient per unit mass, for radiation
$\hat{\kappa}_\nu$	$\equiv \kappa_\nu/\bar{\kappa}_\nu$
λ	thermal conductivity coefficient
$\hat{\lambda}$	$\equiv \lambda/\lambda_a$
μ	viscosity coefficient
$\hat{\mu}$	$\equiv \mu/\mu_a$
ν	frequency of radiation
$\hat{\nu}$	$\equiv \nu h'/k' T_a$
ν_{ik}'	stoichiometric coefficient for species i appearing as a reactant in reaction k
ν_{ik}''	stoichiometric coefficient for species i appearing as a product in reaction k
ρ	density of the gas mixture
$\hat{\rho}$	$\equiv \rho/\rho_a$
σ'	Stefan-Boltzmann constant
σ_ν	scattering coefficient per unit mass, for radiation of frequency ν, for scattering from direction $\mathbf{\Omega}$ to direction $\mathbf{\Omega}'$
$\bar{\sigma}_\nu$	average scattering coefficient per unit mass, for radiation

$\hat{\sigma}_\nu$	$\equiv \sigma_\nu / \bar{\sigma}_\nu$
τ	stress tensor
$\hat{\tau}$	$\equiv \tau / \rho_a V^2$
$\bar{\tau}_T$	representative turbulent stress
τ_T	turbulent stress tensor
$\hat{\tau}_T$	$\equiv \tau_T / \bar{\tau}_T$
$\mathbf{\Omega}$	a unit vector
$\mathbf{\Omega}'$	a unit vector
∇	gradient operator in coordinates $\hat{\mathbf{x}}$
$(\nabla \mathbf{v})$	dyadic

Subscripts

a	ambient atmosphere
ad	adiabatic; identifies adiabatic lapse rate of the atmosphere
i	a chemical species in the gas $(i=1, 2, \cdots, N)$
k	a chemical reaction $(k=1, 2, \cdots, M)$
l	a type of fuel or a chemical constituent of a fuel $(l=1, 2, \cdots)$
T	turbulent
w	wind
α	a geometrical quantity $(\alpha=1, 2, \cdots)$
ν	frequency of radiation

Superscripts

$\hat{}$	identifies nondimensionalized variables
$(\ )^T$	transpose of a tensor

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APPENDIX A

Atmospheric Properties

A scale height for the atmosphere does not appear in the list of dimensionless groups because its value is determined as a solution to the equations that have been given in Table 1. In an ambient stagnant atmosphere, the equation for the vertical pressure gradient is $dp/dz=-\rho g$, and therefore the atmospheric scale height is $z_a \equiv p_a/\rho_a g$. A dimensionless parameter involving z_a is $z_a/L=p_a/\rho_a gL=\pi_1/\pi_2\pi_3$, which involves the specific heat ratio γ, the Mach number M, and the important buoyancy parameter π_2. Since π_2 must be kept constant in reasonable mass-fire scaling and γ seldom can be varied, the Mach number must be kept constant in order to achieve proper scaling of the scale height of the atmosphere. This observation imparts an additional significance to the Mach number in mass-fire scaling.

The purpose of defining π_{28} as shown in Table 2 instead of by means of the simpler formula $(dT/dz)_a L/T_a$ rests on the meteorological concept that if a postulated value of $(dT/dz)_a$ is less than $(dT/dz)_{ad}$, then the postulated atmosphere is unstable, and convective fluid motions will occur in it. The value of $(dT/dz)_{ad}$ is defined by the solution to the equation of state, the equation $dp/dz=-\rho g$, and the isentropic relationship between p, ρ and T; for an atmosphere of constant specific heat ratio γ and constant molecular weight m_a, the adiabatic lapse rate is readily shown to be

$$(dT/dz)_{ad}=-[(\gamma-1)/\gamma](\rho_a T_a/p_a)g$$
$$=-[(\gamma-1)/\gamma](m_a/R')g=\text{constant},$$

so that π_{28} can be written alternatively as

$$\pi_{28}=-(dT/dz)_a\gamma R'/m_a(\gamma-1)g.$$

The question of whether the ambient atmosphere is stable will probably be of greater importance regarding mass-fire behavior than will the precise value of $(dT/dz)_a$ (compared with T_a/L, for example), because the degree of stability affects the response of the atmosphere to a buoyancy source and therefore the structure of a plume above a mass fire (and hence, quite possibly, other mass-fire characteristics). This prejudice constitutes the reason that the group containing $(dT/dz)_a$ is referred to $(dT/dz)_{ad}$. The choice of reference becomes important only when various parameters (particularly Mach number) are neglected.

The groups π_{25}, π_{26} and π_{27} require no discussion beyond that contained in Table 2.

ABSTRACTS

A. Prevention of Fires and Fire Safety Measures

Coffee, R. D. (Eastman Kodak Company, Rochester, New York) "Dust Explosions—An Approach to Protection Design," *Fire Technology* **4,** 81 (1968)*

Related Section: **A**

Subject Headings: **Dust explosions;** *Severity indexes; Vent ratios.*

The author suggests an empirical approach to calculating vent ratios from data available in the literature. Calculations are based upon Severity Indexes tabulated by the Bureau of Mines and the vent ratio nomograph of Schwab and Othmer once correlation factors have been determined. A procedure for determining correlation factors is explained.

Hill, J. E. and Almgren, L. E. (Gage-Babcock & Associates, Inc., Westchester, Illinois) "Fire Protection Criteria—Alaska Oil Producing Platforms," *Fire Technology* **4,** 214–220 (1968)

Related Section: **A**

Subject Headings: **Oil platform;** *Fires*

R. M. Fristrom

Oil drilling and producing platforms present a number of fire hazards. Fire protection practice in Alaska is reviewed, and found to vary widely.

Hilado, C. J. (Union Carbide Corporation) "Flammability Tests for Cellular Plastics—Part I.," *Fire Technology* **4,** 32–45 (1968)

Related Sections: **A,** *B, D*

Subject Headings: **Plastic flammability;** *Fire endurance; Flame spread; Ignition.*

G. A. Agoston, Abstracter

The author begins by outlining the major heat exchange mechanisms occurring in the combustion of a cellular plastic. He emphasizes the relative importance of

* Abstract from *Fire Technology.* By permission.

heat exchange to and from the surroundings in the case of burning low-density cellular plastics. Thus the severity of a flammability test can be altered appreciably by the manner and extent to which the burning sample is confined.

Six important flammability characteristics of cellular plastics are cited. All are in some respect a measure of fire hazard.

1. Ease of ignition of the plastic or its pyrolysis products. Some measures of the ease of ignition are autoignition temperature, ignition sensitivity, and critical oxygen index.

2. Flame spread or rate travel of the flame front. Some measures are burning rate, burning extent, flame spread factor, and flame height.

3. Fire endurance, the resistance offered by the cellular plastic to the passage of fire normal to the exposed surface. For example, an intumescent layer of char formed upon exposure to fire could resist flame penetration. Some measures are penetration time and resistance rating.

4. Fuel contribution, the heat produced per unit weight or volume of cellular plastic. Some measures are heat evolution factor and fuel contribution index.

5. Smoke density, the degree of light obscuration.

6. The products of pyrolysis and combustion; carbonaceous char, volatile gases, and smoke particles. Some aspects of possible importance are the formation of a liquid phase, the collapse of the form structure, and the toxicity of the gases.

Flammability tests generally evaluate one or more of the first five characteristics. The second, flame spread, has received the greatest attention in recent years. The sixth is principally in the domain of analytical chemistry rather than of physical testing.

The author describes briefly the essential features of over twenty established flammability tests. These were originally designed for solid materials but they may be applied to cellular plastics. He classifies the tests according to specimen sizes: small-scale (maximum dimension less than 12 in.), medium-scale (maximum dimension between 12 and 48 in.), and large-scale (maximum dimension exceeding 48 in.). He designates the position of the burning surface in each test systematically by its angle with respect to the horizontal (0° for a horizontal upper burning surface; 90°, vertical burning surface, flame traveling upward; 180°, horizontal lower burning surface; 135°, inclined lower burning surface, flame traveling upward; 240°, lower burning surface, flame traveling downward; 270°, vertical, flame traveling downward; etc.). The heat source is rated as low, moderate, or severe depending upon the extent of its influence on flame spread. The effect of the surroundings (i.e., test chamber configuration and construction) in promoting the propagation of flame is classified as high-feedback or low-feedback, depending upon the extent to which the heat generated is permitted to escape.

This paper thus provides a useful survey of available tests. The long list of references (85 items) includes the publications giving the flammability tests in detail.

Shorter, G. W. (National Research Council, Ottawa, Canada) "The Fire Protection Engineer and Modern Building Design," *Fire Technology* **4**, 206–212 (1968)

Related Section: **A**

Subject Heading: **Building design for fire protection engineers.**

R. M. Fristrom

The development of information and tests for fire endurance in modern building designs reviewed for the fire protection engineers.

Simard, A. J. (Forest Fire Research Institute, Ottawa, Canada) "The Moisture Content of Forest Fuels: I. A Review of the Basic Concepts. II. Comparison of Moisture Content Variations above the Fibre Saturation Point between a Number of Fuel Types. III. Moisture Content Variations below the Fibre Saturation Point," *Forest Fire Research Institute Information Reports* FF-X-14, 15, 16 (July 1968)

Related Sections: **A**, *J*

Subject Headings: **Moisture content of forest fuels**; *Wood.*

A. A. Brown, Abstracter

This is an important subject to the forest fire fighter and to the administrator of wild lands, because ease of ignition and rate of combustion of forest fuels are directly related to their moisture content.

The study is reported in some depth. It starts with a critical review of the basic concepts of the manner in which dead plant materials gain or lose moisture, and of the existing knowledge in this field; then in the light of computer analyses of new experimental data, the author proceeds to examine existing assumptions and practices in the measurement and prediction of fuel moisture and to set up a revised set of conclusions in respect to both. This results in a significant contribution to the understanding of this subject.

The study consists of three papers in series. The first is devoted to the review of the basic concepts held by previous workers in this field. The second focuses on the variations in moisture content above the fibre saturation point of woody fuels. The third paper consists of a similar study of the variations in moisture content of forest fuels below the fibre saturation point. New features in papers II and III are the complete utilization of computer equipment in the analysis of experimental data. The stated purpose of the complete study was: (1) to determine which environmental factors influence fuel moisture, (2) to determine the extent of their influence, (3) to develop regression equations, where possible, to predict fuel moisture directly from meteorological observations.

In the first paper, the factors governing the gain or loss of moisture are considered in two groups. The first consists of the external or meteorological factors affecting deposition and evaporation of moisture where gain depends on rain and dew and loss depends on atmospheric vapor pressure, temperature, and humidity. The second group consists of internal factors in the fuel or fuel bed, which influence the total amount of moisture the material can gain or lose, and the rate at which this change can take place under a given set of meteorological conditions.

The effect of rain and dew on the gain in moisture content are direct and well understood, but not so readily measured. The amount of precipitation can be measured directly but its effect on the moisture content of fuels depends on its duration as well as the amount. Dew is not easily measured and it varies with the environment, since it depends on night cooling of surfaces below the dew point of the air. It derives from two sources, distillation (upward movement from warmer soil) and downfall (downward movement from the atmosphere). Distillation is independent of wind, but downfall is dependent on moderate air movement, exceeding about one mile per hour. On this basis estimating equations that are moderately successful in predicting the amount of dew, are quoted by the author.

Moisture losses through evaporation from a water surface are also well understood. But conventional weather measurements to predict loss of moisture from forest fuels become complex. The temperature of the surface of the fuel is very important. As its temperature increases, the amount of water vapor the adjoining air can hold, or its evaporation potential, sharply increases also. This temperature depends on solar radiation striking the surface, less that reflected from it, the evaporation from the surface, and the wind speed. The effect of these factors may be calculated, but the temperature of the fuel surface deviates from the air temperature depending on the physical properties of the surface and its exposure.

When related to a natural area, transpiration from living vegetation also depletes moisture from the fuel complex. Since evaporation and transpiration both move in the same direction, and within certain limits respond to temperature changes in the same way, they are often combined by the term evapotranspiration and estimating formulas for their combined effect are applied. Such estimates are reasonably successful for herbaceous vegetation but less so for forest areas.

The internal factors that affect how much moisture a fuel can gain or lose and at what rate, comprise the second group of variables. As the moisture content of a piece of wood is lowered, the holding forces become stronger and the energy necessary to remove one gram of water becomes greater. This increase, called the differential heat of desorption was computed by Byram, who then devised formulas to describe the drying of fuels.

The reasons for the increasing energy required to remove moisture from wood are a combination of capillary action and of valence bonds linking water to the cellulose molecules. This moisture is known as bound water.

For any given combination of external factors, when the vapor pressure of the water in the wood equals that of the atmosphere, there is no gain or loss of moisture, and the system is said to be at equilibrium moisture content. The equilibrium moisture contents of various fuels at given temperatures and relative humidities have been computed. It is somewhat lower for absorptive conditions than for desorptive conditions.

The movement of moisture through fuel is complex and not yet fully understood. It is usually referred to as diffusion. The more important factors are temperature gradient, vapor pressure gradient, moisture content gradient and mechanical factors such as capillary flow, shrinkage or swelling, gravity flow, and mechanical pressure gradients. It varies a great deal with species and condition of wood in woody fuels and with physical characteristics of fuel beds.

The differential rates of drying that result from the diversity of physical characteristics of fuels, and from the position each happens to be on a drying curve in a natural environment, defy precise prediction. Yet they can be classified in a meaningful way. This has been accomplished by adoption of the concept of a time-lag constant. This defines fuels according to the time required to lose 63% of the moisture required to reach equilibrium moisture content under some standard drying regime. The weakness of the time-lag constant as seen by the author is that wetting, short of complete saturation, cannot be accurately described in this way.

The theoretical fuel moisture content model developed by Linton in 1962 for situations below the fibre saturation point and above the fibre saturation point are then presented and discussed. This discussion provides the guide lines for the experimental data and its treatment discussed in papers II and III.

Paper II, concerns moisture changes in components of forest fuel above the saturation point. To obtain data for this study samples of foliage and twigs of white spruce, maple, white pine, jack pine, and red pine were used. The eventual objective is prediction of the moisture content of forest duff and litter or of the natural fuel bed. This introduces the factors of structure and arrangement within the bed. However, study of these factors was deferred in order to compare the effect of internal differences of components due to age and species. Moisture movements in all samples above the saturation point were assumed to be in the form of liquid water.

The specific questions for which answers were sought were: (1) the total amount of water that can be held, (2) the maximum rate of water absorption, (3) the rate of water loss, (4) the effect of age of needles, (5) the effect of size of twigs, (6) the effect of bark on twigs, (7) other questions raised by the data.

All samples were first air dried at room temperatures, then weighed. Then they were soaked until they reached the saturation point, then they were oven dried and again weighed. All gains and loses of moisture are expressed in terms of oven dry weight.

The first problem was the significant loss of weight following the soaking. This amounted to an average of 15.6% of the oven dry weight of foliage samples and 10.2% of the twig samples. Most of this loss was shown to consist of solubles which could be recovered through distillation.

The total amounts of water absorbed by the samples varied from 134% for new red pine needles to 388% for old maple leaves. Old or weathered needles, foliage, and twigs absorbed water rapidly. New foliage and twigs absorbed it more slowly. Old and new foliage gradually approached the same water content. The water content of twigs remained much farther apart at saturation. As the diameter increased the water holding capacity decreased. The drying of the samples followed a smooth curve much more closely than the wetting of the same samples. Old or weathered foliage or twigs gave up moisture much more rapidly than new material. Twigs with bark gave up moisture at a slower rate. It was concluded that the waxy surface of new needles and other foliage and the bark on twigs both act to obstruct diffusion of moisture. So they slow up both wetting and drying. The curves for jack pine needles taken from this publication well illustrate the general trends.

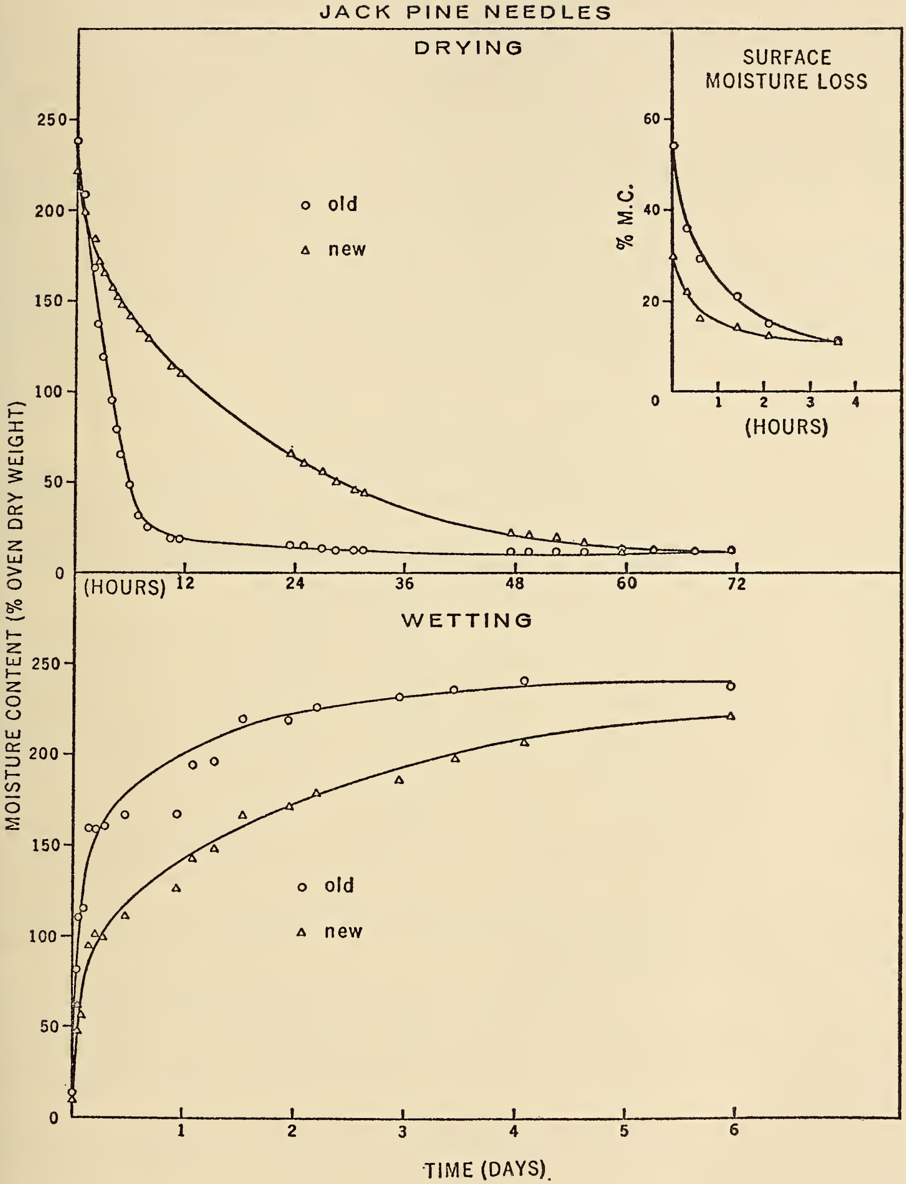

Fig. 3. Moisture content as a function of time.*

* Figures and tables numbered as in original article.

Moisture content variations below the fibre saturation point are the subject of paper No. III of this title.

The data used were from experimental field measurements made in 1966 and 1967. These were made for both slow and fast responding fuels. The fast drying fuels were represented by match splints, jack pine needles, and aspen leaves. The slow responding fuels were litter beds with fuel weights per square foot ranging from 0.383 to 1.292 pounds. This corresponds to a weight of fuels per acre from less than one ton to over 20 tons.

The fuels were exposed under four different conditions: (1) under wooden cover in the open, no sun, (2) under plastic cover in the open, full sun, (3) under plastic in a forest stand, (4) no cover in a forest stand.

The basic weather variables correlated with moisture changes in the fast responding fuels were relative humidity, temperature, wind, and day length. For convenience, relative humidity deficit (RHD = 100-RH) was substituted for relative humidity in the computations. Measurements of temperature and RHD were used in several forms; a single observation at the time of moisture measurement, averages for two-hour, four-hour, and six-hour periods preceding measurement, and a twelve-hour day average, and a twelve-hour night average.

The same variables were correlated with moisture changes in the slow responding fuels except for the time intervals. Single observations at time of measurement, twelve- and twenty-four hour averages and maximum and minimum values were used. These were correlated with the daily change in the logarithm of the moisture content. This variable was also correlated with fuel weight.

All data were analyzed by means of a computer using multiple regression techniques. As was to be expected, moisture content of fuels under the forest canopy remained higher than in the open. However, the diurnal cycle resulted in faster and more pronounced changes in the open with the lowest moisture contents under the plastic shelter. The match splints maintained the lowest average moisture content at 14.6, the jack pine needles were next at 16.1, and the aspen leaves were highest at 21.6. The author notes that this tendency of hardwood leaves to maintain an equilibrium moisture content 6% higher than wood, has been confirmed by studies by the U.S. Forest Service. These differences between fuels in the absence of rain, which tend to increase with shading and with increasing moisture content, are pointed out by the author as highly significant. They reveal some of the faults of basing estimates of moisture in forest fuels beds on the moisture content of a calibrated stick of wood.

The author found too that fine fuel moisture did not change rapidly in the environments sampled contrary to the usual assumption. He found too in the computations that vapor pressure deficit, VPD, had a higher average correlation with moisture content change than the final value in both daytime and nighttime observations.

The effect of wind was not pronounced. Apparently its significance was limited to whether or not there was enough circulation to maintain a fresh supply of air at the fuel surface.

One further significant factor was the tendency for correlations to be poorest where samples were exposed to full sun. Under such circumstances the difference between fuel surface temperatures and ambient air temperatures were great and did not parallel each other. The author suggests that fuel surface temperature or a function of ambient temperature and hours of sunshine would give better correlations with fuel moisture in the open.

Computations were carried out to determine the best three variable combinations for predicting fast responding fuel moisture. No two equations used the same three variables to estimate fuel moisture because of the environmental differences between timbered and open sites. The more accurate regression equations were those for the stand, with an error of only three percent. Among the series of equations the predictor variables that most often appeared were "starting moisture content," "equilibrium moisture content," "relative humidity minimum," and "relative humidity minimum times temperature."

For the slow responding fuels the correlation between a computed number representing the change in the logarithm of moisture content times weight, with various selected weather variables is quoted from the author's Table 13. Key to the symbols used is as follows. RHD = relative humidity deficit, TP = temperature, VPD = vapor pressure deficit, W = weight, DL = day length, SR = solar radiation.

TABLE 13

Correlations between selected weather variables and ΔLMC×Wt.

Variable	Noon	Day	Night	24-hour	Maximum	Minimum
RHD	0.320	0.500	0.619	0.596	0.381	0.076
TP	0.578	0.718	0.608	0.673	0.648	0.561
VPD	0.682	0.712		0.706	0.696	0.558
W	0.047	0.258	0.076	0.119		
TP×RHD	0.599	0.780	0.653	0.795	0.725	0.239
DL×RHD	0.663	0.690	0.532	0.751	0.683	0.051
DL×TP	0.463	0.718	0.473	0.710	0.708	0.208
DL×TP×RHD	0.790	0.812	0.532	0.835	0.804	0.134
DL		0.640				
SR		0.640				

In this table the twenty four hour average values have the highest correlation with daily drying, but twelve hour averages and the afternoon maximum are also good. Temperature, relative humidity deficit, and day length are the most important variables in predicting daily drying. It was found that environmental conditions must be averaged over a longer period of time to maintain accuracy in predicting daily drying of deeper fuel beds. The author found that by multiplying noon temperature and relative humidity deficit by day length, a function was created that was almost as good for predicting daily drying as the twenty four average condition. At the latitude in which the measurements were carried out, variation in day length is a very important factor. It has no doubt been too much neglected in similar studies in the United States.

Stanzak, W. W. and Harmathy, T. Z. (National Research Council, Ottawa, Canada) "Effect of Deck on Failure Temperature of Steel Beams," *Fire Technology* **4,** 265 (1968)

Related Section: **A**

Subject Headings: **Steel beams, thermal failure of;** *Heat sink.*

R. M. Fristrom

It has been suggested that the heat sink characteristics of decks affect the temperature at which structural failure of steel beams occurs in fire. A series of fire tests fail to support this contention. They indicate that the time to failure is influenced by the heat sink but the actual failure temperature is not.

Way, D. H. and Hilado, C. J. (Union Carbide Corporation) "Fire Tests on Thermal Insulation Systems for Pipes," *Fire Technology* **4,** 271–283 (1968)

Related Sections: **A,** *F*

Subject Headings: **Insulation, fire tests on;** *Fire damage; Fire hazard.*

Authors' Summary and Conclusions

Thermal insulation systems used to conserve heat and refrigeration in industrial plants should be evaluated in the same manner as construction materials insofar as fire performance is concerned. Several insulation systems examined in large-scale tests show a wide variety of behavior.

Conclusions

None of the thermal insulation systems tested presented a significant fire hazard with the exception of those systems employing vegetable cork and cellular polystyrene. The hazard presented by vegetable cork is its tendency to continue burning under the weather barrier covering, and the hazard presented by cellular polystyrene is its tendency to produce combustible gases and combustible liquids. Cellular polyurethane, although a combustible insulation material, presented no significant fire hazard in a properly designed system because of its tendency to form char.

Satisfactory fire protection was provided only by systems employing calcium silicate, magnesia, diatomaceous earth, asbestos fiber, and asbestos fiber/perlite compositions, installed in two layers with staggered-joint construction. In general, no thermal insulation material in single-layer systems employing stainless steel outer jackets provided adequate fire protection.

With all the thermal insulation systems tested, fire damage would require partial or complete replacement. Only the weather barrier covering would require replacement in the case of systems employing asbestos fiber/perlite compositions. The weather barrier covering and the outer layer of insulation material would require replacement in the case of systems employing double-layer, staggered-joint installations of calcium silicate, diatomaceous earth, asbestos fiber, and cellular glass. All other systems would require complete replacement. Fire damage to magnesia insulation consisted primarily of damage from water application.

B. Ignition of Fires

Eisner, H. S. (Safety in Mines Research Establishment, Sheffield, England) "Aluminium and the Gas-Ignition Risk," *The Engineer* **223**, 259–260 (1967)*

Related Sections: **B**, *A*

Subject Headings: **Aluminium, ignition danger;** *Ignition hazard; Rust; Steel, rusty.*

Aluminium equipment is increasingly used for the storage, handling and transport of gaseous and liquid fuels. Designers and users of such equipment should be aware of the gas-ignition risk involved in the use of aluminium. Aluminium and other light alloys, when struck by rusty steel, may produce hot spots or sparks capable of igniting a flammable atmosphere and thus leading to an explosion; and smears of aluminium formed on a rusty steel surface, when struck by some other hard material, can similarly produce ignition. This article summarizes the experimental evidence relating to this hazard, and discusses safeguards against ignition.

Fenimore, C. P. (General Electric Research and Development Center, Schenectady, New York) "Inhibition of Polystyrene Ignition," *Combustion and Flame* **12**, 155 (1968).

Related Sections; **B**, *D*

Subject Headings: **Inhibition.**

See *Fire Research Abstracts and Reviews* **10**, 123 (1968).

* Reprint of Safety in Mines Research Establishment Abstract. By permission.

Moysey, E. B. and Muir, W. E. (University of Saskatchewan, Saskatchewan, Canada) "Pilot Ignition of Building Materials by Radiation," *Fire Technology* **4**, 46–50 (1968)

Related Sections: **B**, *D*, *G*, *I*

Subject Headings: **Pilot ignition, by radiation**; *Flame spread.*

G. A. Agoston, Abstracter

Fire can spread from one building surface to another in close proximity by the mechanism of heat radiation and convection. For large distances of separation, flaming brands are the only means of fire spread. At intermediate distances, volatile pyrolysis products from a heated surface may either ignite spontaneously or become ignited by flaming brands. The flaming-brand ignition of pyrolysis products, termed "pilot ignition," is the subject of this study.

In the test procedure used, a flat sample (8 cm×16 cm) faced directly a vertically mounted radiation panel (12 in.×18 in.) of the type employed in ASTM E162. The radiation intensity was varied by adjusting the distance between sample and radiation panel; the maximum intensity obtained was 0.6 cal/sq cm sec. The pilot flame was 2.5 cm long, burning upward, and issued from a horizontal tube 0.6 cm directly above the front top edge of the sample.

Plotted data are presented showing the pilot ignition time decrease with increase in the radiation intensity for the following unweathered unpainted materials: cedar, spruce, Douglas fir, Douglas fir plywood, hardboard, fiber insulating board, and asphalt shingles. Another series is presented for weathered (3 months' exposure) painted cedar (paint coatings: white latex, white enamel, red oil base, and white oil base) and for weathered unpainted cedar. The values for painted cedar are substantially the same as for unweathered unpainted cedar, probably owing to paint scorching. Weathered unpainted cedar required somewhat higher intensities. Aluminum paint was tested as well; ignition was obtained after 15 minutes' exposure to an intensity of 0.59 cal/sq cm sec, whereas the other painted surfaces ignited at about 0.40 cal/sq cm sec. Surface temperature measurements (with embedded thermocouples) were made as a function of time during a test. These showed that the aluminum paint was a much better reflector of radiant heat than the other paints or the bare wood.

Cedar samples covered with asbestos cement and metal sheet were tested. Although ignition could not be obtained with the available equipment, plots of surface temperature versus time were obtained at a radiation intensity of 0.59 cal/sq cm sec. These showed the protection offered by painted or dirty steel and by asbestos cement boards and shingles and the relatively superior protection offered by clean shiny aluminum and galvanized steel sheets.

A preliminary series of tests was performed to show the effect of an air current upward past the face of the sample. A velocity of 25 cm/sec reduced the time for pilot ignition at low radiation intensity but had little effect at high intensities. At air velocities above 100 cm/sec the time for ignition was increased.

Finally the authors present the following maximum radiation levels to which some materials can be exposed safely: sawn lumber and plywood, 0.35 cal/sq cm sec; manufactured hardboard, 0.27; asphalt shingles 0.30; asbestos cement on wood, 0.50; shiny galvanized steel or aluminum on wood, 1.5 approximately; painted or dirty metal cladding on wood, 0.55. These intensities are slightly less than those required for ignition after 15 minutes' exposure, but in most cases the damage would be severe.

Shkandinskiy, K. G. and Barzykin, V. V. "Characteristics of Gas Ignition by a Hot Surface with Allowance for Diffusion and Hydrodynamics," *The Physics of Combustion and Explosives* 4(2), 176 (1968) In Russian.

Related Sections: **B**, *G*, *H*, *I*

Subject Headings: **Gas ignition, by surface**; *Convection.*

Authors' Conclusions—Translated by L. J. Holtschlag

In the study of the characteristics of ignition of a material, an examination is usually made of the simplest model, assuming that heat is released homogeneously as a result of zeroth or first order reactions and that heat is propagated through the material only by thermal conduction. Such a model does not account for the convective motion taking place in the gases and, therefore, the applicability of the model to gas systems is in doubt. In the present paper, which was written to clarify this problem, an attempt is made to account for the effect of hydrodynamic and diffusion processes as well as the effect of the temperature-dependence of the coefficients of heat conduction and of diffusion on the ignition characteristics.

C. Detection of Fires

Lawson, D. I. (Joint Fire Research Organization, Boreham Wood, England) "Fire Detection Using Laser Beams," *Fire Technology* **4**, 257–264 (1968)

Related Sections: **C**, *A*, *N*

Subject Heading: **Fire detection.**

P. L. Start, Abstracter

A new commercial application for the laser beam could be fire detection. While it is possible to obtain monochromatic light with the aid of filters, laser light is both monochromatic and coherent. All the waves are in phase, implying that a laser beam has a very small divergence and can be focused to a small diameter spot.

There are two principal ways by which a laser beam could be used for fire detection. The fire will cause changes in the refractive index of air below a room ceiling and the change will modify the beam direction. Alternatively, the presence of smoke particles would cause both absorption and scattering of the light.

In a simple case, a small fire of 25 Btu/sec in a 12 ft high room was calculated to be able to deflect a 100 m laser beam about 5 cm. A photoelectric cell could be positioned to hold an alarm system silent until the beam was deflected. An interferometer system can also be used. Under normal circumstances, the recombined components of a split laser beam will be in phase. When the temperature of one path alters, relative to the other, the beams will drift in and out of phase, and a photoelectric cell sited at the recombination point will produce an alternating output. The change in the quality of the output signal will actuate the alarm. It is difficult to calculate the performance of either of these detection systems if a turbulent regime is set up as a result of the fire.

The scattering of laser light by smoke particles occurs almost exclusively at low angles so that any smoke particles can be seen by looking towards the laser nearly along the beam. Analytical assessment of the performance of such an optical scattering system is very difficult, because the amount and direction of the scattering is dependent on both the particle size and the wavelength used.

Preliminary experimental work has shown that with the beam deflection system, a small fire would cause a shift of 0.5 in. in a 200 ft long laser beam.

Practical considerations suggest that suitably designed mirrors could be used to make the beam traverse a compartmented area such as a suite of offices. Two difficulties must also be considered. While only a small fraction (about 10 μW) of the total power (1 mW) of the laser could enter the human eye, the beam must be positioned so that persons would not look directly towards the laser. Secondly, most of the detectors described would be actuated by accidental interruption of the beam and the system requires modification to prevent false alarms.

Compared with the cost of smoke detection systems it is suggested that the laser system could be competitive for protecting single areas greater than 7000 ft^2 and office suites exceeding 4000 ft^2.

D. Propagation of Fires

Berlad, A. L. and Lee, Shao-Lin (State University of New York at Stony Brook, New York) "Long Range Spotting," *Combustion and Flame* **12,** 172 (1968).

Related Section: **D**

Subject Headings: **Spotting, long range;** *Brands; Fire brands.*

See *Fire Research Abstracts and Reviews* **10,** 129 (1968)

McGuire, J. H. (National Research Council, Ottawa, Canada) "The Spread of Fire in Corridors," *Fire Technology* **4,** 103–108 (1968)

Related Sections: **D,** *A*

Subject Headings: **Corridors, fire spread in;** *Fire spread.*

See *Fire Research Abstracts and Reviews* **10,** 126 (1968)

Thomas, P. H., Heselden, A. J. M., and Law, Margaret (Joint Fire Research Organization, Boreham Wood, England) "Fully Developed Compartment Fires—Two Kinds of Behavior," *Joint Fire Research Organization Fire Research Technical Paper No. 18* (October 1967)

Related Sections: **D,** *G, I*

Subject Headings: **Compartment fires, behavior of;** *Radiation; Windows.*

R. M. Fristrom

This paper provides an analysis of the problem of compartment fires based on work both within and without the Fire Research Station. Fully developed fires are those which have reached maximum burning rate. This usually implies that the compartment is beyond salvage and will burn to completion.

Two regimes are distinguished: one in which the burning rate is limited by air access (small ventilation openings), and one in which the burning rate is limited by the fuel and is almost independent of the opening (large ventilation openings) and is, therefore, a perturbed open fire. Burning rate is limited by fire load density. Where the window limits the air access the two governing factors are the window area and the pressure differential between top and bottom of the window since the circulation consists of air entering the bottom of the window and burned or partially burned gases leaving the top of the window. With small windows the pressure differential is due to the stagnant stack of hot gas and proportional to the square root of the window height. In the case of large openings the air intake is limited by entrainment in the plume. For a given compartment size, window controlled fires appear to obey the equation of Kawagoe[1]

$$R = kA_wH^{1/2}$$

In this equation: R is the rate of fuel consumption (kg/min), k is a constant ranging between 5 and 6, H is the window height (m) and A_w is the window area (m^2).

If the window opening does not limit air, access burning rate is controlled by the fuel loading density and size.[2] It might be considered a perturbed open fire. Scaling between compartment sizes is proportional to the floor area.

A final point made in the paper is that there is a good correlation between the intensity of radiation from a window and the burning rate per unit window area.

This implies that the effective maximum temperature of the fire depends on the fire load per unit window area.

The discussion is reasonably clear and convincing. A point which could have been discussed in more detail is the range over which this scaling is applicable. The implication in the paper is that it is applicable from the experiments through the range normally found in houses, i.e., linear dimensions between a fraction of a meter and a few tens of meters.

References

1. Kawagoe, K.: "Fire Behavior in Rooms," *Japanese Ministry of Construction Building Research Institute Report No. 27*. Tokyo, Japan (1968)
2. Webster, C. T., Raftery, M. M., and Smith, P. G.: "The Burning of Wall-Ventilated Compartment Fire. III. The Effect of the Wood Thickness," *Joint Fire Research Organization Fire Research Note No. 401* (1960)

Waterman, T. E. (IIT Research Institute, Chicago, Illinois) "Room Flashover—Criteria and Synthesis," *Fire Technology* **4,** 25–31 (1968)

Related Sections: **D,** *G, L*

Subject Heading: **Flashover, in rooms.**

J. Ahern, Abstracter

This is a report on the first phase of a three-phase program intended to provide a means for predicting flashover during fire buildup in a room. This report deals with full-scale studies and real fire synthesis. In the article, the author describes in detail the basic factors involved and the phenomenon of fire buildup in a room following ignition of some of its contents.

The experiments described in this report on phase one fall into two categories—those including real room contents and those involving simplified fuel arrays (synthetic fires). All were full-scale and were conducted in an instrumented test chamber designed to represent a typical residential room.

The author summarizes the work with a series of ten conclusions, which will have an important bearing on the following phases of the project. Out of the tests conducted, it was found that the simulation of the initiating fire could be greatly simplified by the use of either wood cribs or gaseous fuels. It was concluded that propane presents the most desirable method for controlling the time rate of burning and simulating the initial stages of a room fire.

As indicated, this report covers the first phase of a three-phase program. When the entire program is completed, it is expected that a generalized data base will have been developed from which estimates of established fires in urban structures can be made. The final results are to be in the form of a computer code which includes information on item-to-item fire spread, ignition of fuel complexes, the frequency of occurrence and location of room combustibles, and the occurrence of room flashover.

Zembrzuski, M. (Technischen Hochschule, Wroclaw, Poland) "Combustion of Volatile Components and Double Ignition in the Burning of Coal Dust," *Energietechnik* 17(5), 205–206 (1967) In German.

Related Sections: **D,** *H, B*

Subject Headings: **Coal dust;** *Dust.*

H. M. Cassel, Abstracter

Individual charcoal particles of high volatile content fall down a vertical furnace kept at constant temperature. Burning times are recorded on rotating film photos. The combustion proceeds in four distinct periods: t_1=preignition period; t_2=gas combustion; t_3=intermission period; t_4=solid combustion.

Table 1 presents observed t_2-values in milliseconds as function of particle diameter in 10^{-6} m and furnace temperature in °K.

TABLE 1.
Observed t_2-values in milliseconds as function of particle diameter in 10^{-6} m and furnace temperature in °K.

ϕ	1173	1372°K
200	18	43
300	38	60
350	47	66
400	60	82

The author explains the spectacular increase of t_2 with temperature by the increase in released volatile matter, estimating a molar heat of vaporization at ca 400 cal.

However the suggestion that for constant temperature the burning time ought to be proportional to the square root of ϕ is not compatible with the data. Rather the reverse relation ($t_2 \simeq \text{const.} \times \phi^2$) appears as an approximation in the right direction. This can be derived on the basis of diffusion controlled burning.

E. Suppression of Fires

Ghosh, A. K. and Banerjee, B. D. (Central Mining Research Station, Dhanbad, India) "Use of the Carbon-Hydrogen Ratio as an Index in the Investigation of Explosions and Underground Fires," *Journal of Mines, Metals & Fuels* XV(11), 334–340 (1967)

Related Sections: E, *G*

Subject Heading: **Underground fires.**

G. S. Pearson, Abstracter

This paper calculates the carbon-hydrogen weight ratio in the pre-explosion gas from the results of analyses of post-explosion gases thus avoiding the difficulties in interpreting the post-explosion gas composition. The computed carbon-hydrogen ratio can be used to distinguish whether explosion resulted from methane or from the more violent coal-dust explosions.

Carbon-hydrogen weight ratios are computed both for experimental and for mine explosions reported in the literature and are tabulated and compared to the ratios deduced by Jones and Trickett.[1] In general, agreement is found between both ratios, and the conclusions as to the nature of the explosion are in accordance with the observations and circumstantial evidence recorded for the various explosions. The extension of the C/H ratio to analyses of the gases in sealed areas of the mine is discussed and measures for fire fighting dependent on the C/H ratio are suggested. Difficulties in obtaining reliable C/H ratios may result from solution of the combustion products in underground water, nonuniform mixing of the combustion products, and dilution by gases released from the strata after the underground explosion.

Reference

1. Jones, J. H. and Trickett, J. C.: "The Examination of Gases Resulting from Explosions in Collieries," *Colliery Guardian 189* (4893), December 1954.

G. Combustion Engineering

Bellamy, L.,* Barron, C. H., and O'Loughlin, J. R. (Tulane University, New Orleans, Louisiana) "A Critical Zone Analysis of Reverse Jet Flame Stabilization," *Combustion and Flame* **12**(2), 107–114 (1968)

Related Sections: **G**, *J*

Subject Headings: **Reverse flame, jet stabilization**; *Blowoff.*

T. C. Adamson, Jr., Abstracter

The analysis of a reverse jet flameholder generally involves a simplified model, characterized by a so-called critical zone in which recirculated hot gases continually ignite the incoming, cool fuel-air mixture. This paper describes the work done in an effort to substantiate the hypothesis that the stability characteristics result from this critical zone, which was analyzed as an adiabatic homogeneous reactor.

The analytical calculations involved writing equations relating the mass flows of the air, fuel, and the water which was used to cool the reverse jet, in the critical zone. A global reaction rate expression for the propane air reaction was employed, with arguments given for using a higher activation energy than that given in the original development of the rate expression. Other necessary relations were constructed from experimentally found correlations. Longwell's stability criterion was used to predict blowoff.

* Present address: Monsanto Company, St. Louis, Missouri.

Experimental stability limits were obtained from a standard two inch combustion tunnel with a water-cooled reverse jet. Since the global rate equation was valid only for lean mixtures, comparison of calculated and experimentally found blowoff velocities could be made only for equivalence ratios less than one. In this region, the comparison was good. Also, the range of values found for the critical zone volume agreed well with estimates presented by previous authors.

Fendell, F. E. and Smith, E. B. (TRW Systems, Redondo Beach, California) "Diffusion-Flame Shape in the Wake of a Falling Droplet," *AIAA Journal* **5**(11), 1984–1988 (1967)

Related Sections: **G**, *D*, *I*

Subject Headings: **Diffusion flame shape;** *Buoyancy, and droplets; Droplet burning analysis, with buoyancy.*

H. A. Becker, Abstracter

The following problem is analyzed: a fuel droplet burns in a uniform oxidant stream directed counter to the pull of gravity. The droplet is regarded as a point source of fuel and a point sink for heat. The Lewis number is unity. Chemical reaction is supposed direct, one-step, exothermic: $bO+dF\rightarrow eP$.* Reaction rate is infinite and the flame-front thickness consequently infinitesimal (Burke-Schumann model). Effects of composition and temperature on gas density are linear (Boussinesq approximation), resulting in isopycnic mixing. The simplified conservation equations for mass, energy, and momentum are then written in the boundary layer approximations and reduced to ordinary differential equations by a similarity transformation. The equations are solved for a Prandtl number of unity.

The original contribution consists in predicting the effects of buoyancy (natural convection) on the flow field and the flame front. The flame is expanded both radially and longitudinally by natural convection.

This paper is another step in the mathematical modeling and analysis of laminar-flow droplet burning. The results will have no practical application as such, but may improve the theoretical framework for experimentation.

Gaskill, J. R. and Veith, C. R. (Lawrence Radiation Laboratory, University of California, Berkeley, California) "Smoke Opacity from Certain Woods and Plastics," *Fire Technology* **4**, 185–195 (1968)

Related Sections: **G**, *H*, *I*

Subject Heading: **Smoke opacity.**

G. S. Pearson, Abstracter

This paper determines the opacity of smoke produced by radiant heating of samples of wood and plastics using a smoke chamber similar to that built at the

* Where O is the oxidizer species, F is the fuel species, P is the product species, and b, d, and e are stoichiometric coefficients.

National Bureau of Standards,[1] but with some modifications. A gas flame is used to induce ignition when measurements are required for samples burning with a flame.

The smoke opacity is determined photometrically and the optical transmission data are used to compute a specific optical density, D_s, given by

$$D_s = (V/AL)\ \log_{10}(F_0/F_t)$$

where F_0 and F_t are the incident and transmitted fluxes, V is the volume of the smoke chamber, A the sample surface area, and L the path length. Results are presented in the paper for: (a) maximum D_s; (b) time when it occurred; (c) maximum rate of increase of D_s averaged over a 2 minute period; (d) time when it occurred. Values are also given for the smoke obscuration index given by

$$SOI = D_m \times R / D_{s-16}$$

where D_m and D_{s-16} are the maximum specific optical density and the time at which the specific optical density reached a value of 16. R is the average of the linear rates for each of the four 20 per cent smoke intervals between 10 and 90 per cent of D_m.

Experiments reported here are for a heat flux of 2.5 W cm^{-2}, both smoldering and flaming conditions, and for either a closed chamber or one with a ventilation rate of 3, 6, 12 or 20 changes per hour. Samples were 3×3 in., $\frac{1}{4}$ in. thick (exposed area 2.56×2.56 in.).

The materials examined were oil-tempered hardboard (in comparative studies with the National Bureau of Standards), a range of woods and eleven plastics (acrylic, polyethylene, polystyrene, polytetrafluoroethylene (P.T.F.E.), phenolic canvas laminate, and polyvinyl chloride). The results for the wood samples showed that denser smokes result from smoldering woods and the values of D_{s-16} are about

TABLE 1.
Smoke densities—effects of ventilation

Material	No ventilation		6 Air changes/hr.		20 Air changes/hr.	
	Smold.	Flaming	Smold.	Flaming	Smold.	Flaming
Hardboard	25	5	7	1	2	0
Marine plywood	25	1	10	0	2	0
Red oak	35	1	15	1	3	0
Redwood	30	8	10	3	3	0
Black walnut	80	1	60	2	8	0
White oak	80	4	30	1	7	0
Acrylic FR UVA	25	360	10	350	1	240
Acrylic HR UVA	3	10	1	20	0	15
Acrylic HR UVT	3	35	1	40	0	20
Polyethylene	65	20	—	—	—	—
Phen. Lam. NFR	60	190	20	90	2	35
Phen. Lam. FR	45	10	25	9	1	3
PVC-Rigid-Filled	70	2400	15	525	5	165
Polystyrene	21	900	5	1175	1	1165

half of those obtained under flaming conditions. Under ventilating conditions, some woods (red oak, white oak, and black walnut) require about twice as much ventilation as the others to reduce the density to a value of 100 to 150. The smoke obscuration indexes (Table 1) for smoldering woods and plastics are of the same order (25 to 80). Burning woods had values of less than 10, whereas burning plastics had a very wide range of values from 10 to 2400. Burning plastics were also unusual in that when ventilated little or no decrease in smoke intensity was observed regardless of ventilation rate for 5 of the 7 materials tested.

These experiments are to be extended to a further 20 materials, to both lower and high oxygen contents in the atmosphere, and to a higher radiant heat exposure. A similar series of experiments on the toxicity of the smoke is planned.

Reference

1. Gross, D., Loftus, J. J. and Robertson, A. F.: "A Method of Measuring Smoke from Burning Materials," *STP-422, 1967, American Society for Testing and Materials,* Philadelphia, Pa.

Hollander, Tj. (University of California, Santa Barbara, California)* "Photometric Measurements on the Deviations from the Equilibrium State in Flames," *AIAA Journal* 6(3), 385–393 (1968)

Related Section: **G**

Subject Heading: **Equilibrium deviations, in flames.**

R. Long, Abstracter

In this article topics on the physics of flames, which comprise part of the program of the Flame Research Group of the State University of Utrecht, are reviewed. Fifty-five references are quoted.

The possibility that flame gases are not in equilibrium and the consequent difficulty of defining the temperature has been realized for some time and "temperatures" corresponding to different aspects of the flame such as the velocity of the particles and the population ratio of the various energy levels have been determined by many investigators. The "temperatures" are named after the processes to which they apply, e.g., translational temperature, excitation temperature, etc.

In the first reaction zone chemical energy released is not yet equipartitioned among the various degrees of freedom. Radicals leave this zone in concentrations exceeding their equilibrium values and then gradually recombine. Since radiative and heat losses to the burner also occur, the flame temperature reaches a maximum at some height above the burner and then decreases. One cannot speak of general thermodynamic equilibrium since there is a net transport of heat, radiation, and mass throughout the flame but one may still speak of a local equilibrium characterized by a local temperature if the rate of transport is slow compared to the rate at which energy is equipartitioned.

* Tj. Hollander is a Research Associate in the Flame Group at the State University of Utrecht, The Netherlands. He was on leave at the University of California.

Equilibrium of translational and rotational degrees of freedom is established rapidly and although equipartition over the vibrational degrees of freedom proceeds more slowly a serious lag in this is not to be expected in the flames studied.

Outward radiation leads to depopulation of the higher energy levels of the particles with respect to their lower levels. Only at the center of strong resonance lines does radiation equilibrium exist. The author quotes Snelleman's 19 results obtained by a photoelectric line reversal method. Calculated flame temperatures are compared, at different heights above the burner, with measured temperatures. The good agreement supports the view that the majority of the flame molecules are present in equilibrium concentrations.

In the remainder of the paper some deviations from the equilibrium state in laminar, premixed flames at atmospheric pressure are discussed in detail. Meker-type flames are used and the flames studied are $CO/O_2/N_2$; $H_2/O_2/N_2$; and $C_2H_2/O_2/N_2$, (sometimes Ar is used as a diluent). Metal vapor is introduced into the middle part by means of a liquid sprayer or by evaporating dry pure salts.

The slow recombination of the radicals H, OH and O, which are found in excess concentrations in the reaction zone, is considered. In the work quoted $CO+O+X \rightleftharpoons CO+X^*$ is the predominant reaction responsible for the initial rise in temperature. The O concentration as a function of rise-time t can be calculated.

The mechanism for OH and K chemiluminescence is considered and in H_2 flames the predominant reaction is claimed to be $H+OH+X \rightleftharpoons H_2O+X^*$. In the C_2H_2 flame this is also the most important but $CO+O+X \rightleftharpoons CO+X^*$ also contributes.

The background emission in CO and C_2H_2 flames has been measured photometrically and its dependence on temperature and on CO and O concentration and on wavelength investigated (continuous emission is absent in H_2 flames). The reaction $CO+O+(M) \rightleftharpoons CO_2+(M)+h\gamma$ is involved.

Radiative nonequilibrium and departures from the Saha ionization equilibrium of metal vapor in the flame respectively, are discussed.

The dissociation energies of Ca, Sr and Ba oxides have been determined on the assumption that dissociation equilibrium did exist at the measured temperature and the results compare satisfactorily with others from flame photometric work. The reactions which may explain the results are considered.

Ramiah, M. V. and Goring, D. A. I. (Pulp and Paper Research Institute of Canada and McGill University, Montreal, Canada) "Some Dilatometric Measurements of the Thermal Decomposition of Cellulose, Hemicellulose, and Lignin," *Cellulose Chemistry and Technology* **1**, 277–285 (1967)

Related Sections: **G**, *H*

Subject Headings: **Thermal decomposition, of cellulose, hemicellulose, and lignin;** *Kinetics; Wood.*

B. Greifer, Abstracter

The thermal decomposition of cellulose, hemicellulose, and lignin macromolecular constituents of wood were studied. The rates of gas evolution in the 110° to 173°C temperature range permitted apparent activation energies to be calculated for first-order chemical kinetics. Results are presented for thermal decomposition of the following materials:

Birch Xylan	potassium salt obtained by KOH solution extraction of birch wood under nitrogen
Pine Glucomannan	barium hydroxide precipitate of the aqueous NaOH extract of chlorite holocellulose
Spruce Dioxane Lignin	by acidolysis in dioxane
Spruce Periodate Lignin	by periodate oxidation and hydrolysis of sawdust
Cellulose ICR-1	bleached paper grade softwood sulfite pulp
Cellulose ICR-3	bleached acetate grade softwood sulfite pulp
Cellulose R	by methanolic NaOH treatment of commercial diacetate
Cellulose Avory C	solid obtained by drying an aqueous gel of microcrystalline cellulose

Experimental

Mercury displacement in a Bekkedahl type of glass dilatometer was used to measure (1) T_m, the minimum temperature at which gases evolved, and (2) V_{gas}, gas volumes evolved at elevated temperatures. V_{gas} values, evolved gas volumes (mm^3 at NTP/gm), were plotted against t, time (minutes) at different decomposition temperatures.

Results

The $V_{gas} \times t$ data points for each sample were fitted by least square lines passing through the origin (t_0, V_0). The slopes increased with increasing decomposition temperatures. The rate of gas evolution, K, at each temperature was given by the equation

$$K = (1/\omega_1)(dV_{gas}/dt) \times 60$$

where K = rate of gas evolution in mm^3 (NTP)/hr gm; V_{gas} = evolved gas volume in mm^3 (NTP); t = time (minutes); ω_1 = weight (gm) of sample discs, pellets, granules, etc.

Plots of log K vs $1/T_{abs}$ (also linear) showed that the decomposition reactions were following first-order kinetics. Table 1 tabulates the apparent activation energies E (kcal/mole) as given by the relation $E = [-d \log K/d(1/T)] \times 4.57 \times 10^{-3}$

TABLE 1.
Decomposition temperatures and activation energies for the pyrolysis of samples of cellulose, hemicellulose and lignin

Sample	T_d (°C)	E (kcal/mole)
Birch Xylan	117	46
Pine Glucomannan	127	50
Spruce Dioxane Lignin	130	52
Spruce Periodate Lignin	145	108
Cellulose ICR-1	156	153
Cellulose ICR-3	170	141
Cellulose R	164	123
Cellulose Avory C	164	155

along with a "decomposition temperature" T_d defined as the temperature (°C) at which gas evolution was 1 mm^3 (NTP)/hr gm.

Several speculations were presented to explain (1) the marked differences in thermal stability of the wood polymers, in the order cellulose>lignin>hemicellulose; and (2) the relatively high activation energies for cellulose decomposition, 123–155 kcal/mole, several times greater than the 31–50 kcal/mole reported by previous authors.

The T_d values for cellulose (considered to be almost wholly crystalline) were taken to indicate a "structural transition temperature" as well as a "chemical decomposition temperature" where crystal lattice forces were broken down. The initial cellulose depolymerization was followed by scission of the 1,4-glucosidic linkages, and the monomers so formed rearranged to levoglucosan which fragmented to yield volatile low molecular weight products. In contrast to cellulose, birch xylan was completely amorphous. T_d and E for this hemicellulose (Table 1) were considered to reflect the chemical stability of the polysaccharide rather than its physical state. Pine glucomannan, a partially crystalline linear chain, was more stable to pyrolysis than xylan because its chains had a greater degree of order. The heat stability of the two amorphous lignins could not be explained by these arguments but it was speculated that their stability could be characteristic of their chemical make-up.

The high activation energies for cellulose decomposition were defended by pointing out that the sensitivity of the dilatometric method permitted gas evolution to be measured orders of magnitude lower than in previous studies (10^{-6} gm/g hourly weight loss) and this was detected at lower decomposition temperatures (156° to 170°C compared with 180° to 291°C for other workers). At these low temperatures, the rate of pyrolysis was very low, and E was high. It was predicted that E might fall to below 50 kcal/mole at higher temperatures in line with values of other workers; and the order of stability cellulose>lignin>hemicellulose might well be reversed at those higher temperatures.

It was concluded that this investigation did not constitute a definitive study of the pyrolysis of wood components. The results merely indicated that the various wood polymers differed markedly in their resistance to gentle pyrolysis. More detailed knowledge of macromolecular composition is necessary before the thermal stability of cellulosic products derived from wood can be controlled.

Reed, S. B. (Watson House, The Gas Council, London, England) "A Unifying Theory for the Blowoff of Aerated Burner Flames," *Gas Council Research Communication GC141*. Presented at 33rd Autumn Research Meeting of the Institution of Gas Engineers, London, November 1967. *The Institution of Gas Engineers Journal* 8(3), 157–168 (1968)

Related Sections: **G**, *J*

Subject Headings: **Flame blowoff theory;** *Flame stretch; Stretch.*

J. M. Singer, Abstracter

The flame-stretch theory of blowoff, previously considered by the author[1] is further developed and clarified. The flame-stretch blowoff theory is based on the well-known concept of Karlowitz[2] that the increase in area of a combustion wave results in a reduction of the reaction rate in the flame, and final extinguishment for severely divergent flame propagation. Despite good agreement between experimental results and the boundary velocity gradient theory,[3,4] the author suggests that the principle of flame-stretch provides additional insight into the flame blowoff phenomenon and can correlate burner tube blowoff data better than the boundary velocity gradient theory. Other flame phenomena such as ignition and bluffbody stabilization may be regarded as flame-stretch limited.

In the flame stretch theory developed by the author, a critical value of Karlovitz's simularity factor (K) exists for flame blowoff. The author derives an equation for the relationship between K and other measurable quantities at blowoff that distinguishes between flames that have a primary reaction zone only, and both a primary and secondary reaction zone.

$$K = g_B \eta_0 / Su = 0.23[1 + (X^{6.4} - 1)\alpha] \tag{1}$$

where g_B = boundary velocity gradient at blowoff, η_0 is the characteristic preheat zone thickness $= k/(\rho c_p Su)$, k = thermal conductivity in the unburned state, ρ = mass density of gas mixture in the unburned state, c_p = specific heat at constant pressure of unburned gas, Su is the normal burning velocity, X = fuel concentration expressed as fraction of stoichiometric, and α is a constant equal to zero for flames with no secondary combustion zone, and unity for flames with a secondary combustion zone. The boundary velocity gradient relationship, g_B = const. Su^2, follows as a special case of Eq. (1).

Other possible uses of the flame-stretch theory are suggested: vitiation of combustion air, retention flames, interchangeability of gases, diffusion flame stability, and preferential diffusion effects.

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4. Harris, M. E., Grumer, J., von Elbe, G., and Lewis, B.: "Burning Velocities, Quenching and Stability Data on Non-Turbulent Flames of Methane and Propane with Oxygen and Nitrogen," *Third Symposium on Combustion, Flame, and Explosion Phenomena*, Williams and Wilkins Company, Baltimore, Maryland 1949, p. 80

Simon, H. D. (Abteilung Feuerungstechnik des Institutes für Gastechnik, Feuerungstechnik und Wasserchemie der Universität Karlsruhe) "Messung von Emissionsschwanken in turbulenten Diffusionsflammen," [Measurement of Emission Fluctuations in Turbulent Diffusion Flames], *Chemie Ing. Techn.* **40,** 121–128 (1968) In German.

Related Sections: **G,** *I*

Subject Headings: **Turbulent diffusion flames;** *Emission; Radiation Eddy; Free radical.*

H. A. Becker, Abstracter

Radiation from free radicals in turbulent free-jet city-gas diffusion flames has been studied with a photo-optical probe. Spatial resolution was around 5 mm, but data have been interpreted as point values of the emission per unit volume. Nozzles 10 mm and 16 mm in diameter were used. The investigated region extended 110 nozzle diameters downstream.

Emission fluctuations were characterized as to probability distribution, intensity (rms amplitude), and frequency spectrum. Absolute intensity shows a strong maximum in the region of stoichiometric mean composition. Relative intensity rises from around 3% on the flame axis to above 100% near the edge. Spectra are similar in shape to those for velocity, concentration, and temperature in cold jets. From the spectral density at zero wave number, integral scales were computed.

Because it is experimentally difficult to characterize turbulence in flames, it seems necessary when something is found which can be measured, to suppress the temptation to infer too much from the results. These results are about *emission* fluctuations. Any similarity to fluctuations in velocity, temperature, or concentration must be largely confined to the low wave-number (large "eddy") end of the spectrum. The high wave-number end is here associated with the chemical reaction fronts and could not be observed with a probe as coarse as 5 mm diameter. At high wave-numbers the spectral density must be strongly attenuated by volume-averaging. Thus the reported values of intensity and integral scale have considerable uncertainty, and the microscales have no certain meaning at all.

In summary, a valid photo-optical method of studying free radical emission has been developed. Interesting data on turbulent diffusion flames have been obtained, but accurate interpretation of these results must wait until the effects of volume-averaging are known.

Moin, F. B. and Shevchuk, V. U. "The Phenomenon of Flame 'Splattering' during the Burning of Premixed Gases in a Flow System," *The Physics of Combustion and Explosives* 4(2), 209 (1968) In Russian.

Related Section: **G**

Subject Headings: **Flame "splattering", in premixed burning;** *Combustion, turbulent; Turbulent combustion.*

Authors' Conclusions—Translated by L. J. Holtschlag

During pulsating burning of premixed mixtures, flame may splatter from the combustion chamber into the mixing zones at speeds higher by more than one order than the flashback speed. The main factor governing flame splatter is the amplitude of the pressure pulsation, the magnitude of which depends on the dimensions of the combustion chamber, the flow speed, the temperature and composition of the mixture, and on the resistance of the system at the exit from the combustion chamber.

H. Chemical Aspects of Fires

Leach, S. J. and Slack, A. (Safety in Mines Research Establishment, Sheffield, England) "The Accuracy of Sampling Probes in Very Thin Methane Layers," *SMRE Research Report No. 252* (1967)

Related Sections: **H,** *A*

Subject Headings: **Sampling methane layers;** *Parallel-disc probe; Errors; Flow disturbances.*

Authors' Summary

When a sampling probe is introduced into a methane roof layer, small flow disturbances occur which can reduce the concentration of methane sampled by the probe. The report discusses the reasons for this effect and describes experiments with methane layers and nitrous-oxide layers which show that the sampled concentration is reduced by a negligible amount except for very thin layers. However, in very thin layers with steep concentration gradients certain types of sampling probes may lead to large errors; tests with several types of probes are described in the report. The effect of the probe sampling rate was investigated and shown to be negligible up to 1 liter/min. A parallel-disk probe has been developed which is independent of flow direction and gives concentrations close to the true values.

Kosik, M., Kozmal, F., Reiser, V. (Slovak Technical College) and **Domansky, R.** (Slovak Academy of Sciences, Bratislava, CSSR) "Pyrolysis of Beechwood at Low Temperatures. I. The Present State of Knowledge of the Mechanism of Pyrolysis of Wood Polysaccharides," *Holz-Forschung und Holz-Verwertung* 20(1), 11–15 (1968) In German.

Kosik, M., Geratova, L. (Slovak Technical College), **Rendes, F.** and **Domansky, R.** (Slovak Academy of Sciences, Bratislava, CSSR) "Pyrolysis of Beechwood at Low Temperatures. II. Thermography of Beechwood and Its Components," *Holz-Forschung und Holz-Verwertung* 20(1), 15–19 (1968) In German.

McKay, G. D. M. (Forest Products Laboratory, Ottawa, Canada) "Effect of Inorganic Salts on the Pyrolysis of Cellulose," *Forest Products Journal, Canada* 18(5), 71–75 (1968)

Lipska, A. E. and Wodley, F. A. (U.S. Naval Radiological Defense Laboratory, San Francisco, California) "Isothermal Pyrolysis of Cellulose—Kinetics and Gas Chromatographic/Mass Spectrometric Analysis of the Degradation Products," *Report under Office of Civil Defense Work Unit No. 2531C (NTDL-TR-68-89)* (March 22, 1968)

Satonaka, Seiichi and Kobayashi, Seikichi and Kawashima, Yasuhiro "Fire-Retardation of Wood," *Research Bulletins of the College Experiment Forests, Hokkaido University, Sapporo, Japan* XXV(1), 235–264 (1967) In Japanese with English summary and translations of figures and captions of tables.

The following review compares these five papers. They are supplementary, although they make use of very different methods of study. The reviewer's comments to indicate especially cogent agreements or differences among the authors are enclosed in brackets.

F. L. Browne, Reviewer

"Pyrolysis of Beechwood at Low Temperatures. I. The Present State of Knowledge of the Mechanism of Pyrolysis of Wood Polysaccharides—*M. Kosik, F. Kozmal, V. Reiser, and R. Domansky.*

Related Section: **H**

Subject Heading: **Pyrolysis of beechwood.**

Different views of the mechanism of pyrolysis of wood polysaccharides are reviewed critically (55 references).

In the first stage of wood pyrolysis, up to 240°C, there is little loss of weight but changes occur in the wood components. The first changes are loss of free and sorbed water, releasing of old and formation of new hydrogen bridges, and then hydrolysis of β-glucosidic bonds. Oxygen, which can hardly be excluded from the micropores, speeds depolymerization of cellulose to values as low as 180 to 200 and forms oxycellulose which decarboxylates even below 200°C to increase formation of carbon dioxide and carbon monoxide. In the presence of air the content of carboxyl groups increases up to 335°C. Hemicellulose is the wood component most sensitive to pyrolysis; it shows loss of pentosans even below 100°C and rising content of unhydrolyzable substances, possibly humins, at 160°C. Conversion of lignin to aromatic substances has been observed below 180°C.

Above 240°C wood polysaccharides lose weight substantially and yield an abundance of liquid products, chiefly levoglucosan. Formation of levoglucosan is the most important reaction in the pyrolysis of cellulose. Different opinions about its mechanism are:

(1) Hydrolysis of cellulose to glucose and its slow conversion to 1,2-anhydro-D-α-glucopyranose, which converts to levoglucosan at temperatures as low as 110°C, is improbable because pyrolysis of glucose yields almost no levoglucosan and no glucose remains at temperatures over 240°C. But if the split in cellulose occurs in the bond between carbon atom 1 and the oxygen of the β-glucosidic bond, 1,2-anhydro-D-α-glucopyranose can result from formation of an ethylene oxide bridge between the first and second carbon atoms and then splitting of the ethyleneoxide bridge and a Walden inversion yield levoglucosan.

(2) The β-glucosidic bonds in cellulose might split so as to form biradicals of two kinds, either of which could stabilize as levoglucosan.

(3) Application of heat is thought to change pyranose units of cellulose to a B_1 isomer, then dehydration produces 1,6-anhydro-β-D-glucopyranose end groups from which levoglucosan is formed by chain splitting. The C_1 isomer leads instead to formation of 5-hydroxymethyl-2-furanaldehyde and 1,6-anhydro-D-α-glucofuranose.

(4) Oxidation or dehydration of polysaccharides at 150° to 240°C forms dehydroxycellulose which precludes subsequent formation of glucosan so that pyrolysis at 240° to 400°C leads to intermediates and their recombinations to produce tar and aromatics and eventually (400° to 700°C) a graphitic residue. This seems to be the most probable mechanism.

(5) Inorganic substances can materially affect the velocity of pyrolysis and the character of the decomposition reactions. Using the concept of Lewis acids and bases, the proton in the free electron pair of a Lewis acid can add to a hydroxyl group of a glucoside unit, water then splits off to leave a carbonium ion, which then stabilizes by forming a double bond with a neighboring carbon atom from which a proton breaks off to regenerate the Lewis acid to repeat the process with another hydroxyl group of the glucoside unit. Analogously the proton accepting electron pair of a Lewis base can add to a hydrogen atom of a glucoside unit, water split off to produce a carbanion that stabilizes by double bonding to a neighboring carbon atom from which the Lewis base is regenerated.

(6) Lewis catalysts may favor formation of intermolecular ether bonds between the sixth carbon atom of one and the fourth of the other molecule, splitting the glucosidic bond after which release of water produces a carbonyl group on the first carbon of one fragment and a tetrahydrofurfurol end group on the other fragment.

(7) A recent proposal assumes irreversible decomposition of carbonium ions in the presence of Lewis acids through addition of a proton to the oxygen of the β-glucoside bond. The pyranose unit then splits between the first and second carbon atoms to form an unsaturated product containing aldehyde and enol groups and

can change into volatile carbonyl compounds. Elimination of water yields aliphatic double compounds.

Promotion of ion dehydrations and limiting the radical-like decomposition of the polysaccharide chains seems to be determining for increasing the thermal stability of wood.

"Pyrolysis of Beechwood at Low Temperatures. II. Thermography of Beechwood and Its Components"—*M. Kosik, L. Geratove, F. Renden, and R. Domansky.*

Related Section: H

Subject Headings: **Pyrolysis of beechwood;** *Thermography differential, the soul analysis.*

Powdered beechwood (*Fagus silvatica*) and its isolated components were subjected to differential thermal analysis (DTA) in a newly described apparatus in which heated nitrogen or carbon dioxide flowed at controlled rate through the stationary sample and comparison standard (aluminum oxide and sea sand). The samples were subjected also to thermogravimetric analysis (TGA).

The DTA curves for wood and for all components show an endothermal region from 100° to 150°C with nadir at 120° to 130°C which corresponds to evaporation of water but nearly disappears for wood that before test had been heated to 350°C in the absence of air. For hemicellulose there are nadirs at 120° and 140°C, the second of which can be seen also for 4-*O*-methylglucuronoxylan and for D-xylose, revealing endothermal breakdown of polysaccharide chains.

For both the celluloses and the hemicelluloses strongly exothermal oxidative processes occur from 150° to 300°C with peaks at 200° to 250°C, after which there is a marked endothermal region with nadir at some point between 260° and 350°C where the primary pyrolytic decomposition peters out. The scope of the exothermal reactions increases as the amorphous portion of the cellulose increases (cellulose < oxycellulose < decrystallized cellulose). The temperature of the endothermal nadir depends on the initial degree of polymerization (cellobiose 260°, microcrystalline cellulose 285°, Whatman cellulose 310°, sulfate cellulose 330°C). Exothermal decomposition of products of the primary pyrolysis then takes the DTA thermograms back to the exothermal region. Above 400°C the exothermal processes slowly fade away.

At 150° to 200°C the DTA thermograms of lignin, methanol lignin, and hydrolyzed lignin have a slight exothermal peak attributable to structural changes in the macromolecule. Otherwise the thermogram is uneventful below 400°C. Very similar thermograms are obtained for isolated lignin and for wood that before testing had been repeatedly heated to 350°C out of contact with air. Hence the lignin component has little effect on the DTA thermogram of beechwood below 350°C.

Thermogravimetric analysis showed that lignin, the most stable component, loses less than 15% of its weight whereas cellulose and beechwood lose more than 80% up to 400°C. The TGA curves for 4-*O*-methylglucuronoxylan (hemicellulose, the least stable component), cellulose, and beechwood reveal two distinct stages of pyrolysis. In the first stage the loss in weight is slight. In the second stage decomposition goes on very rapidly within a small range of temperature. [No mention is made of a third stage, clearly evident in the data in which there is slow loss of weight above 350°C. Lipska and Wodley in a report abstracted later in this review recognize the three stages.] The following kinetic data were obtained:

Activation Energies of Pyrolysis of Beechwood and Its Components

	1st Stage (zero order)			2nd Stage (first order)		
Test Material	Temp. °C	Weight loss, %	*E* kcal.	Temp. °C	Weight loss, %	*E* kcal.
Beechwood	170–220	5.5	15	240–310	47.3	31
Holocellulose	120–200	5.4	13	—	—	—
Cellulose	220–300	5.0	18	300–380	55.1	58
Lignin	200–320	3.9	8	—	—	—
4-*O*-methylglucuronoxylan	100–160	9.5	11	180–290	43.2	24

[Curves in Fig. 6 of the original report are numbered erroneously; they should read: (1) lignin, (2) beechwood, (3) cellulose, (4) 4-*O*-methylglucuronoxylan.]

"Effect of Inorganic Salts on the Pyrolysis of Cellulose—Pyrolysis of Untreated Cellulose"—*G. D. M. McKay*

Related Sections: **H**, *A*

Subject Heading: **Pyrolysis of cellulose.**

Purified Whatman cellulose containing less than 0.1% ash was pyrolyzed in dry, oxygen-free nitrogen. At 275°C the slow weight loss was less than 5% after 1 hr. Above 300°C weight was lost increasingly rapidly as the temperature increased. At 325°C a stable residue of 17% was reached in 45 min and at 350°C a stable residue of 11% in less than 20 min. [Perhaps because of greater purity of the cellulose, the region of slow weight loss extended to higher temperature than was found for cellulose by Kosik, Geratova *et al.* in the preceding abstract.]

Infrared spectra of residues from cellulose pyrolyzed at 325°C for various times from 0 to 60 min showed that up to 30 min, where the weight loss was 67%, there was little change in the spectrum but radical alterations appeared at 45 and 60 min where the residues had reached stable weight.

Gas chromatograms obtained by flash pyrolysis of 1 mg samples of the above residues showed little change before but significant change beyond 45 min. Perhaps the composition of the residue remains nearly unchanged until the weight loss reaches 70%, although bands attributed to C=C and C=O bonds become prominent early.

Residues from samples pyrolyzed at 350°C for times of 0, 5, 10, 15 and 30 min were subjected to differential thermal analysis (DTA). The curve for unpyrolyzed cellulose displayed four reaction zones (1) an endotherm caused by evaporation of extra cellulosic water, (2) an endothermal loss of water to form dehydrocellulose, (3) strongly endothermal depolymerization and volatilization of tar formed from previously unreacted cellulose, (4) exothermal decompositions of the dehydrocellulose into gaseous products and char. The curves for residues previously pyrolyzed for 5 and 10 min showed four zones with diminishing intensity of zones (1) and (2). The curve for the 15-min pyrolyzed residue, where weight loss exceeded 75%, still showed zone (3) suggesting that depolymerization still occurred but for the 30-min residue, where weight loss was 84%, the curve was merely a steadily rising exotherm. Perhaps reactions (2), (3) and (4) all compete for the original cellulose and their relative importance can vary with the relative time spent at the several levels of temperature.

Retention of the essential carbohydrate features of the infrared spectra until the weight loss exceeds 70% and its confirmation by both gas chromatograms and DTA implies that the cellulose decomposes by an unzipping from the end of the cellulose chain leaving the rest of the chain intact except for increase in C=C and C=O bonds from concurrent dehydration. Other suggestions from the findings are that the early weight loss derives primarily from the amorphous regions of the cellulose [compare Kosik, Geratova *et al.* in the preceding abstract], that glucopyranose rings persist to an advanced stage of pyrolysis, that dehydration must be intra- rather than inter-molecular, and that an unzipping mechanism suggests a constant rate of production of levoglucosan throughout the pyrolysis.

"Isothermal Pyrolysis of Cellulose—Kinetics and Gas Chromatographic/Mass Spectrometric Analysis of the Degradation Products"—*A. E. Lipska and F. A. Wodley*

Related Section: **H.**

Subject Heading: **Pyrolysis of cellulose.**

For this and a previous report (Lipska and W. J. Parker USNRDL-TR-928 Nov. 4, 1965) untreated white α-cellulose was pyrolyzed isothermally in a fluidized bath in a nitrogen environment. Weight loss was measured over the range 276° to 298°C in the previous work and at 315°, 335°, and 360°C in the present work. Isothermal pyrolysis proceeds in three regions, (1) very rapid decomposition and about 10% weight loss, (2) linear weight loss until 70% loss, (3) exponentially decreasing weight loss to a constant residual weight of 16%. The ratio of the weight loss in region (1) to that in (2) is 4 at 288°C and decreases as temperature rises to 1.1 at 350°C. The three phases of pyrolysis were confirmed by measurements with a time-of-flight mass spectrometer, where the degradation products were directly generated in the mass spectrometer by the pyrolysis of untreated α-cellulose at 298°C.

A single activation energy of 42 kcal/mole was found for the range 276° to 360°C, based on zero-order weight loss rates in the region (2). [Kosik, Geratova *et al.* in the second abstract in this review found an activation energy of 58 kcal/mole for cellulose at 300° to 380°C, treated as a first-order reaction.]

Comparison of weight loss measurements on cellulose treated with 2% potassium bicarbonate with those of untreated samples indicated that at 300°C active pyrolysis of the retardant treated samples was completed in 20 min leaving a residual weight of 33%; whereas the active pyrolysis of the untreated samples at the same temperature was completed in $2\frac{1}{2}$ hrs yielding a residual char of 17%.

Gas chromatographic/mass spectrometric analysis of the volatile degradation products of the untreated and potassium bicarbonate treated samples pyrolyzed at 315° and 300°C respectively indicated that: (1) there is little difference in either the quality or relative quantity of volatiles generated during the three different phases of pyrolysis [compare last paragraph of the preceding abstract of McKay's report]; (2) the fire retardant, potassium bicarbonate, does not markedly change the types of degradation products having molecular weights below about 110, although it does change their relative concentrations; the quantity of water and carbon dioxide relative to that of the other components, and the rate of product generation are markedly increased in the treated samples [compare mechanisms (5), (6) and (7) in the preceding abstract of report of Kosik, Kozmal and Reiser]; (3) the initial rapid weight loss in both cases is not due to desorption of water, but primarily to decomposition of the cellulose molecules.

"Fire-Retardation of Wood"—*S. Satonaka, S. Kobayashi, and Y. Kawashima*

Related Sections: **H**, *A*

Subject Headings: **Fire retardation, of wood;** *Thermogravimetric analysis; Xylan; Cellulose; Lignin; Dilydrogen ammonium phosphate; Cresyl phosphates; Pyrolysis, paper.*

Birchwood, its main constituents, xylan, cellulose, and lignin, and filter paper treated with diammonium hydrogen phosphate were pyrolyzed in a simple thermogravimetric balance. Rapid decomposition of xylan began below 100°C, of treated filter paper at 160°C, of lignin and of wood at 200°C, and of cellulose at 250°C. At 450°C less than 10% of the original weight of xylan, wood, or cellulose was left but 36% of the weight of lignin and 29% of that of treated filter paper remained. [The results differ markedly from the findings of Kosik, Geratova *et al.* and of other investigators in that unusually low temperatures of beginning rapid decomposition are reported for xylan, wood, and lignin and that for cellulose is higher than for any of them.]

A combustion apparatus for treated paper was a glass cage with a sheet of paper 6 cm wide by 13 cm tall clamped in a frame that could be advanced by remote control until the lower edge of the paper centered over a gas flame 2 cm high. Paper treated with at least 5.0 to 6.5% of dicyandiamide and phosphoric acid mixture, of Pyrosote (zinc chloride, ammonium sulfate, boric acid, sodium dichromate mixture) or of diammonium hydrogen phosphate, when burned, lost less than 10% of its weight. Paper treated with 27.2% of chlorinated paraffin lost only 17.6% when burned. Weight losses of paper treated with more than 25% of trimethyl, triethyl, triphenyl, or tricresyl phosphate were from 48 to 69%.

Untreated and treated paper was pyrolyzed at 700°C in a pyrolysis pipette and the gases evolved were analyzed in a gas chromatograph having a 2.0 cm column of active carbon at 170°C and helium carrier gas at 120 cc/min. Chemicals found effective as fire-retardants in the preceding paragraph greatly increased the yield of water and decreased the yield of combustible gases (chiefly carbon monoxide) in the evolved gases whereas the ineffective chemicals did neither. The gases from paper treated with diammonium hydrogen phosphate contained little ammonia.

I. Physical Aspects of Fires

Fletcher, B. (Safety in Mines Research Establishment, Sheffield, England) "Mass Transfer from an Axial Source in a Turbulent Radial Wall Jet," *Journal of Fluid Mechanics* **30**(1), 1–8 (1967)*

Related Sections: **I**, *G*

Subject Headings: **Mass transfer axial;** *Jet diffusion.*

This paper considers the mixing of a turbulent radial wall jet with a secondary fluid introduced into the impingement area of the wall jet so as to form a steady axisymmetric state. Similarity of the concentration profiles perpendicular to the wall has been assumed and, by solving the momentum and mass flow equations, the concentration distribution through the layer and a similarity exponent giving the variation of concentration along the wall have been determined.

Fletcher, B. and Leach, S. J. (Safety in Mines Research Establishment, Sheffield, England) "Theoretical Study of Longitudinal Diffusion into a One-Dimensional Turbulent Flow of Matter from a Source Moving at the Flow Velocity," *SMRE Research Report No. 251* (1967)

Related Section: **I**

Subject Heading: **Longitudinal diffusion, turbulent.**

Authors' Abstract

This is a theoretical investigation into the dispersion of gas emitted into a turbulent stream of air in a pipe, from a source moving at the main stream velocity.

* Reprint of Safety in Mines Research Establishment Abstract.

A virtual coefficient of diffusion is used to combine the effects of velocity variation across the pipe and turbulent diffusion, and the mean concentration over a cross section is derived as a function of time of emission, distance from the source, emission rate, cross-sectional area, fluid density, and a friction coefficient. A possible application of this investigation is to the build-up of toxic gas around a diesel locomotive moving along a mine roadway with the velocity of the air stream.

Foehl, J. M. (Anaconda American Brass Company, Waterbury, Connecticut) "Flow Characteristics—Copper Sprinkler Conductors," *Fire Technology* **4,** 169 (1968)*

Related Sections: **I,** *A, N*

Subject Headings: **Copper sprinkler conductors;** *Flow, hydraulic; Hazan-Williams factors.*

A comparative computer investigation of flow characteristics of copper conductors in hydraulically calculated sprinkler systems indicates that a Hazan-Williams *C* factor of 140 is conservative. The study challenges the appropriateness of the Hazan-Williams formula for sprinkler systems design and proposes alternate formulas.

Kennedy, M. and Taylor, G. (Safety in Mines Research Establishment, Buxton, England) "Temperature Distributions Downwind of Stationary Mine Fires," *British Journal of Applied Physics* **18,** 349–356 (1967)

Related Sections: **I,** *G*

Subject Heading: **Temperature distributions, downwind of fires.**

J. de Ris, Abstracter

This paper presents an experimental and theoretical analysis of the transient heat transfer within a ventilated duct. The temperature variations with time and distance are examined downwind of a heat source instantaneously imposed on a turbulent air current. The heat source simulates a fire and the downwind wall temperature distribution indicates the duct length heated by the fire at any given instant.

The authors simplified their mine fire study by using a 30 ft long, $2\frac{1}{2}$ in. square passage. The buoyance factor $\Delta\rho g D/\rho V^2$ for this narrow passage ($D = 2.5''$) is sufficiently small to permit a one-dimensional analysis of the turbulent gas phase

* Abstract from *Fire Technology.* By permission.

convection. By eliminating the complicated full-scale buoyancy effects, the authors were able to obtain a better understanding of the heat transfer processes. This work has been recently extended by Roberts and Clough[1] to include the effects of flame spread.

The heat transfer in mine roadways and other ducts is idealized by considering horizontal passages of constant cross-sectional area and shape through a medium of constant thermal conductivity, k_w, density, ρ_w, specific heat, C_w.

Since typical mine ventilating velocities, V, range from 50 ft/min to 500 ft/min, there is a considerable time delay before thermal disturbances at $x=0$ can be observed several thousand feet downwind. Thus it is convenient to relate the disturbance at x to the time parameter $\tau=t-x/V$ which is a measure of the time after the disturbance reaches position x.

At time $t=0$ the heat source is turned on causing a constant gas temperature, T_g^0, at $x=0$. The subsequent downstream gas phase and duct surface temperatures are then measured. Both the experiment and analysis show that the wall temperature at $x=0$ varies as

$$T_w^0=T_g^0\{1-\exp[(h^2\tau)/k_w\rho_wC_w]\ \mathrm{erfc}[(h^2\tau)^{1/2}/k_w\rho_wC_w]\}$$

where h is the gas phase to wall heat transfer coefficient. The analysis treats the wall medium as a semi-infinite solid.

The experimental data show that the gas and wall temperatures appear to decrease exponentially with distance downstream when evaluated at constant, τ. Using this exponential observation the authors deduce that the downstream wall temperature varies as

$$T_w(x)=T_g^0\left\{1-\exp\left(\frac{h^2\tau}{k_w\rho_wC_w}\right)\mathrm{erfc}\left(\frac{h^2\tau}{k_w\rho_wC_w}\right)^{1/2}\right\}$$

$$\times\exp\left[\frac{-hpx}{VA\rho C}\exp\left(\frac{h^2\tau}{k_w\rho_wC_w}\right)\mathrm{erfc}\left(\frac{h^2\tau}{k_w\rho_wC_w}\right)^{1/2}\right]$$

where p is the passage perimeter, A its area, ρ the gas density and C the gas specific heat. Although the authors do not verify this equation experimentally, the reviewer notes that this result satisfies the governing equations and boundary conditions provided $h^2\tau/k_w\rho_wC_w\ll 1$.

Finally one can show that the characteristic heat penetration depth into the duct walls is $2(k_w\tau/\rho_wC_w)^{1/2}$ which is of the order of 2 or 3 in. for the experiment. Since one expects to find the same heat penetration depth for a full-scale mine wall, the effects of curvature (of the mine's cross-sectional area) can be ignored, thereby permitting the wall to be treated as a semi-infinite solid.

Reference

1. Roberts, A. F., Clough, G.: "The Propagation of Fire in Passages Lined with Flammable Material" *Combustion and Flame 11*(5), 365–76 (1967).

Nelson, H. E. (General Services Administration, Washington, D.C.) "Radiant Energy Transfer in Fire Protection—Engineering Problem Solving," *Fire Technology* **4,** 196–205 (1968)

Related Sections: **I,** *A, G*

Subject Headings: **Radiant energy transfer;** *Ignition; Transport.*

J. Richmond, Abstracter

A simple graphic method of estimating radiant energy transfer from rectangular surfaces is developed. Although heat transfer by conduction and convection may also occur, in some cases radiation may predominate, such as heat transfer from hot external walls, fire doors, or fire barriers, and fire-resistive membrane ceilings.

Radiant energy transfer differs from the other two modes of heat transfer in that it travels in straight lines and is a function of the absolute temperature only, independent of temperature differences between radiator and receiver (as long as these differences are large). Radiant energy flux can be calculated from the Stefan-Boltzman law

$$I = laT^4,$$

where I is the radiant emission, l is the emissivity, T is the absolute temperature, and a is the Stefan-Boltzman constant (1.356×10^{-12} cal/cm^2 sec °K^4). A black body is an ideal radiator which absorbs all incident radiation, reflects none, and has an emissivity of 1.00. In the rest of the paper, black body radiation is assumed, and only geometric factors are considered. Proper corrections can be made for emissivities less than 1.00.

Radiant energy falling on a target varies as the inverse square of the distance from a point source; as the first power of the distance from a line source, and independently of distance from an infinite plane source. For all practical purposes, a fire-resistive ceiling suspended any normal distance beneath a floor is an infinite plane source with respect to most points on the underside of that floor. Radiation transferred from various points varies as the cosine of the angle drawn from the respective lines of sight.

Hemispherical radiation from points on plane sources is considered, and configuration factors are computed for various rectangular shapes and non-dimensional distance. The configuration factor is defined as that fraction of the total radiation flux leaving a radiator that is incident upon a point on the target. Configuration factor, ϕ, is plotted against S/W, for various values of L/W, for all practical values of these quantities. L is the long dimension of the radiator, W is its width, and S is the distance between the center of the radiator and the target point. Most intense transfer, of course, occurs perpendicular to the center of the radiator.

Obstacles to radiation can come from smoke or haze, and from glass. Window glass, for example, will transmit about 55% of the incident energy.

A table is also provided for critical intensity levels for autoignition or pilot ignition of various building materials, for a dry specimen exposed for 15 minutes or less. Pilot ignition is a simulation of ignition by a flying brand. The values of critical level vary between about 0.2 and 1.0 cal/cm^2 sec. A critical value for pain and blistering of human skin is 0.25 cal/cm^2 sec.

Two practical examples are given, using this method. One involves the impact on evacuees using a stairwell that passes by a hot firedoor, and gives critical distances from that door for various door temperatures. The other problem solves the case of a glass barrier in front of a thick fire acting as a black body. Critical distances for pain on the skin or ignition of clothing are calculated.

Rosenhan, A. K. (Mississippi State University, State College, Mississippi) "Water Net—A Computerized Design Aid," *Fire Technology* **4,** 179 (1968)*

Related Sections: **A,** *N*

Subject Headings: **Water net computerized design;** *Hydraulic.*

Water Net makes it possible to perform hydraulic analyses with ease. The complexity of the system to be analyzed is limited only by the user's imagination and the capacity of the computer being used. The user need not have been trained in computer programing.

Editor's Note: This paper is a qualitative description of a program developed to solve hydraulic problems. Terms are defined, but no indication is given of the program details, the computer language used, or the machines on which the program is useful. Details are presumably available from the author.

Sukomel, A. S., Tsvetkov, F. F., and Kerimov, R. V. (Moscow Power Institute, Moscow, USSR) "A Study of Local Heat Transfer from a Tube Wall to a Turbulent Flow of Gas Bearing Suspended Solid Particles," *Teploenergetika* **14,** 77–80 (1967)

Related Sections: **I,** *G*

Subject Heading: **Heat transfer.**

J. de Ris, Abstracter

The problem of heat exchange between a dust-laden turbulent flow and a surface has, to date, received relatively little attention. This problem is related to the turbulent heat transfer from a smoky gas to a surface.

The paper reviews the current knowledge and presents experimental data on the entrance region local heat transfer rates over a wide range of (a) particle sizes (65 μ to 290 μ); (b) particle mass flow concentrations (0.5 kg/kg to 23 kg/kg) relative to the gas mass flow. In addition the effects of several different carrier gases were measured.

The experiment consisted of an insulated approach tube connected to a uniformly

* Abstract from *Fire Technology.* By permission.

heated test section. Thermocouples measured the tube wall temperature along the test section. The Nusselt number is defined as

$$\mathrm{Nu} = qD/(T_{\mathrm{wall}} - T_{\mathrm{mix}})k_{\mathrm{gas}}$$

where q is the wall heat flux, D is the tube diameter, and T_{wall} is the local wall temperature. Finally T_{mix} is the average bulk mixture temperature calculated from the equation

$$T_{\mathrm{mix}} = T_{\mathrm{initial}} + [qDx/(G_{\mathrm{gas}}C_{p\ \mathrm{gas}} + G_pC_{p_p})]$$

where T initial is the initial gas temperature (at $x=0$), x is the distance along the test section, $G_{\mathrm{gas}}(G_p)$ is the total gas (particle) mass flow, and $C_{p\ \mathrm{gas}}(C_{p_p})$ is the associated gas (particle) specific heat. This Nusselt number definition would be most appropriate if the gas and particles were in thermodynamic equilibrium; however this is not generally the case for particles greater than 100 μ in size.

The experimental data indicates that:

1. The Nusselt number decreases with a rise in mass concentration G_p/G_{gas} ratio when this concentration ratio is less than 3; Nu increases with concentration for larger values of concentration.
2. The length of the initial thermal (entrance) section is considerably greater for particle-laden-gas flow than for clean gas flows.
3. The Nusselt number significantly increased for large temperature differences (~500°C) due evidently to radiation.

The best, presently available, theory (Ref. 1) is not in good agreement with these experimental results. This lack of agreement can possibly be attributed to the, as yet, undetermined effect of particle damping of the hydrodynamic turbulence intensity, as well as the lack of thermal equilibrium between the gas, particle surface and particle interior.

From the standpoint of fire research, a considerably better understanding of the related physical processes probably must be acquired before these results can be confidently applied to fire research problems.

Reference

1. Depew, C. A., and Farbar, L.: "Heat Transfer to Pneumatically Conveyed Glass Particles of Fixed Size," *Trans. ASME, Series C,* 1963 **85**(2), 164–172.

Waterman, T. E. (IIT Research Institute, Chicago, Illinois) "A Calorimeter for Separating Radiative and Convective Heat," *Fire Technology* **4**, 109 (1968)*

Related Section: **I**

Subject Headings: **Calorimeter**; *Heat flux.*

Often the experimenter is faced with the necessity of measuring heat flux and determining how much is transmitted by radiation and how much by convection.

* Abstract from *Fire Technology.* By permission.

The author describes a recently developed device which measures total flux and radiant flux separately. With these two quantities known, it becomes a simple matter to determine the amount of convective heat.

J. Meteorological Aspects of Fires

Countryman, C. M. and Fosberg, M. A. (Forest Fire Laboratory, U.S. Forest Service, Riverside, California), **Rothermel, R. C.** (Intermountain Forest and Range Experiment Station, Missoula, Montana), and **Schroeder, M. J.** (U.S. Weather Bureau, Riverside, California) "Fire Weather and Fire Behavior in the 1966 Loop Fire," *Fire Technology* **4**, 126–141 (1968)

Related Headings: **J**, *D*

Subject Headings: **Fire weather**; *Fire propagation; Propagation.*

O. P. Cramer, Abstracter

The authors reconstruct the fire behavior that resulted in the death of 12 experienced fire fighters. They also describe in detail the characteristics of Santa Ana weather and accompanying fire behavior. The weather during the day of the Loop Fire is uniquely described by utilizing numerical analysis techniques.

The tragic incident that drew attention to the Loop Fire apparently occurred late in the afternoon of November 1 in a small, steep, south-facing draw off Pacoima Canyon at the west end of the San Gabriel Mountains about five miles northeast of San Fernando at the edge of the Angeles National Forest.

The day's Santa Ana winds had subsided and the fire was moving slowly downslope against the wind. It was being easily held along a bulldozed line. When the fire reached the end of the line in a steep draw, a combination of heavier fuels, eddy currents, and thermal effects triggered a small fire run up the side of the draw and into the base of a steep and narrow chute in which a crew was working. The fire was estimated to have moved from the base to the top of the chute in one minute. After this run, the fire continued upcanyon movement against the wind with occasional rapid runs up steep narrow draws to the top of the ridge.

Though the authors found no unusual fire behavior, they point out that when fuels become as dry as they were that day the fire situation can often be in a delicate balance. A quick and violent change in fire behavior can be triggered by any slackening in air flow, a surge of heat from heavier fuels, an eddy current, the fire reaching different topography, or a combination of these factors.

The fuel involved in this event was estimated by mapping burned stumps and remnants, then comparing with nearby unburned areas of similar species, size, and density. The authors derived a fuel loading in the tragedy area of 1.6 lb/sq ft of sumac including heavy litter of dead material. This was estimated to produce

12,800 Btu/sq ft. The estimated peak energy output was 3332 Btu/ft/min in the first 30 sec with flame temperatures of 2500°F or higher.

The narrow chute acted like a chimney concentrating the flame and reflected heat in its throat. The men in the lower part of the chute were subjected to near maximum temperature.

The fuels involved were exceptionally dry, having been exposed to dry winds and high temperatures for extended periods. Under such conditions the potential energy of the fuels can be released very quickly and violent fire activity results. There had been 24.7 days of Santa Ana conditions in the preceding two months. During the afternoon of November 1 the temperature had been in the low 90's and the humidity 18 to 22%. Fuel stick moisture readings were in the range of 3 to 4%. Winds were light and convection alone could account for the rapid movement of the fire.

Weather conditions in the general area of the fire were subjected to numerical analysis at three-hour intervals to determine dynamic characteristics of the airflow. This procedure was possible because 29 observation stations were in the vicinity. Values of wind and the vertical component of vorticity were computed for each of 35 grid points. Strength of the Santa Ana was computed as the area integral of the kinetic energy in the surface boundary layer. Sea level potential temperature maps and wind cross sections were also prepared.

These analyses showed typical weakening Santa Ana conditions at 4 p.m. Vertical motion was slightly downward. There was no evidence of a wind shift, but small eddies were formed by jet-like flow emerging from canyons.

Though not a factor in explaining this fire's behavior during the tragic event, the use of numerical dynamic analysis of mesoscale weather to examine a problem fire situation is new in fire analyses.

L. Operations Research, Mathematical Methods, and Statistics

Triner, E. G. (Serendipity Associates, Chatsworth, California) "Fire Loss Reduction—An Analytical Approach," *Fire Technology* **4**, 310 (1968)*

Related Sections: L, *E*

Subject Heading: **Fire loss reduction.**

The process of analysis can be employed to improve the capability to translate resources into a reduction in fire losses. Only by this type of integrated approach can we achieve the benefits required from the resources invested.

* Abstract from *Fire Technology.* By permission.

Wilde, D. G. (Safety in Mines Research Establishment, Buxton, England) "Fires in Mines—Recent Experience," *Colliery Guardian* **215,** 629–632 (1967)

Related Sections: **L,** *A*, *C*

Subject Headings: **Mine fires;** *Statistics*

R. M. Fristrom

This paper is a survey of the statistics on mine fires occurring during the period 1961–1966. The number of outbreaks, locations, sizes, causes, and the materials burned are discussed. Figures on causes are compared with figures for the period 1940–1950. Tests to assess the effectiveness of fireproofing of timber by impregnation are described. It is concluded that the principal causes of some 60 mine fires that occur each year are frictional heating and electrical failures; that the risk in intake airways is higher than in all other locations combined; and that the materials most commonly burned are coal (particularly when it is finely divided) and the lubricating oils. The fire risk in mines is not, however, fully represented by the statistical evidence. It is also suggested that wider use should be made of automatic forms of fire detector, and that fire-resistant emulsions rather than mineral oils should be used in hydraulic equipment. A further conclusion is that while fire-retardant treatment by impregnation greatly reduces the fire hazard presented by timber, it cannot be relied upon to save life in every case if the timber is attacked by a well-developed fire.

N. Instrumentation and Fire Equipment

Friedman, R. (Atlantic Research Corporation, Alexandria, Virginia) "Experimental Techniques for Solid-Propellant Combustion Research," *AIAA Journal* **5**(7), 1217–1223 (1967)

Related Sections: **N,** *D*

Subject Headings: **Experimental techniques for solid-propellant combustion.**

A. S. C. Ma, Abstracter

Experimental techniques developed as part of scientific studies in five research fields relating to solid-propellant combustion were reviewed, excluding those utilized in empirical investigations. The reason for the slow progress was attributed partly to the incomplete theoretical understanding of the controlling parameters in some cases and partly to the difficulties arising from the small thickness to be investigated and from the high temperature and pressures prevailing in the combustion zone.

In the combustion zone, the basic problem remained to be the accurate determination of the surface temperature. Relative merits of the embedded thermocouple method and the infrared emission method were discussed in depth. Procedures of examining the suddenly quenched specimens were described, although the validity of the method was generally questionable. Several novel techniques on temperature distribution developed for *in situ* flame investigation and on composition distribution were briefly introduced. Also, listed were some suggestions for obtaining successful results from direct cine-photography.

The experiments on composite solid-propellant combustion were idealized because of the difficulties in performing quantitative tests on the propellants. One class of experiments dealt with the behavior of one ingredient of the propellant in isolation and studied the oxidizer self-deflagation, the binder pyrolysis, or the combustion of single particles of metal ingredients in oxidizing atmospheres. Other studies were also made of fuel-oxizer interactions in different geometrical arrangements, and of gaseous combustion systems to simulate aspects of solid-propellant combustion.

The basic objective of ignition studies was to determine the relative contributions of gaseous, condensed-phase, and surface reactions to the preignition energy release. But, the immediate objective was to determine the ignition delay as a function of heat flux applied to the surface. The latter required the technique of producing a heat flux of the order of 100 cal/cm^2/sec, radiant or convective. Many devices were discussed under the light of whether the basic objective was fulfilled and whether the reaction was selfsustaining after ignition, defined as the first detectable emission of light.

The distinct phenomena related to extinguishment of solid-propellants were of great interest: (1) the lowest steady-state ambient pressure at which combustion would maintain itself; and (2) the transient extinction resulting from very rapid pressure decrease. In neither case, was there a complete theoretical understanding of the controlling factors; therefore, design and interpretation of experiments needed care.

On the acoustic interaction, the author summarized the view of treating the combustion zone as a region of gas generation under the influence of a traverse acoustic wave with a phase lag. The occurrence of amplification depended on the relative magnitudes of the acoustic admittance and the acoustic damping of the flame. The experimental measurement of acoustic admittance vs frequency for the propellant at the pressure of interest became the main task. As the result of attempts made over the last decade, data were obtainable from T-burners, several types of which had been discussed in good detail.

Hickey, H. E. (University of Maryland, College Park, Maryland) "An Approach to Evaluating and Maintaining Sprinkler Performance," *Fire Technology* **4**, 292 (1968)*

Related Sections: **N**, *A*

Subject Headings: **Sprinkler performances**; *Hydraulic calculation.*

The author presents a conceptual framework for hydraulically calculating sprinkler demand curves based upon a modular loss system. He established an interrelationship between a low module and the demand requirements of a sprinkler system in terms of water density required to control a fire at the modular level and to supply supplemental hose streams for completing extinguishment.

* Abstract from *Fire Technology*. By permission.

Koohyar, A. N., Welker, J. R., and Sliepcevich, C. M. (University of Oklahoma, Norman, Oklahoma) "An Experimental Technique for the Ignition of Solids by Flame Irradiation," *Fire Technology* **4**, 221–228 (1968)

Related Sections: **N**, *B*

Subject Headings: **Ignition, by flame radiation**; *Radiation ignition cabinet.*

F. R. Steward, Abstracter

This paper describes a "flame ignition cabinet" that is used to determine the ignition characteristics of cellulose fuel samples when the source of irradiation is a buoyant diffusion flame. The advantage of this type of apparatus is that it corresponds more closely to the ignition encountered when a fire is spreading through a structure than the more conventional thermal radiation sources, such as carbon arcs, tungsten filament lamps, gas fire panels, or solar furnaces. The spectral distribution of radiation from a flame of burning combustibles is considerably different from that emitted by the above mentioned conventional sources.

The cabinet encloses a flat rectangular sample mounted between two line buoyant diffusion flames so that it is irradiated on both sides. Air is drawn through the cabinet from below by an exhaust from which also discharge the combustion products. The burners use liquid fuel whose flow rate is controlled by a constant siphon head.

During the period of irradiation the weight of the sample and its surface temperature are measured continuously by a Statham Load Cell and a total irradiation pyrometer, respectively.

Some initial data is given which indicate the temperature of the surface and the rate of weight loss (volatile evolution) at the point of ignition. These quantities have often been used in the past to correlate the ignition characteristics of cellulose materials.

Koohyar, A. N., Welker, J. R., and Sliepcevich, C. M. (University of Oklahoma, Norman, Oklahoma) "The Irradiation and Ignition of Wood by Flame," Fire Technology **4**, 291–294 (1968)

Related Sections: **N**, *B*

Subject Headings: **Ignition, by flame**; *Flame radiation; Cellulose; Radiation.*

F. R. Steward, Abstracter

This paper presents data on the spontaneous and piloted ignition characteristics of five different species of wood—fir, mahogany, oak, pine, and redwood. The data were taken by exposing the samples to irradiation from a line buoyant diffusion flame with a level of irradiation between 0.275 and 0.855 cal/cm^2 sec. Both one- and two-sided heating were employed.

An attempt to correlate the data on the bases of two previous methods (one employing a critical rate of volatile evolution criteria for ignition by Sauer,[1] and the other a fixed surface temperature criteria for ignition by Simms[2]) gave poor results.

Two additional models are proposed in which it is assumed that the irradiated material is opaque to the irradiation, inert to chemical reaction, and with physical properties independent of temperature. One model assumes the material has a finite thickness; the other that it is semi-infinite. The difference between this model and that proposed by Simms[2] mentioned above is that surface-convertive cooling is neglected. The data are well correlated by the solution to the differential equation when multiplied by a factor which represents the fraction of heat entering the material. The data fell mainly in the region where the material is semi-infinite. However, in the opinion of the reviewer this does not represent a correlation of the ignition data since any data taken on the surface temperature of the sample as a function of time should fall on this curve if the material is opaque and inert. The point of ignition is irrelevant.

In order for an irradiated cellulosic material to ignite, it is necessary to form a combustible mixture in the volatile stream at a point where the temperature is high enough for this mixture to ignite. Thus, in order to obtain a complete picture of ignition phenomena it is the opinion of the reviewer that an analysis of the mass and heat transfer in the gas phase is also essential.

References

1. Sauer, F. M.: "The Charring of Wood during the Exposure to Thermal Radiation—Correlation Analysis for Semi-Infinite Solids." *Interim Technical Report AFSWP-838, Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service.*
2. Simms, D. L.: "Ignition of Cellulosic Materials by Radiation." *Combustion and Flame* **6**(4), 293–300 (1960).

Palmer, K. N. (Joint Fire Research Organization, Boreham Wood, England) "Explosion Suppression and Relief Venting," *Chemistry and Industry* **23**, 936–942 (1967)

Related Sections: **N**, *A*, *B*, *F*

Subject Headings: **Relief venting, of explosions**; *Ignition, sources of explosions; Bursting discs; Relief panels.*

J. Ahern, Abstracter

In this article, the author discusses the problems presented by explosions within industrial equipment and duct work as well as those which may occur in rooms containing combustible air gas mixtures. The relationship between flame spread and venting is discussed with attention given to the size, type, and location of venting devices. Considerable attention is given to the elimination of ignition sources where explosion potential exists.

The author points out that in the majority of applications, light-weight relief panels are recommended over the use of bursting discs because of the inertial factor presented. Valuable information is presented on the venting of industrial ovens. The article concludes with a good discussion on desirable data on flame arrestors and automatic explosion suppression systems.

McGuire, J. H. (National Research Council, Ottawa, Canada) "Control of Smoke in Building Fires," *Fire Technology* **3**, 281–290 (1967)

Related Sections: **N**, *A*, *F*

Subject Headings: **Smoke control**; *Ventilation.*

J. Ahern, Abstracter

The control of smoke in a building fire presents one of the most difficult, and also one of the most important, factors from the standpoint of safety to life in modern structures. The tremendous development in completely sealed structures, in which the only openings are doorways, presents a continuing threat to life of the occupants from even a small, smoky fire.

In this article, the author presents several approaches to the problem of controlling the movement of smoke to permit safe evacuation of a building.

It is pointed out that modern mechanical ventilation systems will probably distribute smoke throughout much of the building unless extensive modifications are made in present control systems. The conclusion is reached that the complicated arrangements required to meet this problem are probably not justified, when merely switching off all mechanical ventilation provides an acceptable alternative. This alternative can only be used, however, if the stairwells are completely smoke free.

In this article, the author describes in detail several methods in accomplishing this highly desirable result. The author also discusses in some detail the use of air injection into critical areas to control smoke migration and outlines not only the advantages but points out the dangers involved in the event the area also becomes involved in fire.

This article opens up many interesting possibilities related to the control of smoke in buildings and points out the need for further work in this important area. As we continue the development and construction of large, completely sealed structures which house great numbers of people, this will become a matter of vital concern in the protection of the occupants.

Walker, J. D. and Stocks, B. J. (Canada Department of Forestry and Rural Development) "Thermocouple Errors in Forest Fire Research," *Fire Technology* **4,** 59–62 (1968)

Related Sections: **N,** *J*

Subject Headings: **Thermocouple errors;** *Flame temperature; Temperature.*

B. Greifer, Abstracter

An empirical method of correcting for radiation errors of thermocouples is presented. "True" flame temperatures are measured by extrapolating readings to zero thermocouple diameter.

Discussion

Thermocouples used to measure forest fire temperatures read low if the flames are less than 5 ft thick, because the thermocouples radiate heat to cooler surroundings outside the flames. This radiation error is usually minimized by shielding; or by calculating its magnitude and correcting for it. Often, a heat balance cannot be calculated for a thermocouple because some thermal parameters are missing, such as thermocouple emissivity, flame opacity, etc. A simple empirical procedure is described which depends on the fact that the radiation loss varies inversely with the ratio of the radiating surface area to the unit volume. In the limiting case, zero-diameter thermocouples should give "true" temperature readings. The method involves plotting measurements made with a series of thermocouples of different wire sizes, and extrapolating to zero diameter.

Experimental

Four bare chromel-alumel thermocouples of diameters 0.005, 0.010, 0.020, and 0.032-in. respectively were exposed (1) to the outside edge of a small alcohol flame, (2) to the center of this alcohol flame, (3) 0.5 in. above an 0.5 f.p.m. moving laboratory fire 1 ft high and 4 in. thick, in a 2.5 ft bed of dry, red pine needles, (4) to two large fires, 18 in. thick and 3 to 4 ft high in white pine wood.

TABLE 1.
Average recorded temperatures (°F) in various flames and true temperatures estimated by extrapolation to zero wire diameter

Flame	Average temperature (° F) Thermocouple wire diameter (in.) 0.032	0.020	0.010	0.005	Estimated temperature at zero diameter
Alcohol, edge	1,132	1,395	1,528	1,610	1,720
Alcohol, center	995	1,202	1,454	1,490	1,610
Pine needles	1,409	1,535	1,746	1,873	2,000
Pine wood	1,532	1,580	1,672	1,744	1,810

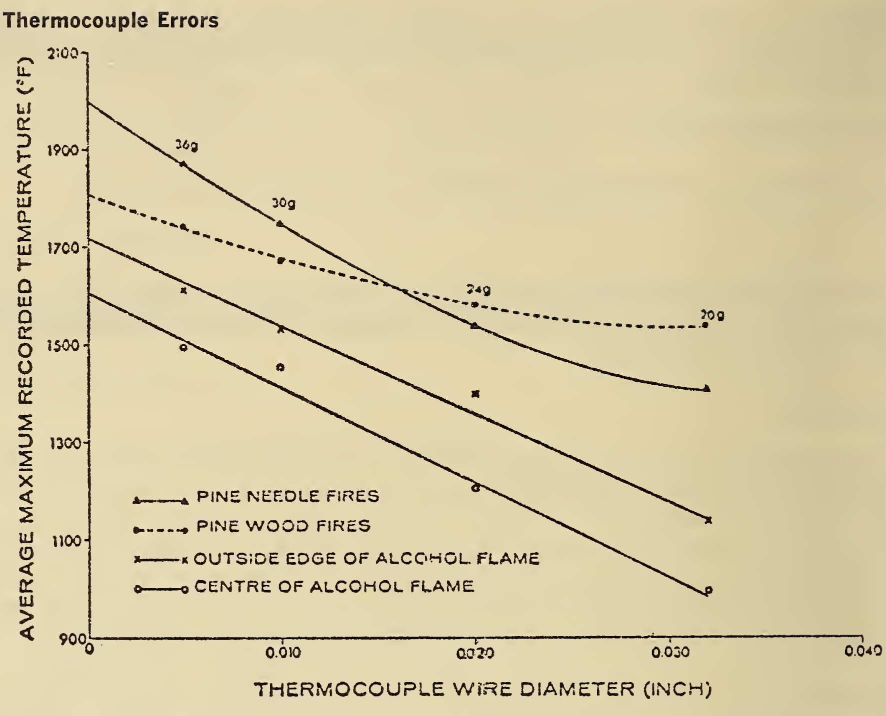


FIG. 1. The effect of thermocouple wire diameter on temperature measurements.

The average maximum temperature of two to six measurements on each fire (Table 1) was plotted vs thermocouple wire diameter (Fig. 1).

By extrapolating the graph to zero diameter the "true" maximum flame temperature was estimated for each fire.

Conclusions

(1) There are appreciable thermocouple errors in measuring temperatures of small flames, less error in larger flames, and presumably negligible error in 5 ft thick flames.[1]

(2) These errors are roughly proportional to wire diameter, and are the same for any given thermocouple size, in any small flame.

(3) Extrapolation of the graph to zero wire diameter gives the highest temperature, and this is taken as the "true" flame temperature with zero radiation loss from the thermocouple.

(4) A satisfactory estimate should be possible in the field with only two thermocouples of, say, 0.010 in. and 0.032 in. diameter wire, exposed close together.

Reference

1. McAdams, William H.: *Heat Transmission,* McGraw Hill, N. Y. (1954) pp. 252–264.

Webb, W. A. (Underwriters' Laboratories, Inc., Chicago, Illinois) "Effectiveness of Automatic Sprinkler Systems in Exhibition Halls," *Fire Technology* **4**, 115 (1968)*

Related Sections: **N**, *A*, *E*

Subject Headings: **Sprinkler systems**; *McCormick Place Fire.*

In co-operation with Mayor Daley's Committee to investigate the McCormick Place Fire, Underwriters' Laboratories tested the effectiveness of automatic sprinkler systems in a simulated exhibition hall having ceiling heights of 30 ft and 50 ft. The results may prove surprising to some who doubt the value of sprinklers in high-ceilinged structures, such as McCormick Place.

Zenin, A. A., Glazkova, A. P., Leypunskiy, O. I., and Bobolev, V. K. "Flame Radiation Measurement by Microcalorimeters," *The Physics of Combustion and Explosives* 4(2), 196 (1968) In Russian.

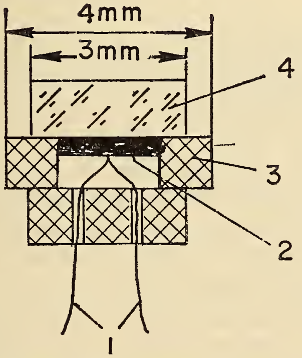
Related Sections: **N**, *I*

Subject Heading: **Microcalorimeter, for radiation.**

Authors' Conclusions—Translated by L. J. Holtschlag

1. A method has been developed and verified for measuring the density of the radiant flux Figs. 1 and 2 from the flame of a hot condensed material using microcalorimeters of low thermal inertia.

2. A study was made of the effect of the Al content and of the size of the Al particles on the density of the radiant flux from the flame of a model stoichiometric mixture of NH_4ClO_4+polyformaldehyde. It was shown that q increases with



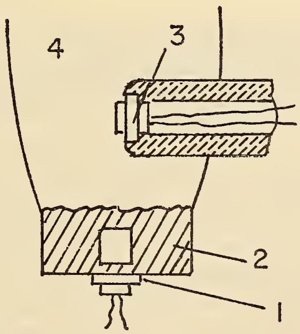


FIG. 1. Diagram of microcalorimeter. (1) thermocouple; (2) copper disk; (3) annulus, inner dia. 2 min.; (4) quartz window.

FIG. 2. Diagram of how the radiant flux measurements were made (calorimeter 1) and how the radiation (calorimeter 3) was measured in the flame (4) of the burning sample (2).

* Abstract from *Fire Technology*. By permission.

increasing pressure and Al content. A suggestion was made as to the cause of the growth of q with increasing pressure.

3. An estimate was made of the radiation capability ϵ of hot Al and corundum particles in the flame of the compounds being studied; $\epsilon = 0.13–0.15$ at 40 atm.

4. An examination was made of the effect of the radiant flux on measurements of the temperature distribution at the surface of the hot compounds under study by means of thin thermocouples and it was shown that this effect can be neglected.

O. Miscellaneous

Grant, D. B. (Canadian Underwriters Association, Montreal, Canada) "The Wabush Mines Fire," *Fire Technology* **4,** 229 (1968)*

Related Section: **O**

Subject Heading: **Wabush Mines Fire.**

How could a five-million-dollar fire occur in a seemingly low hazard industry? The author discusses one such fire and examines the lessons learned from it. It takes careful study to determine if well-known fire protection principles are being violated.

Books

Scientific Fire Fighting by **J. O'Hanlon** (Privately published by Hubert A. Howson, 233 Broadway, New York, New York 10007) (1968) 95 pp. $2.00

Subject Heading: **Fire fighting, scientific.**

R. M. Fristrom

This small soft bound volume provides a description of a number of historically important fires, together with a discussion of the author's analysis of the important scientific factors involved. A background of miscellaneous scientific information is given.

The science is elementary since the intended audience is the lay public and line firemen. Because this level of exposition was chosen, little of the scientific background will be new to the average fire research worker. Nevertheless, the book is worth perusing because it documents the judgements of an experienced Fire Officer on the factors governing a number of historical fires and fire situations and the scientific level on which an educated fireman views the problem. Such information is usually only obtained from experience or by word of mouth. The book contains a number of practical observations by an astute observer who was firmly convinced that fire problems are explainable and can be reduced to a Science. Fire Science lost a convincing advocate with the untimely death in 1966 of Assistant Chief O'Hanlon of the New York City Fire Department.

* Abstract from *Fire Technology*. By permission.

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Under the terms of its Congressional charter, the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and autonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

THE NATIONAL RESEARCH COUNCIL was organized as an agency of the National Academy of Sciences in 1916, at the request of President Wilson, to enable the broad community of U.S. scientists and engineers to associate their efforts with the limited membership of the Academy in service to science and the nation. Its members, who receive their appointments from the President of the National Academy of Sciences, are drawn from academic, industrial and government organizations throughout the country. The National Research Council serves both Academies in the discharge of their responsibilities.

Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

THE COMMITTEE ON FIRE RESEARCH functions within the Division of Engineering to stimulate and advise on research directed toward the development of new knowledge and new techniques that may aid in preventing or controlling wartime and peacetime fires. The Committee was established in December of 1955 at the request of the Federal Civil Defense Administration. It is supported by the Office of Civil Defense of the Department of the Army, the U.S. Department of Agriculture through the Forest Service, the National Science Foundation, and the National Bureau of Standards.

Volume 11 1969 Number 2

Fire Research Abstracts and Reviews

National Academy of Sciences
National Research Council

FIRE RESEARCH ABSTRACTS AND REVIEWS

Robert M. Fristrom, Editor

The Committee on Fire Research

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

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FOREWORD

This issue begins with "A Proposed National Fire Research Program" written by the Committee on Fire Research, National Academy of Sciences-National Research Council, which supplements and up-dates a Program published by the Committee a decade ago. It is a document well-worth reading and considering seriously. The past decade has been one of slow but definite progress in fire research, which the Committee has fostered through its recommendations. The 1969 Program outlines an advance of present practices. It is hoped that many individuals and organizations will contribute to progress in this area during the coming decade.

A comprehensive national fire program, carried out on all levels from practical to academic, is important to our society. This country has the worst fire record of any developed country.[1,2] During his lifetime the average person can look forward to working six to eight months to pay for his share of direct fire costs, and also to a one in three hundred probability of dying from fire. It might be argued that part of this poor record is explained by differences in bookkeeping and statistical methods. We should strive for a fire record that is outstanding, irrespective of the mode of comparison. If the diverse groups in the fire field will cooperate, this is feasible and can be accomplished. During the coming decade, we look forward to a renaissance in the attack on the fire problem.

We are printing a review by E. I. Hale, "Survey of Vapor Phase Chemical Agents for Combustion Suppression." It provides a very useful up-to-date summary.

The issue is concluded by selections from papers presented at the Symposium on Burns and published under the editorship of Dr. Carl Walter and Dr. Anne Phillips. This extensive discussion is a substantial contribution to the understanding of the problems connected with treating the great number of burn injuries during disaster conditions. The Committee on Fire Research and the Office of Civil Defense have done a public service in providing this forum for this problem. Dr. Walter and Dr. Phillips for the Committee and Colonel Kerr for OCD should be complimented on the excellent coverage provided through their organization of the Symposium and the editorship of the Proceedings.

References

1. Berl, W. G.: *Fire Research Abstracts and Reviews 6*(1), Foreword (1964).
2. Lawson, D. I.: "Fire Protection Services in the USSR," *Fire Research Abstracts and Reviews* 7, 1–18 (1965).

R. M. Fristrom, *Editor*

A PROPOSED

NATIONAL FIRE RESEARCH PROGRAM

Recommended by the Committee on Fire Research
Division of Engineering—National Research Council

Related Sections: O, *A,B,C,D,E,F,G,H,I,J,L,M,N,O*

Subject Heading: **Fire Research Program, National**

PREFACE

In 1959 the Committee on Fire Research and the Fire Research Conference, of the Division of Engineering of the National Research Council, issued a Proposed Fire Research Program. The dearth at that time of basic research directed toward a fundamental understanding of the phenomena of ignition, fire growth, and fire spread was emphasized; and a plea was made for more sophisticated studies of fire phenomena, using the modern tools of applied mathematics, thermodynamics, fluid mechanics, chemical kinetics, and operations research. In detailing the program, emphasis was put on forest fires, partly because the forest, complex as it is structurally, presents a more nearly uniform fuel to burn than does the city; and a principle of scientific research on related problems difficult to understand is to attack the simpler ones first.

The growth in basic research on fire phenomena since the first Proposed Program was issued has been small but significant; an increasing number of scientists and engineers have initiated programs aimed at a more fundamental understanding of fire behavior. More impressive have been the advances in areas of applied research. Improved airborne attack on forest fires, progress in the modeling of firespread through the forest, the use of airborne infrared observation both to detect fires and to follow the movement of fire fronts, the estimation of ignition probabilities in buildings subjected to nuclear attack, and the estimation of related firespread through cities—these are a few of the problems on which significant progress is being made by the Forest Service and the Office of Civil Defense, sometimes working together. This research progress has not been matched by efforts on the peacetime fire problems of cities. The passage of the Fire Research and Safety Act of 1968 is a clear recognition of our national need for increased activity to prevent and suppress fire. A new statement of a program on fire research, with emphasis on the city, is therefore timely. It does not replace the earlier Proposed Program issued by this Committee; it complements it.

This proposed program was developed through studies funded by the National Science Foundation, National Bureau of Standards, U.S. Forest Service, and the Office of Civil Defense, Department of the Army by agreement with the National Academy of Sciences.

Copies available from Executive Secretary, Committee on Fire Research, National Research Council, Washington, D. C. 20418.

Introduction

"The magnitude of present civil losses from large fires and the potential fire destruction consequent on nuclear bomb attack need no emphasis. The explosive growth of science and engineering has multiplied our fundamental scientific knowledge, the complexity of our material goods and services, and the hazards from fire; growth in our knowledge of how to cope with fire has not kept pace with these other growths."* The total annual cost of fire in the United States in 1961 was estimated at about $5 billion. This included loss from actual physical damage plus the costs of fire departments, fire protection, and insurance operation. It did not include the waste of resources in building construction associated with strengthening other than the weakest links in the chain of fire prevention, nor did it include economic losses due to interruptions in industrial effort. A more recent estimate which allowed in part for the factors omitted above put the annual United States fire loss at $10 billion. More important and not expressible in dollars is the annual loss of some 12,000 lives in fire, a figure shockingly higher per capita than that in any other nation.

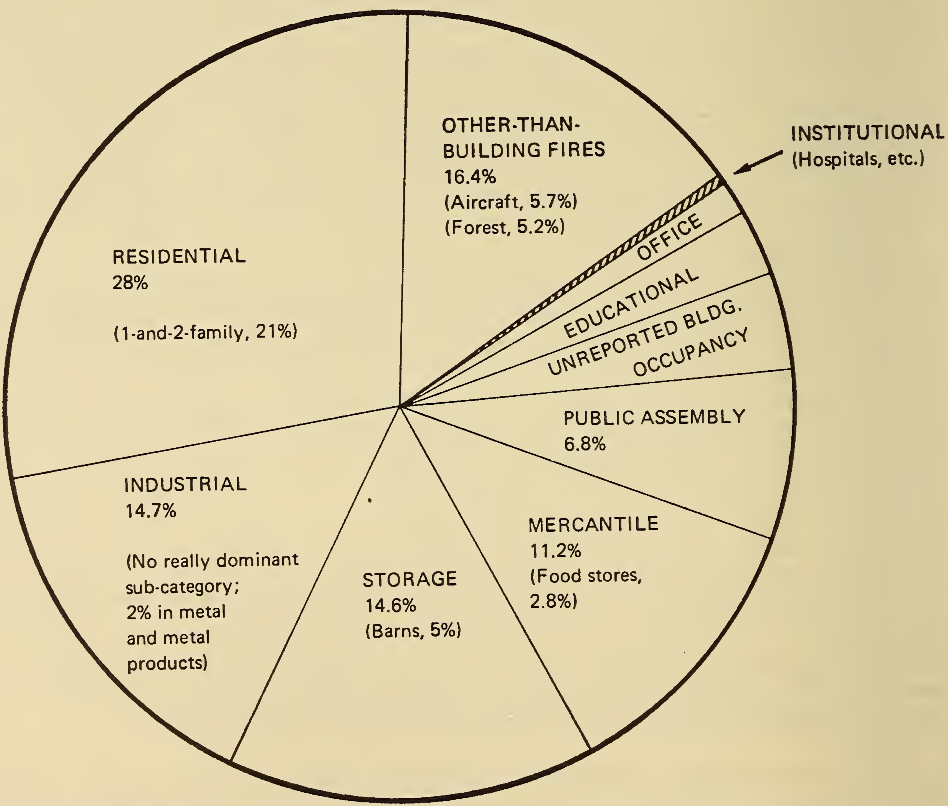

FIG. 1. U.S. Fire Losses, by Occupancy. (In each class, the largest sub-class appears in parentheses; all percentages are on basis of total dollar-value.)

* Quoted from the 1959 Proposed Fire Research Program of the Committee on Fire Research.

A clearer identification of our national fire problem comes from consideration of the kinds and causes of fires. Figure 1 shows the distribution of U.S. fires by occupancy, and indicates dwelling fires to be the largest category; but it gives no weighting to dollar loss. Figure 2 indicates the distribution of causes of fires; it emphasizes the lack of knowledge of exact causes of fires accounting for about one-third the total dollar loss.

Reduction of fire losses comes from action along many fronts, and research is only one of them. The chief stimulants to any research which reduces the national total susceptibility to fire are the following: a) conflict on test procedures; b) code improvement activities; c) profit from manufacture; d) reduction of fire loss. These generate a certain amount of research effort, mainly and properly of an applied character. Basic research on a better understanding of the phenomena of ignition, growth, and spread of fire, however, needs more stimulation than comes from the above. A manufacturer of gas turbines or furnaces has no trouble visualizing the relation of fundamental combustion research to his operation for profit. But unfriendly combustion—fire—is a manifold problem, with little prospect that company-sponsored basic research on a particular phenomenon of fire will relate to that particular company's next fire. Consequently, the nation's basic fire-research effort must come primarily from Federal agencies, the universities, and other

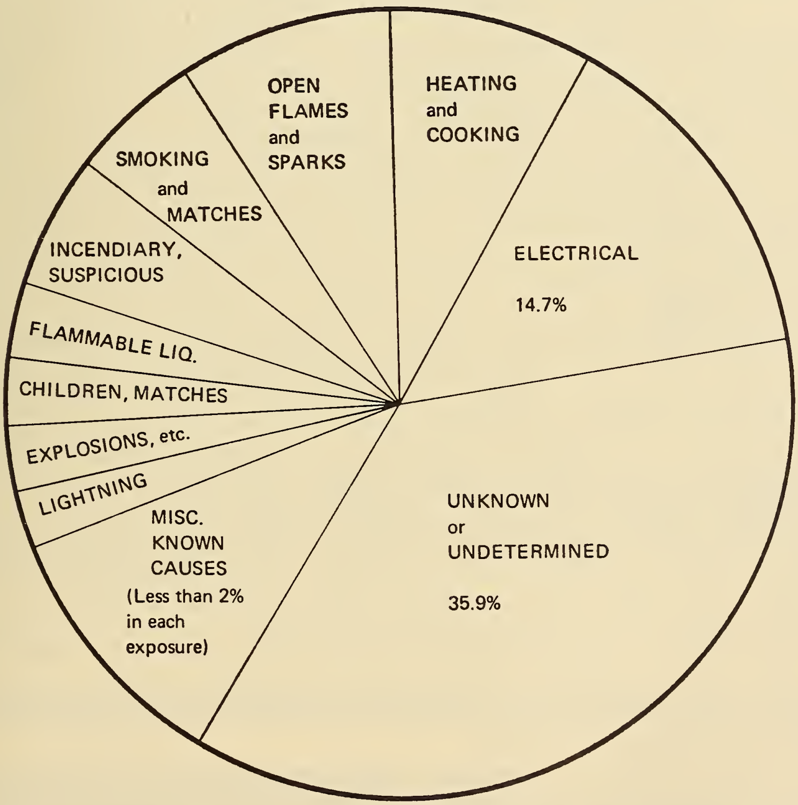

FIG. 2. The Cause of U.S. Building Fires, 1965. (Dollar loss as a measure.)

nonprofit organizations operating in the public interest. At least as important as basic fire research is the enormous applied or *ad hoc* research effort necessary to obtain answers to practical questions. This research will be initiated by manufacturers, testing laboratories, private industrial research organizations, government agencies and, to a lesser extent, the universities. All these groups and organizations have a legitimate interest in a broad picture of fire research needs, with details occasionally filled in where generalizations would be too vague. Presentation of that picture is the objective of these paragraphs.

Logical organization of any presentation of fire-related activity is difficult. One conventional division is into the areas: 1. Prevention, 2. Ignition, 3. Detection, 4. Growth, and 5. Extinguishment. But consider *growth* of fire. A fire prevention study might be keyed to the concept of striving so to build a structure as to cause the ignition of any of its parts to die out rather than grow and propagate; and a project to study the factors affecting growth might thus be launched by a group charged with responsibility for *prevention.* Or an interest in *extinguishment* techniques might lead to the realization that in many fire situations the manner of growth profoundly affects the timing of different extinguishment activities. Similarly, *detection* and *ignition* are closely related. Further to confuse the attempt to set up mutually exclusive categories, the gathering and interpretation of statistical data or the pursuit of an operations research project might pertain to any of the above five headings; but discussions of *statistics* or of *operations research* activities are properly kept together because of the similarity of disciplines involved in the pursuit of different problems by use of one of those tools. A grouping of fire activities into more or less mutually exclusive categories is helpful, but many problems which cut across such a division merit separate consideration; and the best presentation of a program is not necessarily the most logical one. The five divisions of fire activity listed above will be used, but they will be supplemented by separate discussion of important problems not specific to one of the five.

Fire research spans a wide spectrum of interests, and essential contributions to a balanced research program come from widely diverse disciplines. The practical man—the fire-fighter, the fire-service executive or planner, the writer of codes and standards, the fire-protection engineer—determines what practical questions require answers and, often, how applied research should be planned to answer them. Design of basic fire research, however, raises the always difficult question of how far back toward fundamentals the researcher should go—how much he should sacrifice in practicality in idealizing his problem to the point where its fundamentals are identifiable—in order to obtain results which illuminate practical fire problems, correlate apparently independent experiments, broaden the bases for generalizations, or suggest new approaches to important practical problems. Decisions in this area of basic research are best made by those with basic-research experience, the scientist and the research engineer. But the decisions will be importantly influenced by the input from fire specialists with wide practical experience. The need for dialogue between these two divergent fire-interested groups can not be overemphasized. Although this presentation is primarily a proposal for research, it does not refrain from mentioning activities which are research-related, though not in themselves research.

This is not a "balanced" program in the sense of spelling out detail equally in its various subdivisions. Absence of any detail would leave most readers with no real picture of the meaning of the general phrases used. Complete detail would be tedious to read—and never properly complete. The choices made as to where to amplify the program by detailed technical suggestions are arbitrary; they reflect biases of interest of the writers which only by accident will agree with those of the reader; but if the details—or their omission—stimulate the reader to think what he would have proposed instead, they have served their purpose. If parts of the exposition appear too elementary, it is hoped that the reader will remember the need of others for the background he has. Many readers wishing only a broad picture will wish to skip the detailed suggestions concerning approaches to basic research problems.

1. Fire Prevention

This is an area in which many, perhaps most, of the activities of importance are not research, though many of them are served by research. A representative rather than comprehensive list of activities follows, with but a partial identification of how research could be helpful:

a) Strengthening of codes and standards affecting construction materials and methods, building subunits, ventilation systems, exits, etc. In many cases a better technical basis should be provided for establishing a code or standard.

b) Code enforcement improvement.

c) Operations research study on effectiveness of building inspections by fire department personnel. Should private dwellings be included?

d) Examination of validity of clothing flammability tests, of tests on walls, floors, roofs, etc., as new materials of fabrication become available.

e) Further study of combustion-prevention additives, including coating agents to retard oxidation as well as quenchers of ignition or combustion.

f) Reduction of static-electric discharges, by addition of conductivity-improvers to stored liquid combustibles or by radioactive-source ionization of vapor spaces.

g) Better understanding of the ignition hazards of heating explosive or detonatable gas mixtures by sonic resonance, shock waves from sudden gas release, or decomposition of accumulated solid or liquid combustible on walls.

h) Education in housekeeping to reduce fire hazards.

i) Education of the technical user of fire-protection technology—the architect, the builder, the city planner.

j) Basic to fire prevention is a *thorough understanding of the physics and chemistry of combustion.* Consequently, research in many of the areas to follow is pertinent; and it becomes the obligation of any practically oriented group having fire-prevention responsibilities to put demands on research groups to obtain answers to technical questions that arise.

2. Ignition

An examination of the mechanism of the ignition process should have the following practical objectives:

a) Comparing materials of construction

b) Furnishing guidance to the chemical industry in its search for new materials

c) Predicting safe limiting ambient temperature and safe thermal input to a surface; and recognizing clearly, in empirical testing for acceptability, the difference between these two criteria

d) Determining the effects of shape, size, and moisture content

e) Determining the effect of protective coatings

f) Establishing aging characteristics in relation to ignition

g) Establishing more precise and more easily usable rules for estimating the flammability limits of gas mixtures

Accomplishment of these objectives will necessitate a fundamental study of the chemistry of the ignition process, the diffusion of heat and matter through organic materials, and the physics and chemistry of ignition wave propagation. Simultaneously, the development of better empirical tests for acceptability of materials and for establishing their safe exposures should be pursued. Examples of areas meriting both a basic study of mechanism and an empirical evaluation to produce presently usable conclusions are spontaneous ignition and ignition by hot spots, sparks, or firebrands.

3. Detection

A fire detection device may be designed to implement direct fire-extinguishing action, such as the opening of a sprinkler head by the melting of a low-melting alloy; it may be designed to warn occupants and to signal a distant point for aid; it may change the vulnerability of a building, such as by closing a fire door or resetting the ventilation controls. A case can be made for the claim that the reduction in annual fire losses would be greater per dollar spent in research on cheaper and better fire detection devices than in any other fire-research area.

This subject offers an outstanding example of the importance of research in areas not obviously related to fire. The mobility of ions in gases—their movement in an electric field—is found to be affected by the presence of fine particulate matter. This fact, combined with modern electronic circuit technology, permits the early detection of a fire by the action of traces of condensed vapors evolved from the fire; these act to decrease a radioactively induced ion current in the detector. Among the fundamental studies needed to supply a background for fire-detector development are these:

a) A study of early-stage gaseous products of thermal degradation associated with the ignition process—chemical composition, particulate matter size and composition, optical and electrical properties

b) Determination of the thermal output of early-stage combustion of various materials and typical building subsystems—flame radiation, surface radiation, and the energy in the gases

c) Study of convective dilution and of the convection of hot products to remote points, including a study of mixing rates in enclosures of various shapes and with various temperature fields

Much of the research needed on detectors is empirical or developmental in character. This includes:

d) Development, by manufacturers or others, of more efficient techniques of optimization of the placement and adjustment of detectors. A possible approach would be to install detectors in more places than economically justifiable; to measure their response to each of many fires, set at points identified by a fire engineer as being typical; to recommend a preferred placement of detectors if the final total number is to be 2, 4, 8, etc.; and to repeat the whole sequence in buildings of different types. The end product would be a better manual on the placement of detectors.

e) Comparison of early-stage fire response—quality and quantity of heat and gaseous products—of different building materials and subassemblies, *in situ*. This tests the synergistic effects, on results such as obtained under (a) and (b), of building configuration, etc.

The above-mentioned fundamental and empirical studies have the broad common objective of producing better and cheaper detection devices. So much effort, however, can be effectively aimed directly at this objective as to warrant a separate subheading.

f) Search for better and cheaper detection:

1. Multiple-response studies. A better identification of fire and the elimination of response from nondangerous sources can come from a correlation of several signals—signals either from several points or from several types of sensors, or both. Electronic-calculation assemblies have become so cheap as to make this entirely feasible.

2. Replacement of multiple sensors by a single sensor responsive to thinly distributed fire-sensitive material. (Example: development of a chemical, applied as a coating at many points, which evolves readily detectable gas when mildly heated; coverage of area with a few grams per hundred square yards. A microencapsulated odorant might possibly be used.)

Improvement of circuitry, including:

1) Cheap processing of many-sensor data
2) Use of lighting circuits to carry fire messages

3. Development of cheap local detector-alarms, such as a thermally released propellant vapor used to blow a whistle. Tuned remote pick-up of the acoustic signal could be added.

g) System Studies. The trade-off involved in accepting poorer detectors at lower cost presents a difficult problem. Answering the question of whether or when investment in many local detector-alarms is better than installation of a smaller number of more elaborate and reliable systems challenges the generally accepted criterion of absolute reliability, and necessitates analysis of many simulated fire situations by a disinterested operations team. The simulation of events associated with ignition and fire-spread in various typical situations could be used to compare the performance of different sprinkler and detector systems and arrays. Experimental support would be needed to verify the validity of the simulation.

4. Fire Growth

The continued burning of an ignited material at any spot on its surface depends on its past history and its present environment; and the burning of an assembly containing the material depends on interaction among the burning processes of its separate elements of surface. When one realizes that "environment" includes chemical composition and temperature of ambient gas and intensity of the external radiation field, that a quantitative statement of "past history" is necessarily long and difficult, and that "interaction" among complex phenomena is multiply complex, one concludes that a quantitative understanding of fire growth, even in a well-defined system, is a hardly attainable goal, at least for some time. In any search for directly usable generalizations arrived at in a reasonable time, the growth of fire in an assembly of material of direct practical interest *must* be studied empirically. Examples are studies of burning rate (mass loss, or heat liberation rate) versus time, as affected by shape, material of construction, point of ignition, draft conditions. Concurrently with such studies, and helping to guide or illuminate them, there must be a series of more fundamental studies, analytical and experimental, of small parts of the problem. These would include studies of geometrical configurations—idealizations of pieces of practical systems—capable of answering some of the questions in the area of interaction of fluid mechanics, mass and energy transport, and chemistry, such as the following:

a) Burning at a vertical surface

1. The gas-phase transport process (two-dimensional). Velocity and composition field as affected by height of surface, shape of bottom approach, and combustibility of material. Analysis of turbulent diffusion rates of oxygen and fuel gas to the reaction zone.
2. Internal transport and reaction processes (two-dimensional), including diffusion of moisture, thermal decomposition, diffusion of decomposition products.
3. Upward and downward propagation of reaction zone along the surface.
4. Effect of modification of environment by products of another fire.
5. Changes in the above problems associated with special environments. For example, space research and hospital safety introduce such new factors as removal of g-field, change of total pressure, change of oxygen fraction. These can produce such profound changes as to generate truly new problems.

A better understanding of these phenomena could have a strong effect on wallboard design, panel rating methods, and choice of wall materials by architects and builders.

b) Burning on the underside of a horizontal surface—ceiling fires. Studies similar to those under (a) above, but with different modes of escape of combustion products.

c) Propagation of a fire front over and above a horizontal surface covered with combustible material. Study of the two-dimensional problem, with fuel type representative of (1) a continuous plane, wood, or plastic, (2) a floor covering, (3) a bed of leaves, needles, grass, or brush, (4) a forest, (5) Los Angeles. This difficult problem has begun to receive attention in a number of research centers, where both operations-research models and physical-simulation models have been studied. The second of these will require enormous effort before any practically significant findings come out of it. Its study underlines the similarity of the mathematics of widely different propagation processes—fire-resistance evaluation of plastic-covered panels, propellent burning in solid-fuel rockets, spread of epidemics, forest fires, and large-scale fire-spread in cities.

d) The movement of confined gases under the influence of heat. Growth of most fires is well known to be limited by oxygen access, in turn influenced by the air flow pattern. Ability to predict gas flow can thus be at the common center of such diverse problems as life hazard from smoke and toxic gases, local fire growth, fire spread to remote points, operation of fire-detection devices, and fire-fighting tactics. When should the top of a building be opened by firemen to minimize spread; when does opening it increase the spread? Should air displacement by vitiated air or foam be considered? Unlike many aspects of the fire problem, the aerodynamics of natural-convection-controlled combustion, though by no means simple, *is* simple enough to hold promise of sufficient progress along basic lines to produce significant practical consequences early.

e) Among the more practical problems of fire growth are these:

Establishment of a standard shape for the time-temperature curve of fires. Fires, generally, can be characterized by three periods of combustion—roughly exponential growth, vigorous burning, and subsidence; and the fractional time occupied by any one of these periods tends to be, very roughly, the same for different fires. The establishment of an average standard shape of the temperature-time curve, leaving the scale factors for time and temperature as parameters, would provide a sounder basis for the solution of many problems of testing materials and building subunits and many problems of operations analysis related to fire growth and decay. Figure 3 illustrates the type of curve to be expected from analysis of data on many fires, a curve characterized by the two parameters t_c, the characteristic time of the fire, and $T_{max}-T_0$, the peak temperature rise above

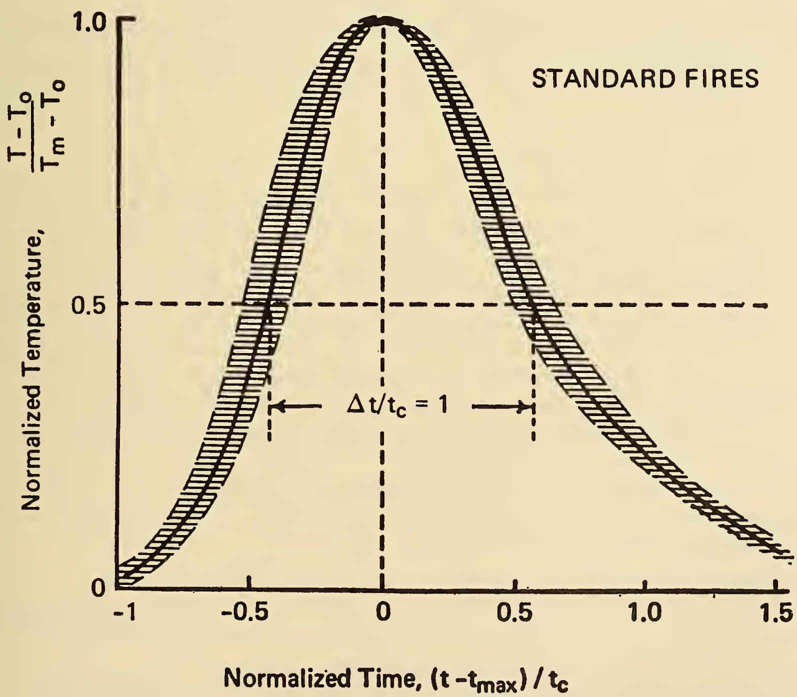

FIG. 3. Standard Shape of Time–Temperature Curve to be Expected from Analysis of Many Fires.

ambient. The curve should preferably be chosen to conform to a simply constructed algebraic formula containing not more than one arbitrary constant which would become a third parameter in studies of the interaction of fire and materials.

f) Data collection on fire growth in relation to rate of loss of economic value of buildings. Valid data of this kind are difficult to accumulate. They would provide background material for a mathematical model of fire growth for operations research.

g) Increase in fire hazard consequent on juxtaposition and associated interaction of building subunits with each other or with combustible contents which, separately, are of low hazard. (see Section 7, Building-Component Hazards)

h) Movement of fire in buildings. Basic laboratory studies of natural convection, supported by field data: stairwell effects; influence of ventilating systems; transport along corridors.

i) Fire jump. Analytical and experimental models, and full-scale studies, directed to the problems of effects of building type and frontage, wind, and humidity on the propagation, by radiation and/or firebrands, of fire across a space.

5. Extinguishment

Problems related to extinguishment include organization of fire departments (size of units, disposition of stations, number of men per unit), kind and quality of equipment available, knowledge of target as affected by prior organized inspection procedures, prior training programs, city traffic problems, decisions on rescue and on fire-fighting tactics, adequacy of water supply. Clearly the optimization of solutions to these problems calls for participation by fire departments, state and county fire organizations, equipment manufacturers, fire research laboratories, operations analysis teams.

a) Fire Department Activities

1. Since prior knowledge of a building can affect the attack on a fire in it, inspection is recognized as an important part of extinguishment as well as of prevention. Many communities could benefit from following the pattern set by the nation's best fire departments (there is a tendency for a department to claim that its own inspection activity is vigorous, effective, and adequate, while that of others is not; competent groups will welcome external assessment). Long-range improvement based on central data storage and on communication, when needed, of information pertinent to a fire under attack is a project well worth pursuing. The amount of effort allocated to inspection is a good subject for operations research.

2. Training programs vary enormously in quality among fire departments. Techniques should be developed for transferring knowledge of how to set up good programs, such as conferences or educational movies prepared by acknowledged first-rank fire-fighting services.

3. Equipment assessment. Capabilities and limitations, identified in training, practice, and actual fire-fighting. There is need for development of organizational procedures whereby, as a result of a fire department's registering its complaint or desire to remove certain equipment limitations, action is taken. This could be direct action by manufacturers if warranted by the market for the equipment or, if the market is too small, by a federally sponsored research and development organization.

b) Manufacturers of Fire-Fighting Equipment

The need for reliability of products appears to have fostered an excessive conservatism of outlook on the part of the manufacturers of fire-fighting equipment. While they can properly look to research groups outside their own organizations for suggested innovations, they should also maintain a vigorous and continuing search for new and better ways to build their equipment. The placement of a light or a hose connection, more sophisticated control equipment, better stowage, more attention to weight reduction, better means of communication—these are a few possible areas of improvement which merit evaluation by use.

c) Fire Research Laboratories

1. Improvement of fire and fire-fighting demonstrations. This problem is usually left to the fire department. But the fire research engineer should be an expert in designing experiments and should therefore be in a position to redesign fire demonstrations to bring out more effectively the generalizations it is hoped the fireman will reach by watching the fire or participating in the demonstration. Large planned fires are expensive and deserve more planning to optimize their educational value. The possibility, as educational tools, of model fires scaled in size and time merits consideration; but the difficulties of valid scaling (See Section 11) must be borne in mind.

2. The action of water on fire. Despite the many studies of this problem, our quantitative knowledge is quite limited, our *understanding* (used in the sense of the physicist) negligible. Study of water patterns from sprinklers is usually keyed to an immediate objective, such as evaluation of relative merits of two splash plates, establishment of permissible separation of sprinklers over a specified combustible floor loading, effect of water pressure, etc. As an example, more information is needed on the history of a droplet entering a fire, as a function of both average fire intensity and its variation, of droplet size, and of mass rate of water per unit floor area and its variation.

3. Foam. Where water is in short supply foam can be important. If in addition foam can be shown greatly to reduce water damage, that is another plus. But much remains to be done to prove the claimed reduction in damage, to free the firefighter from accusations of poor judgment when he departs from the more conventional attack on a fire.

4. Thickeners and water-suspended fire-suppression agents. The success of these in forest-fire fighting and the clear evidence of the inefficiency with which they are delivered by plane to a fire both warrant more research effort.

There are many problems incapable of being classified under one of the five main headings cited in the introduction to this proposal, because they cut across several. Some of the more important of these will be treated separately.

6. Life Hazards

a) Progress in reducing our annual loss of life by fire—the second highest cause of accidental death in the United States—will be greatest if we know what problems most justify effort. These problems may be identified by detailed studies of fire statistics of the reasons for fire deaths in various situations. For example, did the victim fail to awake or fail to find an existing exit; or was there no exit; or could the exit not be reached safely?

Some of the problems which are believed to be important are:

b) Interaction of fire and people. How should equipment be designed to serve the maximum number of users? How much is normal behavior modified by the emotional reaction to fire? Do professionals and amateurs require different equipment?

c) The hazards of smoke and toxic gases.

d) Escape from fire. What probable reduction in risk in a private dwelling is achieved by the optimum expenditure of $50? The staggering complexity of this problem has caused it not to be asked by "experts." But it and many others of comparable difficulty deserve an answer.

7. Building-Component Hazards

Let "fire hazard" be here defined as the chance that local ignition would grow to envelop local combustible units (a combustible table, chair, bookcase, wall panel, floor, ceiling panel, etc.) which would in turn liberate enough heat to cause fire propagation throughout a significant part of a building structure. It is well known that the fire hazard produced by the presence of two different combustible units in juxtaposition in a room is significantly greater than the sum of the hazards due to each unit if present alone. When we consider the ever-expanding choice among raw materials to use in constructing each building subunit and the countless number of combinations possible within a single building, the problem of rating the overall hazard of the building or of obtaining a quantitative measure of the effect of proposed substitutions is depressingly complex. But conscientious architects and builders need the guidance of a rating system having some validity. The prospect of being able to develop a method of estimating the overall hazard from knowledge of performance of the parts is unknown; but a project to try to advance in that direction is well worthwhile.* Without it we have nothing but a total-building test. The fact that building fire hazard is profoundly affected by occupancy—not under control of the designer—complicates the problem but makes its solution, modified by occupancy, no less pressing.

Understanding interaction among building subunits exposed to fire demands a more complete understanding of single subunit exposure. Tests of subunits consist conventionally of establishing life in a specified cycle of thermal punishment. More completely to describe a subunit, its response to a variety of punishments must be established; but "variety" must be limited to prevent the problem from

* As an illustration only: *Let the separate hazards from the presence of two combustible units in a room be H_1 and H_2, and suppose that the total hazard, when the two units are separated in a room by the clearance distance D, can be represented by $(H_1+H_2)[(M+D/D_0)/(1+D/D_0)]$. This relation, wholly unsupported by data, at least has a reasonable structure. When the combustible units are in contact ($D=0$), the bracketed term has the value M, the multiplying factor due to immediate juxtaposition. As D increases, the bracket decreases in value from M toward 1, and at a rate dependent on D_0. Experiments would be directed at determining the constants M and D_0, and their variation with the type of combustible units involved. Clearly, it is quite improbable that any such "law of synergism" would take the particular form suggested here. Clearly, also, the gap between any solution of the problem and its practical application will be slow to close.*

becoming unmanageable. If a standard fire curve shape is agreed upon (see Section 4), the thermal performance of subunits could be expressed as a series of responses to fires of standard shape, but differing in values of $T_m - T_0$ and t_c, varied over the range of interest. This proposed treatment of the problem calls for much testing, but in the long run *very much less testing* than the total-building test method. (The program would include a study to determine whether the major independent variables in thermal punishment of a building subunit are in fact $(T_m - T_0)$ and t_c rather than, for example, intensity and duration of irradiation.)

8. Field Studies of Building Fires

No matter how sanguine one may be about the prospect of learning how to predict total-building response to fire from knowledge of the building parts and shape, the need for full-scale tests is obvious. Not infrequently an old building or building complex becomes available for destruction, and an opportunity for field tests arises. More often than not the opportunity must be passed up because of the enormity of the problem of getting ready for a good test. There is much need for development of a mobile test-unit for use in field studies. It would consist of a truck equipped with a supply of temperature-measuring and composition-measuring devices capable of short-distance broadcasting of their signals to receiving equipment mounted in the truck. Gas velocity and direction and radiation intensity are other desirable measurements. This problem has been in a sense solved for meteorological balloons and satellites; but what is needed here is to trade off the extreme shortness of the telemetering distance for a cost of the signal senders that is low enough to justify letting them be destroyed by the fire. The availability of several such mobile units distributed over the country would make possible a participation in many fire studies that could yield valuable data. The gap that tends to exist between the objectives of the test engineer and those of the analyst or basic fire researcher would be lessened; the latter would be encouraged to plan in advance a critical test to tell him whether his analysis of full-scale fire phenomena is on the right track.

9. Validation of Empirical Fire Tests

A well-designed standardized fire test subjects the device or structure tested to what is hopefully a "representative" fire exposure. On analysis, this may prove to consist of a mixture of exposure to high temperature and—very different—exposure to thermal flux, the two judiciously mixed in the "right" proportions by making the test conform to a well-identified operating procedure. Said another way, the merit of the object tested is a weighted mixture of merits of different kinds; and the test constitutes an arbitrary and automatic weighting process which has the virtue of giving the decision-maker a single figure of merit. A little consideration indicates that the strength of such an empirical test is also its weakness: (1) Results of the test may not guide the producer of new materials or new combinations in a direction which, judged by the public interest, is optimum; (2) as the nature of building construction changes, the nature of the exposure (the weighting process) changes, and the results of the standard test slowly lose validity; (3) in matters of interaction between combustible units in an enclosure, it may be necessary to assess the different kinds of fire resistance of a unit separately rather than to be content with an empirically weighted overall resistance. This all adds up to an argument for backing up each of our accepted fire tests with a continuing study of the fundamental fire phenomena which underlie it, a study directed toward maintaining, by agreed-upon slow change when warranted, the validity of the test for application to materials, material combinations, and fabrication techniques of today and tomorrow—not of yesterday.

10. Gathering of Fire Data

It is axiomatic that research funds should be spent where most needed. Effective distribution of fire research effort depends partly on knowledge, based on past experience, of what the fire hazards really are and where they are greatest. If most of the lives lost in fires are shown by a statistical study to be associated with fire escape problems, that is where research should be focused; if not, then elsewhere. If life loss in places of public gathering is shown to be related to loss of illumination, city or state codes and standards should be responsive to the new knowledge. It thus becomes clear that the gathering of statistics on fire can supply information which is at the heart of research planning and fire legislation. And just as good statistics act on research planning, research planning generates the need for new statistics. Every good research planner has a list of questions, "Is it true that, etc.?" the answers to which can only come from a knowledge of what kind of fire damage we are experiencing.

The above suggests the need for two kinds of statistics on fire:

a) Continuous recording of data on all major fires, standardized as carefully as possible over the nation and, to the extent possible, over the world. These data, if reported in the same way in different places, would permit comparison of such effects as climate, social stability, materials of construction, and codes and standards on the incidence of fire; they would categorize fire hazards; and they would show the change in the picture with time.

b) For many problems, however, including probably some in the above category, no "standard" fire report will be entirely adequate. Needed in addition is statistics gathering which is responsive to a specific problem, and which terminates when the problem is solved. The effect of an experimental change in a particular fire-fighting procedure, when there are two views on what the best procedure is, might be established by careful statistical studies over alternating periods of following each procedure. At least one State Fire Marshal's Office has had impressive success with statistics-gathering in relation to codes and standards, and associated changes.

Data collection presents the temptation to collect more and more detailed information. If data collection is not to degenerate into a futile expenditure of effort, present judgment of future interests must be applied in setting the limits of collection.

11. Physical Modeling

The assessment of the fire hazard associated with a particular industrial storage problem or combustible unit or the determination of how to apply sprinklers to it, cannot today be carried out by any means other than full-scale testing. And because fire has a randomness that forces multiple replication of experiment, full-scale experiments are generally so expensive that we do not appraise as many systems or combinations as we should. As an example, a million-dollar fire in a sprinklered storage-warehouse containing stacked rolls of newsprint paper a few years ago led to a test series initially estimated to cost about $12,000. A thousand tons of paper were bought to make full-scale tests, the appropriation to cover costs was raised, and the expenditure grew finally to $300,000. But there are still unanswered problems of water and sprinkler needs, and more tests are planned. A recent test on styrofoam as a fire hazard involved burning styrofoam costing $17,000 as scrap. Examples like these underline the need for a way to gain at least some of the knowledge about a combustible unit by scale-model tests on it.

In 1959 the Committee on Fire Research sponsored a symposium on the use of models in fire research. Several other technical meetings since then have devoted sessions to modeling, and the term is not infrequently used by the fire engineering fraternity. There is clear evidence, however, that the term is not understood by many who use it. If a 30-meter diameter oil pool is set afire, the combustion pattern and the oil consumption are not at all modeled by a fire in a 3-centimeter oil pool. The balance among forces—buoyancy, turbulent shear, viscous shear—is entirely different in the two cases; the balance among heat transfer mechanisms—convective movement, radiation, conduction from the rim of the pool—is entirely different. Modeling is achieved only when the ratios of these quantities are the same in model and prototype, and combustion is unfortunately a field in which the number of these dimensionless ratios arising is typically large. Since the matching of a large number of ratios is usually impossible, fire modeling consists in part in identifying which ratios are important and which may be left unmatched without producing excessive distortion of the results, and in part in finding how to design an experiment which allows a larger number of ratios to be matched.

Learning how to use models in fire tests calls for sophisticated analysis and sophisticated experimentation. It has great practical consequences in fire-control engineering, and deserves vigorous pursuit.

12. Operations Research

Although discussion of various problems susceptible of attack by the methods of operations research (OR) could be put under appropriate subheads above, the similarity of the philosophy of approach to such problems justifies discussing them together.

Operations research on fire is concerned with problems of strategy, tactics, and allocation of resources. The resources available for the control of fires derive from a single ultimate resource, *money*; and we need to have some quantitative understanding of the return, in lives and property saved, on a given expenditure. A city administration can allocate money to buildings, equipment, salaries, training activities, fire-prevention activities of its fire department, and corresponding items related to traffic, the police, medical services, civil defense, and private citizens and their homes. Two examples of questions related to such allocation are these: How would the dollar-value of halving the number of firehouses, and doubling the complement of men and equipment in each, compare with the cost of reaching most fires somewhat later but with more equipment? And what is the value of encouraging, through signs, line-painting, and public education, the presence of open fire-lanes in heavy traffic? Such specific questions as these are hard enough to answer, but a host of them must be studied before it will be possible to assess with assurance such broad matters as the relative values of additional men and additional equipment.

The first step in attacking such problems is to analyze relevant data, beginning with those presently available (from which all the useful information has by no means been extracted) and going on to statistics collected for the purpose of answering well-defined questions (Section 10b). The second, most important, and most difficult step is to construct mathematical models of the phenomena under study. Such models can range in scope from fire operations in an entire city down to something as narrow as the relative worth of alternative vehicles.

An important operations modeling problem, which might prove tractable even at this time and whose solution would be enormously useful, is that of modeling the time-course of a fire under various conditions of fire-suppression activity. To build such a model one must be able to describe a fire in a relatively simple way. Total output of energy as a function of time and of building type might be a good way, general enough to apply to a considerable variety of fires and at the same time susceptible of modification by data obtained in field or laboratory studies. The essential feature of such a model would be its representation of the effects of various levels and kinds of fire-fighting at each stage of the fire.

Two approaches to the construction of such a model should be taken. The first, using presently available techniques, should aim at a relatively crude description of the progress of a fire under various conditions—something as simple as a family of time-temperature curves such as described in Section 4e. The second, presently far from practicable, should incorporate detailed physicochemical information about the propagation of fires, and should eventually lead to a much more accurate description of fire behavior. Models of the behavior of a single fire form a link between such long-term allocation problems as the proper use of fire-department funds and short-term or specific problems involving fire-fighting devices, techniques, and tactics.

The important but obscure problem of fire following a nuclear attack has received extensive study, and models have been developed which make predictions of firespread and extent of damage. Some of the assumptions that have had to be made, particularly those related to post-attack conditions, are not verifiable. Peacetime fires, on the other hand, can be better modeled since the input to the operations modeling process is experience with such fires, and the output is similarly capable of verification by peacetime experience.

Two things should be stated about OR in conclusion. First, its early successes were based on insistence upon clearly formulated objectives for systems under study. A classic example was the agreement, in 1942, that the purpose of air patrol of the Atlantic seaboard was to minimize enemy sinkings of Allied shipping rather than to maximize our sinkings of Axis submarines; and enunciation of this doctrine resulted in improvement of our coastwise shipping system. Second, the success of any study of a fire-fighting system must be based on an accurate understanding of the interaction of fires and their behavior with the system in question. Operations research on fire and physical research on fire must be conducted with vigorous interaction.

Conclusion

As implied above, these comments have been addressed to so broad a spectrum of readers as possibly to have left many of those most vitally interested in fire quite unsatisfied. Many additional areas meriting study could have been outlined, and the excellent work of existing organizations could have been described; but inclusion of these items would not change the conclusion which emerges from any thoughtful and objective study of fire in America. That conclusion is:

A significant increase in our fire research activity, with careful attention to a judicious balance of basic and applied research so organized that they feed and stimulate each other, is not just warranted; it is required.

Comments on
A Proposed National Fire Research Program

Fire research is a multidisciplinary subject involving elements of aerodynamics, chemistry, meteorology, physics, and other areas. Its ultimate goal should be threefold: (1) The fundamental understanding of the various problem areas of fire; (2) The organization of this information into an effective scientific and engineering discipline so that fire problems can be dealt with from a general understanding as contrasted with present day ad hoc empiricism; and (3) The dissemination of this information through publication, teaching, and the collection of necessary engineering and scientific parameters for practical use.

The individual scientific disciplines of fire research are developing rapidly and many are already well understood. However, the possibility of general application of this knowledge to routine problems is remote at present. This is due both to the complexity of the problems and because the practitioners in the field are, generally speaking, specialists—experts in their own field but only vaguely familiar with developments in related fields. As a result, the application of fundamental knowledge to fire problems has been fragmentary and generally disappointing. Nevertheless, the prospects are excellent for long-range programs connecting the present day empirical fire science with the main body of fundamental science and engineering. This optimism is based on the steady growth of the basic sciences accompanied by the rapid expansion of computer capacity, which has doubled every 18 months for the past two decades and promises to continue this growth. Thus, both those fire problems that are difficult because of a lack of basic understanding and those that are difficult because of pure complexity should ultimately find solutions.

The exploitation of the opportunity provided by these developments requires positive long-range programs to organize the basic disciplines into usable fire science. It is to foster these developments that this National Fire Research Program and its predecessor were written.

Robert M. Fristrom

REVIEWS

Survey of Vapor Phase Chemical Agents for Combustion Suppression*

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Related Sections: **E**, *G*, *H*, *I*

Subject Headings: **Combustion suppression**

Introduction

A review of the literature of combustion suppression at the present time can rely heavily on previous surveys to provide coverage up to late 1966. For the past twelve years, ever since a comprehensive survey by Friedman and Levy,[1] thorough reviewing of inhibition literature has continued by competent workers in the field. The first five references of this report list these surveys in chronological order. Friedman and Levy summarized the work to 1957 and then added two supplements to the original in the next two years.[2] Skinner[3] thoroughly covered the following two years in a survey intended to continue the previous three reports, and likewise added supplements in 1962 and 1964.[4] In 1966 Fristrom[5] compiled a review of inhibition literature in the same vein as those just mentioned. He brought to the task the credential that he is editor of *Fire Research Abstracts and Reviews* (FRAR). This publication is a repository of abstracts of literature dealing with combustion suppression, from basic research on flames to fire fighting. Also in 1961 and 1964 Berl[6,7] compiled reviews of fire research. With the exception of references 6 and 7, the cited reviews have emphasized coverage of laboratory-scale research on combustion suppression. Less attention has been given to studies of larger scale fires in these publications.

In view of these exhaustive surveys, the task of reviewing the literature prior to 1966 is greatly lightened. The indicated approach to a survey, therefore, is to selectively review certain important publications of earlier years to provide background and to obtain understanding of flame inhibition. Approximately 40 publications falling into this category have been critically reviewed. These then provide a framework for coverage of the literature of combustion suppression of the past three years. It develops, however, that since 1966 there has been a large decline in the number of papers dealing with basic inhibition studies. The emphasis has turned to study of the structure of flames containing inhibitors, which approach promises to provide important understanding of inhibition processes.

The principal sources for this review, in addition to the cited publications, have been *Fire Research Abstracts and Reviews*, *Combustion and Flame*, the *Combustion*

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Symposia volumes, various types of government and industrial reports, and two machine searches provided by NASA and by DOD.

The scope of the review is limited to chemical suppressants, both homogeneous and heterogeneous, acting mainly on hydrocarbon or hydrogen flames with air or oxygen. Inhibition by purely physical action such as smothering or cooling is not dealt with as such. Studies of both premixed and diffusion flames are included. The types of measurements used to evaluate inhibitor effectiveness are considered, and possible chemical reaction mechanisms by which they act are discussed. Appended to the report are lists of chemical inhibitors and their reported effectiveness. While the emphasis is on fundamental studies, consideration has also been given to application of principles to practical fire control. A discussion is included on requirements of suppressants for flight vehicles.

Methods of Determining Inhibitor Effectiveness

The terms inhibitor and suppressant are used synonomously and can, but do not always, imply extinguishment. They seem to connote a stronger effect than retardant. Friedman and Levy[1] have defined an inhibitor as a substance which makes it more difficult for a flame to burn. Inert additives such as argon, then, are inhibitors. However, only those substances which inhibit by chemical action in the combustion wave are considered in this report. The effect is manifested by a change in a flame property such as burning velocity or flammability limit.

It hardly needs to be established in this survey that certain substances act chemically to suppress combustion, but it is instructive to consider two examples: (1) Many covalent halides are strong suppressants, and 6.1 per cent of CF_3Br added to a *n*-heptane–air mixture of any composition will prevent propagation.[8] The Br atom has the key role since it takes 26 per cent of CF_4 to cause extinction of the same flame. (2) Trace amounts of certain substances such as the inflammable iron pentacarbonyl, $Fe(CO)_5$, exhibit a powerful inhibiting effect on hydrocarbon flames, the burning velocity of a *n*-hexane–air flame being reduced 30 per cent for a 0.017 per cent addition.[9,10] These pronounced inhibiting effects can only be accounted for on chemical grounds, and in later sections the chemistry is considered and possible reaction mechanisms are discussed. However, besides demonstrating chemical suppression, the above examples are meant to bring up the question of just how these effects are measured.

In general there are three principal methods used to measure and study inhibition of flames. These are the determination of: (1) the narrowing of the flammability limits; (2) the reduction in burning velocity (both apply to premixed flames); and (3) the influence on diffusion flames. Taking each in order, a common and meaningful way in which to measure suppression effects is by mapping the composition flammability limits for mixtures which contain various amounts of added inhibitor. In a diagram of per cent fuel as abscissa versus per cent inhibitor, the limits will close in with increasing additive and the cure will go through a maximum. This maximum is commonly called the peak percentage, and represents the amount of inhibitor necessary to prevent propagation for any composition. The method was used to obtain the data of Table I (see page 92), and in many other publications, for example references 11 through 14. A technical point should be mentioned in regard to flammability limits. They can depend on the dimensions of the apparatus and this parameter is usually neglected. It could be important when scaling predictions are attempted. As an example of such a type of discrepancy,

TABLE I

Extinguishing effectiveness of agents evaluated in reference 8. Experimental conditions: *n*-Heptane-air mixture with flame propagation through tube at room temperature and 300–500 Torr pressure

Compound formula	Compound name	Peak percentage
CBr_2F_2	Dibromodifluoromethane	4.2
CBr_3F	Tribromofluoromethane	4.3
$CF_3CHBrCH_3$	2-Bromo-1,1,1-trifluoro-propane	4.9
$CBrF_2CBrF_2$	1,2-Dibromotetrafluoroethane	4.9
CF_2ICF_2I	Tetrafluoro-1,2-diiodethane	5.0
CH_2Br_2	Dibromomethane	5.2
CF_3CF_2I	Pentafluoroiodoethane	5.3
$CF_3CH_2CH_2Br$	3-Bromo-1,1,1-trifluoropropane	5.4
CH_3CH_2I	Ethyl iodide	5.6
CF_3CF_2Br	Bromopentafluoroethane	6.1
CH_3I	Methyl iodide	6.1
$CBrF_3$	Bromotrifluoromethane	6.1
CH_3CH_2Br	Ethyl Bromide	6.2
$CH_2BrCF_2CH_3$	1-Bromo-2,2-difluoropropane	6.3
$CClF_2CHBrCH_3$	2-Bromo-1-chloro-1,1-difluoropropane	6.4
$CHBr_2F$	Dibromofluoromethane	6.4
$CBrF_2CH_2Br$	1,2-Dibromo-1,1-difluoroethane	6.8
CF_3CH_2Br	2-Bromo-1,1,1-trifluoroethane	6.8
$C_6F_{11}C_2F_5$	Perfluoro(ethylcyclohexane)	6.8
1,3-$C_6F_{10}(CF_3)_2$	Perfluoro(1,3-dimenthylcyclohexane)	6.8
1,4-$C_6F_{10}(CF_3)_2$	Perfluoro(1,4-dimethylcyclohexane)	6.8
CF_3I	Trifluoroiodomethane	6.8
CH_2BrCH_2Cl	1-Bromo-2-chloroethane	7.2
$CClF_2CH_2Br$	2-Bromo-1-chloro-1,1-difluoroethane	7.2
$C_6F_{11}CF_3$	Perfluoro(methylcyclohexane)	7.5
C_7F_{16}	Perfluoroheptane	7.5
CH_2BrCl	Bromochloromethane	7.6
$CHBrF_2$	Bromodifluoromethane	8.4
$CClF_2CCl_2F$	1,1,2-trichlorotrifluoroethane	9.0
$CBrClF_2$	Bromochlorodifluoromethane	9.3
HBr	Hydrogen bromide	9.3
CH_3Br	Methyl bromide	9.7
$CF_2{=}CHBr$	2,2-Difluorovinyl bromide	9.7
C_4F_{10}	Perfluorobutane	9.8
$SiCl_4$	Silicon tetrachloride	9.9
$CBrF_2CBrClF$	1,2-Dibromo-2-chloro-1,1,2-trifluoroethane	10.8
$CClF_2CClF_2$	1,2-dichlorotetrafluoroethane	10.8
CCl_4	Carbon tetrachloride	11.5
$CF_3CHClCH_3$	2-chloro-1,1,1-trifluoropropane	12.0
$CF_3CH_2CH_2Cl$	3-chloro-1,1,1-trifluoropropane	12.2
$CClF_3$	Chlorotrifluoromethane	12.3
CF_3CF_3	Hexafluoroethane	13.4
CCl_2F_2	Dichlorodifluoromethane	14.9
$CHCl_3$	Chloroform	17.5
CHF_3	Trifluoromethane	17.8

TABLE I (*Continued*)

Compound formula	Compound name	Peak percentage
$CHClF_2$	Chlorodifluoromethane	17.9
C_4F_8	Octafluorocyclobutane	18.1
SF_6	Sulfur hexafluoride	20.5
BF_3	Boron trifluoride	20.5
PCl_3	Phosphorus trichloride	22.5
HCl	Hydrogen chloride	25.5
CF_4	Carbon tetrafluoride	26
CO_2	Carbon dioxide	29.5
H_2O	Water	>8*
$(C_2F_5)_2NC_3F_7$	Heptadecafluoro(*N*,*N*-diethylpropylamine)	>8.5
CH_2Cl_2	Dichloromethane	>11

* Concentration limited to vapor pressure of liquid water. Other data indicate that water vapor is less effective than CO_2 as an inhibitor.

it was found that the amount of $AlCl_3$ vapor needed to extinguish methane-air flames differed by a factor of >2 in two independent studies.[15,16] The difference was attributed by Friedman and Levy[15] to the different apparatus and ignition sources.

Another common method to evaluate inhibiting effects is by measuring the burning velocity. Such experiments are usually performed in open-tube burners, as flammability tests often are. The velocity method has the disadvantage that usually the extinction conditions are not determined. The results are reported as the amount of additive needed to reduce the velocity by a certain amount. This method was used to obtain the data of Table II and in other publications.[12,17]

Next, the measurement of suppressing influence of chemical additives on diffusion flames is considered. The rationale for studying inhibitors in a diffusion system is that it more closely approximates real fire situations. Against this must be weighed the complicating factors of diffusion flames which are, for purposes here: (1) no measurable fundamental property such as burning velocity, and (2) dependence of inhibiting effect on streaming velocity. These objections are serious for annular or flat diffusion flame burners. Nevertheless, some useful studies have been carried out using these types.[18,19] There is another burner which is a great improvement for diffusion flame studies. This is the opposed-jet burner[20] which consists of two coaxially-opposed tubes through which fuel and oxidant flow, meeting in a space between and forming a diffusion flame. The aforementioned objections are substantially overcome by the opposed-jet system. In this type of burner, as the streaming velocities are increased, a point is reached at which an opening appears in the center of the flame. This opening is reproducible and represents the point at which mixing rate of reactants exceeds the chemical reaction rate. It provides a convenient parameter, referred to as apparent flame strength, to use to evaluate effectiveness of inhibitors; the stronger the inhibitor the lower the flow velocity at which the flame "breaks." Two investigations have been reported in which this technique was used to study inhibition.[21,22]

TABLE II

Summary of additives tested in reference 9. Volume percent refers to amount needed to reduce burning velocity of stoichiometric n-hexane–air burner flame by 30%. Compounds marked with an asterisk were not reported in reference 9 but were listed in prepublication abstract.

Additive	Volume %	Additive	Volume %
N_2	8	$SnCl_4$	0.19
Co_2	6.8	$TiCl_4$	0.19
n-C_6H_{14}	1.05	$SiCl_4$	0.56
Cl_2	3.3	$SiHCl_3$	2.9
Br_2	0.7	*SO_2Cl_2	1.36
CCl_4	1.38	*$SOCl_2$	1.80
$CHCl_3$	1.87	*S_2Cl_2	1.05
BBr_3	0.18	$Si(CH_3)_4$	1.5
PCl_3	0.15	$Fe(CO)_5$	0.017
*$POCl_3$	0.19	$Pb(C_2H_5)_4$	0.015
$PSCl_3$	0.13	CrO_2Cl_2	<0.024
PBr_3	0.15		
$PSBr_3$	0.15		
$(CH_3)_3PO_4$	0.26		
*$(C_2H_5)_3PO_4$	0.27		
*$AsCl_3$	0.39		
*$SbCl_3$	0.22		

There is one other method of measuring inhibitor effectiveness which should be mentioned. This is the determination of quenching distances for inhibited premixed flames;[23,24] however, it is rarely used.

Chemical Inhibitors

Chemical additives are usually categorized as homogeneous or heterogeneous inhibitors depending upon whether they enter the flame as vapor or solid, respectively. They are believed to act to suppress combustion by scavenging active chain carriers early in the combustion wave. However, vapor additives may not necessarily act to suppress combustion by entering into homogeneous chemical reactions; and solid additives may not act via heterogeneous reactions. Consider some examples to clarify this. Compounds such as the alkyl halides which are gaseous inhibitors, certainly react homogeneously; further analysis of this is given later. Solid additives, e.g., $KHCO_3$, may act heterogeneously by providing surface for radical deactivation. Alternately, solids may gasify in the flame and their vapors may then be the principal inhibiting species, acting homogeneously.[25] Conversely some compounds, e.g., tetraethyllead, titanium tetrachloride, iron pentacarbonyl, which are vapor as they enter flames, may be reduced or oxidized to the metals or metal oxides and these solid species could actually be the retarding agents.[9,34] The mode of action of many chemicals is obscure, and there may be no fundamental basis for the usual classification. Nevertheless it is a useful breakdown, properly qualified, and will be used below.

Homogeneous Inhibitors

The alkyl halides are the most common fire suppressants of this class and have received the most study. Table I (see page 92) lists 56 compounds, mostly alkyl halides, which have been tested as inhibitors and ranked in decreasing order of effectiveness. Other studies in which several such chemicals have been invesgated include references 9, 17, 24, although not nearly so many were tested.

Several points and generalizations can be made in regard to these halogen-containing compounds. Three very common inhibitors, CH_2ClBr (commonly called CB), CH_3Br and HBr, are roughly in the middle of the list of Table I. CF_3Br, a "Freon" fire suppressant, is somewhat better than CB. CF_4, C_2F_6, C_4F_{10}, and C_7F_{16}, which are not believed to display any chemical action in suppressing combustion, rank in the order expected on the basis of their heat capacities. The following tabulation compares inhibitors on the basis of the type of halogen (peak percentage listed on right):

CF_4	26
CF_3Cl	12.3
CF_3Br	6.1
CF_3I	6.8

The ranking as given is in the expected order of decreasing strength of the CF_3—X bond, excepting for the iodine which is comparable to the bromine compound. Similarly, ethyl bromide and iodide are approximately equal in effectiveness, but CH_3I is significantly better than CH_3Br. Rosser, Wise and Miller[17] observed an excellent correlation between inhibitor effectiveness and number of bromine atoms per molecule. The rate of flame speed reduction increased linearly with increasing Br content of a number of methane-derivative inhibitors plus Br_2 and HBr. However, such a correlation is poor in the Purdue list[8] as the first four items on the list attest. There is also no similar relation for any of the other halogens.

The preceding deals with additives which cause the extinction of premixed flames as distinguished from some lesser inhibiting effect. In general, relatively large amounts of chemical inhibitors must be added to completely prevent deflagration, which raises the question of their cooling effect. For example, Br_2 is probably the most effective extinguishant, but this has a peak percentage of $\sim$2.5% in methane–air.[12] The peaks in these two systems occur at 3 and 9% fuel, respectively. Thus the amount of added inhibitor is quite high relative to the amount of fuel, and even higher in the case of substances other than bromine. No doubt the additives that extinguish act to some extent as flame-temperature depressants. There is a paucity of data on this aspect of inhibition, but one study has yielded some interesting results. Simmons and Wolfard[18] have calculated the temperatures for stoichiometric CH_4- and C_2H_6-air flames with and without the peak concentration of Br_2, and these are shown below:

	Flame Temperature	
Hydrocarbon	Without Br_2	With Br_2
CH_4	2224°K	2117°K
C_2H_6	2263°K	2172°K

The peak concentrations occur very near stoichiometric. Addition of bromine lowers the flame temperatures somewhat; however, the temperature of the normal limit mixtures in the absence of Br_2 is 1550°K. Clearly, in the Br_2 case at least, the temperature depressing effect is secondary. One would guess that it might not be in the case of, say, CF_3Br inhibiting heptane flames.

In this report chemical additives are considered on a gas volume basis. Low molecular weight agents, however, have an advantage when considered on a weight basis, and weight or liquid volume may be the proper basis for certain fire control applications. Thus water, a physical extinguishant with a molecular weight of 18, emerges as superior to many chemical extinguishants if only weight is considered. It is much less attractive on a liquid volume basis since its density is much below halogenated organic compounds. Also its high heat of vaporization and the necessity of delivering such a high molar quantity to the site of a fire offset its weight advantage.

There are compounds which produce strong inhibiting effects when added in much smaller amounts than those so far considered. Many of these substances will not cause extinguishment but they will retard combustion. The most familiar example would be the use of tetraethyllead in preventing engine knock, ~0.1 weight per cent being effective. Lask and Wagner[9] have examined the effect of a great variety of additives on a *n*-hexane–air flame. These comprise volatile inorganic substances and are collected in Table II (see page 94) together with the per cent of each needed to reduce the burning velocity by 30 per cent. The first seven compounds are listed for comparison. The majority of the additives are halogenated and as can be seen from the list, some are no more effective than alkyl halides while others are roughly five times as effective. It would have been desirable to have included a brominated fluoroalkyl for comparison, although presumably about 1% of such an additive would be required. The last three members of the list show extraordinary retarding ability and are effective in quantities of an order of magnitude lower than the other candidates. It is noted that most of the substances listed in Table II are based on elements in groups IIIA to VIA of the periodic chart. Examination of the list along these lines, however, does not disclose any consistent trends.

The influence of chemical inhibitors on diffusion flames requires separate discussion. Simmons and Wolfhard[18] made a study of inhibition of hydrocarbon–air flames by methyl bromide using a flat diffusion flame burner. They made the discovery that approximately an order of magnitude more CH_3Br must be added to the fuel gas stream than to the air stream to effect extinction. The amount added to the air is of the same order as that for premixed flames. The explanation is that in the diffusion flame reaction zone the reactants are present in stoichiometric proportions. For CH_4/air, for example, this ratio is approximately 1/9, which means that 9 times as much air as fuel will diffuse into the flame. It will bring with it 9 times as much inhibitor as the fuel will. Hence, when inhibitor is in the fuel it needs to be present in large excess to diffuse into the flame in sufficient quantity to prevent propagation. It was also noted that a separate CH_3Br-air flame was established adjacent to the main diffusion flame. These observations with CH_3Br were borne out by Critz[19] who also examined the effect of CF_3Br on diffusion flames of hydrocarbons. Similarly CF_3Br must be present in the fuel stream in large excess over that in the air stream.

One other study of diffusion flame inhibition must be considered. Friedman and Levy[21] measured the "breaking point" of inhibited CH_4-air flames in an opposed-jet burner. The ranking of the inhibitors they tested is $CH_3Cl < CCl_4 < CH_3Br \pm CF_3Br$, which is in reasonable agreement with premixed flame results.

Last, in connection with homogeneous inhibition, the suppression of premixed H_2-air flames should be mentioned. By measuring reduction in burning velocity, Miller *et al.*[26] screened a large number of substances—hydrocarbons, organic and inorganic halides, and other types of compounds—for their inhibiting effect. A few comments can be made about the findings since they contrast with results for hydrocarbon-air systems. Hydrocarbon additives are generally better inhibitors for H_2-air flames than alkyl halides. Methane and methyl bromide are, however, approximately equal in strength and both are better than CF_3Br and CF_2Br_2, which are likewise approximately equal to each other. These last two, however, are much better inhibitors than CF_4. The ranking of the hydrogen halides is $HI > HBr \gg HCl$ (see reference 11) as it is in hydrocarbon flame inhibition, although HBr, for example, is only one-half as effective as methyl bromide in extinguishing H_2-air flames. These observations are of value in writing chemical inhibition mechanisms (see below) for the H_2 and hydrocarbon flames. Another finding which is important for this purpose, as well as being of practical value, is the discovery that methane-NO_2 flames are practically unaffected by alkyl halide additives, while ammonia–air flames are affected much as hydrocarbon–air flames are.[17,23]

Heterogeneous Inhibitors

As with homogeneous inhibitors, a great variety of salts and other powders have been tested for their suppression effect on flames. The alkali metal salts in particular exhibit extinguishment power and have been extensively studied, especially the carbonate, oxalate and halide compounds. The chemical nature of the solid determines the strength of the suppressing effect to an extent, but a property of equal importance is the surface area. These two topics will be discussed in order.

There have been a number of studies reported in which quite a few powders have been investigated in each.[16,25,27–32] There is difficulty comparing the results of different investigations because of the nonuniformity of data reporting. The work of Friedrich[31] can serve fairly well to illustrate the role of the chemical nature of the solid. Powder of 44 μ particles was dispersed, using a screen, as a dust cloud into diffusion flames of H_2, CO, and illuminating gas. The choice of this study has the disadvantage that the work was not carried out by a highly controllable technique, but a great many substances were tested. Considering only the results for illuminating gas, the carbonates of the alkali metals were roughly twice as effective as the halides. Although the data are somewhat inconclusive, it appears that wet oxalates are an order of magnitude better than carbonates. This same study shows that the bicarbonates of Na and K are less effective than the carbonates, which observation is generally supported in references 25 and 28. Of these two bicarbonates, which are widely used in extinguishing fires, $KHCO_3$ is the better (see also references 25, 32, 33).

The order of effectiveness within the alkali metal series is $Li < Na < K$ as established in the older literature (see reference 1). The study of Friedrich[31] is in agreement with this ranking although he finds Li compounds to be only slightly less effective than those of Na. Furthermore, rubidium compounds are better than than potassium, but the trend fails with cesium which shows poorer suppressing power. The point must be made that the actual alkali-metal atoms themselves play no role in the inhibition process. Friedman and Levy[21] have added Na and K vapor to methane–air flames and found no effect on flame strength. Based on analysis of their own and others' results they proposed that gaseous KOH is the inhibiting species.

To illustrate the importance of surface area of the powdered inhibitors, data from the work of Dolan and Dempster[27] can be cited. In this study, methane-air mixtures were ignited in open-end tubes and suppression and quenching points were determined. These represented the amount of inhibitor dust necessary to prevent ignition (suppression point) and to prevent the flame from propagating the full length of the tube (quenching point). Larger amounts of powder were requ.red to suppress than to quench; data on quenching are shown below for $NaHCO_3$ powder covering a threefold variation in weight added.

Specific Surface	Quenching Point	
Area (cm^2/g)	(g/liter)	(cm^2/liter)
11,500	0.046	0.53
9,600	0.112	0.52
3,200	0.158	0.51

The dependence of the quenching point on surface area is brought out very clearly in these data.

Many of the studies were carried out to try to elucidate the role of salts and other solids in suppressing combustion. Some thought has been given to this problem and it is worthwhile to briefly review some points. The chemical role of solids is undoubtedly to destroy active chain carriers and this can be accomplished in one of two ways. The active species may combine on the particle surface or the solid may vaporize in the flame and gaseous product act as the inhibiting agent. The surface area dependence is consistent with both modes of inhibition. Rosser *et al.*[25] favor the latter and have calculated that significant evaporation of effective solid inhibitor will occur in the flame. They also report, based on collision calculations of radicals with the particle surfaces, that the solids theoretically cannot be as efficient as they are found to be experimentally if they simply act by providing recombination surface. There has been considerable speculation on chemical reaction mechanisms of inhibition assuming that gaseous species from the solids are the inhibiting agents.[1,21,25]

In favor of the alternative mode of inhibition, i.e., radical combination on solid surface, certain points are noted. First, the above collison calculations have been questioned.[5] Also it is well known that coating reaction vessels with certain non-volatile salts, KCl for example, raises the first explosion-limit of the H_2—O_2 system. It is intuitive to suppose that the same role of surface destruction of radical or atoms is played by solids in hydrocarbon flames. It is also noted that chemical inhibitors of any kind must act in the early part of a combustion wave. Accordingly, solids would have to show appreciable vaporization rates at ignition-temperature levels if their mode of inhibition is by gaseous agents. As has been previously mentioned, Lask and Wagner[9] have observed luminous particles originating in the reaction zone when, for example, $TiCl_4$ vapor had been added to flames. Miller and Vree,[34] in a study of ions and spectra of a low-pressure CH_4 flame inhibited with $Fe(CO)_5$, have observed emissions from atomic Fe, FeO and a continium attributed to hot particles in the upstream region of the flame. They interpreted their results as indicative that inhibition by volatile metallic compounds proceeds via very small particles formed in the cooler regions of the flame.

In favor of neither mechanism of inhibition, but germane to the subject is a calculation of Dolan and Dempster[27] who have shown that solid additives lower the flame temperature a great deal. Typically, enough of an alkali halide to suppress combustion will lower the temperature of a CH_4-air flame from ~1800 to 1500°C. The flame temperature at the flammability limit for the uninhibited mixture is ~1300°C.

Structure and Chemical Reaction Mechanism of Inhibited Flames

Two topics which are integral parts of the inhibition picture have received attention: (1) microstructure of flames containing inhibitors; and (2) postulated inhibition reactions and how they obstruct the normal reaction pathways. It is appropriate to note at this point that study of the pressure dependence of burning velocity of inhibited flames, which one would think might contribute substantially to understanding the inhibition process, has received practically no attention. It appears that only one such study has been carried out.[10] This involved methane-O_2 and -air flames inhibited with iron pentacarbonyl. It was found that the suppression effect decreases with decreasing pressure and at 0.1 atm is virtually nil. The discussion below dealing with the above mentioned topics is limited to flames inhibited with volatile halogen-containing additives.

There are three elements which constitute the microstructure of a flame: the aerodynamic flow field; the temperature profile; and the composition profiles of the chemical species through the wave. The determination and interpretation of these are described in references 35 and 36. Several groups have made contributions in the area of structure of inhibited flames, notably Levy *et al.*,[37] Fenimore and Jones,[38–40] Wilson and Fristrom,[41,42] and Bonne, Jost and Wagner.[10] This approach to the study of combustion suppression holds promise of providing understanding of the fundamental chemical processes of inhibition.

The composition profiles are obtained using quartz microprobes and these are the most valuable data. When properly analyzed by separating the diffusion and chemical reaction components, they yield the reaction rates of various species through the flame. As an example, consider a few pertinent results for a CH_4—O_2 flame inhibited with HBr.[42] CH_3Br was found to have been formed in the early part of the flame. The profile of the net reaction rate of CH_4 was shifted to a higher temperature region than in the uninhibited flame. It was sharper and narrower and the effect was more pronounced for HBr than for the less effective inhibitor HCl. These results demonstrate that the inhibitor must be impeding chain reactions in the lower temperature part of the flame where these reactions normally begin to become rapid. In the inhibited flame, the ignition temperature is thus raised. The authors describe the inhibited flame as consisting of four zones—preheat, inhibition, primary reaction, and the post-flame region (in which CO conversion occurs and radicals recombine).

The chemical reaction mechanism of inhibition is not known with certainty, but the important reactions of hydrocarbon and hydrogen flames are known;[43] hence, it can be postulated how inhibitors might interfere with them. This has been done by several authors[3,17,38,41,44,45] and the following is a brief summary of how brominated additives could react, using CH_4 as an example.

The active species in this flame are H, O, OH, and CH_3, and some chain and chain-branching reactions are:

$$H + O_2 \rightarrow OH + O \quad (1)$$

$$O + CH_4 \rightarrow ON + CH_3 \quad (2)$$

$$OH + CH_4 \rightarrow H_2O + CH_3 \quad (3)$$

$$CH_3 + O_2 \rightarrow CH_2O + OH \quad (4)$$

$$CO + OH \rightarrow CO_2 + H \quad (5)$$

Reaction (3) is believed to account mainly for the disappearance of fuel. Reaction (5) is the principal route to CO_2 production, the CO arising from CH_2O. Inhibition presumably can be effected by HBr, for example, if it reacts with H, O, OH, or CH_3 via:

$$HBr + H \rightarrow H_2 + BR \quad (6)$$

$$HBr + O \rightarrow OH + Br \quad (7)$$

$$HBr + OH \rightarrow H_2O + Br \quad (8)$$

$$HBr + CH_3 \rightarrow CH_4 + Br \quad (9)$$

Any of these reactions might hinder the normal flame propagating mechanism.

The fate of the bromine atom in the above reactions has been considered. This is equivalent to the problem of how Br_2 or other brominated additives besides HBr inhibit flames, since it has been postulated that these act by first decomposing to yield Br. Rosser *et al.*[17] suggest that once Br is formed it reacts by

$$CH_4 + Br \rightarrow HBr + CH_3 \quad (-9)$$

which is the reverse of reaction 9. As Skinner[3] has pointed out, it is hard to see how this reaction could then lead to hindrance of the mechanism if (7) or (8) were the important inhibiting reaction. For example, the couple (−9) and (8) have the effect of producing one CH_3 radical for each OH inactivated, but the main role of each OH is to react with CH_4 to produce one CH_3 anyway (reaction 3). A similar condition exists with the couple (−9) and (7) and reaction (2). Thus, it would appear that if (−9) is an important part of the inhibition reaction sequence for bromine-containing compounds other than HBr, it must act either coupled to (6) to suppress reaction (1) or by interfering with some reactions other than (2) and (3), possibly reaction (5). Both these possibilities are unattractive since reactions (1) and (5) are probably less important than (2), (3), and (4) in driving the combustion. An alternative reaction suggested by Wilson[41] is simply

$$OH + CH_3Br \rightarrow H_2O + CH_2Br$$

This has the advantage that it destroys a key radical, OH, but it does not explain why, for example, CH_3Br is more effective than CH_3Cl, nor can it be generalized to include CF_3Br. It is interesting to note that it is an unsettled question whether in fact [OH] is increased or decreased in inhibited flames,[41,42] although excited [OH] is decreased.[17,22]

If inhibition is principally by impeding reaction (1) it seems more reasonable that it would occur in the same way as it is believed to in the H_2-air flame;[11,38] that is directly by

$$Rx + H \rightarrow Hx + R.$$

and

$$Rx + H \rightarrow \cdot R'x + H_2$$

or

$$Hx + H \rightarrow H_2 + x$$

These reactions are consistent with the previously noted findings that CH_4 and CH_3Br are equally effective in inhibiting the H_2-air flame; that they are twice as good as HBR; and that CF_3Br, for example, is only a mediocre inhibitor.

Considerations in Practical Fire Control, and Requirements of Suppressants for Flight Vehicles

Laboratory-scale experiments conducted on burner flames are chosen by scientists for study because of their reproducibility and manageability and because they offer the most ideal system in which to discover general principles. It is a fact that inhibitors that are effective in flame studies are also effective on fires. There are problems involved in scaling and applying results to practical fires, however, not the least of which is the fact that usually solid or liquid materials are involved as the combustible rather than fuel gas. This immediately introduces a gasification step into the process, which may in fact be the rate limiting step. Fenimore and coworkers[46–48] have reported studies of materials flammability and the inhibition thereof. A recent meeting of the Eastern Section of the Combustion Institute dealt with this topic extensively.[49]

It may sometimes be possible to take advantage of this gasification step for suppression purposes. The combustion of most materials occurs in a stable diffusion flame above the material surface. Heat from the flame is transmitted back to the condensed phase causing vaporization. The vapors enter the flame, react exothermically, and continue the cycle. In addition to inhibiting combustion in the flame zone, the material itself can be treated to suppress its vaporization rate or render its pyrolysis products less flammable. For example, chlorinating polyethylene makes it much less flammable by suppressing its vaporization.[47]

Similarly, the ignitability of material offers another parameter to attack in attempting to desensitize. A bibliography on ignition is given in reference 9, but special mention may be made of the studies of Simms[50] and Broido and Martin.[51] A simplified description of the ignition process is helpful in seeing how to approach the problem of reducing flammability from this standpoint.

A combustible is brought to a state of steady burning by application of energy, either thermal or radiant. The energy must be supplied for a certain time and at a certain flux level until the temperature gradient within the material reaches that which is present during steady burning. When the surface temperature reaches approximately the steady-state value, gasification occurs at an appreciable rate. It is noted that the delivered flux must produce a temperature gradient as steep as or *less* steep than that of steady burning—if a steeper profile is present, a flash may result but no self-sustaining combustion will be obtained. The time for the heat buildup in the material is known as the ignition time and is determinable from the thermal properties of the material and the known flux. Whether ignition will actually occur depends upon whether the gas products that emerge from the material at the surface temperature produce a hypergolic mixture with the atmosphere. If they do or if the ignition flux is by a high-temperature thermal source, a steady diffusion flame will develop (if appreciable condensed-phase heat release or adsorption occurs, the foregoing is an over-simplified description). As can be imagined, additives that inhibit the gasification or the flame reactions may be effective in suppressing ignition as well as steady burning. However, one important point is brought out by the work of Broido and Martin[51] in their study of the effect of $KHCO_3$ added to cellulose. This is that substances added to materials which inhibit the flame reactions may act as catalysts of the pyrolysis process.

The rate of flame spread over surfaces is another process of importance in fires. This subject has been reviewed,[52] and in addition to the obvious properties of a material such as chemical composition, the following variables can be listed as exerting dominant effects in certain situations: moisture content; roughness of surface and edges; orientation of material (for example, flame propagating up or down a sample); size of sample. In addition, heat transfer by convection and radiation in larger scale fires can exert a most importance influence which may be absent in laboratory studies. These affect not only flame spread but all other aspects of post-ignition combustibility including suppression.

The foregoing is intended to highlight some of the considerations involved in fire control. In what follows, the requirements for a fire suppressant for flight vehicles are briefly discussed. For military aircraft, especially relatively high temperatures are often encountered. Omitting consideration of the means of containing suppressant, the high temperature condition imposes the specifications of thermal stability on the inhibitor. Secondly, its vapor pressure at high temperature cannot be prohibitive. Other requirements are low toxicity (and low pyrolyzed toxicity), low corrodibility, nonconduction of electricity, etc. These are discussed in references 53–56. In meeting these requirements, it is desirable not to compromise certain low temperature properties such as freezing point, viscosity, etc., but obviously some trade-off will always be necessary. Workers at National Engineering Science Company have evaluated a variety of halogenated compounds for possible use as extinguishing agents for the Supersonic Transport. The list of these substances, 34 in all, is presented in reference 56. A number were found to meet specifications similar to those mentioned above and also to exhibit suppressing strength approximately equal to CH_2ClBr as measured by the authors. Poor thermal stability was the principal reason many of the substances were unsuitable. To meet this requirement a compound had to be thermally stable at 350°F for 18 hours under the conditions of the test.

The same group at NESC has carried out an interesting study[57] attempting to obtain synergistic enhancement of halogenated inhibitors by adding certain radical initiators. They report the effect to be marginal or nonexistent for the systems they investigated. In another study Barduhn *et al.*[58] attempted to adsorb halogenated agents onto powders. The powders were carbon, alumina, silica gel, etc., which are not used as fire suppressants by themselves. They found that carbon with adsorbed CF_3Br is as effective as commercial bicarbonate powder. The possibility suggests itself of adsorbing alkyl halides onto normal flame inhibiting powders.

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ABSTRACTS

A. Prevention of Fires and Fire Safety Measures

Moll, K. and McAuliffe, J. (Stanford Research Institute, Menlo Park, California) "Public Capabilities for Preventing and Extinguishing Ignitions from Nuclear Attack," *Report No. NOO22867C2–35, OCD Work Unit 2522G, SRI Project MU-6501, NRDL-TRC-68-45, Office of Civil Defense* (November 1968).

Related Sections: **A,** *E*

Subject Headings: **Public extinguishing capabilities;** *Public relations Civil Defense personnel; Manpower studies; Training; Attitudes; Behavior performance (human); Fire extinguishers; Fire safety, fires, safety, civil defense systems, passive defense.*

Authors' Abstract

This study estimates the present and potential capabilities of the general public to prevent and extinguish ignitions resulting from nuclear attack. It analyzes the probabilities of residential ignitions in San Jose, California, and the reductions possible through several alternative programs for encouraging self-help fire countermeasures.

The most effective type of countermeasure is to shield windows by painting, coating, covering, or other methods. A quickly implemented program to combine this and other self-help preventive countermeasures in an effort requiring 8 man-hours per household could reduce the number of home ignitions by as much as 65%. A last-minute prevention program requiring only a man-hour per household could reduce ignitions by as much as 40%. Extinguishing measures are not likely to reduce ignitions by more than 25% under conditions of extensive casualties and disrupted services.

Overall, the most promising program involves instructing the population by mass media, and inspecting household prevention efforts, plus recommending use of garden hose or other commonly available equipment (not specially procured extinguishers) to fight fires. Such a program could quickly mobilize the capabilities of the general public, which are many times as great as those of organized fire forces.

Law, Margaret (Joint Fire Research Organization, Boreham Wood, England) "Fire Protection in the Process Industry Building—Plant and Plant Structures," *Joint Fire Research Organization Fire Research Note No. 725* (September 1968).

Section: **A**

Subject Headings: **Fire protection;** *Structural elements; Equipment fuel; Storage.*

Author's Abstract

The way fire spreads and the principles of structural fire protection are outlined. The necessity for having fire stops in ventilating systems and in suspended ceilings is shown. The furnace test for building elements specified in B.S. 476: Part 1: "Fire tests on building materials and structures" is described.

Fires in flammable liquids, which are different from more conventional building fires and from the furnace test, are discussed. Flame temperatures and the sizes of flames from pools of liquid are described. The rates of heating for structures and storage vessels which may be surrounded by fire or heated by radiation from flames in a nearby bund are given. Methods of estimating the amount of protective material to insulated structures and vessels are provided. This protection is compared with the amount needed in the standard furnace test.

Factors influencing the choice of protective materials are discussed.

Parker, W. J., Corlett, R. C., and Lee, B. T. (U. S. Naval Radiological Defense Laboratory, San Francisco, California) "An Experimental Test of Mass Fire Scaling Principles," *Report under Contract USNRDL-TR-68-117, OCD Work Unit 2536F* (December 1968).

Related Sections: **A,** *E*

Subject Headings: **Mass fire scaling;** *Temperature distribution, above fires; Velocities, inflow and updraft; Flambeau Fire.*

Authors' Abstract

Electrical models based on partial scaling principles neglecting molecular transport parameters (as characterized, for example, by a Grashof number Gr), have been built at NRDL to scale the gross flow features of a mass fire down to laboratory size. The scaling rules require that the model be geometrically similar to the prototype, and that heat release rate per unit area be scaled as the square root of the characteristic horizontal dimension L. To the extent that these principles are valid, gas temperatures will be the same, and velocity scales as $L^{1/2}$, at homologous points of model and prototype flow fields.

Data in this paper were obtained with a model which consists of a 2×2 ft sq array of 60 electrical heating elements with a total electrical power dissipation of 4.7 kilowatts. Inflow air velocities at the edge of the model and updraft velocities in the air column above the model are measured with a hot wire anemometer. Air

temperatures in the column are measured with a bare chromel-alumel thermocouple. Dioctyl phthalate is sprayed on the heating coils to produce a dense smoke which simulates the smoke column above the fire.

The heating rate used in the model was scaled down from the estimated heating rate 18 min after ignition in the June 1966 Project Flambeau fire. The scaled up inflow velocity measured at 1 in. above the surface on the model compared favorably with the field measurements of the inflow velocity at the scaled up elevation of 50 ft at the Flambeau fire. Photographs of the smoke column above the model were similar to those taken above the Flambeau fire.

Although the data so far taken must be regarded as preliminary, the possibility of scaling the gross features of mass fires down to laboratory size models appears promising.

Vines, R. G. (Fire Research Section of the Chemical Research Laboratories, C.S.I.R.O., Australia) "The Forest Fire Problem in Australia—A Survey of Past Attitudes and Modern Practice," *Australian Science Teachers' Journal* (November 1968).

Related Sections: **A**, *F*

Subject Headings: **Forest fire problem, in Australia.**

R. M. Nelson, Jr., Abstracter

Large destructive wildfires occur annually in Australia despite efforts of fire control authorities to protect their lands by suppressing all fires immediately. It is questionable whether a policy of complete protection is practical or economically feasible, and foresters in Western Australia have turned to large-scale controlled burning to solve the bushfire problem. Conservationists, opposing this approach, argue that the total environment should not be destroyed for the sake of fire protection alone.

A. R. King has studied extracts from early Australian literature which deal with effects of colonization on forest ecology in that country. King concluded that in colonizing Australia the white man has:

a. changed the forest from open stands of even-aged trees to uneven-aged trees in dense undergrowth by excluding fire,
b. reduced the forest area burned annually through his protection efforts,
c. produced more devastating bushfires by causing buildup of fuels.

If King's conclusions are correct, a policy of controlled burning would tend to return the forest to its original state.

The author believes that fuel reduction accomplished with careful, controlled burning offers a more positive policy of forest conservation. He favors re-establishment of the original forest, in which fire played an important part. On the other hand, a policy of complete protection is undesirable because it disturbs older ecological patterns which have always included fire. Also worth considering is the low probability that complete protection can ever be achieved.

A method of aerial, prescribed burning, developed in Australia, has been in use there since 1967. It involves the dropping of incendiary capsules from an aircraft onto predetermined ground targets. A special machine primes the capsules and ejects them at a maximum rate of one every two seconds from a plane flying over the area to be burned. The capsules burst into flames about 30 sec after landing and ignite the surrounding fine fuel. They are ejected so as to form a grid of spot fires which eventually burn together and extinguish themselves. Spacing of the grid is determined by the factors which affect fire intensity. The method is applicable in either flat or mountainous terrain.

In 1967 almost half a million acres of Western Australian forests were burned using this aerial technique. Ten to fifteen thousand acres can be burned in one afternoon using a single aircraft. Total application cost, including the aircraft, is about 10 cents per acre.

Widginton, D. W. (Safety in Mines Research Establishment, Sheffield, England) "A Method for Assessing the Effective Inductance of Components Used in Intrinsically Safe Circuits," *SMRE Research Report No. 254* (1968).

Related Sections: **A**, *B*, *I*

Subject Headings: **Safe circuit**; *Ignition; Discharge, Flammability, Ignition energy.*

Author's Abstract

When an inductive circuit is interrupted , a discharge takes place between the separating contacts. The energy of this discharge is the primary factor which determines whether or not it is possible to ignite a surrounding flammable atmosphere. Where the circuit contains air-cored inductors the discharge energy can be calculated from a knowledge of the value of inductance and of the source voltage. However, this calculation may not be possible for circuits containing iron-cored inductors, because it is not possible by conventional methods to assign a suitable value of inductance to such components. This paper describes a method by which discharge energies in circuits containing iron-cored inductive components can be assessed by using a simulated-discharge technique; from the energy values a value of effective inductance can be found. The new method is much more rapid than ignition testing, and can be applied at normal working currents as a means for assessing intrinsic safety.

B. Ignition of Fires

Averson, A. E., Barzykin, V. V., and Merzhanov, A. G. "Dynamic Ignition Regimes," *Physics of Combustion and Explosions* 4(1), 20–30 (1968). In Russian.

Section: **B**

Subject Headings: **Ignition regimes.**

Translated by L. J. Holtschlag

An approximate method relating to the ignition condition (ignition begins as soon as the heat supply from the external source equals the heat supply from the chemical reaction) is used to examine dynamic ignition regimes, i.e., regimes in which the characteristics of heat transfer between the external source and the material being ignited are explicitly time-dependent. Also considered for some particular cases are constant surface temperature and heat flux for Newtonian heat exchange with a constant temperature source. The results are compared with those of other authors, yielding good agreement with numerical calculations. The given approximation method makes it possible to formulate new schemes for the calculation of the kinetic parameters.

Zimont, V. L. and Trushin, Yu. M. "Ignition Delays of Hydrocarbon Fuels at High Temperatures," *Physics of Combustion and Explosion* **3**(1), 86–93 (1967). In Russian.

Related Sections: **B**, *G*

Subject Headings: **Ignition delays**; *Kerosine; Benzine.*

Authors' Conclusions—Translated by L. J. Holtschlag

Given are experimental data on the induction time of gaseous hydrocarbon fuels ($T-1$ kerosine and $B-70$ benzine) and of propane at temperatures of 900° to 1100°K as obtained by injecting the fuel into a hot air stream; it is found that under identical conditions all three fuels have essentially the same induction times. The induction time is deduced to be pressure- and concentration-dependent. On this basis an empirical formula is found for the induction period which gives a satisfactory description of the experimental data and can therefore be recommended to estimate the induction time of hydrocarbon fuels in the temperature interval 900° to 2400°K.

C. Detection of Fires

Cheney, N. P. (Forest Research Institute, Canberra, Australia), **Hooper, R.** (Forest Department, Northern Territory Administration, Darwin, Australia), **MacArthur, D. A., Packham, D. R., Vines, R. G.** (CSIRO, Melbourne, Australia) "Techniques for the Aerial Mapping of Wild Fires," *Australian Forest Research* **3**(4) 3–20.

Section: **C**

Subject Headings: **Aerial mapping**; *Wildfires.*

J. H. Dieterich, Abstracter

This paper summarizes the techniques currently being used in Australia to map wildfires from the air. Visual fire mapping, use of near infrared, and use of medium and far infrared techniques are discussed—including some of their limitations. A considerable portion of the paper is devoted to mapping fires at night.

In visually mapping fires from the air, the relative success of each such mission depends upon the visibility. During active burning periods in the daylight hours, a good portion of the edge of the fire is usually visible and accurate mapping is possible. When burning conditions change and convective activity is much less pronounced, it becomes difficult to see the fire perimeter and ground features in order to map them accurately. The helicopter is recognized as being the best observation platform from which to visually map the fire, but there is only limited use of rotary-wing aircraft in Australia for such purposes.

The image converter is a convenient device that operates in the near infrared region (0.7–2 μ) and provides a change in contrast in the image by using an assortment of filters. The image converter functions by being receptive only to light that is not scattered to any significant extent by thin and diffuse smoke. When using the image converter for detection or mapping, the most effective observations are made while looking away from the sun. Thick smoke limits the use of the near infrared devices and, when back scattering of light occurs simultaneously while looking into the sun, the effectiveness of the image converter is further reduced.

Using an image converter in a light plane has other disadvantages. Using the instrument while in rough flying weather can be tiring, the instrument is not entirely foolproof, and the operator needs considerable practice with the instrument to use it effectively. However, an experienced operator may be able to make useful estimates of fire intensity, and the instrument may be an improvement over visual observations because the flames can be more clearly seen.

The authors suggest that there are a number of areas where our knowledge is deficient concerning the use and application of sophisticated infrared equipment. For instance, does the nature of the smoke above a large fire change with time; or, are the transmission characteristics of smoke altered by initial condensation of moisture on the particles?

Using instruments that operate in the medium (2–5 μ) and far (>5 μ) infrared improve penetration of dense smoke, but the equipment becomes less sensitive to the sun's reflected light and it may be difficult to pick up the surroundings about a fire. Using the medium-to-long wave infrared devices requires careful interpretation of the "picture" because contrast depends upon temperature differences rather than variations in the intensity of reflected light.

It is suggested that the most useful regions of infrared wave length are between 2.0–2.5 μ and 8.0–13 μ. The first range gives reasonable smoke penetration; and because of daytime solar reflection, terrain recognition is relatively easy. The 8.0–13 μ range will give sensitive detection of spot fires and smouldering lightning fires. An ideal combination would be to use the longer wave length for fire detection and the shorter wave length for mapping. Building this capability into one instrument, and utilizing a navigational system that would permit precise location of detected fires, would be an ideal combination. (NOTE: Currently being tested by Project Fire Scan, Northern Forest Fire Laboratory, Missoula, Montana.)

Described also in this paper is a technique for mapping fires at night *without* the aid of infrared sensors. This system involves the use of a ground-located, portable, nondirectional beacon and a light aircraft equipped with auto pilot, instrument-rated pilot, navigator, and observer-plotter. The plane flies a course over the fire so that the perimeter is seen by the observer (fire perimeter is thought to be more easily recognizable at night than in the daytime); the flight route is plotted using as many long, straight runs as possible and still keep over the fire perimeter. When the course is completed, the end point will not necessarily coincide with the starting point and wind corrections are made to "close" the course.

Nocturnal plotting has been done operationally on two occasions with limited success. More experience is needed before it can be determined if the nocturnal plots are accurate enough to be of much value.

Johnson, J. E. (Pyrotronics, Inc., Union, New Jersey) "Engineering Early Warning Fire Detection," *Fire Technology* **5**, 5–15 (1969).

Section: **C**

Subject Headings: **Fire detection.**

G. A. Agoston, Abstracter

The author discusses the engineering principles involved in the design of systems for detecting fires in the incipient stage. Ionization chambers used for detecting small air-borne particles have been adapted to this application.

Ionization of oxygen and nitrogen molecules in the air within the detector is produced by alpha-particle bombardment from a radioactive source. The ions move toward two electrodes across which a voltage is applied. In the presence of combustion particles, the rate of flow of the ions is reduced and a higher voltage results. This voltage increase is used to actuate an alarm.

Smoke particles from most materials tend to be from 0.01 to 1.0 microns in size (a range for which ionization detectors seem to be most responsive). For particles of this size, the rate of settling is very small and can be neglected. If little heat is being generated, transport of the particles is principally by air currents in the area. If there is appreciable heat release, then thermal convection currents can govern the particle path.

The placement of detectors must take into account zones to which combustion products in sufficient concentration are likely to be carried. Proper placement often results in detectors being installed about every 400 to 600 sq ft, but never over 1,000 sq ft. In order to secure a satisfactory degree of response under severe air flow conditions, one detector for every 150 sq ft may be required.

Sometimes the decision of detector placement can be made on the basis of an analysis of air flow patterns determined from building designs. In existing buildings, detector placement can be determined from on-the-spot tests. Distribution patterns of combustion products are obtained with the use of a combustion gas analyzer and small clean-burning fires in metal cans.

Care must be given to adjusting the detector to a sensitivity that eliminates unwanted alarms from traces of particles normally present and yet provides response to an incipient fire within the protected area. The detector should not be mounted in strong air currents, because its sensitivity may be altered and because the sample actually entering the detector may not be representative.

Consideration must be given to the possibility of stratification of products away from the ceiling owing to a thermal barrier formed by a blanket of warm air. The problem is accentuated by peak or sawtooth roofs. A chart is given to relate the proper positioning of the detector (with respect to the ceiling) and the ceiling height. Beams introduce the complication of channeling combustion products. Design information is given which assists in deciding whether the detectors should be installed on the bottom side of the beams or in the beam pockets.

The problem presented by air conditioning systems is discussed briefly. Ionization detectors may be used to shut down systems when smoke is being carried to areas where there is no fire. A good method is to cross sample the duct and to feed this sample to a detector chamber. Detectors may also be located downstream from fans to monitor fires originating in the fan motor or filters.

The author discusses briefly several applications of early warning detection systems and calls attention to the need for establishing performance standards for specific installations (e.g., a computer room).

D. Propagation of Fires

Baldwin, R. and Thomas, P. H. (Joint Fire Research Organization, Boreham Wood, England) "Spread of Fire in Buildings—Effect of Source of Ignition," *Joint Fire Research Organization Fire Research Note No. 729.* (September 1968).

Related Sections: **D**, *B*, *L*

Subject Headings: **Fire spread**; *Statistics; Fire cause.*

Authors' Summary

The statistics of fires attended by the fire brigades show that a markedly higher proportion of fires spread beyond the room of origin when the source of ignition is either malicious or intentional ignition or burning rubbish. Other causes result in different proportions of spreading, but these differences are smaller, and in some cases could have occurred by chance statistical fluctuations.

Baldwin, R. and Thomas, P. H. (Joint Fire Research Organization, Boreham Wood, England) "Spread of Fire in Buildings—Effect of the Type of Construction," *Joint Fire Research Organization Fire Research Note No. 755.* (December 1968).

Related Sections: **D**, *L*

Subject Headings: **Fire spread**; *Columns; Walls; Statistics*

Authors' Summary

The statistics of fires attended by the fire brigades are examined to investigate the influence of certain structural features on the chance of a fire spreading beyond

the room of origin. A statistical analysis shows that there is no significant variation from year to year (1963 and 1964) and that the chance of spread in buildings with timber framed walls is about twice as large as in those with other types of wall. The role of internal columns is not clear and those variations which have been found to be significant may be the result of other features associated with the type of column.

Belyaev, A. F., Frolov, Yu. V., and Dubovitskii, V. F. "Burning Rate of Systems of Condensed Mixtures with Various Degrees of Component Mixing," *Physics of Combustion and Explosions* 4(1), 10–15 (1968). In Russian.

Related Sections: **D**, *G*

Subject Headings: **Burning rate**; *Particle size, NH_4ClO_4 mixing*

Authors' Conclusions—Translated by L. J. Holtschlag

The degree of mixing of the oxidizer and fuel of a heterogeneous mixture system depends on the particle size and the thoroughness of the mixing; the smaller the average spacing between oxidizer and fuel particles, the higher the degree of mixing and the closer the system is to being homogeneous. On this basis experiments were carried out to determine the burning rate of compact stoichiometric mixtures of NH_4ClO_4 and sucrose. The degree of mixing was varied and coarse. It was improved by grinding and thorough mixing through precipitation by the addition of a methanol solution of NH_4ClO_4 and sucrose to cooled petroleum ether with simultaneous grinding in a vibration mill. Three characteristic regions are found: (a) a flat burning front, the rate increasing linearly with pressure; (b) gradual transition from a flat front to torch burning along the fuel-oxidizer boundary; (c) torch burning.

Burgoyne, W. A. and Roberts, A. F. (Imperial College, London, England) "The Spread of Flame across a Liquid Surface. I. The Induction Period (with P. Q. Quinton); II. Steady-State Conditions; III. A Theoretical Model," *Proceedings of the Royal Society* **A308,** 39–79 (1968).

Related Sections: **D**, *H, I*

Subject Headings: **Flame spread**; *Alcohols.*

I. Glassman, Abstracter

These three papers represent one of the most complete experimental efforts on flame spreading published to date. The first part deals with the processes leading to flame spread when the fuel is ignited by use of a wick, the second reports flame propagation under various conditions and the third is an attempt to model theoretically the steady propagation process. The most significant aspect of the work is that it reports for the first time in the general literature Roberts' finding[1] of the importance of convection in the liquid.

The trends reported by the authors in discussing their experimental data are all very interesting; however, the data must be considered only qualitative in nature and apparatus dependent. Further, this reviewer cannot agree with many of the explanations and analyses offered to explain the experimental observations. The biggest criticism is that the authors basically used narrow channels and seemed to ignore in their discussions the effect of the side walls on processes occurring in the liquid.

In Part I, an asbestos wick is placed across the center of a long channel filled with an alcohol (isopentanol, hexanol, or butanol). The wick protrudes above the liquid surface. After ignition, the flame establishes itself 2 to 3 mm from and parallel to the exposed portion of the wick. After an induction period, the flame begins to propagate across the fuel surface. The induction period varies from a few seconds to as great as 3 min and depends upon the fuel, its depth and bulk temperature. If one ignores the times for very thin films, then the induction period increases with fuel depth and levels off at a value which must be equal to the depth of thermal penetration in this convective system. As would be expected, the closer the bulk temperature is to the flash point, the shorter the induction period and less the effect of channel depth. The induction period is explained on the basis of flow patterns observed and temperature fields measured. The authors describe a pattern of two eddies in the flow near and beneath the flame. They explain the existence of these eddies on the basis of buoyancy effects. Considering the location and direction of the eddies and the close proximity of the flame to the wick, this reviewer believes it is more likely that the flow pattern is induced by a variation in surface tension[2] brought about by a temperature gradient at the surface near the flame. In order to calculate the conditions at the wick (temperature and fuel vapor pressure) the authors make drastic assumptions. In particular, the one that the rate of consumption per unit area in the wick diffusion flame is the same as in a premixed stoichiometric flame has no basis and consequently the fact that the numbers found appear realistic is strictly fortuitous.

In Part II, steady-state propagation rates are reported as a function of depth, width, initial liquid temperature, and water content of the fuel. The propagation rate increases with decreasing depth, increasing width, increasing initial temperature, and decreasing water content. Most experiments, except those concerned with width were carried out in channels 3.3 cm wide. These channels were formed by inserting large asbestos sheets in the fluid. The sheets protruded high above the surface in order to shield the flame from air currents. The authors claim the width effect is due to heat losses from the flame to the asbestos sheets. The reviewer's work leads him to believe the effect is more likely due to heat losses from the liquid fuel to the sheets.

An important aspect of Part II are those experiments in which the initial fuel temperature is greater than the flash point and vapor phase phenomena control. Under temperature conditions which give a stoichiometric fuel–air ratio above the surface, propagation rates of the order of 200 cm/sec are obtained. These values are at least 4 to 5 times normal laminar flame propagation speeds for stoichiometric mixtures. The authors propose the expansion of gases through the flame as the effect which causes an acceleration of the flame front and a displacement of unreacted gas ahead of the flame.

Another interesting experimental contribution is the effect of superimposed disturbances on the flame propagation rate. For liquids at temperatures below the flash point, when the liquid was made to flow in the direction of flame propagation, the propagation rate became the stagnant rate plus the flow velocity. Flow in the opposite direction reduced the propagation rate to very low values but never reversed it. Air flows both with and against the direction of flame propagation had strong effects on the propagation rates when the liquid was at temperatures above the flash point. However, for liquids below the flash point, no effects were observed until the air velocity reached a velocity about 100 cm/sec. In either case, the flame would not spread against air velocities in excess of 190 cm/sec.

The theoretical model in Part III considers the liquid thermal conductivity as anisotropic, with the value in the direction of the propagation and liquid convection much greater than the real value. In this manner they attempted to account for the effects of the convection. They, then, solved the two-dimensional heat conduction equation in the liquid under the condition that a strip of width $2b$ (the flame) moved over the surface of the liquid and imparted a heat flux, Q, to the surface. They obtained a relation between the velocity (v) of the heat source and the surface temperature rise (θ_F) at the leading edge of the heat source. One must note that it is not possible to solve for the eigenvalue v (the flame propagation rate) from the manner in which the problem has been posed. One of the results of the analysis is that as (θ_F/fuel depth)$\rightarrow 0$, the ratio of the convective heat term to the heat flux to the liquid must approach 1. Since this ratio approaches unity, the conductive in the liquid vanishes. Thus, the problem has been formulated so that if one travels with the heat source (flame), the convection term, which in this limit is the sole means of heat transfer, takes heat from the control element (i.e., is in a direction opposite to that of flame propagation) and the formulation does not give the correct physical description of this problem.

Irrespective of some of the above criticisms, Roberts' thesis work must be considered a pioneering effort and everyone working in the field should read both the thesis and these three papers.

References

1. Roberts, A. F.: *Ph.D. Thesis, University of London*, 1959.
2. Glassman, I., and Hansel, J. G.: "Some Thoughts and Experiments on Liquid Fuel Flame Spreading, Steady Burning and Ignitability in Quiescent Atmospheres," *Fire Research Abstracts and Reviews, 10,* 217 (1968).

Seigel, L. G. (United States Steel Corporation, New York, New York) "The Projection of Flames from Burning Buildings," *Fire Technology* **5** 43–51 (1969).

Related Sections: **D**, *I*

Subject Headings: **Burning buildings.**

G. A. Agoston, Abstracter

This paper presents some results of a study of the characteristics and dimensions of flame projecting from burning buildings. The work was undertaken because of the need to find means of protecting structural steel in exterior applications.

The relevant theory of gas jets projecting from an opening into a body of still air is discussed briefly. The following equation relating flame projection to combustible content is developed by a simple transformation from existing theory:

$$x = KrLA_f/A_0^{1/2}T_x \qquad (1)$$

where x is the distance from the window measured along the center line (ft); r is the burning rate (%/min); L is the fire load (lbs/sq ft of floor area); A_f is the floor area (sq ft); A_0 is the area of window opening (sq ft); T_x is the temperature at distance x on the flame centerline °R; K is a constant.

In obtaining the above, the similarity of heat and mass transport is assumed. No provision is made for buoyancy, heat loss, or continuing combustion in the flame. Some jet center line temperatures were estimated with radiant heat transfer taken into consideration. These are compared with measured flame temperatures. The measured values are significantly higher close to the building, suggesting that combustion is still taking place in the projection flame.

Equation (1) is used as a basis in correlating the results of temperature traverses in flame projecting from a test chamber. Tests were conducted under maximum burning rate conditions (i.e., with sufficient air supply) using 1½ in. square fir lumber arranged in cribs. A plot of x_{1000} versus $LA_f/A_0^{1/2}$ for 20 tests suggests the linear relationship

$$x_{1000} = 0.052(LA_f/A_0^{1/2}) - 1 \qquad (2)$$

where x_{1000} is the maximum distance from the window where the temperature is 1000°F. The data were obtained for L varying from 5 to 20 lbs/sq ft and for A_f varying from 12 to 48 sq ft.

In addition a plot is presented showing the maximum burning rate for square stick wood crib fires versus the stick size. This can be represented by

$$b = 3.4r_{max}^{-0.60} \qquad (3)$$

where b is the stick size in inches.

If the burning rate r_{max} is taken to be 3.9%/min for 1½ in. square lumber [from Eq.(3)], Eq. (2) can be written in more general form as follows:

$$x_{1000} = 0.013(r_{max}LA_f/A_0^{1/2}) - 1 \qquad (4)$$

The projection of flame is specified by a temperature of 1000°F because steel members are not seriously affected below this temperature. Flame projection can be estimated using Eq. (4) when the fire load and burning rate are known. When they are not known, Eq. (2) may often be used to provide a conservative estimate. Studies are in progress to supply more suitable information on the burning rates of building materials.

Thomas, P. H. (Joint Fire Research Organization, Boreham Wood, England) "Fires in Old and New Non-Residential Buildings," *Joint Fire Research Organization Fire Research Note No. 727.* (September 1968).

Related Sections: **D**, *L*

Subject Headings: **Non-residential fires;** *Building age; Fire spread statistics.*

Author's Summary

A new method of examining the fire brigade reports shows that for 1963 there were differences between the extent of fire spread in buildings built since 1950 and older buildings. There is a reduced tendency for fires to spread upward in such new buildings.

G. Combustion Engineering

Artemenko, E. S. and Blinov, V. I. "Ignition, Combustion, and Extinction Tempertures of Liquids in Containers," *Physics of Combustion and Explosions* **3**(4), 542–545 (1967). In Russian.

Section: **G**

Subject Headings: **Ignition, combustion, and extinction temperatures.**

Authors' Summary—Translated by L. J. Holtschlag

A study was made of the ignition, combustion, and extinction temperatures of amyl alcohol at various levels in the containers, which were quartz tubes of diameters 22, 36, 56, and 80 mm. It was found that the ignition temperature increases with increasing distance (h) between the liquid and the edge of the container, in fact, at a progressively faster rate as a certain limit depth is approached. The combustion temperature in the narrow tubes varied according to a complex law, but at diameters beyond 50 mm remained essentially constant with increasing h, dropping only as the limit depth was approached. At the limit depth the curves of the ignition and combustion temperatures closed, delineating a certain region. Below the limit depth the surface temperature of the ignited surface increased rapidly with time. If the distance between the liquid and the edge of the burner was greater than the limit depth, the heated liquid ignited and then quickly extinguished. The extinction temperature of the liquid proved to be somewhat lower than the ignition temperature, but the difference between the combustion and ignition temperatures did not exceed 10°C.

Babkin, V. S., V'yun, A. V., and Kozachenko, L. S. "Determination of Normal Flame Velocity from the Pressure Record in a Constant-Volume Bomb," *Physics of Combustion and Explosions* **3**(2), 362–370 (1967). In Russian.

Related Sections: **G**, *D*

Subject Heading: **Flame velocity.**

Authors' Summary—Translated by L. J. Holtschlag

The normal flame velocities of stoichiometric mixtures of benzene, *n*-heptane, and isooctane with air were determined from the time records of the pressure in a spherical constant-volume bomb. Equations are first derived for calculation of the normal velocity and the fractions of combustion products. The expansion factors are determined from charts due to Tottel *et al.* Photographs show that after ignition of the mixture by a weak electric spark the initially smooth sphere of flame gradually becomes wrinkly and then cellular. The cells grow as a result of the increase in surface, and at the same time they subdivide. The data indicate that the velocity has a tendency to change with temperature and pressure in the same way as an unperturbed laminar flame, suggesting that the velocities of the cellular flames are close to the normal velocities of unperturbed laminar flames.

Bakkman, N. N. "A Stoichiometric Coefficient Reflecting the Elemental Composition of Fuel and Oxidizer," *Physics of Combustion and Explosions* **4**(1), 16–19 (1968). In Russian.

Related Sections: **G**, *H*

Subject Heading: **Stoichiometric coefficient**

Author's Introduction—Translated by L. J. Holtschlag

The coefficient α (ratio of weight and volume fractions of oxidizer and fuel in a given mixture and in a stoichiometric mixture) characterizes the ratio for components in gaseous or condensed mixtures. At a given value of α the oxygen balance in various mixtures may differ considerably. The stoichiometric coefficient is defined in such a way that a specific value of the coefficient corresponds to any fuel or oxidizer (or any mixture). Examples are given for one-component systems (oxidizer with C, H, and other atoms; fuel with O, Cl, and other atoms) and two-component systems (two oxidizers with C, H, and other atoms; oxidizer with C, H, and other atoms plus a "pure" fuel; and oxidizer with C, H, and other atoms plus a fuel containing O, Cl, and other atoms).

Blackshear, P. L., Jr., Murty, K. A., and Wood, B. D. (University of Minnesota, Minneapolis, Minnesota) "Fire Research: A Collection of Papers and Work Done during the Year Ending September 1, 1968," *Report under Contract USNRDL-TRC-68-67, OCD Work Unit 2531A.* (September 1968).

Related Sections: **G**, *H*, *I*

Subject Headings: **Fire research**; *Cellulosic fuel; Pyrolysis; Fire model; Flame temperature; Attenuation coefficient; Radiation and/or convection; Smoulder spread.*

Authors' Abstract

A unified theory of pyrolysis and combustion of isolated cellulosic fuel elements is postulated in an attempt to understand the influence of the physical and chemical description of the fuel on the mass loss rates and the temperature history.

Progress in experiments designed to simulate a mass fire is described in section II. The main topics discussed are (1) method for measuring attenuation coefficient at any position in the flame, (2) preliminary results of temperature measurements in the flame. (3) burning rate measurements by measuring mass loss with time and (4) apparatus for measuring local convection and/or radiation heat flux. An extensive bibliography concerning the theoretical aspects of radiation and convection coupling in radiating gases is also given in this section.

Section III is concerned with a first model of smoulder spread on cellulosic fuels. Predictions agree well with the data available in the literature.

Borisov, A. A., Kozenko, V. P., and Kogarko, S. M, "Detonation Limits of Methane–Oxygen Mixtures Diluted with Argon or Helium," *Physics of Combustion and Explosions* **3**(2), 398–401 (1967). In Russian.

Related Sections: **G**, *D*

Subject Heading: **Detonation limits.**

Authors' Summary—Translated by L. J. Holtschlag

The experiments were conducted in a smooth copper tube 65 mm in diameter and 4.5 m in length. The detonation was initiated by exploding a small volume (50–100 cm³) of a stoichiometric mixture of CH_4 plus O_2 at an initial pressure one atm. The steadiness of the propagation rate and the presence of spin were checked by the trace method from walls covered with carbon black. In addition, the propagation rate of the detonation was measured with ionization gauges at distances of 3 and 4 m from the initiator. The results were used to determine the dependence of limit pressure of propagation of spin detonation on the degree of dilution of the CH_4+O_2, Ar, or He. The limit pressure decreases approximately by

a factor of two upon dilution of the mixture with 25% argon. The difference in the results for CH_4+O_2 mixtures diluted with argon or helium can be explained as the effect of energy losses on the limit characteristics of the wave. The specific losses chiefly responsible for this behavior could not be determined, because the heat-conduction and gas dynamic losses increase simultaneously when the mean molecular weight of the mixture decreases.

Hoare, D. E. and Li, Ting-Man (University of Dundee, Dundee, Scotland) "The Combustion of Simple Ketones. I. Mechanism at 'Low' Temperatures," *Combustion and Flame* **12**(2), 136–154 (1968).

Related Sections: **G**, *H*, *I*

Subject Headings: **Combustion of ketones;** *Oxidation.*

F. Falk, Abstracter

A comprehensive analysis of the low temperature reaction products of the oxidation of simple ketones was carried out in order to elucidate the nature of the radicals produced. Simple ketones, i.e., acetone, methyl ethyl ketone and diethyl ketone, were chosen in order to minimize the possible products. Research by Barnard and Honeyman[1] indicated that methyl hydroperoxide was the intermediate responsible for chain branching at the "low" temperature (284°C) in the acetone-oxygen system and suggested that the transition to the "high" temperature mechanism was due to the increased importance of an alternative reaction for the methyl radical. At low temperature it appeared that methyl hydroperoxide was formed while at higher temperature (498°C) formaldehyde was the more likely product.

The apparatus in which the reaction took place has been described previously.[2] After a desired reaction time, the products were admitted into an evacuated sampling tube directly, or via a cold trap. They were analyzed by a pye-argon gas chromatograph or a conventional one with a katharometer as detector.

The oxidation of acetone was studied at a temperature of 330°C and 110 mm of mercury; the diethyl ketone at 279°C and 50 mm of mercury; and the methyl ethyl ketone at 310°C and 100 mm of mercury. The initial ketone-oxygen mixture in all of the tests was 1 to 1. It is clear, based on studies of cool flame limits and the maximum rate of oxidation versus temperature,[2] that under these conditions the reaction occurs by the "low" temperature mechanism. Graphs are presented in the paper showing partial pressures of the various products as a function of time in the early portion of the reaction. For acetone the major products were carbon monoxide and formaldehyde, in addition to water. Some carbon dioxide, methanol, and hydrogen peroxide were also found.

Only a trace of acetic acid was detected in the early stages and a trace of organic peracid was found in the later stages of the reaction. Organic peroxides occurred to a very small extent, if at all, and they can not be considered important in the early stages of the reaction. The addition of up to 1.6 mm of hydrogen peroxide to the mixture reduced the induction period but did not completely eliminate it.

With diethyl ketone the major products in the initial stages of the reaction were carbon monoxide, acetaldehyde, formaldehyde, carbon dioxide, and water. Methanol was somewhat less important and ethylene, hydrogen peroxide, and acetic acid were present in even smaller amounts. In the final stages of the reaction, methane, ethylene-oxide, acetone, and ethane appeared. At the time of maximum rate of oxidation, traces of methyl hydroperoxide and perpropionic acid were found. However, the amounts were negligible relative to the amount of hydrogen peroxide. The addition of hydrogen peroxide to the reaction appeared to retard the reaction.

With methyl ethyl ketone the reaction products in the early stages of reaction were in decreasing order, hydrogen peroxide, formaldehyde, acetaldehyde, ethylene oxide, methanol, and propylene oxide. Carbon monoxide and dioxide were detected only after 240 and 310 minutes, respectively, while methane, ethane, and ethylene were not detected even after 310 minutes. A trace of acetic acid was detected after 240 minutes. No acetone was found.

In the discussion following the presentation of the experimental data the authors review the products formed and attempt to infer the mechanims, or rather, the most likely reactions. In all cases they consider the first step to be hydrogen extraction followed by addition of an oxygen molecule. As pointed out by the authors this can be followed by formation of a hydroperoxide by subsequent extraction of a hydrogen atom from another molecule or an isomerization, i.e., $R'OO \rightarrow R''OOH$. Branching is then caused by decomposition or oxidation of the hydroperoxide of the $R''OOH$. The absence of appreciable amounts of ethylene and ethylene oxide indicate that the major initial attack is on the carbon having secondary hydrogens rather than on the one with primary hydrogens. This is, of course, to be expected on the basis of relative bond strengths.

The formation of the major reaction products can be explained by the decomposition of ketonyl peroxy radical in one of the following ways:

1. $$R{-}CO{-}\underset{\substack{|\\ O{-}O}}{CH}{-}R' \rightarrow R + CO_2 + R'{-}CHO$$

2. $$R{-}CO{-}\underset{\substack{|\\ O{-}O}}{CH}{-}R' \rightarrow RO + CO + R'{-}CHO$$

3. $$R{-}CO{-}\underset{\substack{|\\ O{-}O}}{CH}{-}CH_2{-}R \rightarrow R{-}CO{-}CH{=}CHR + HO_2$$

Additional products can be formed from the further oxidation of the products indicated above.

For the case of acetone the authors conclude that the yield of carbon dioxide indicates that reaction 1 takes place for 25% of the $OH_3{-}CO{-}CH_2O_2$ radicals. If the remainder reacts according to 2 then the methanol yield indicates that

$$CH_3O + O_2 \rightarrow CH_2O + HO_2$$

is twice as fast as

$$CH_3O + CH_3{-}CO{-}CH_3 \rightarrow CH_3OH + CH_3{-}CO{-}CH_2$$

These results are in general agreement with Hoare and Whytock's[3] results from the photo-oxidation of acetone.

In respect to diethyl ketone the large amounts of carbon monoxide indicate the combustion of aldehyde intermediates. The ethyl radicals from reaction 1 are apparently being oxidized to aldehydes rather than to ethylene as would occur at higher temperatures. Although aldehydes are produced and react throughout the reaction period they do not appear to be the cause of chain branching since their maximum concentration is not approached until long after the maximum rate of reaction has been achieved.

The high yield of hydrogen peroxide in the case of methyl ethyl ketone implies that reaction 3 is the important propagation reaction for this ketone.

From this study it is concluded that unlike the oxidation of hydrocarbons, combustion of simple ketones can occur by isomerization of RO_2 by a mechanism not involving hydrogen transfer and production of hydroxyl radicals.

References

1. Bernard, J. A. and Honeyman, T. W.: *Proceedings Royal Society A279*, 236, 248 (1964).
2. Hoare, D. E., Li, Ting-Man, and Walsh, A. D.: *Eleventh Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, Pennsylvania (1967) p. 879.
3. Hoare, D. E. and Whytock, D. A.: *Canadian Journal Chemistry 45*, 865 (1967).

Lyubchenko, I. S. "Estimate of a Solution and Asymptotics of the Steady-State Problem of Flame Propagation in a Homogeneous Gas Mixture," *Physics of Combustion and Explosions* **4**(1), 56–68 (1968). In Russian.

Related Sections: **G**, *B*, *H*, *I*

Subject Headings: **Flame propagation**; *Thermal explosion; Thermal ignition.*

Author's Introduction—Translated by L. J. Holtschlag

An examination is made of the conditions under which formulas asymptotic with respect to the propagation rate of the front of an exothermic reaction can be constructed. Three cases are studied: similarity of the concentration and temperature fields, a mixture of gases of different molecular weights, and flame propagation in a condensed medium without a gas component. The method can be used to study not only the thermal theory of the combustion of gases and condensed materials without gas, but also processes with a clearly defined interface. It is also applicable to the quasi-stationary problem of a thermal explosion and of thermal self-ignition of gas mixture in a flow.

Podymov, V. N. and Chuchalin, I. F. "Effect of the Thickness of the Diffusion-Temperature Layer on Flame Height," *Physics of Combustion and Explosion* **4**(1), 91–94 (1968). In Russian.

Section: **G**

Subject Heading: **Flame height.**

Authors' Introduction—Translated by L. J. Holtschlag

The dimensionless flame height of a free diffusion flame torch is determined by solving the diffusion equation under the assumption that the thickness of the diffusion-temperature layer varies periodically, resulting in periodic fluctuations in flame height. The mechanism of sinusoidal or near-sinusoidal oscillation of flame height can be explained, at least qualitatively, only on the basis of the molecular radical diffusion of oxygen. It is observed that the law of flame-height variation obtained by the authors agrees qualitatively with the experimental data in the range of small amplitude fluctuations.

Sokolik, A. S., Karpov, V. P., and Semenov, E. S. "Turbulent Burning in Gases," *Physics of Combustion and Explosion* **3**(1), 61–76 (1967). In Russian.

Related Sections: **G**, *H*, *I*

Subject Heading: **Turbulent burning.**

Authors' Conclusions—Translated by L. J. Holtschlag

1. A new method, with isotropic turbulence artificially generated in a closed volume (bomb), has been developed for the experimental study of turbulent burning under widely varying physical-chemical conditions. The absolute intensity of the turbulence can be varied from 1 to 10 m/sec by regulating the speed of rotation of the agitators. The turbulent burning rate $u_T = u_B/\epsilon_T$ is obtained as the speed of the turbulent flame relative to the fresh gas by measuring, with high-speed schlieren moving pictures, the apparent speed of the spherical front of the turbulent flame, u_B, and by determining the actual degree of expansion, ϵ_T, in the turbulent flames (measurement of the volumes of normal and turbulent flames, yielding the same pressure increase).

2. Measurements of the rate of turbulent burning made over a wide range of normal burning velocities, but at constant temperatures, showed that u_T is determined not by the normal burning velocity but by the combustion temperature and rate of chemical reaction in the flame.

3. The dependence of the rate of turbulent burning on the rate of chemical reaction in the flame, $\bar{w}_p$, reflects the accepted mechanism of flame propagation. For a mechanism analogous to a normal flame we find $u_T = (\bar{w}_p)^{1/2}$. But if it is

assumed that the turbulent flame propagation by way of discontinuous (pulsating) ignition over a path of the Lagrange scale we find that $u_T=[l_l/\tau_p]$, so that $u_T \sim \bar{w}_p$. A check of the two alternative mechanisms was made by the method of macrokinetic characteristics.

4. Based on the example of hydrazine dissociation flame, a model reaction that takes place by way of direct chains, the macrokinetic characteristics were determined from the change in rate of turbulent burning with the dissociation temperature, on the one hand, yielding $E_э=34$ kcal/mole, and with the pressure, on the other hand, yielding $n_э=2.4$. This is close to the characteristics obtained either from a kinetic scheme or from shocktube experiments: $E_э=37$–40 kcal/mol, and, for $n_э$, from measurements of the normal flame speed $n_э=2.0$.

5. Based on the example of propane-air flames it is shown that it is possible to determine the macrokinetic characteristics from the change, with combustion temperature and with pressure, of the quantity τ_p, as computed from the time between the instant of appearance and disappearance of ionizing current. The thus-obtained characteristics coincided with the values for $E_э$ and $n_э$ obtained from experiments with a normal flame on the basis of the thermal theory of burning.

6. The results, in addition to verifying the correctness of the treatment of turbulent burning as propagation by way of pulsating ignition, also indicate that the reaction mechanism is the same and that the overall reaction rates in turbulent and normal flames are equal.

Stark, G. W. V., Evans, Wendy, and Field, P. (Joint Fire Research Organization, Boreham Wood, England) "Measurements of the Flow of Combustion Gases from Ventilated Compartments," *Joint Fire Research Organization Fire Research Note No. 722.* (August 1968).

Section: **G**

Subject Headings: **Ventilation**; *Building fires; Burning rate, combustion products.*

Authors' Summary

Measurements of the composition of combustion gases, withdrawn from different points of a vent at the top of one face of a 0.9 m cubical compartment, have shown that the gases withdrawn from the centre of the vent and 2 cm below the ceiling of the compartment have about the same composition as the average composition of all the evolved combustion gases for a fire disposed centrally on the floor of the compartment.

Comparison with calculated rates of evolution of combustion gases from data obtained from the above sampling position, by mass balance and heat balance methods, has shown that the rate of flow may be estimated with good accuracy by the use of a simplified form of the equation proposed by Kawagoe, provided that a discharge coefficient of 0.9 is incorporated in the equation.

Errors in measurement introduced by neglect of water vapor formed during combustion are small.

Takata, A. N. and Salzberg, F. (IIT Research Institute, Technology Center, Chicago, Illinois) "Development and Application of a Complete Fire-Spread Model," *Final Report under Contract USNRDL NOO22867C1498, OCD Work Unit 2538B*. (June 1968).

Related Sections: **G** and **L**; *M*, *H*, *I*

Subject Heading: **Fire spread model.**

Authors' Summary

The objective of this study is to develop a complete model for calculating the initiation and spread of fire resulting from an attack on an urban area, and to apply the complete model in predicting the time-dependent fire damage to the cities of Detroit, Albuquerque, and San Jose from a 5 *MT* burst. The scope of work includes the following:

"The model to be developed shall include specification of input information required, explanation and justification of the calculational and estimational procedures used, and estimation of the accuracy of credibility with which the values of the input parameters are known. This model shall take into account fire spread by radiation, by firebrands, and by convective heating, and shall be capable of being used for the prediction of ignition-limit contours and of fire-limit contours at 1-hour intervals from *H* hour and for the production of maps of sample areas showing buildings in which sustained fires occur and the nature and extent of these fires within each building at 1-hour or smaller intervals after *H* hour." The model was applied to the calculation of the time-dependent fire damage that would occur in the cities of San Jose, Detroit, and Albuquerque for the attack conditions specified by OCD.

This report is prepared in 4 volumes. Volume I covers the development of techniques to determine the initiation and spread of fire in urban areas and the development of computer codes to perform the computations; Volumes II, III, and IV cover the fire damage to Detroit, Albuquerque, and San Jose, respectively, at times ranging from 0 to 28 hours after a 5 *MT* burst.

A summary of the content of each volume follows:

Volume I

Volume I covers the analysis, data and computer codes to determine the fire damage to urban areas. The urban areas are described in terms of several hundred square tracts which differ from one another according to the composition and size of their built-up area and the separations to built-up areas in adjacent tracts. The composition of the built-up areas is described in terms of the heights, sizes, and density of the buildings which in turn are used to determine the number of windows and the separations between buildings. Each tract includes a similar description of the window coverings, the window openings, and the room content.

Two codes were developed to predict the initiation and spread of fire in each of the tracts. The Ignition Code predicts the per cent of buildings ignited by the fireball in various categories of built-up areas as a function of the composition of each built-up area and its distance from ground zero. The Fire Spread Code predicts the spread of fire within and between tracts as a result of radiation and firebrands at intervals of 15 minutes.

Volume II

Volume II describes the fire damage to the 662 tracts used to represent Detroit and its suburbs. In this city the 5 MT burst occurs on the ground and ignites buildings as far as 8 miles from ground zero. The peak burning occurs approximately $2\frac{1}{2}$ hours after the burst at which time approximately 9.8 per cent of the buildings in the Detroit area are on fire. Subsequently, the number of fires decreases at a modest rate and remains substantial even after 28 hours. At this time approximately 0.9 per cent of the buildings are burning, 49.0 per cent of the buildings have been destroyed by fire 15.4 per cent of the buildings have been severely damaged by blast and 35.6 per cent of the buildings remain relatively free of damage.

Volume III

Volume III describes the fire damage to the 373 tracts used to represent the city of Albuquerque. In this city the 5 *MT* burst occurs at 14,500 ft and ignites buildings as far as 16 miles from ground zero. The peak burning occurs 2 hours after the burst at which time approximately 15.9 per cent of the buildings in Albuquerque are on fire. Subsequently, the number of fires decreases at a modest rate to 0.1 per cent at 28 hours. At this time approximately 57.0 per cent of the buildings have been destroyed by fire, 25.7 per cent of the buildings have been severely damaged by blast, and 17.3 per cent of the buildings remain relatively free of damage.

Volume IV

Volume IV describes the fire damage to the 646 tracts used to represent the city of San Jose and its surroundings. In this city the 5 *MT* burst occurs at 14,500 ft and ignites buildings as far as 13 miles from ground zero. The peak burning occurs 1 hour after the burst at which time approximately 13.2 per cent of the buildings in the San Jose area are on fire. Subsequently, the number of fires decreases at a modest rate to 0.4 per cent at 28 hours. At this time approximately 56.0 per cent of the buildings have been destroyed by fire, 25.7 per cent of the buildings have been severely damaged by blast, and 18.3 per cent of the buildings remain relatively free of damage.

A number of important results have been found from these studies—the most noteworthy of which are the following:

- The pronounced differences in the ranges over which ignitions are produced by variations in the burst altitude. The ground burst in Detroit yielded an ignition radii of 8 miles while the air bursts at 14,500 ft over San Jose and Albuquerque yielded ignition radii of 13 and 16 miles, respectively. These differences are due to differences in the densities and composition of the air through which the radiation must pass.
- The large variation in the percentages of buildings ignited in the various types of tracts at comparable distances from ground zero. Differences of as much as 100 to 200 per cent are not uncommon. The largest percentages are found in tracts consisting of large residential buildings with low building densities.
- The irregular and diffuse pattern of the fire damage. This is caused by the variations in the ignition percentages and differences in the fire-spread

capabilities from tract to tract. Only towards the late stages of a fire would one expect anything approaching a fire front.

- The large number of buildings destroyed by fire compared with blast. In Detroit over 3 times as many buildings would be destroyed by fire as by blast. A factor slightly in excess of 2 would be procured in Albuquerque and San Jose.
- The fact that fires could persist for a couple of days. This indicates the important role that can be played by available fire-fighting and rescue personnel and equipment located at large distances from the city.

The most serious sources of error in predicting the fire damage are the difficulty of identifying the composition of the various ignitable materials in rooms and windows and the rough estimates used for the probabilities of firespread by firebrands. The 50 per cent confidence interval for the damage predictions is estimated to be about ±25 per cent.

Critique—F. A. Williams, Abstracter

It is worthwhile to have computer programs for calculating the fire damage that would result from nuclear attack. Thorough knowledge of urban fire behavior highly qualifies the IITRI group to construct such codes. The competently designed probability-oriented program described in these reports requires about ten minutes of computer time on the 7094 to calculate the initial distribution of fires immediately following the nuclear burst and another ten minutes to trace the development of the fires for about 24 hours. This is a reasonable choice of running time, and the section of type and amount of input data for describing the city, etc., is also reasonable. The calculations apparently can be made for any American city on the basis of a sufficiently thorough survey of the city. I believe that the principal item requiring further discussion is the degree of confidence that one can place in the results.

The 50 per cent confidence interval for the ultimate fire damage prediction of the fire-spread code is stated to be estimated at ±25 per cent. No indication is given in the reports as to how this numerical estimate was obtained. It is merely stated that the dominant source of error in the ignition code is the difficulty of identifying fuel composition (and therefore ignition energies), that the major source of error in the fire-spread code is the estimation of probabilities of fire spread by firebrands (which was obtained from World War II data on spread probability versus building separation distance for Darmstadt and Hiroshima, by assuming no brands in Darmstadt, by subtracting the Darmstadt curve from the Hiroshima curve to get the brand contribution to spread in Hiroshima, and then by assuming that the probability of brand spread in U.S. cities will be half that of Hiroshima), and that the next most important errors in the fire-spread code are the data used to represent the cities and the times adopted for the various stages of burning in individual structures. Presumably, the confidence estimate arises in a nonmathematical way from the experience of those who worked with the codes.

Numerous assumptions are present in the analysis which probably do not appear in the estimate of confidence level. For example, all exterior ignitions are explicitly disregarded at the outset—for both the ignition code and the fire-spread code—so that fires originating in outside rubbish piles, etc. are not taken into account. In evaluating probabilities, statistical independence is assumed for every input probability distribution so that, for example, the joint probability of an adjacent building having a given height and a given separation distance is taken to be the product of the probability of the building height and the probability of the separation distance—the correlation expressing the likelihood that taller buildings would be separated by greater distances is thereby tacitly ignored. Although the wind direction is considered in calculating fire spread by brands, the wind velocity is ignored because of insufficient data. There are many other assumptions such as these which probably have not been considered in establishing confidence levels. The assumptions are, of course, essential for developing a manageable program. But, in my opinion, they make it impossible to assign rational confidence levels to the results.

There seems to be a tendency in the results of the fire-spread code for the fires to continue to spread slowly to large distances at long times even in the presence of substantial firebreaks, so long as no human fire-control efforts are undertaken. This is probably due to the way in which spread by firebrands is treated and may also be influenced by the ways in which tracts and spreads within them are characterized (for example, humidity, which may sometimes be high enough to retard spread, is not taken into account explicitly as an input variable). The final impression, made beautifully clear in a series of overlay maps for each of the three cities in volumes II, III and IV, is the spectre of a virtually all-consuming fire slowly sweeping to every corner of the city. It is indeed conceivable that this is the most probable outcome and I believe that the results shown in the present reports should be interpreted as IITRI's best educated guess at the most probable outcome. However, I feel equally certain that there are many seasonal and atmospheric conditions under which little or no fire spread will occur. Nevertheless, the predictions certainly could come true. Let us pray that they do not.

Thomas, P. H. (Joint Fire Research Organization, Boreham Wood, England) "The Movement of Smoke in Horizontal Passages against an Air Flow," *Joint Fire Research Organization Fire Research Note. 723.* (September 1968).

Related Sections: **G**, *D*

Subject Headings: **Smoke movement**; *Ducts.*

Author's Summary

Experiments, mainly in a 90 cm×90 cm wind tunnel, on the movement of hot gas and smoke, show that a certain minimum air velocity is necessary to prevent the smoke flowing back, upstream, in a passage.

These experiments confirm the theory that the critical air velocity to prevent such backflow in a horizontal duct increases as the cube root of the heat release rate.

If this heat release is expressed as the area of wood burning at $\frac{1}{40}$ in. per minute per unit width of duct, the critical velocity U_c is

$$U_c \approx 30W^{1/3}$$

where U is in cm/sec and W is the area of wood per unit width in cm.

Varshavskii, G. A. and Germeier, E. M. "Diffusion Theory of Combustion of a Liquid Hydrogen Droplet," *Physics of Combustion and Explosions* **3**(2), 263–241 (1967). In Russian.

Related Sections: **G**, *I*

Subject Headings: **Droplet combustion**; *Diffusion flames; Heat transfer.*

Authors' Summary—Translated by L. J. Holtschlag

A theoretical study is made of the combustion of a droplet of liquid hydrogen in still air on the basis of the diffusion theory of a liquid fuel droplet. It is assumed that the inner region between the combustion zone and the droplet consists of two spherical layers. The first one, closest to the surface of the droplet, is filled with gaseous hydrogen, its outer boundary is an isothermal surface. Condensed nitrogen particles which do not participate in heat and mass transfer are in a state of dynamic equilibrium in a thin region adjacent to the interface. The second layer, between the isothermal surface and the combustion zone, is filled with a gas mixture of variable composition, from pure hydrogen on the sphere to pure nitrogen at the combustion front. The relative dimensions of the two dividing surfaces are found and the vaporization rate of a burning droplet is determined (given in tabular form).

H. Chemical Aspects of Fires

Azatyan, V. V., Romanovich, L. B., and Sysolva, S. G. "Determination of the Reaction Rate Constant of the Hydroxyl Radical and Hydrogen," *Physics of Combustion and Explosion* **3**(1), 77–85 (1967). In Russian.

Section: **H**

Subject Headings: **Reaction rate, $OH+H_2$**; *Kinetics.*

Authors' Conclusions—Translated by L. J. Holtschlag

The reaction rate constant of the OH radical with H_2 was determined by the ignition limit method. The reaction mechanism is represented as $H_2+O_2=2OH$ termination (4); O+wall→termination (5); OH+wall→termination (6). The experiments were carried out in a vacuum static arrangement. The various rates of the above reactions are derived mathematically. The rate k_1 for the $OH+H_2$ reaction at 540, 550, 570° are $k_1 \times 10^{13}$ cm/mol^{-1}sec^{-1}=3.2, 3.3, 3.6. The random error does not exceed 10%. The relatively narrow temperature interval prevents exact individual determination of the value of the activation energy and pre-exponential factor of the rate constant of this reaction.

Basevich, V. Ya. and Kogarko, S. M. "Kinetic Calculations of Low-Temperature Oxygen Flames with Hydrogen and Carbon Monoxide," *Physics of Combustion and Explosion* **3**(1), 98 (1967). In Russian.

Section: **H**

Subject Headings: **Flame kinetic calculations**; *Rate constants; Flame propagation.*

Authors' Summary—Translated by L. J. Holtschlag

The degree of accuracy with which the combustion rate in a flame can be described is given for mixtures of O, H, and CO at various pressures and known reaction rate constants. The normal flame propagation rates were measured in a spherical bomb with central spark ignition; the temperature in the combustion zone was recorded on an oscillograph via a platinum resistance thermometer. The flame speed was determined from the visible rate of propagation (by scanning with a single thermometer or by installing three thermometers) or was computed from a measured temperature profile. A computer program was used in the calculations, making it possible to integrate a system of six differential equations representing the balance of the material in the flame zone for H_2, OH, H, O, HO_2 and CO. The accuracy of the calculation is characterized by a root-mean-square deviation of 0.09–0.20 relative to the experimental values.

Korobeinichev, O. P., Bol'dyrev, V. V., and Karpenko, Yu. Ya. "Use of an Impulse Mass Spectrometer to Study the Kinetics of Fast Processes during High-Temperature Decomposition of Ammonium Perchlorate," *Physics of Combustion and Explosions* **4**(1), 33–38 (1968). In Russian.

Section: **H**

Subject Heatings: **Kinetics of decomposition**; *Pyrolysis.*

Authors' Summary—Translated by L. J. Holtschlag

A time-of-flight mass spectrometer was used to study the formation kinetics of the primary products which were NH_3 and $HClO_4$ of thermal decomposition of ammonium perchlorate at high temperatures (260°–500°C), when the reaction rates are high. The flash method was improved insofar as the methods for heating the specimen and for measuring the temperature are concerned, so as to be able to study the kinetics of fast reactions during isothermal decomposition of the solids. Two test series were carried out, one with a tungsten filament as the inertia-free heater, the other with a titanium filament. The mechanism of primary decomposition was confirmed to be protonic. The rate of decomposition is determined and the temperature-dependence is plotted. The results can be used to calculate the burning rates of solid fuels based on ammonium perchlorate; the method can be used to study other fast reactions of the thermal decomposition of solids.

I. Physical Aspects of Fires

Abrukov, S. A., Kurzhunov, V. V., and Mezdrikov, V. N. "Investigation of the Effect of an Electric Field on a "Humming" Flame by the Method of High-Speed Schlieren Photography," *Physics of Combustion and Explosions* **3**(1), 155 (1967). In Russian.

Related Sections: **I**, *G*

Subject Headings: **"Humming" flames;** *Resonant jets.*

Authors' Summary—Translated by L. J. Holtschlag

The experiments were carried out with a tube resonator containing the "humming" flame of propane and brass electrodes set up in the working section of a Toepler shadow instrument (frame speed of 1000 per sec). The studies were made with horizontal and vertical Foucault knife edges in the focal plane of the instrument. The experimental results revealed that at a certain degree of flame ionization the electric field has an appreciable effect on the structure and shape of the combustion zone. Periodic variations in flame surface area accompanying the vibration regime cease; at the same time the diffusion jet becomes turbulent. This leads to interruption of feedback in the self-oscillating system and the vibration combustion regime decays.

Danson, R. (Safety in Mines Research Establishment, Sheffield, England) "The Temperatures Developed during Oblique Impact of Two Bodies," *Pyrodynamics* **5**, 39–44 (1967).

Section: **I**

Subject Heading: **Impact temperatures.**

Author's Abstract

As part of a program of research into the ignition of gases by hot surfaces produced by friction, thermoelectric measurements have been made of the temperatures developed during the oblique impact of a mild-steel plate and specimens of a copper-nickel alloy. It has been found that the rubbing speed attained during impact rather than the impact energy is the key factor in determining the temperatures reached, although the maximum temperature is limited to the lower of the two melting points, i.e., that of the alloy. The possibility of methane–air being ignited during oblique impact is discussed briefly in the light of the results.

Vines, R. G. (Fire Research Section of the Chemical Research Laboratories, C.S.I.R.O., Australia) "Heat Transfer through Bark, and the Resistance of Trees to Fire," *Australian Journal of Botany* **16,** 499–514 (1968)

Section: **I**

Subject Heading: **Heat transfer, through bark.**

R. M. Nelson, Jr., Abstracter

In the investigation of possible damaging effects of controlled burning in Australian forests, experiments were carried out to measure cambium temperatures of several Australian species subjected to a range of fire intensities. Living trees were exposed to heat from actual ground fires or from a King radiometer, The radiometer, a 5.5- by 7.5-in. radiant panel heater, was placed 1 to 2 in. from the outer bark at heights from ground level to 5 ft up the trunk. Its heat output was about 1.5 cal/cm^2/sec. Temperatures at the cambium and in the outer and inner bark were measured with chromel/alumel thermocouples.

Trees with bark thicknesses less than ½ in. were exposed to spreading fires of intensities of the order of 50 Btu/ft/sec. The maximum observed temperature rise at the cambium was about 20°C, indicating that in mild fires cambium temperatures should remain below the accepted lethal temperature of 60°C. Higher-intensity fires were used to test bigger trees (roughly 9 to 15 in. in diameter) with bark thicknesses from about ¼ to ¾ in. The trees were surrounded with fuel piles which produced flames 25 ft high for nearly 3 min. Maximum cambium temperatures decreased with increasing bark thickness. The results indicate that only trees with bark of ½-in. thickness or greater are likely to survive in an intense fire.

Subsequent experiments with the King radiometer were carried out in spring and autumn on a number of species, most of which were 6 to 15 in. in diameter. Even though heating of the bark was localized, cambium temperature variations during heating were similar to those of actual fires. Response rates in terms of time for cambium temperature to increase by 40°C were reasonably well correlated to bark thickness with a single curve. The small differences among species and times of year were accounted for by differences in bark moisture content and structure. Table 1 shows averages of the experimental results. The term *response time* refers to the timelag in temperature change at the cambium.

TABLE 1

Heat Response and Bark Thickness

Bark thickness (in.)	Response time (min.)	Rate of temp. rise (°C./min.)	Total time (min.) for 40° rise
¼	1	14	4
½	2½	7	8½
¾	4½	5	12½
1	7	3½	19

Cooling rates of the cambium in experiments with fire were about 5 times slower than in radiometer experiments. Though some of this difference may be attributed to extensive versus localized heating other observed effects in experiments on thermally insulated portions of the outer bark suggested that cooling mechanisms associated with vertical flow of fluids were operating in the trees. One of these effects was an unusually rapid cooling of the cambium followed by a slight temperature increase and then a slower decrease when the radiometer was removed from trees in which cambium temperatures had risen above 60°C. However, similar effects were noted in the fire experiments in which trees were practically engulfed by flames. The nature of the mechanism is uncertain, but apparently cooling is associated with the death of cells in the inner bark or in the xylem.

Heat transfer in bark was modeled mathematically on the basis of conduction in a semi-infinite slab subjected to a constant heat flux for a given time. Variables such as bark moisture and external convection and radiation were neglected in the model. For any thickness, the temperature rise depends on the heat flux and bark thermal diffusivity. The model gave excellent agreement with results in Table 1, indicating that cambium temperatures are determined chiefly by bark thickness during a fire.

The experimental techniques described in this paper were also used to measure soil temperatures associated with controlled burning and to investigate possibilities of damage from controlled burning in pine plantations. These topics are discussed n two brief appendices.

J. Meteorological Aspects of Fires

Taylor, R. J., Bethwaite, F. D., Packam, D. R., and Vines, R. G. (Commonwealth Scientific and Industrial Research Organization, Australia) "A Meso-Meteorological Investigation of Five Forest Fires," *CISRO Division of Meteorological Physics Technical Paper No. 18* (1968).

Section: J

Subject Heading: **Forest fires.**

O. P. Cramer, Abstracter

Though not a meso-meteorological study in the usual sense, this article reports on certain properties of large smoke plumes originating from routine, extensive, prescribed, hazard-reduction fires in forests of western Australia.

The burns investigated were conducted in November and ranged in size from 26.2 to 61 km². They were ignited around midday on days when inversions were present near 1500 m, making conditions unfavorable for deep convection. The terrain was gently undulating, and the forest was composed mainly of jarrah in the north, dense sections of karri in the south, and poor quality jarrah and tea-tree scrub on the flats. Ignition was by incendiary devices dropped throughout the intended burn area from aircraft, about five acres burning from each set.

The fuel, consisting of litter and combustible scrub on the forest floor, ranged from 3 to 5 tons/acre of which 60 to 90% was consumed by the fire with no apparent damage to the forest environment. Maximum fire intensity was reached two to three hours after ignition, and the burns were completed by nightfall. The heat yield of this fuel was judged to be 4000 cal/gm based on laboratory yields of 5200 cal/gm. A fuel loading of 1 T/acre corresponds to heat production of 100 cal/cm^2.

A 10,000 acre burn typically remained at maximum intensity for approximately two hours consuming fuel at the rate of 12,000 T/hr, equivalent to 2 cal/cm^2/min over the entire area.

At the peak of the fire, temperature soundings were made by instrumented aircraft on the upwind and downwind sides. On three fires when fairly steady wind with height permitted comparison, the authors found dry adiabatic lapse rates on both sides of the fire with the downwind sounding averaging warmer by 0.6°, 2.3°, and 1.3°C respectively for the approximate 550 m depth of the plume. The warming was about the same at all heights.

Using the above measurements and knowing the average wind flow as determined by pilot balloon observation near each fire, the authors computed the amount of heat flowing away from the fire by evaluating $\int \rho c_p \Delta T u \, dz$ between ground and inversion level where ρ is the mean air density, c_p the specific heat at constant pressure, ΔT the temperature excess of the downwind sounding, u the mean wind speed, and Z the height.

They compared the heat carried away from the fire with heat generated by the fire by evaluating $\int H \, dx$ where H is the heat input in cal cm^{-2}min^{-1}, and x is the downwind coordinate or width of the fire. There was good agreement between estimates of heat produced and heat advected away.

Horizontal traverses were also flown through the plumes, these at constant attitude at 65 kts. Vertical motions were recorded by altimeter readings every 10 sec and by accelerometer. Accelerations in the range ±0.55 g were recorded, and no difficulty in controling the aircraft was experienced. Typically, a downdraft was noted immediately outside the plume, an updraft immediately inside, irregular motion within, and an updraft before emerging. Vertical motions on a scale of hundreds of meters showed a clear difference between heated and unheated air, whereas no difference could be detected in smaller-scale motions.

The authors concluded that since the calculated amount of heat released by each fire agreed well with the measured amount of heat carried away by the wind, the estimates of fuel quantities and burning rates on which the calculation of heat release was based would seem to be correct.

K. Physiological and Psychological Problems from Fires

Ballas, T. (U. S. Naval Applied Science Laboratory, Brooklyn, New York) "Electric Shock Hazard Studies of High Expansion Foams," *Fire Technology* **5**, 38–42 (1969).†

Related Sections: **K**, *A*

Subject Heading: **Electric shock hazards.**

Authors' Discussion

General guidelines that may be obtained from the data presented herein are as follows. The electrical shock hazard of high expansion foam varies inversely with the distance between conducting points in the foam medium; varies inversely with the age of the foam; varies directly with the conductivity of the water constituent of the foam; and varies directly with the conductivity of the foam liquid concentrate, but only when the concentrate is in solution with demineralized water or fresh water. The high conductivity of sea water canceled the effects of a low conductivity foam liquid concentrate.

The minimum safe distances from live voltage sources and the minimum foam aging periods for current flow to drop below human safety limits, both of which are shown in this paper, can be useful guidelines for estimating the shock hazard characteristics of high expansion foams. These requirements, however, should not be extrapolated much beyond the parameters of the experiments described in this paper. Other conditions, such as higher voltages (higher than 440 volts), larger voltage sources (control panels in lieu of small switch boxes), foams of lower expansion ratio, and other foam formulations and water sources might well necessitate more stringent requirements.

Since other investigators[1] have indicated that high expansion foam can be used safely on sensitive electronic apparatus and instruments with a minimum of damage to the equipment, it is a good possibility that high expansion foam will be used to protect spaces aboard surface ships and submarines that contain electronic gear. In these particular spaces, it is reasonable to expect that the foam system will utilize fresh water or demineralized water (in lieu of sea water) for the purpose of limiting the conductivity of the foam. In this case, it would be desirable from a safety point of view, for foaming agents to be developed with low conductivity.

TABLE 1
Electrical conductivity of foam constituents (micromhos cm)

Constituent	Water type			Foam-liquid concentrate
	Demineralized	Fresh	Sea	
Water only	2.6	156	41,000	—
Foam A	105*	205*	41,000*	240
Foam B	867*	1,177*	41,000*	10,463

* 2 per cent solution of foam liquid concentrate in water.

† Taken from *Fire Technology*. By permission.

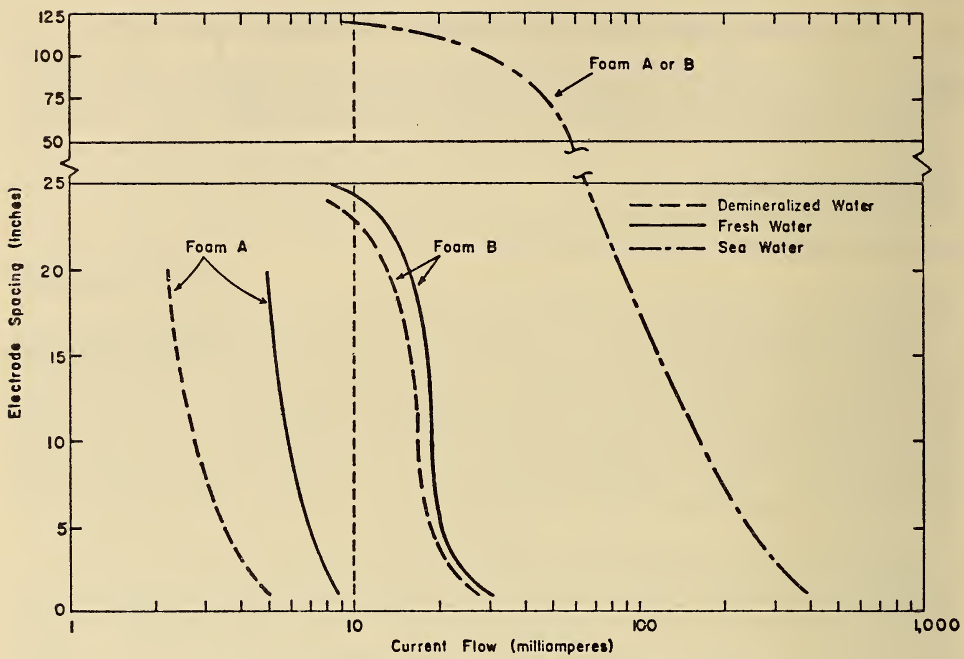

Fig. 1. Current flow data for freshly generated foams.

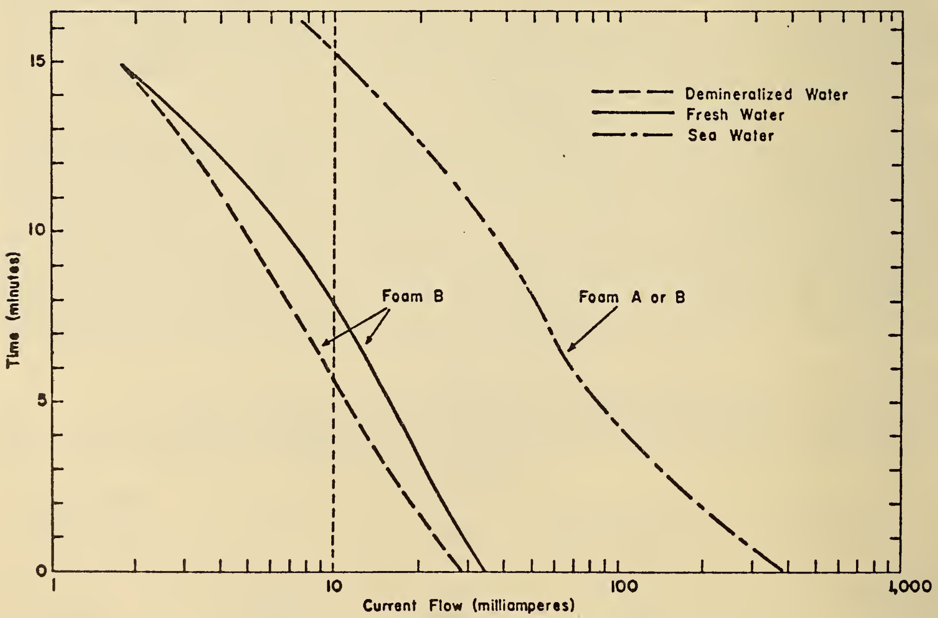

Fig. 2. Current flow data for aged foams.

Reference

1. Spencer, Eric W.: "The Effect of High Expansion Fire Extinguishing Foam on Operating Electronic Equipment," *ASSE Journal* (September 1964).

Nash, Sheila F. (Joint Fire Research Organization, Boreham Wood, England) "Analysis of Fire Prevention Slogans," *Joint Fire Research Organization Fire Research Note No. 733.* (November 1968).

Section: **K**

Subject Headings: **Fire prevention slogans;** *Brigade; Education; Publicity.*

Author's Summary

An analysis of fire prevention slogans written by the public, and of fire prevention literature produced by local authority fire brigades, indicates that the public are largely unaware of the technical aspects of fire prevention, and that the fire brigades could make useful changes in the balance of subject matter in their fire prevention literature.

L. Operations Research, Mathematical Methods, and Statistics

Chandler, S. E. (Joint Fire Research Organization, Boreham Wood, England) "Fire Deaths in the First Nine Months of 1968," *Joint Fire Research Organization Fire Research Note No. 734.* (November 1968).

Section: **L**

Subject Headings: **Fire deaths;** *Fatalities; Fire statistics.*

Author's Summary

A preliminary survey of fatal fires in the first nine months of 1968 shows that there have been 597 deaths in 467 fires; 68 of these fires resulted in more than one death. These figures show a welcome reduction in loss of life due to fire during the third quarter of the year.

The most serious incidents during the quarter involved a hotel and a house converted into use as flats, accounting for four and three deaths respectively. Five firemen have died through injuries received whilst fighting fires up to now this year.

Miller, C. F. (Stanford Research Institute, Menlo Park, California) "Appendixes 1 through 7 to the Hamburg Police President's Report on the Large-Scale Air Attacks on Hamburg, Germany, in World War II," *Report under Contract NOO228-67-C1519, NRDL-TRC-68-47* (*OCD-NRDL*). (*December 1968*).

Section: **L**

Subject Headings: **Hamburg Fire;** *Civil Defense; Air raid defense; Property damage by fire; Shelter; World War II.*

Author's Abstract

This document presents information on air attacks and on civil defense preparations and accomplishments in the city of Hamburg, Germany, up to the time of

the large-scale attacks that began on July 25, 1943. A map summary of bombed sites; numerical and graphical summaries of the air attacks; a map of security police groups, sectors, and precincts; and a diagram of the organization and structure of the security policy are presented. The bulk of the document consists of a chronology of police bulletins, pamphlets, orders, and organization plans for emergency service situations. A civil defense system was developed in response to preconceived and observed effects, from the covering of windows to the preparation of shelter rooms, to poison gas protection, to blast protection, to shelter habitability, and finally, to the recognition of fire as the major hazard to be faced.

Schubert, R. "Examination of the Building Density and Fuel Loading in the Districts Eimsbüttel and Hammerbrook in the City of Hamburg as of July 1943," *Report under Contract NRDL-TRC-68-65, OCD Work Unit 2536D by Stanford Research Institute, Menlo Park, California. Taken from the German text of Ing. Schubert.* (January 1969).

Section: **L**

Subject Headings: **Fuel loading, in Hamburg;** *Civil Defense, fire statistics; Fire risk classification; Structure classification; Conflagrations; Fire storms.*

Stanford Abstract

The first part of this document presents a summary of building coverage and fuel loading in the conflagration areas of Eimsbüttel and Hammerbrook in the city of Hamburg as of July 1943. Detailed descriptions are given of methods for structural classification of buildings and for computation of equivalent wood fuel values of component parts of the buildings as derived from building plans. Exemplary procedures are given. The second part of the document is a statistical summary of population and housing before and after the air raids of July and August 1943. An appendix suggests a method for the classification of buildings according to damage risk, depending on the amount, kind, and distribution of flammable materials that comprise the structure and its contents. Supplementary and tabular conclusions of this report suggest that it is possible to gain insight into the conditional factors that are important or even decisive in the development of a fire storm as a result of widespread incendiary bombing.

N. Instrumentation and Fire Equipment

Bergman, I. "The Metallized Membrane Electrode—Polarographic Atmospheric Oxygen Monitoring and Other Applications," *Nature* **218,** 266 (1968).

Related Sections: **N,** *H*

Subject Heading: **Polarographic oxygen monitoring.**

Abstract issued by Safety in Mines Research Establishment, England.

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This letter describes a novel form of electrode that has been designed primarily for polarographic monitoring of atmospheric oxygen. A membrane of non-porous material that has, nevertheless, a high permeability to oxygen is metallized by depositing upon one side first a thin porous layer of gold and then a similar layer of silver. The membrane is clamped into an electrolytic cell with an area of the metallized side in contact with the electrolyte and with a defined part of this area on the non-metallized side exposed to the atmosphere under test. An advantage of this form of electrode is the avoidance of a thin layer of electrolyte between membrane and electrode: in polarographic oxygen-measuring instruments at present available, the presence of such a layer renders the measurements sensitive to evaporation of the electrolyte and to other modifications of the diffusion path. A membrane electrode formed with a metal in the platinum group may be used as a hydrogen electrode, and other applications of metallized membrane electrodes include power generation by a fuel cell and detection of basic or acidic gases.

Griffin, O. G. "Mine-Rescue Breathing Apparatus—Consideration of Requirements, Existing Designs, and Recent Developments," *Transactions of the Institution of Mining and Metallurgy, Section A* **77,** 27–33 (1968).

Section **N**

Subject Headings: **Breathing apparatus;** *Oxygen; Air.*

Abstract issued by Safety in Mines Research Establishment, England.

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Breathing apparatus used in rescue and recovery work in mines is almost entirely of the self-contained closed-circuit type. The paper states the physiological requirements that should be fulfilled by such apparatus, and discusses the standards that are prescribed for the approval of mine-rescue breathing apparatus in various countries. The paper then describes a number of apparatuses that are currently available in Western Europe. These apparatuses can be divided into the groups according to the source of the oxygen supply which may be either compressed oxygen or liquid air/oxygen. It is suggested that the liquid–oxygen type of apparatus has decided advantages over any other type.

Harris, G. W. and Maguire, B. A. "A Personal Gravimetric Dust Sampling Instrument (SIMPEDS)—Preliminary Results," *Annals of Occupational Hygiene* **11,** 195–201 (1968).

Section: **N**

Subject Heading: **Dust sampling.**

Abstract issued by Safety in Mines Research Establishment, England.

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A new personal gravimetric airborne dust sampling instrument, built into a miner's cap-lamp and battery assembly, is described. The instrument (SIMPEDS) uses a cyclone elutriator, samples at 1.85 l/min and collects the airborne dust on a membrane filter for subsequent weighing and analysis. Results with a prototype instrument suggest that it oversamples by about 10 per cent compared with the MRE and SIMGARD gravimetric dust sampling instruments. SIMPEDS satisfies safety requirements for use in British coal mines.

Melinek, S. J. (Joint Fire Research Organization, Boreham Wood, England) "The Darkening of Irradiated Wood Surfaces," *Joint Fire Research Organization Fire Research Note No. 738* (December 1968).

Section: **N**

Subject Headings: **Darkening of wood;** *Pyrolysis; Wood; Radiation measurement.*

Author's Summary

The degree of darkening of wood surfaces has been used to estimate the amount of heat received by a surface in circumstances where many rough measurements obtained with little effort are preferable to a few highly accurate measurements. Griffiths and Heselden have calibrated blocks of wood for this purpose. It is of interest to explore the use of the rate of darkening as a measure of the incident heat flux. Accordingly, the results obtained by Griffiths and Heselden have been re-examined. It is shown that the darkening follows a first order law and time constants are obtained for several incident flux densities. An activation energy is obtained from the variation of the time constant with the surface temperature of the wood and an equation is derived giving the intensity of irradiation as a function of the degree of darkening and the time of exposure.

It is shown that the rate of darkening, as measured by the reflectivity of light from a tungsten filament lamp, has rate constants very similar to that governing the rate of pyrolysis.

O'Dogherty, M. J., Young, R. A., and Lange, A. (Joint Fire Research Organization, Boreham Wood, England) "The Performance of Water-Type Extinguishers on Experimental Class A Fires," *Joint Fire Research Organization Fire Research Note No. 731.* (September 1968).

Section: **N**

Subject Headings: **Extinguisher (hand operated), water;** *Jets; Tests; Wood.*

Authors' Summary

The work described in this report was carried out on wood fires using water jet extinguishers of $1\frac{1}{4}$ and 2 gal capacity (5.7 and 9.1 liters). The report describes tests carried out to the requirements of French and West German standards and experiments conducted with an experimental crib, of constant cross-sectional dimensions, to study the effect of increasing the length on the extinction time and the quantity of water used to extinguish the flames. A study was also made of the effect of the pre-burn time of a German standard crib on the extinction time and the re-ignition time.

Phillips, H. "A Three-Colour Quantitative Schlieren System," *Journal of Scientific Instruments* **1,** 413–416 (1968).

Section: **N**

Subject Headings: **Color schlieren;** *Methane analysis.*

Abstract issued by Safety in Mines Research Establishment, England.

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A colour schlieren system was designed to make instantaneous measurements of the changing methane distribution in a stratified methane/air mixture in a 10 cm wide plastic-walled container. The usual light source was replaced by a grid made of strips of coloured gelatin, and the returning light beam was interruped by a monochrome grid slightly displaced from the focus of the colour grid. The monochrome grid selected the colours to be transmitted, and an image composed of horizontal coloured bands was formed. Displacement of the bands indicated a change in refractive index gradient in the methane/air mixture. Methods of calibration by both calculation and experiment are described.

Proctor, T. D. "A Laser Technique for Measuring the Surface Area of Small Concentrations of Dust Particles Suspended in Air," *Journal of Scientific Instruments* (*Journal of Physics E*) **1,** 631–635 (1968).

Section: **N**

Subject Heading: **Dust concentration.**

Abstract issued by Safety in Mines Research Establishment, England.

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The paper describes the use of a continuous-wave helium–neon laser to measure the surface area of small (less than 3000 particles/cm^3) concentrations of dust particles, of size less than 5 μm, suspended in air. The suspension is passed through a size-selector to remove particles greater than 5 μm in size, and then into a chamber between one of the laser mirrors and the end of the laser tube. Scattering and absorption of radiation from the cavity by the dust particles causes a change in the amount of radiation reflected back into the laser tube, which in turn produces a reduction in the intensity of the output beam. The relationship between the surface-area concentration of the airborn dust and the change in output intensity is derived and experiments with an instrument of this type are described and discussed.

Ramsey, G. S., Lavigne, P. A., and Fraser, D. G. (Forest Fire Research Institute, Ottawa, Canada) "Experimental Hose Coupling Devices," *Forest Fire Research Institute, Department of Forestry and Rural Development Information Report FF-X-17*. (September 1968).

Section: **N**

Subject Headings: **Hose couplings.**

R. M. Fristrom

Descriptions are given of several new designs for hose couplings.

O. Miscellaneous

Dynes, R. R. (Disaster Research Center, The Ohio State University, Columbus, Ohio) "The Functioning of Expanding Organizations in Community Disasters," *Report under Contract Office of Civil Defense, OCD-PS-64-66, Work Unit 2651A, Report Series No. 2* (September 1968).

Section: **O**

Subject Headings: **Community disasters**; *Sociology; Planning; Organizational coordination.*

Author's Abstract

Expanding organizations refer to those which have latent disaster responsibilities but must develop a new group structure to achieve them. Case studies are presented of three kinds of expanding organizations—Red Cross, The Salvation Army, and local civil defense. It is suggested, in disaster operations, that such organizations (1) are weakly institutionalized in the community, (2) generally have extra-community ties, (3) have general and thus vague disaster tasks, (4) change their major functions, (5) radically change their structure, (6) have minimal experience as a work group, (7) have vague boundaries and (8) are often caught between two conflicting reference groups. Such organizations have difficult problems of adaptation. They find it difficult to control demands and to effectively utilize volunteers. Expansion itself creates a number of operational problems without adequate opportunity to institutionalize such changes. In particular, interorganizational relationships are affected and organizational legitimacy becomes problematic. On the other hand, the utility of expanding organizations in disaster operations is its flexible form, designed to cope with increased community demands.

MEETINGS

Plastics—Fire—Corrosion An International Symposium on Corrosion Risks in Connection with Fire in Plastics.* Stockholm, April 24, 1969.

Prepared and organized by: Swedish Corrosion Institute, Swedish Fire Protection Association, Swedish Plastics Federation.

Sponsored by: Research Foundation of the Swedish Fire Insurance Companies.

Purpose: While burning or under heat, certain types of plastic materials give off gases which are corrosive to different materials. In the event of a fire, this involves a considerable risk of severe secondary damage to building materials, machines and metallic articles of components. Even small amounts of certain plastics may cause heavy corrosion damages if expensive equipment is exposed to their corrosive fumes.

The main purpose of the symposium was to throw light upon the various factors influencing corrosion risks in connection with fire in plastics and to gather experience concerning measures to prevent such corrosion.

Subjects:

I. Composition of gases from burning plastic materials

II. Corrosion damage caused by plastic materials in connection with fires

III. Prevention of corrosion due to burning plastic materials

1. Measures concerning building construction
2. Selection of plastic materials for electrical insulation, building purposes, packaging, etc.
3. Measures concerning storage of plastics
4. Use of temporary corrosion preventives

Svenska Brandforsvarsforeningen
Kungsholms Hamnplan 3
S-112 20 Stockholm
Sweden

* The symposium was held in connection with "SKYDD-69," a Fire Protection and Prevention Congress and Exhibition, April 21–27, 1969 in Stockholm.

Workshop on Mass Burns National Academy of Sciences, Washington, D. C. March 13–14, 1968

Section: **K**

Subject Heading: **Mass burns**

The following excerpts are from papers presented at the Workshop on Mass Burns, sponsored by the Committee on Fire Research, National Academy of Sciences-National Research Council, and the Office of Civil Defense, March 13–14, 1968. The full text* of the papers is available as a volume edited by Drs. Carl Walter and Anne Phillips. It provides an overview of the multifarious problems involved in the treatment of large numbers of burn cases during disaster conditions. By its nature the problem is interdisciplinary even though its essence is medical. The medical problems cannot be divorced from operational, logistical, and physical problems of the setting.

R. M. Fristrom

DEFINITION OF ASSIGNMENT

HOWARD W. EMMONS

Abbott and James Lawrence Professor of Engineering,
Gordon McKay Professor of Mechanical Engineering, Harvard University
Chairman, Committee on Fire Research, National Academy of Science—National Research Council

Welcome to the Workshop on Mass Burns, under the sponsorship of the Committee on Fire Research of the National Academy of Sciences—National Research Council and the Office of Civil Defense.

* * *

This particular symposium on mass burns has grown from the fact that it is clear that, should there be an atomic disaster (or some other large-scale disaster), we might have in our cities a very large number of burned persons; such large numbers in fact that the medical profession and normal medical facilities would be swamped. What could the problems be? What would be done about them? What must all of us be prepared to do under those conditions? This is the general subject of this workshop.

This workshop has been organized in two parts with an introduction to the problem as seen by the Office of Civil Defense, and a discussion of various aspects as seen by the Committee on Fire Research. The two portions of the program were put together by Colonel James W. Kerr, of the Office of Civil Defense and Dr. Carl W. Walter of the Committee on Fire Research. For further introduction I will turn the meeting over to Dr. Walter for presentation of the part of the program in which he has been active in the preparation.

* Copies of the Proceedings are available only by purchase from: Clearing House for Federal Scientific and Technical Information, U. S. Department of Commerce, Springfield, Virginia 22151. Cost is $3.00 for paper copy; $0.65 for microfiche. Order No. AD689495.

PURPOSE OF THE SYMPOSIUM

CARL W. WALTER, M.D.

Clinical Professor of Surgery, Harvard Medical School
Co-Chairman of the Symposium

The care of patients who have been burned is a serious problem in any organized community with the customary medical resources. The care of a population inflicted with thermal burns under disaster conditions devoid of medical resources is an incomprehensibly enormous challenge. Obviously the goals and standards of care must differ. Attention to the detailed needs of the individual becomes submerged in the struggles for survival of the community.

Preservation of survivors and prompt restoration of the injured to the manpower pool impose restrictions on resources and require sorting of the injured. Resources must be diverted to salvage those with a predictable morbidity; humane alleviation must be extended those with oppressive morbidity or predictable mortality.

A well-planned program of self-help affords the community the greatest potential recovery. This workshop has been organized to review the problem of burns, and to marshal data that will permit experts in systems analysis, logistics, mass behavior, and government to apply their skills in planning for the defense of an isolated community that has been largely destroyed by a disastrous fire.

Participants have been instructed to focus on the education of a non-medical audience, whose principal interest is civilian defense, and on what to expect from thermal trauma; how to recognize the potential survivors, what measures of self-help can decrease the severity of the illness, how and what to provide in terms of food and water supplies, space and personnel, how to educate the public and train surviving personnel during the weeks or months necessary for the devastated community to reorganize itself and become self-sustaining.

JAMES W. KERR, *Colonel, USA* (*Ret.*)

Staff Director, Support Systems Division (*Research*), *Office of Civil Defense*
Co-Chairman of the Symposium

Medical research has been carried out by or sponsored by Civil Defense for 15 years or more. During most of that period we have benefited by close association with the National Academy of Sciences, especially with the various advisory committees such as the Committee on Fire Research. This workshop focuses on one of the major problems of nuclear disaster, which is, of course, the statutory area of concern to the Office of Civil Defense. That is not to say that mass burns are unique to nuclear war; Dr. Walter's remarks have made this clear.

* * *

By comparison with the giants in the medical research field, OCD's efforts are quite small. Atomic Energy Commission, Defense Atomic Support Agency, National Institutes of Health—all these have been known to have medical research budgets that exceed the total OCD research effort. Even in OCD, a major emphasis is on fire effects and countermeasures, exceeding the medical budget several times over. This is because nobody else is sponsoring much fire research, so we step in; and everybody else is sponsoring medical work, so we are quite selective.

The medical research sponsored by OCD can be broken down into three general categories. There are papers from all these areas.

1. Systematization of information or problem definition. Casualty description, case load prediction, feasibility and appropriateness of certain courses of action, all are evaluated in projects of this type. Examples are the Dikewood paper on casualty description and the University of Rochester paper on flash burns.

2. Buying into other agencies' programs. Dr. Edward L. Alpen's paper on long term and combined effects of radiation discusses one such piece of work. Where a large effort is needed, OCD cannot handle it alone, but in programs of interest there is usually room for a bit more funding, and the possibility of fitting OCD needs.

3. Filling identified needs. Analytical programs, (i.e., Category 1 above) usually point out areas that need attention. We then pursue actively the topics judged most urgent and most feasible of solution by a research approach. Dr. Carl Jelenko's paper on water loss and caloric demands is an example of this category.

Let me mention one further attribute of OCD medical research. In a word, it is often controversial. The nuclear war problem is too big and too pressing for OCD to put on blinders, institutional or otherwise, when it comes to pursuit of knowledge. In another metaphor, we have to work both sides of the street. We have been known deliberately and simultaneously to sponsor work by scientists holding opposing views.

It has been my intention to point out both the breadth and the limitations of OCD's research program. Let us hear from our researchers. The variety of their subjects will indicate the scope of our efforts, and the inter-relationships of the subject matter will tie into the mass burn question, setting it all in proper perspective.

MASS PSYCHOLOGY

The Determinants of Behavior under Emergency Conditions

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Section: K

Subject Heading: **Mass psychology.**

In considering determinants of behavior under emergency conditions, this discussion will be confined to the relatively uninjured survivors of an emergency situation, be it large or small, and to the personnel involved in rescue efforts, including medical care.

Behavior under emergency conditions is dependent upon a number of variables, such as the nature and intensity of the traumatic agent, the presence of others, such as loved ones, and whether individuals involved constitute an untrained heterogeneous group, or a homogeneous, cohesive group such as a combat unit.

* * *

While this topic has been covered rapidly I hope the impression has been left that we have considerable information on the factors determining behavior in disaster. Fortunately, there is practically no severe mental illness produced by the disaster itself. Most of the breakdowns are temporary, but there may be severe reaction as a residual, following one's failure to function.

In conclusion, there is abundant evidence that disaster training reduces the amount of non-effective behavior occurring under emergency conditions.

CLOTHING BURNS*

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Related Sections: **K**, *A*, *B*

Subject Heading: **Clothing burns.**

In order properly to discuss the characteristics of a specific type of burn injury and its significance, it is necessary first to have some concept of what a burn is and to consider the mechanisms that produce burn trauma.

A skin burn is the injury which results from application of heat to the skin surface; the degree to which cells are damaged by heat is proportional to both the intensity and duration of temperature elevation. Because the layers of the skin themselves have some insulating qualities and because there are body mechanisms capable of removing heat, it is obvious that the depth to which damage extends is also related to the intensity and duration of heat application. Thus, if the skin surface is raised to a temperature of 70°C (158°F), some cells of the surface epidermal layers are destroyed in one second; deeper cells are spared with this duration of application but if the same heat is maintained, deeper damage occurs. If the heat energy applied to a given cell is slight, damage will consist only of a temporary alteration of enzyme activity and the cell may recover completely. Slightly greater heat kills cells immediately by coagulation of proteins or by actual incineration. Therefore, in a given burn wound one would anticipate finding most severe cell damage or destruction at the surface of the skin and in the center of the wound

* [A burn which destroys the full thickness of the skin is much the same, whether it is caused by an intense flash of heat, by exposure to flame or to scalding liquids. The same is true of less deep burns. The end result is not necessarily different because the injury was inflicted in one way or another. However, certain types of burns seem to have importance in the lay mind or in the public press, and it is also true that some modes of burning have characteristics which may be of interest when it comes to sorting burn casualties in a disaster, so it may help to look at clothing burns, flash burns, and scalds separately. This paper concerns clothing burns.—Editor's Note].

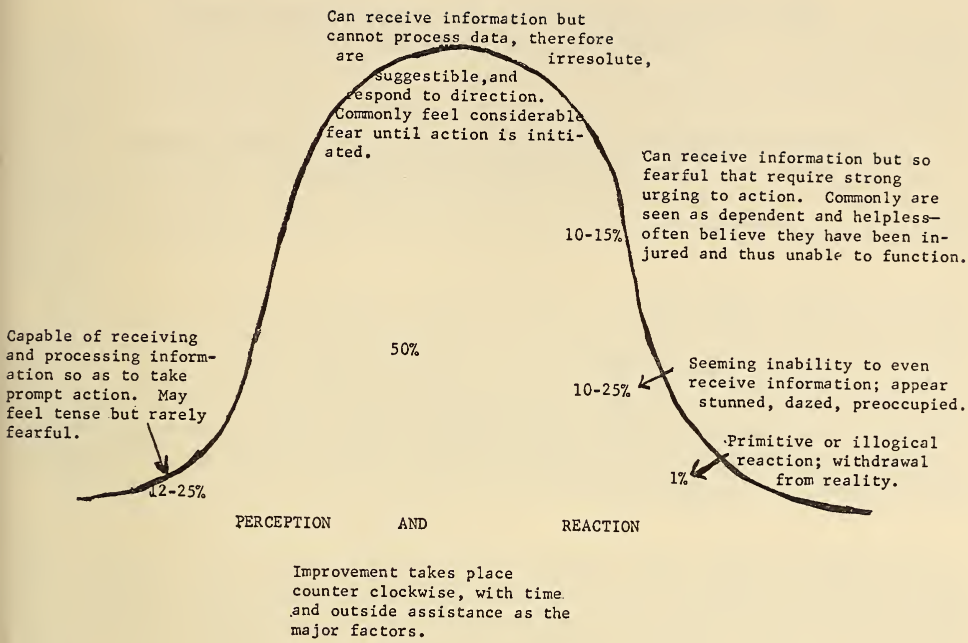

FIG. 1. Communication Model.

while in deeper layers and at the periphery, marginal damage would be seen. Where the total thickness of the skin is destroyed (full-thickness or deep burns, what doctors call "third degree burns"), the involved area is dry, leathery, and contracted. This area of skin will subsequently separate from the living deeper layers and slough,* leaving an open wound which must be repaired surgically (covered with a skin graft) if invasive infection and disfiguring or deforming scars are to be avoided. A burn which involves only the surface layers (partial thickness or superficial burns, the so-called first and second degree burns) will heal, grow a new surface covering spontaneously, unless secondary factors such as infection or interference with circulation intervene. In second degree partial thickness burns, blistering usually occurs because damaged blood vessels at the interface between the burned and unburned layer leak fluid readily and rapidly. It must be emphasized that partial thickness burns can be of variable depth (very superficial to very deep) and the course of the deeper burns can be much more serious.

* * *

A number of satisfactory techniques for treating cotton to make it flame-resistant have been developed in recent years. Such flame-retardant treatments are available not only to the fabric or clothing manufacturer, to produce "permanent" flame resistance, but also to laundries and cleaners. Satisfactory home-treatment chemicals can be applied to cotton fabrics as part of a washing cycle, to decrease flammability of the clothing between launderings. It is obvious that the answer to the clothing burn problem rests ultimately in proper education of the population so that such retardant treatment is not only used but demanded.

* Slough = separation of dead tissue from living tissue.

THE CHARACTERISTICS OF FLASH BURNS AND HOW THEY ARE PRODUCED

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Related Sections: **K**, *I*

Subject Heading: **Flash burns.**

Flash Burns and Nuclear Weapons

A flash burn is produced by a brief exposure to radiant thermal energy. In civilian life exploding fuel is the most common cause. Men in the armed forces sometimes suffer flash burns while firing cannons. Many inhabitants of Hiroshima and Nagasaki received flash burns.

* * *

If we know the size of the weapon, can we predict how severe a burn it will inflict at various distances from ground zero? Within limits, yes; precisely, no. We and others have accumulated data from nuclear weapons tests and from the laboratory, and from them some prediction can be made. However, I have often found engineers, physicists, statisticians, and others going badly awry in their interpretations of the data, and I would like to point out some of the chief pitfalls in the construction of burn prediction (dose-response) tables.

1. The skin is not a passive receiver; it reacts to thermal radiation. The type of reaction varies with the irradiance and with the exposure time. At least one type of reaction of the superficial portion of the skin can protect against injury of the deeper parts.*

2. It is commonly supposed that for any given radiant dose (or radiant exposure) the greatest injury will be inflicted by delivering that dose in the shortest time. This is true of only the milder burns produced by the lower radiant exposures. When higher exposures (more severe burns) are considered, the inverse relationship between exposure time and depth of damage breaks down completely.

3. Even with the same radiant exposure, exposure time, and pulse shape, and a nearly constant skin temperature and skin pigmentation, the "standard deviation" of the depth of injury can be appallingly large when one considers that at one end of the scale the burn is merely a painful nuisance and at the other a life-threatening injury.

Tissue destruction is determined by a time-temperature relationship, and the higher the temperature the less time it takes to destroy cells. Above a certain temperature *practical* differences in exposure time are probably of little importance. In regard to skin, so far, exposure time and radiant exposure can be translated into a time-temperature relationship only over a narrow range. As radiant thermal

* One factor in the skin's reaction to heat is its circulation. Exposure to heat dilates the blood vessels permitting more blood to rush through the heated part. Heat is conducted away from the exposed skin by the circulating blood unless the heat is so great as to coagulate the blood. Elderly people with poor circulation in their feet occasionally burn them in bath water which is not too hot for their hands.—Editor's Note.

energy is applied to the skin, some is reflected, some is transmitted, and some is absorbed. Pigmentation of the skin obviously affects the percentage reflected; the whiter the skin, the greater the reflectance, the less the damage from a given exposure. The circulation in the skin must also affect the ultimate time-temperature relationships and must play a part in determining the severity of the injury. Therefore, a skin simulant which ignores the reaction of the skin and the circulation of the skin is of some use in predicting no burn-mild burn injuries, but it is of little use in predicting the depth of injury from higher radiant exposures.

The eye

The eyes are a special problem. The lens of the eye concentrates thermal radiation so that a very small radiant exposure can burn the retina. This injury is not the same as flash blindness which is also a problem with nuclear weapons; the injury I speak of is a burn which destroys part of the retina. How disabling the damage will be depends on the direction the subject is looking in relation to the fireball, the size of the weapon, and the distance between subject and fireball.

Abstracts of some of the reports on which the conclusions in this paper are based will be found in the Appendix.

FLASH BURNS

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Related Sections: **K**, *I*

Subject Heading: **Flash burns.**

Flash burns are produced when the exposed skin is subjected to sufficient radiant energy or heat delivered as pulse or flash. Such burn injuries are frequent in clinical practice and result from explosions such as from gas or oil stoves and electrical arcs as from high tension short circuits. These injuries occur because the pulse of radiant energy delivered in a short time impinges upon unprotected skin. In contrast, sunburn is a radiant energy injury occurring over a much longer period of time from a constant energy source.

* * *

These experiments emphasize the importance of physical factors in the production of flash burns. In particular, it is believed that the thermal rate of delivery and the spectral composition of the incident radiation are important factors influencing the effective thermal dose delivered. It is also apparent that in addition to producing flash burns, explosions may produce burning clothing or secondary fires which may produce an even greater source of thermal energy delivered over a longer time period with a resultant deeper burn injury. The potential for thermonuclear explosions to cause flash burn is evident as is its propensity for causing secondary fires.

Generalizing from clinical experience, flash burns as a rule are second degree burns of exposed surfaces such as the face and hands which are ordinarily best treated by local cleansing and by exposure therapy. Many do not require hospitalization. When treated in this way, they heal typically in 10 to 14 days without significant scar or deformity.

SCALDS

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Section: **K**

Subject Heading: **Scalds.**

The formal definition of a scald is "an injury to the body caused by contact with hot water, liquids, or steam." This definition would at first appear to be clear-cut and self-explanatory. However, upon examination of the literature and discussion with others, discrepancies become apparent, especially with reference to injuries caused by "hot liquids." What do they include? Are these aqueous fluids, such as hot water, tea, coffee, or soups, or should molten tar, boiling oil, or liquid metals be included?

The term, "scald," to have meaning to the physician ultimately in charge of treatment of the patient, must be used with identification of the agent producing the injury. At any rate the bodily injury is a burn, as noted in the Encyclopedia Britannica which states "the term scald, referring to injuries from hot water or steam had almost completely dropped out of medical literature by the early 1960's, and all of these injuries are now usually called burns." Sevitt states that in terms of changes in the tissues, burns from *hot liquids* are essentially the same as those due to hot solids. Thus, a scald is merely one variety of thermal burn.

* * *

Summary

The term, "scald", i.e., a burn caused by contact with hot water, liquids, or steam, is being dropped from contemporary medical literature. Today, a scald is an acute, open wound for which definitive treatment is now well standardized. In a mass disaster, scalds are likely to be fewer in number than burns due to other causes. Like other thermal injuries, the temperature of the causal agent and the duration of contact with the body determine the severity of tissue damage. However, in scald incidents, heat-retaining clothing saturated with hot liquids may increase the intensity of the burn.

Scald by steam can produce serious respiratory tract injuries in addition to body surface burns; a patient with burns of the face and neck should be suspected of respiratory injury.

Prompt first-aid care by personnel arriving at the disaster site should be directed towards minimizing further tissue damage and relieving pain. However, local therapy of associated severe injuries will take priority over treatment of burn

injuries. Care given to the victims should in no way conflict with later definitive treatment upon arrival at the hospital. The relief of pain, an important part of initial care, is both necessary and humane. While the pain suffered by the burn victim often is not as severe as that suffered by the observer, certain measures such as cold applications and shielding of the scald areas from the air may have pain-relieving effects.

Initially, the severity of the scald may be deceptive as regards extent and depth; the more extensive the burn injury, the greater is the loss of fluid from the circulation and the more grave is the prognosis. Today, however, treatment is standardized and no scald injury is considered beyond salvage.

THE BURN SURFACE AS A PARASITE

Water Loss, Caloric Demands, and Therapeutic Implications

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Section: **K**

Subject Heading: **Burn surface.**

Water is Lost through Burned Skin

In a mass disaster, when both food and water may be available only in limited quantities, the Civil Defense allowances of these materials per person may be totally inadequate for the burned patient's needs. A burn may be thought of as a parasite, drawing from its host water, protein, and other substances which the host needs for its survival. An uninjured person who is not perspiring may lose from 1.15 to 2.0 quarts of fluid a day through his lungs and skin, depending on the temperature of his environment. The fluid losses from a burn wound are far in excess of those from intact skin and may amount to 2 gallons per day, or more if the burn is large enough. If, during the first 48 hours after injury, no more fluid is given to an extensively burned patient than he would need in health, the uncompensated loss of fluid from his circulation may cause shock, and if sufficiently severe, death. After the first 48 hours, the danger of shock is lessened, but inordinate fluid losses will continue from the burn surface.

Heat is Lost Necessitating a High Food Intake

To make matters worse, evaporation of moisture from the wound surface saps not only the body's water stores but its energy stores as well. When water evaporates from the burned surface, cooling results and the body loses heat. The larger the burn wound, the more water loss and the more heat or energy loss. The patient's fat and protein stores must supply the energy for his heat loss; and large amounts of food are necessary to replace these losses.

Measurement of actual water losses in a large man (70 kg with 2 sq meters of body surface), who had a 50 per cent burn, showed a first day loss of 10,800 ml from the burn surface, dropping to 5,280 ml the second day. The heat loss occasioned by evaporation of this fluid (plus normal water loss from his intact skin) and the energy consumed in carrying on the body's metabolic processes, resulted in an enormous total caloric consumption, 8,353 calories the first day and 5,137 the second. To feed such a patient only his normal basal requirement of 2,100 calories would be to leave him a deficit of 2,600 calories from the third day after injury. He would lose approximately a pound a day on the basis of the unmatched caloric expenditure.

* * *

Summary

The burned surface (eschar) may be thought of as a parasite upon the body surface which depletes the body of water and calories. The magnitude of the water and caloric losses that can be anticipated are discussed, and certain of the features of the eschar are defined in terms of its chemical and physical structure. Certain methods are suggested which may allow the alteration of the eschar in such a manner that water and caloric losses can be diminished toward the level of intact skin. In particular these methods will use the eschar itself and will enable the therapist to control infection and the production of toxic materials from the deeper layers of eschar. The problem of water, caloric loss, and infection in the management of large numbers of burned patients is discussed.

PULMONARY COMPLICATIONS OF BURNS

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Section: **K**

Subject Headings: **Pulmonary complications of burns.**

If you know that a year from today you would find yourself the only person with any medical knowledge, faced with the care of 500 burned patients following a disaster, with only civilians to help you, would you like to know about the respiratory complications of burns? Whether you are a psychiatrist, or a bacteriologist, or an orthopedic surgeon, whatever your specialty, the public will demand that you play your role as a doctor and treat the burned victims. You may want to know the answer to these questions: What is the most common pulmonary complication? Why does it occur? How can I recognize it? What are its signs and symptoms? How can I distinguish patients with impending respiratory difficulties from the ordinary run of burned patients when I first see them? What importance do the respiratory complications have to the victim's survival? What treatment should I give, if any? Are there any simple steps which can be taken to avert the more serious respiratory complications in those patients who are not so badly burned as to be beyond hope of salvage?

THE PREVENTION OF SEPSIS IN BURNS

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Section: **K**

Subject Heading: **Sepsis in burns.**

The Problem

Burns almost invariably become colonized by bacteria unless strenuous precautions are taken to prevent contamination. In superficial burns bacterial growth causes little obvious damage, and the skin quickly heals from the layer of living skin cells in the floor of the burn. In deep burns, however, the growth of certain types of bacteria is likely to cause adverse effects (infection). If the burns are of relatively small extent, the main damage caused by bacteria may be to destroy skin grafts put on by the surgeon after the slough has separated (two or three weeks after the injury); some living tissue adjacent to the burn may be invaded and destroyed by the action of bacterial toxins, but severe general illness and death due to infection are rare in such cases. In more extensively burned patients, bacterial colonization of the burn may cause both local damage and severe general illness, with fever, loss of weight, and sometimes bacterial invasion of the blood stream (septicemia); infection may be extended in this way to the kidneys, the brain, and other organs, and the patient is likely to die.

* * *

If burns are complicated by exposure to ionizing radiations, the risk of infection, even in patients with smaller burns, is greatly enhanced. For this reason it is desirable to include antibacterial defense as an essential component in the treatment of all burned patients including those with minor burns and those likely to die (categories 1 and 2) when exposed to thermonuclear attack or other radiation hazard. Otherwise, they may serve as a bacterial reservoir to infect not only those who might otherwise survive with treatment but also the uninjured as well.

SORTING OF BURN CASUALTIES

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Section: **K**

Subject Heading: **Burn casualties.**

The triage* of casualties that occur in a community as a result of a major disaster and that inundate the surviving medical facilities, presents a major problem to

* Triage: sorting, generally with respect to subsequent management.

all of the various personnel charged with casualty care. Triage is a process of sorting the casualties into three general patient categories: those for whom no medical treatment would be of value, those that do not need immediate medical attention, and those that have a good chance of survival if treated in the available medical facilities.

GRID OF APPROXIMATE MORTALITY PROBABILITIES														
% Body Area Burned	Age - Yrs.													
	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65+
68 or more	1	1	1	1	1	1	1	1	1	1	1	1	1	1
63 - 67	1	1	1	.9	.9	.9	.9	1	1	1	1	1	1	1
58 - 62	1	1	.9	.8	.8	.8	.8	.9	1	1	1	1	1	1
53 - 57	.9	.9	.8	.8	.7	.7	.7	.8	.8	.9	1	1	1	1
48 - 52	.8	.8	.7	.7	.6	.6	.6	.7	.8	.8	.9	1	1	1
43 - 47	.7	.7	.6	.5	.5	.5	.5	.6	.7	.7	.8	.9	1	1
38 - 42	.6	.5	.5	.4	.4	.4	.4	.5	.5	.6	.7	.8	.9	1
33 - 37	.5	.4	.3	.3	.3	.3	.3	.4	.4	.5	.6	.7	.9	1
28 - 32	.4	.3	.2	.2	.2	.2	.2	.3	.3	.4	.5	.6	.7	.9
23 - 27	.2	.2	.1	.1	.1	.1	.1	.2	.2	.3	.3	.5	.6	.8
18 - 22	.1	.1	0	0	0	0	.1	.1	.1	.2	.2	.3	.5	.7
13 - 17	0	0	0	0	0	0	0	0	0	.1	.1	.2	.3	.5
8 - 12	0	0	0	0	0	0	0	0	0	0	0	.1	.2	.3
3 - 7	0	0	0	0	0	0	0	0	0	0	0	0	.1	.2
0 - 2	0	0	0	0	0	0	0	0	0	0	0	0	0	.1

FIG. 3. Mortality grid according to age and percent of total body surface area burned (Ref. 7). Reading from the grid, the mortality probability for a 26 year old burn victim with a 40% burn is 0.4. It can be predicted that she will live. For a patient of 58 with the same extent of burn the probability is 0.8. The outlook for this patient is bad.

* * *

Summary

The principles involved in sorting burn casualties have been briefly discussed, and data from a large series of patients treated at a burn center in a teaching hospital have been used to show what factors affect mortality under those conditions. The limitations to extrapolating these data to fit the massive disaster situation have been mentioned previously, and this difference must be stressed again.

Two established methods that are frequently used to predict burn injury mortality have been shown, these being the use of the LA_{50} values for different age groups and the mortality grid. A test analysis, using admittedly a small number of patients, of the accuracy obtained with the mortality grid has shown this method to yield a high degree of error in the group of patients wherein triage becomes critical. A new method of analysis (for this purpose) has been discussed, and the preliminary use of a prediction equation based upon this type of analysis with the same group of patients resulted in a higher degree of accuracy. Further refinements of this method, an evaluation of the effect of various new and promising treatment regimes now being tried, and a realistic evaluation of the effect of "combined" burn and non-burn injuries are all needed. When these data are available the problems of triage should be lessened appreciably.

THE EFFECT OF TOPICAL CHEMOTHERAPY AND USE OF HOMOGRAFT SKIN AS A BIOLOGICAL DRESSING ON BURN MORTALITY

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Section: **K**

Subject Headings: **Chemotherapy;** *Homograft skin.*

In order to evaluate the prognosis of any burn injury, at least four features must be considered: the size of the burn; its depth; the specific area of the body involved; and the age of the patient.

* * *

Summary

The mortality experience of the US Army Surgical Research Unit with burn injury prior to and following the institution of an aggressive, effective program for the prevention of burn wound infection is presented. Statistically significant improvement of survival has been observed with this regime. This improvement is confined to burns of moderate size. The prevention of burn wound infection in patients with burns exceeding 75 per cent of the total body surface has not improved the likelihood of survival in these patients.

LOGISTICS OF BURN THERAPY—PERSONNEL, SUPPLIES, AND SPACE: MILITARY EXPERIENCE

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Related Sections: **K,** *L*

Subject Heading: **Logistics of burn therapy.**

The transposition of data from our military experience with a 60-bed burn-care ward to the logistic problems entailed in the treatment of 500 or 5,000 casualties in a mass disaster is difficult and full of speculation. Hopefully, we have some basis for that speculation.

* * *

Special Problems of Nuclear Disaster

What kind of patient population would we be dealing with if a thermonuclear weapon were detonated? Because radiant heat passes in a straight line and will hit anything that is exposed, the number of people who would have burns of the hands and face will probably be higher than in our normal burn population. The number with burned hands will exceed the 75 per cent we find in our usual burn population. The number with burns of *both* hands will probably be higher than the 50 per cent that we see today. This is important, because the individual who has his hands burned is incapable of using them for much and, therefore, has to be helped in many ways. In addition, 66 per cent of your patients would have face burns. This means that within 12 to 18 hours these people will be unable to see because their eyelids will be swollen shut. They will have to have somebody to lead them around and to show them what to do. The victim may have *only* face and hand burns. He may be able to walk, but he cannot see where he is going, so somebody has to take care of him. It might be well to pair up in the buddy system the man who has hand burns but his face spared, with a man with the face burn but uninjured hands.

* * *

Summary

It is difficult to be certain what the logistical requirements will be in a mass casualty situation. If we can once define the number of patients that are to be involved, the type of patients that we are going to treat, the compromises we will have to make in the therapy, and really how we are going to treat these patients, then I think we can get some legitimate idea of what the logistical problems would be.

LOGISTICS OF BURN THERAPY—PERSONNEL, SUPPLIES, AND SPACE: CIVILIAN EXPERIENCE

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Related Sections: **K**, *L*

Subject Heading: **Logistics of burn therapy.**

During the past 20 years at the University of Texas Medical Branch approximately 4,000 patients have been admitted for therapy of burns, not including cases treated on an outpatient basis or those hospitalized for reconstructive procedures. More than half, that is 125 per year, have been acute burns. Since ours is a referral service in a State hospital facility and the local population is less than 80,000, we receive a large number of burns of critical extent from other areas. The same is true of the Shriners Burns Unit in Galveston, a 30-bed institute for research and therapy which began admitting burned children two years ago. The mortality rate in our service has been, consistently, above 20 per cent. It is still rising, in part because of a numerical increase in admission of critical cases, but also in part because of the decrease in pediatric burns since the majority of these are treated at the Shriners Hospital. The mortality rate for acute burns in the latter group is about 17 per cent. Including all patients our statistics reflect an over-all mortality of about 12 to 14 per cent. These figures are consistent with those found on similar services elsewhere in this country.

* * *

Conclusion

Continued and vigorous efforts must be made in the areas of fireproofing of textiles, control of volatile liquids in the home, improvement in heating methods, education of the public in prevention of burns and in means of escape from burning buildings. Meanwhile, as we have stated previously, "It is . . . a twentieth century paradox that while, on the one hand, we are endeavoring to lower the mortality rate and lessen the morbidity period in acute extensive burns through basic research and technical improvements, on the other hand, we are faced with the necessity of evolving a program of minimum standards of burn care to be put into effect in the event of a major disaster. Much work remains to be carried out in both areas. Such meetings as this symposium indicate great interest on the part of workers in many areas toward fulfillment of these objectives.

SOME PRINCIPLES OF PROTECTION AGAINST BURNS FROM FLAME AND INCENDIARY AGENTS

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Related Sections: **K,** *H*, *G*

Subject Headings: **Burns from flames.**

There is a surprising amount of confusion and misunderstanding concerning the subject of flame and incendiary munitions, the resulting medical problems, and their management. Some of this confusion is the result of the circumstances under which casulaties are seen—situations which are often not conducive to precise evaluation. Some is due to the absence of basic scientific information, some is the result of inadequate transmission of existing information. The material in this brief summary is culled from unclassified documents, three of which have not yet

* The opinions expressed in this paper are those of the author or of authorities cited in the references and do not necessarily reflect official opinions of the United States Army.

been released for publication, supplemented by personal observation of patients and by logical deductions.

* * *

Summary

The extent and type of medical problems resulting from exposure to flame and incendiary munitions thus depends on several factors. First, the type of agent used will alter expected results. Second, the environment is an exceedingly important factor. In a large city, such as in the World War II fire bombing of Hamburg, fire storms can result from ignition of flammable materials and a leading cause of death is the exceedingly high environmental temperature rather than burns *per se.* The completeness of combustion, the types of materials, and whether people are in poorly ventilated enclosures help determine the percentage of injury from carbon monoxide and inhalation of toxic fumes.

Where there is much moisture, effects will be less, and they will be less in a rural community where there is much environmental moisture and heavy foliage as compared with a locale where the environment is very dry, water supplies are scarce, buildings are close together, and building materials are readily combustible.

A third factor is the training and alertness of the people involved. Prompt defensive and corrective action makes a very great difference in the severity of injuries resulting from any of these agents.

In conclusion, there is a need to do more detailed quantitative studies on some of the flame and incendiary agents in order to determine their true pathological significance, although from a surgical standpoint "a burn is a burn", with the possible exception of retained white phosphorus. Education and training can be employed now to reduce severity of injuries from future casualties from any of these agents.

TREATMENT OF ACUTE RADIATION INJURY UNDER AUSTERE CONDITIONS*

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Section: **L**

Subject Heading: **Burn Therapy.**

Early in 1966 the Office of Civil Defense requested a committee, since called the TRIMAC Committee, "to define in detail whatever is considered, on the basis of the present state-of-the-art, to be the most sensible plan for the austere medical management of large numbers of radiation casualties and to evaluate several specific courses of medical research which will most adequately improve our ability to cope with the civil defense aspects of radiation sickness."

* Based on report of the TRIMAC Committee, the Committee on Treatment of Acute Radiation Injury under Medically Austere Conditions.

TABLE 1
Austere Conditions in Fallout Shelter*

Period of strict confinement	2–3 days
Total period in shelter	2 weeks
Space per person	8 ft² floor space (no bunks)
Population at risk	Civilian population in area (adults and children); 1,000 persons (spaces)
Power supply	Muscle power only
Food	10,000 calories/space†
Water	14 quarts/space
Sanitation	17.5 gallon drums to store 3.5 gallons/space
Medical	Medical kits for units of 50–65 or 300–325 spaces
Radiation dosimetry	Battery operated CDV-715 survey meter and personnel dosimeters plus instruction manual and simple repair instructions

* Based on current civil defense planning as stipulated in Federal Civil Defense Guide.
† I.e., 714 calories per person, per day; less than half the normal resting requirement.—(Ed.)

* * *

Concluding Comments

The hypothetical shelter conditions postulated are probably unrealistic to some extent in that they preclude the presence of patients with severe burns, lacerations, fractures, or other types and combinations of injury not due to ionizing radiation. In this respect, the clinical descriptions of degrees of radiation injury may also be misleading.

There is likely to be an unduly high index of suspicion with respect to radiation injury as a cause of gastrointestinal symptoms, malaise, and fever. It is particularly important to reserve judgment about the degree of radiation injury in acutely ill patients who have sustained severe burns, fractures, and the like. Severely burned patients will probably become nauseated and vomit; so may patients with fractures. Shock may obscure the symptoms and clinical signs of radiation injury in the severely traumatized patient. Little information about acute radiation injury in infants and children is available, hence a high degree of caution in accepting nausea, vomiting, and diarrhea as infallible signs of severe radiation injury is indicated when evaluating pediatric patients.

Since severe radiation injury would have grave prognostic significance for the patient with severe trauma, an objective attitude about the relative importance of radiation as a cause of observed symptoms is probably advisable. In these patients, as in those with radiation injury alone, the extent of hematopoietic tissue damage may determine the ultimate outcome.

PREDICTION OF URBAN CASUALTIES AND THE MEDICAL LOAD FROM A HIGH-YIELD NUCLEAR BURST*

J. WAYNE DAVIS

The Dikewood Corporation, Albuquerque, New Mexico

Related Sections: **L**, *K*

Subject Heading: **Prediction casualties.**

The effectiveness of planning for a disaster is, in part, dependent upon the accuracy with which the number and type of casualties are anticipated. Mr. Davis' paper is primarily concerned with predicting the casualties which might result from a nuclear explosion over a city. Data, upon which his conclusions concerning nuclear explosion are based, were gathered by the Dikewood Corporation from 35,000 victims from three disasters: (1) the Texas City disaster of 1947 (in which ammonium nitrate fertilizer on board a ship exploded at dockside in Texas City, Texas, with an estimated force of 0.67 kilotons), (2) the atomic bomb explosion at Hiroshima (12.5 kilotons at a height of 1,870 feet), and (3) the atomic detonation at Nagasaki (22 kilotons at a height of 1,640 feet).

Mr. Davis' paper also presents data on fire mortalities and fire phenomena, such as conflagrations and fire storms. Data for the conclusions in this portion of the paper are drawn mainly from fires and conflagrations in nine German cities.

THE PHYSICAL AND BIOLOGICAL ASPECTS OF BLAST INJURY†

ROBERT K. JONES, M.D. AND DONALD R. RICHMOND, Ph.D.

Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico

Related Sections: **K**, *I*

Subject Headings: **Blast injury.**

Introduction

The purpose of this paper is to summarize the status of some of the more significant aspects of blast injury. Using Hiroshima as an example, an attempt will be made to show the relationship between free-field levels of overpressure and

* As summarized and interpreted by the editors. The complete text is included in Appendix C of the *Proceedings*.

† Since 1951 the Lovelace Foundation personnel have had the opportunity to study various aspects of blast injury. This work has been supported largely by the Division of Biology and Medicine of the Atomic Energy Commission and the Defense Atomic Support Agency of the Department of Defense to whom we are most indebted.

various types of blast injury. Finally, the relationship between exposure and the relative number of each type of injury will be illustrated.

* * *

The total casualties resulting from primary blast effects in Hiroshima and Nagasaki will never be known because the victims never reached medical channels. However, it is probable that many of the deaths occurring before 24 hours were due either to primary blast or to other blast injuries which rendered the individual incapable of moving to escape secondary fires. Of those that survived and were included in the population survey used in formulating the blast injury figures, the types of blast trauma sustained by each individual are not specified in many cases. However, it is likely that most were of an indirect secondary or translational type. Thus, burn or radiation victims might be expected to have sustained a variety of superimposed secondary and translational blast injuries. In this workshop, we will be discussing current methods of burn therapy that might be utilized in certain military and civilian mass-casualty situations. During our deliberations, it should be borne in mind that therapeutic measures developed for uncomplicated burn victims may have to be significantly modified when one treats persons who have sustained the combined trauma of burn, blast, and radiation.

COMBINED EFFECTS OF RADIATION AND TRAUMA

EDWARD L. ALPEN

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

Related Sections: **K**, *I*

Subject Heading: **Radiation and trauma.**

(Editorial Comment: Mr. Alpen's paper re-emphasizes the need for antibiotics in fallout shelters. He quotes from the work of Hamilton Baxter *et al.*, who found that the tremendous increase in mortality from burns occasioned by the addition of total body radiation could be averted by the addition of streptomycin treatment started 24 hours after the injury and continued for 21 days. A drop in mortality from 99 per cent to 20 per cent was observed as a result of this treatment. Brooks *et al.* made a similar observation in dogs to whom antibiotics were administered prophylactically. Unfortunately, antibiotics are expensive, and many of them have a limited shelf life, some even becoming dangerous if used after the expiration date. Unless nuclear attacks become more probable than they are as of this writing, stockpiling of antibiotics by the government in fallout shelters would seem an unwarranted expense. However, doctors and pharmacists should be taught that when the siren blows, they should take with them to the shelter such antibiotics and pain killers as they can collect as they go by without loss of time in reaching the shelters.)

* * *

Summary

It is clear that the overwhelmingly important problem associated with any trauma related to radiation exposure is the increased susceptibility to infection.

Alteration of body fluid and electrolyte balance may play a significant role, but it would appear that good early management will not fail to account for and adjust to altered requirements. Also, as a further aspect of the increased susceptibility to infection, it must always remain in the forefront of the responsible individual's thinking that active immunization in the post-radiation exposure period will likely be unsuccessful and possibly hazardous.

BURN THERAPY:*

V. Disaster Management—to Treat or Not to Treat?

Who Should Receive Intravenous Fluids?

ANNE W. PHILLIPS, M.D.

Department of Surgery, Harvard Medical School of the Surgical Services, Massachusetts General Hospital, Boston, Massachusetts

Section: **K**

Subject Heading: **Burn therapy.**

Summary and Conclusions

1. Flame burns carry a graver prognosis than burns due to hot liquids.
2. Patients with burns involving less than 25% of body surface usually survive whether treated with parenteral fluids or not (unless other injuries or illnesses are associated with the thermal injury).
3. Burns in patients over 55 years of age generally have a poor prognosis.
4. Burns of more than 55% of body surface generally have a poor prognosis.
5. Burns of more than 50% of the body in patients over 50 years old are highly lethal.
6. With each advancing year over 50 the size of burn which will cause death becomes smaller.
7. In older teenagers and young adults survival after burns of half the body surface is not uncommon.
8. Children under 5 may develop signs of shock with minor burns (15–25% of body surface).
9. Deep flame burns around the nose and mouth, if sustained indoors, decrease the chances of survival.
10. A child with only a 50% chance of survival may require no more fluid than an adult with an 80% chance of survival.
11. Nine basic rules are presented which should aid in determining which patients should receive intravenous fluid therapy in a mass disaster to assure the maximum number of survivors when the supply of available fluids, sterile I.V. sets, or the number of trained personnel is insufficient to cope with all of the injured.

* Reprinted from Annals of Surgery, Vol. 168, No. 6, December 1968.

It should be emphasized that these rules are only to be applied in a disaster so overwhelming as to make optimal care for everyone impossible. At the earliest possible moment normal medical practices should be reinstituted.

12. The composition of the fluids to be administered is considered in a subsequent paper.

REVIEW OF PRESENTATIONS AND RECOMMENDATIONS

Summary

OLIVER COPE, M.D.

Professor of Surgery, Harvard Medical School
Visiting Surgeon, Massachusetts General Hospital, Boston, Massachusetts

Dr. Glass' speech was terribly pertinent and important. It gave us a new perspective. Everyone who may be in authority following a disaster should read it.

I can't possibly summarize all of the speeches in detail, even the medical ones. Instead I am going to talk about four things.

The first is that splendid advances are being made in medical burn research. The quality of the work presented here has been superior. All of us people won't agree about every detail. Each of us puts a little different emphasis on this treatment or that, but, as knowledge develops, we become more secure, and ultimately unanimity of opinion will be reached. Until we know enough, we can't be expected to agree.

The second thing I want to emphasize is that those of us in the medical profession are fortunate, because we are on the constructive side, as society wants us to be. It's very easy to be a doctor. We are wanted. We in medicine are fortunate, too, that we are not bound by any restrictions on our research or our points of view. Society leaves us completely free. For example, if we are investigating the cause of cancer, we can study viruses, or DNA, or RNA or something completely different. We can't know what the important things in cancer are. We are perfectly prepared in medicine to find that the thing that makes cell multiplication run wild may be something as new and different as bacteria were when Pasteur first described them. So that we, in medicine, are in a very, very fortunate position. Contrast this with the political position of the world in which our political leaders are not free to look at things in the open sense that medicine is. The political considerations are bound by tradition, which hampers progress. Medicine has as its objective the improvement of the well-being of all humanity, and we, who have been trained in it or are associated with it, have a bigger obligation than simply to heal the sick. We must try to get our attitude toward society and toward research into world affairs. That is my feeling about this Workshop. We have a purpose. Our Hippocratic Oath in a way gives us a purpose bigger than considerations of burns or disasters, an idealistic, philosophical purpose.

Third, I want to say a few words about morale and triage of patients. In the first year of President Kennedy's administration I was in Washington quite a bit working on shelters for the President's Science Advisory Committee. At that time people were wanting to do psychological studies, experiments, on shelter-living.

At Princeton they cooped up twenty gobs for two weeks to see how they reacted. The psychiatrist pointed out that the experiment was unrealistic. The only way a valid experiment could be made would be to swoop down on a supermarket at eleven o'clock in the morning and take everyone who was there, and put them underground, including the mother who had left three children (seven, five, and three) back home under the care of a twelve-year old baby sitter. How would she react if she were told that there was a disaster, and she was not allowed to return to care for her children?

It is one thing to carry out triage in the military, a disciplined population. It is a very different one that we face, and Dr. Irwin* is quite right, that there is nobody who really knows in most of our communities how to face something of this sort. Suppose a mother with a 5 per cent burn is told that she must leave her five-year old child and go to another center for treatment. Maybe she has a seven- and a nine-year old child, or maybe four or five children. Think of the family situations and the family obligations, and the guilt that would result if the parents deserted their youngsters, even under orders!

Now, in civilian burns we know very well that the morale factor is terribly important in recovery. That is an old clinical bit of knowledge. A depressed patient does poorly. There has to be a will to live. Let me tell you about three patients: one set herself on fire because she knew she had leukemia; the second set herself on fire on the anniversary of her second marriage because she realized that she had divorced the man that she loved and her second marriage was a big mistake; the third was a woman with tuberculosis who was to leave the sanitarium and that night she set herself on fire. In each case the burns could easily have been assumed to be the result of accidents, if no further attempt had been made to understand the patients, establish a rapport with them and help them psychologically. These three women in a sense committed suicide.

Now you may find this hard to believe, but of all the burned children we have seen in Boston, 50 per cent have had an emotional reason for damaging themselves. Consciously, or unconsciously, they have taken the only way they could to get the attention they desperately needed and have burned themselves. They have found a way of getting back at their parents for their neglect, by doing the very things they have been told not to do. It is a kind of accident proneness. In civilian accidents it is not enough to treat the burns. We must inquire into, and alleviate, the cause of the burns.

These children who have burned themselves need very special attention. If they don't get it, they don't eat, they waste away, and mortality is high. If however, they can be reached (and they can now with our better understanding), the mortality rate drops.

We must be careful (I am putting out a word of warning here) about visualizing a triage situation on the basis of either civilian statistics or military statistics. Depending on the victims' will to live the outcome may be far different from what statistics lead us to expect. Victims of a disaster, which is not likely to strike them again, may fare much better than the usual civilian accident victims. We've seen this in wartime. For the civilian, an accident is usually the start of the victim's stress and trouble. For a soldier, who has been in danger and under prolonged stress, the wounds, which incapacitate him from further duty, may represent the end of the period of stress, so that morale soars and recovery is swift.

* In a discussion period afer a paper.

In German concentration camps during World War II, those who had no one to live for succumbed before their fellow inmates who had families outside. Dr. Rusk has found the same thing in his Rehabilitation Center in New York. He tried to find a correlation between recovery from strokes and a whole series of other factors, such as age, severity of the initial stroke, fats in the diet or in the blood stream and so on. But there was only one thing which showed a high correlation with recovery, and that was love. The patients, who had someone who cared about them, did better than those in whom no one was very interested.

Accustomed as we are to modern hospital care, we tend to look with amusement upon hospitals in more primitive areas where the families live with the patients, sleep under their beds, and cook their food. Disaster in those countries is the normal state of affairs, and their response to the problem of inadequate personnel for patient care is a sensible one. If properly instructed, the family can be a tremendous help under disaster conditions, rubbing backs, turning the injured patients to prevent bed sores (or in a bedless fallout shelter the more promptly appearing floor sores), urging the patients to take deep breaths to prevent collapse of their air cells, and to exercise their joints to prevent undesirable clotting in the blood vessels, and positioning limbs in the position of function to minimize later crippling. Probably no one can persuade a burned child to down a few survival crackers better than his parents, when he wants nothing to eat, yet desperately needs calories.

And if the parents are absent or incompetent, others in the vicinity with strong maternal or paternal instincts can be pressed into service. Helpers constantly shifted from place to place or person to person will not put up nearly such a fight to save those in their care as they will if assigned to a few patients for whom they can develop a strong attachment.

Finally, the recommendations that Dr. DeVito and Dr. Hinshaw raised about making clothing fire resistant are so obvious and so concrete and so important that they need no further comment.

All of the other things that need greater intellectual competence will be taken up by my colleagues.

Summary

CHARLES D. FLAGLE, D.Eng.

Special Assistant to the Surgeon General, U. S. Public Health Service, Bethesda, Maryland

One theme runs through all of the papers presented during this Workshop, the problem of the organization of medical care where there is shortage of physicians and nurses.

In one situation after another, classification schemes have been developed according to symptoms or mortality statistics on the basis of which some action can be taken. Schemes have been presented dividing disaster casualties into three categories: the hopeless cases, the cases that will survive with self-care or mutual aid, and those for whom definitive care will increase the likelihood of survival. Because of the urgent need for rapid classification decisions, an effort has been made to find the fewest criteria necessary for patient classification.

These ideas are encountered in everyday life. Decisions are constantly being made as to whether a given patient should be handled under a home-care program, at a nursing home, or in a hospital. Similarly in large clinics, patients are being passed through screening studies. Tests are made by technicians, questions are asked which mimic the processes normally carried out by a physician. In such clinics, simple objective queries and tests are administered by nonprofessional people and interpreted by them as a basis for initial decisions that classify the individual patient. What we have been talking about in this Workshop is a drastic version of the same type of classification problem. Physicians may not be present at the disaster, but they are here at this Workshop, and what should come from this group is the mechanics by which, in a disaster, unskilled people, the "emergent leaders" if there are any, can aid the injured when no physician is free to assist.

Classification is meaningless unless it defines the kind of care to be given. In civilian life an attempt is made to save patients at all cost. Many hours and resources are expended with little thought for anything save the possibility of saving the patient's life.

In a disaster the cost of expending resources, what the economists call the "opportunity cost," must be considered in a different way. The cost of expending resources on patients in once-care category is not just the value of the man hours or the dollar value of the supplies. It is the value of the greater human salvage that might have been obtained from these resources if they had been used in more hopeful cases. In civilian life, failing to treat a patient when he should have been treated is considered a much higher cost than the cost of treating him when he does not need it. In a disaster, unsuccessful attempts to save one patient with moderately severe burns may deprive two less severely burned adults or several children of their chance of life. In no situation are the costs of error in classification so high as in disaster management. Decisions made under uncertainty are a grim challenge. Most of us are trained to think of morality in terms of individuals rather than masses of people. In mass disaster, we must assume new values and attempt to minimize the cost to society as a whole.

The questions that we have to ask are, first, "Do the processes which have emerged from this discussion have a form or a solution that is useful, or is the problem of statistical morality too much to handle in any kind of mechanical mathematical way?" Second, "Is there so much unpredictability in a disaster that no meaningful estimates of costs or probabilities can be found?"

In conclusion, I would like to recommend further research on disaster management to the end that better patient classification and better patient care can be achieved in a disaster.

Perhaps a check list should be developed to aid in disaster planning, a set of questions that can be answered in an objective "yes" or "no" way. Devices such as the cumulative radiation monitor used in atomic maneuvers could be helpful.

Whatever is developed as an aid to the decision process, the cost must be considered.

Summary

ERIC WOLMAN, Ph.D.

Member, Committee on Fire Research
Head, Traffic Systems Analysis Department, Bell Telephone Laboratories, Inc., Holmdel, New Jersey

It is little wonder we have some difficulty in organizing for the treatment of mass burns. We even have difficulties in planning a symposium. I hope it won't come as too much of a shock to Dr. Walter for me to say that it was a surprise to discover that we were not supposed to be concerned with nuclear disaster in view of some of the papers presented in Col. Kerr's part of the program. But I am happy to say that I think I have some recommendations which will be relevant to both. That ought to make everybody happy.

Herman Wouk in the "Caine Mutiny" described the Navy as "a system designed by geniuses to be operated by idiots." I think that describes our purpose here very well. We are beginning here to design a system which will have to be operated, not by idiots, but by laymen under very difficult conditions, and of course, the geniuses are a combination of doctors and civil defense experts.

I am going to try to tie together what has been said in a little different way. My views are not the responsibility of the Fire Committee or Bell Labs, and certainly not of my colleagues in operations research.

First, we have discussed three quite different systems. There is the civil disaster, pure and simple, of which Texas City is a nice example. There is the isolated military disaster, the vast atomic explosion in one city with the remainder of the economy intact, and there is general nuclear war. The things that differ among these are those which Dr. Rittenbury called the determinants of triage, all of the circumstances surrounding the process of triage, and they make such a difference that almost all of the facts that we have learned in this most informative Workshop can be segregated as applicable either to the military or to the civil and isolated military situations separately. That is, the facts almost fail to overlap in their relevance, but not quite.

Certainly these three situations differ a great deal. The example that comes to mind is the fact that in the Texas City disaster, Dr. Blocker mentioned that he got blood from the Dallas blood bank 250 miles away. In a war you cannot always count on getting blood from 250 miles away.

For the civil situation, and even for the isolated military disaster, the one-bomb case, we have accumulated vast quantities of useful advice during this Workshop. The relevance of most of these pieces of information for treatment when somebody is around with the facilities and the skills, even if they are distant and don't arrive on the scene right away, is perfectly clear and I would just like to inject one note of skepticism about that.

I heard a story at dinner last night by somebody who had been involved in a disaster rehearsal at a community hospital. One of the responsible people assigned his three teen-age daughters to running around the hospital upsetting the plan, and the plan fell apart. The girls wrecked the joint. All they did was move prepared supplies from where people thought they were, get in the way of people who were trying to accomplish something, and so on. There was no security in the hospital. That was not part of the plan. This kind of rehearsal is a good thing.

The hard problem is, of course, the problem of general nuclear war. Where do we stand? It is a very tough problem. A number of our speakers have said, "Well, I am not going to talk about that, I am not going to extrapolate statistics into that situation because I have had no experience with it." I don't want to be critical, they are right and it is an impossible extrapolation. I should mention that one of the many definitions of systems engineering which circulates is that systems engineering is the art of making decisions based on inadequate data. I think to the extent that the information that we have gained in this Workshop is to become part of a viable disaster plan for the worst case, or the case of general war—somebody in the end is going to have to make those predictions that nobody is willing to make. There won't be a plan until that is done.

In order to get some of the boundary conditions, I got Jim Kerr to tell me a little about some of the things that he has gained from all of the other meetings on Civil Defense he has attended. You heard him say that he figures the war, if there is one, will last a few days. That may not be a very accurate statement, but it is a mighty useful one from the planning point of view.

On more specific aspects of a nuclear situation, there are several schools of thought. There is an optimistic school, which says there is going to be some warning. It says that a basic food-producing economy and some reasonable level of transportation capability will exist within weeks or at most a month or two after a general attack, so that the people who survive those weeks will have something to survive into.

I won't quarrel with that. I am not educated in that field. I want to make just a comment or two so that we will not let a civilian disaster be taken as business as usual.

For one thing, although as a member of the Fire Committee I am a little more conscious of civil defense problems than the average person, I will tell you this: if there are shelters in my community, I don't know where they are, and if there is a disaster plan in my community, I don't know what it is or who is responsible for it. That is how much civil defense planning has impinged upon my consciousness.

There are a few sticky problems that interfere with the image of medical care that have not been mentioned here. One is disposal of the dead. I would like to read a paragraph from a book which says the following:

"Data from official military sources on an earlier attempt to dispose of the bodies of wartime casualties may illuminate the magnitude of the post-nuclear task. When the United States Army entered Manila in 1944, it faced the problem of burying 39,000 bodies killed during the preceding week. It was soon found that American troops were unable to withstand the work and with few exceptions nausea, vomiting, and loss of appetite occurred. Local laborers were recruited at double pay to place the dead in large pits. Nevertheless, the burial of these 39,000 dead unhampered by such complications as radioactivity required eight weeks."

The second problem is disease. It has been mentioned several times in the context of communicable disease within shelters. One fact that has not been mentioned is that if radiation is a problem, which probably it will not be directly for the very large weapon situation, the birds and rodents die but the insects and bacteria don't, and that is something worth keeping in mind. The surviving organisms may present a difficult, if not ominous, control problem.

I would like to devote one minute to a couple of other quotes, which bear on Dr. Glass' contribution. One of these is by a physician who was in Nagasaki at the time of the drop.

"I was an officer at the College First Aid and Rescue Committee, and I was so conscious of my position, so concerned about doing what I felt was expected of me as an officer of the rescue committee that it was over two full days before I got to my home where my wife lay dead. I discharged my responsibility. What will be my reward in the eyes of my children when they are grown?"

Another remark in that general direction, the same physician observed elsewhere:

"Those who survived the bomb were, if not merely lucky, in greater or less degree, selfish, self-centered, guided by instinct and not civilization."

There were other comments from another physician at Hiroshima:

"Parents half-crazy with grief searched for their children, husbands looked for their wives, and children for their parents. One poor woman, insane with anxiety, walked aimlessly here and there through the hospital calling her child's name. What a weak fragile thing man is before the forces of destruction. After the flash the entire population had been reduced to a common level of physical and mental weakness. Those who were able walked silently toward the suburbs and distant hills, their spirits broken, their initiative gone. When asked whence they had come, they pointed to the city and said 'That way,' and when asked where they were going pointed away from the city and said 'This way'. They were so broken and confused that they moved and behaved like automatons. Their reactions had astonished outsiders who reported with amazement the spectacle of long files of people holding stolidly to a narrow rough path where close by was a smooth, easy road going in the same direction. The outsiders could not grasp the fact that they were witnessing the exodus of a people who walked in the realm of dreams."

Documented pre-attack behavior affords an amusing sidelight on human nature. The following account reveals the degree of variation of response during a fifteen minute interval of warning before the destruction of a small town by a tornado. I will read only the first sentence.

"Behavior during the ten to fifteen minutes under the threat varied in interesting ways. From the sample of our interviews one would judge most of the men went home for their wives, and most of the women tended to go home to their mothers."

This emphasizes Dr. Blocker's remark about leadership. It is very important.

Dr. Phillips set a high standard for us by beginning her paper, if I remember correctly, "What would you want to know if you knew that one year from today you would have the care of 500 burn patients?" So I have asked myself what have I learned that I would like to keep in my mind in case I were, in fact, in a shelter and I had 5, or 50, or 500 burn patients to look after. I am told that I have to do first aid. If it is really first aid, I do it for 24 hours and then a medical team arrives from the next town. Or I do it for two weeks in my shelter and then a medical team arrives from Army headquarters. Perhaps three months from now I am still doing first aid, but I may not know at the time which it is going to be, and probably my actions will be fairly similar up to the time when I am rescued by medical people. Let us look at it in that light.

First there are some universal things that have been mentioned by many people here that apply in every conceivable situation. The most obvious of all is the choice of fabrics. It is pretty clear that everybody here is interested in seeing less untreated cotton worn by people under military attack, and also by children at home.

Another example is the general concept of thermal evasion which is relevant in every situation. In war you can duck behind a building or pull your coat over your head if you are being bombed, but in peacetime you should also pull your coat or a handkerchief over your face in a fire. It is a good thing to know that thermal self-protection applies in every situation. Everyone here is now conscious of the usefulness of immediate self-protection in any kind of a disaster.

Of possibly less universal application, but still relevant, are things which we might call specific instructions. I will give two examples. One is "No live vaccines." If you have irradiated patients on your hands, don't give them live vaccines. I am not a doctor, but I can remember that, and the reasons for it are obvious. Another such specific instruction, but about which there does not appear to be complete unanimity, is to ignore fallout contamination. That is a good instruction, it is easy to remember and to follow.

Now, most of the facts are more specific than that. They are useful to the layman, who could use them in the situations requiring patient sorting and treatment where there were a large number of burn patients. Examples of this are signs given in Dr. Phillips' paper: the signs of restlessness and squeaks in the chest and coughing up carbon particles and blood, and the sore throat, burns near the nose and mouth. All are simple things which I am sure I would find useful.

There are similar simple ideas involving treatment regardless of the supplies available: physical therapy, helping the patient cough, putting the patient in different positions, these are easy things to remember and they don't depend on the resources. There are many others, the notion of getting the patient to lie down, the use of blankets. I don't want to go on. This information is of undeniable applicability even for the layman with absolutely no supplies at his command.

Lastly, what should be done with all this information? There are several things. First is that a lot of the information culled from the papers offered should be published clearly in booklets for use in shelters or distributed to civil defense centers, and at the time of emergencies, or distributed when a warning of a disaster has occurred, as instructions for the general citizen. There should also be journal articles containing this sort of information for doctors. I have read a number of articles in medical journals about treating burns. Most of it is for the up-to-date practicing doctor. I don't know how the editors would feel about articles telling doctors what they should do if they have absolutely no equipment, but I think that would be useful.

The writing that should come out of this Workshop should be in two forms: Proceedings and an elementary do-it-yourself manual. An example is the so-called *Bell System Practice,* which is a document we use in the telephone business to describe, for use by idiots, how to work every conceivable piece of equipment that we have, all $40 billion worth of it, and another example is the *Army Technical Manual,* which is a beautiful one. I would like to close on that note. The technical manuals on survival, as several other people have said, make this point, that the people who survive when they are in a tough spot are the ones who want to survive and are sure they can survive. Thank you.

EDITORS' COMMENTS AND SUMMARY*

DR. CARL WALTER AND DR. ANNE PHILLIPS

Introduction

To outline the proper management for every possible disaster under all possible conditions would result in such a lengthy and complex set of directions as to be almost unreadable. This summary is, therefore, limited in scope, but the general principles set forth should aid in planning for and coping with any mass disaster.

Dr. Glass, in his outstanding paper on mass psychology, explained why it is difficult to persuade people to plan for disaster, especially nuclear disasters. The usual response when fear is aroused is to fight or run away, the so-called "Flight or Fight Reaction." If one does not know how to fight or where to flee, there is one more avenue of escape: running away mentally by denying the existence of the danger. It is because of this type of fleeing that people convince themselves that nuclear warfare is so ghastly it will never really happen and they need not plan for it. For this reason, although planning for disasters including nuclear explosions may be urgently needed, it is better to emphasize the need for plans for peacetime fires and explosions rather than mentioning the hazards of nuclear war.

Basic Principles of Disaster Planning

Education of the Public on Self-Preservation

Self-preservation, important at all times, becomes doubly so in a disaster when help from without may be unavailable. It would seem entirely fitting and proper for the Office of Civil Defense to distribute further information to the public on fire prevention and on what to do in a fire, earthquake, explosion, or other disaster. With respect to self-preservation from burn blast or radiation injuries, the importance of the following should be stressed:

1. Evacuation of burning buildings before carbon monoxide distorts judgement: Carbon monoxide poisoning may lead its victims to waste vital moments saving objects of no consequence, or to make ineffective and irrational attempts at escape.

2. Pre-disaster designation of assembly points or points of communication: Every member of a family or household should be trained to go to a specified meeting place outside the home in the event of fire so that no one will lose his life going back into the fire to rescue others already safe. The selected point should, if possible, provide some shelter against the elements. Every member of a family or household should know how a friend or relative more than 100 miles away can be reached, so that if the family is separated in a disaster, they may have some point of contact outside the disaster area.

3. Protection of the airway to prevent smoke injury: Covering the nose and mouth with any cloth available and breathing quietly and shallowly when in a fire may diminish injury to the lungs.

4. Smothering flames when clothing is ignited and prompt removal of smouldering clothes: Burning clothing may be extinguished by cutting off the air supply. A rug, blanket or coat, thrown over the burning clothes in such a way as to sweep

* The opinions expressed herein are those of the co-editors and do not necessarily represent the views of the Office of Civil Defense or of the National Academy of Sciences.

the flames away from the face may be lifesaving. The flames may also be extinguished by rolling on the floor, which every child should be taught. Smouldering clothes should be removed at once.

5. Proper clothing for times of high fire hazard: Nylon and wool should be worn instead of cotton at times of high fire hazard, since they burn less readily. Garments should have as few free edges as possible. If nuclear disaster seems imminent, women and children as well as men should wear trousers and long sleeves, white preferred.

6. Evasion of injury in a nuclear explosion area: Evacuate wooden buildings if large-scale explosion may be imminent. Seek shelter in reinforced concrete buildings or underground, if possible. If caught outside, drop to the ground, cover your head and hands with your coat and roll to prevent deep burns on one side, or, if good shielding material is close enough so that you can reach it in one or two seconds, sprint to it and drop behind it. After the flash there may be a second or two to find more solid protection against the blast wave. Avoid positions in front of solid surfaces which may reflect the blast waves, doubling, or trebling their damaging force.

7. Evasion of radiation injury from fallout: Every citizen should know where approved fallout shelters are located near his home, school, or place of business. He should be informed that he should brush off any obvious fallout on his person, but that the elaborate showering formerly thought necessary is not needed. Water in the shelter is better saved for drinking. (To prevent people from leaving the shelters early because of thirst, it is recommended that those who can, without loss of time, be urged to take with them a closed container of previously boiled water which they can leave just outside the shelter for future use when water within the shelter is used and the radiation hazard has dropped. These containers should not be taken into the shelter initially, because of space limitations.)

8. First aid and home nursing education: Citizens should be urged to take a Red Cross Aid or Home Nursing Course so that they can better help themselves or their families if they are hurt in a disaster.

Prevent Further Injury

In any disaster the man who acts to prevent further injuries is worth ten who attempt to repair the damage once it is done. If it makes sense following an automobile accident to send someone down the road to slow up approaching cars, it makes even more sense to get the disaster victim away from impending fires, collapsing walls, and other dangers.

For the burned patient, bacteria can be as dangerous as the hurtling truck is to the victim of a street accident. From the moment the victim is first seen, lifesaving measures can be begun by protecting his burn wounds from germs in the exhaled air, germs on the ground (particularly lockjaw germs), and germs on the rescue workers' hands. If the victim is to be transported, whenever possible cover the wounds with the cleanest material available.

For the disaster victim, even more than for the ordinary burn casualty, gentleness should be a cardinal rule for rescue and treatment personnel. Pain contributes

Note: The editors are in agreement with Dr. Ingram that pain aggravates shock and that exclusion of all narcotics from fallout shelter medical supplies is a serious error.

to shock, and in the disaster where there are no supplies to treat either pain or shock, gentleness assumes greater than normal importance.

Achieve the Maximum Number of Survivors by Proper Use of Resources

In this country adequate food, shelter, and medical care are considered the birthright of every man, woman, and child. The phase "survival of the fittest" has been relegated to much the same position as "dog eat dog." Yet, following a mass disaster, if all the victims cannot be cared for, it would be foolhardy to expend precious resources attempting to save those doomed to die (even with the best of hospital care), while caring inadequately for those to whom treatment would spell the difference between death and survival. To expend those resources on others who, through self-help or mutual aid, could survive without them would be an equal folly. The men and women who are to take over management of a disaster situation must be trained to think in terms of the maximum number of survivors (especially useful survivors) to be obtained with the personnel, facilities, and supplies at hand.

In the event of nuclear warfare, survival of the nation demands that "survival of the fittest" be the guiding principle of rescue and treatment personnel.* Under those conditions a nation which withheld medical care from the capable to treat the unfit would be guilty of sapping its own strength, if not actually plotting its own destruction.

When resources are limited, decisions will have to be made which will deprive human beings of their chance of life, however tenuous that chance may be. To achieve the greatest possible number of survivors, it is essential that physicians and nurses (and others, who may have to make these vital decisions) should be given in advance as much information as possible concerning the probability of death or survival under OPTIMAL conditions for victims of varying ages with burns of varying extent. From the conditions prevailing at the time of the disaster they will have to determine how many victims must be treated palliatively, who might be saved if full hospital facilities were available. Many factors will influence their decisions, among them the number injured, the type of associated injuries, the presence or absence of conditions injurious to survival (such as cold or nuclear radiation), the availability of rescue teams, transportation facilities, shelter, food, water, medical supplies, personnel, and the emotional maturity of both the injured and the uninjured, to name only a few.

Information on the probability of survival for various age groups and burn extents is given in Dr. Rittenbury's paper.

In a disaster Dr. Phillips' Adult Age Plus Extent Rule may be of service. That rule states that if the age of an adult burn victim is added to the total extent of burn and the sum is found to exceed 90, the patient will have less than a 50 per cent chance of survival even under hospital conditions. In a disaster with limited resources it might be necessary to confine therapeutic efforts to patients whose age plus burn extent was less than ninety. If the shortage of supplies and personnel

* Since both editors of this publication are over fifty, they are aware that if they were to sustain burns of 35 per cent of body surface in a nuclear war, they, themselves, might be included in the group unfit for treatment. Their personal interests would have to be sacrificed in the interest of those with lesser injuries and/or a longer period of potential productivity.

were more severe, the limit could be dropped to 70 or less. If facilities were better, the limit might be increased to 100 or above.

Designating the Badly Burned for Palliative Treatment May Be a Kindness

During the period from 1939 to 1948, patients who died of burns lived only 3½ days before death. With the improved therapy of today, those who die of burns live 14½ days. For those who die, this must be a rather sterile triumph.

We have grown so accustomed to making heroic efforts to save even the most hopelessly burned, that we tend to forget that we are prolonging the suffering of those who die. Of 76 patients treated at the Massachusetts General Hospital, who would have been excluded from treatment if the Age-Extent Limit of Ninety had been invoked, 64 died despite the best peacetime hospital efforts. In those 64, sedatives were a blessing, but all other therapy only prolonged the patients' ordeals.

Prevent Shock by Replacing the Victim's Fluid Losses

Death claims the untreated burn patient in three major ways—through deprivation of oxygen (in minutes or days), through loss of circulating fluids, leading to shock (usually in 24 to 36 hours), and through infection (in days or weeks).

In a mass disaster without supplies there is little that can be done about respiratory difficulties other than to clear the nose and mouth of obstructing materials. Without antibiotics, management of infection must be largely preventative. Prevention of shock, however, can be attempted as long as any fluids are available. For patients with burns up to one-third of body, surface treatment with fluids (salt solutions and water) by mouth alone has been shown to have no deleterious effect on the survival rate.* For burns above one-third of the body surface, oral fluids may still save lives although not as many as would be achieved with more complex fluids by vein. If doctors, sterile equipment, and intravenous fluids (plasma, blood, dextran, albumin, P.V.P., etc.) are available they should be used for patients with burns just above 25 per cent of body surface for adults,† or 15 per cent for small children. Priority for fluids (whether for use by mouth, by vein, or by rectum) should be given to those otherwise healthy and potentially useful patients who develop signs of shock with the smallest extent of burn. The upper limit of burns to be treated will be determined by the amount of fluid available. It should not be forgotten that elevating the feet increases cardiac return and aids in combatting shock.

Second to Life Itself Comes Preservation of Function

Once life saving measures have been put into effect, the next thought should be preserving the capacity of the victims to function. The hands and feet are particularly important. If the wrists are allowed to bend toward the inside of the elbow and become fixed in that position, the victim's grip will be weak and his hands nearly useless. If his fingers are straight, he will have no grip at all and will have to have someone help him, even to eat. He will be a burden rather than a help to his neighbors. Hands should be splinted with the wrists bent away from

* Douglas Jackson. *Proceedings. International Conference on Burn Injuries.* Edinburgh. 1966.

† Note: This lower limit may have to be dropped if it is found that existing conditions increase the chances of shock in the smaller burns.

the palm (cocked up). Fingers should be allowed to curve gently around a pad of material. If the feet are allowed to drop so that they are no longer at a right angle with the legs, the victim, even after healing if complete, will still need help, as he struggles to walk on tip toes.

Prevent Disasters

Though the prevention of disaster is considered last here, it should be the first thought of everyone concerned with disaster planning. Disaster, according to Webster's Dictionary, "implies an unforeseen mischance bringing with it destruction of life or property or utter defeat." Understanding is, therefore, the best hope of the disaster planner, and education is our finest weapon of defense. The first duty of those in disaster management should be to foresee the possible mischances and plan to prevent them or minimize the danger they may do.

The prevention of future great city fires, like the Chicago Fire of 1871, the Jacksonville fire of 1900, and the Baltimore Fire of 1904, will depend, in part, on the adequacy of our planning and our education of the public. Knowledge must be widespread that the danger of fire depends less on the construction of dwellings and buildings than on the occupancy and on the combustible load within them. The public should be urged to throw all unnecessary combustibles away promptly. Information on other fire prevention measures in homes and factories should be widely distributed before fires occur.

Boston, in 1872, had outgrown its water mains. Designed to cope with fires in buildings three stories tall, they were useless as fire flashed from building to building at the fifth and sixth story level. The Office of Civil Defense might well devote some attention to the size of water mains in communities at highest risk from fire, making recommendations where water supply and delivery will be inadequate in a major fire.

THE NATIONAL ACADEMY OF SCIENCES is a private, honorary organization of more than 700 scientists and engineers elected on the basis of outstanding contributions to knowledge. Established by a Congressional Act of Incorporation signed by Abraham Lincoln on March 3, 1863, and supported by private and public funds, the Academy works to further science and its use for the general welfare by bringing together the most qualified individuals to deal with scientific and technological problems of broad significance.

Under the terms of its Congressional charter, the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and autonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

THE NATIONAL RESEARCH COUNCIL was organized as an agency of the National Academy of Sciences in 1916, at the request of President Wilson, to enable the broad community of U.S. scientists and engineers to associate their efforts with the limited membership of the Academy in service to science and the nation. Its members, who receive their appointments from the President of the National Academy of Sciences, are drawn from academic, industrial and government organizations throughout the country. The National Research Council serves both Academies in the discharge of their responsibilities.

Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

THE COMMITTEE ON FIRE RESEARCH functions within the Division of Engineering to stimulate and advise on research directed toward the development of new knowledge and new techniques that may aid in preventing or controlling wartime and peacetime fires. The Committee was established in December of 1955 at the request of the Federal Civil Defense Administration. It is supported by the Office of Civil Defense of the Department of the Army, the U.S. Department of Agriculture through the Forest Service, the National Science Foundation, and the National Bureau of Standards.

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Fire Research Abstracts and Reviews

National Academy of Sciences
National Research Council

FIRE RESEARCH ABSTRACTS AND REVIEWS
Robert M. Fristrom, Editor

The Committee on Fire Research

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

Editor: Robert M. Fristrom, Applied Physics Laboratory
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FOREWORD

This issue begins with an interesting article, "An Experimental Application of a Computer-Assisted Indexing Technique to *Fire Research Abstracts and Reviews*," by Boris Kuvshinoff, Research Librarian at the Applied Physics Laboratory, The Johns Hopkins University. He describes an application of computer methods to the task of preparing our index. This technique promises to reduce the manual effort in the indexing process and allow more extensive and useful indexing. In addition to facilitating the indexing process, it would be a powerful tool for literature searching. Even in our restricted field, this is becoming a formidable problem. It will require some time to evaluate the usefulness of the system, but the initial results are promising. If the experiment is a success, we will use computer-prepared indexes. Ultimately we would hope to convert the cumulative index to computer operation. If a demand develops, an attempt will be made to make the index tapes available for literature searches by workers in the field. These later developments, however, must wait for debugging and the successful operation of the system.

The second feature in this issue is an excellent, short review, "Review of Latest Developments in Fire Protection," by D. J. Rasbash of the Fire Research Station, Borehamwood, England. Mr. Rasbash is well known to many of the readers of *Fire Research Abstracts and Reviews* and his summary is most welcome.

A new journal is entering the field of fire research, "Combustion Science and Technology," which will be edited by Professor I. Glassman of Princeton University. It should be of considerable interest.

The general outlook in fire research is similar to that in most scientific fields. Programs will be austere, but in most cases work will be continuing. There is some good news, however. We are happy to report that, thanks to the efforts of friends and supporters of fire research, the group formerly at the Naval Radiological Defense Laboratory has been preserved at the Stanford Research Institute under the leadership of Mr. Raymond Alger, who is officially attached to the Naval Ordnance Laboratory. The Navy is taking a new look at fire research. Dr. Lawson, the Director of Naval Laboratories, has set up an interlaboratory committee to survey the efforts of the Navy on fire research, and suggest improvements in the area. Dr. Homer Carhart of the Naval Research Laboratory is chairman of the committee.

The Factory Mutual Corporation has appointed Dr. Raymond Friedman Research Director of its fire research program.

R. M. Fristrom, *Editor*

REVIEWS

An Experimental Application of a Computer-Assisted Indexing Technique to Fire Research Abstracts and Reviews

BORIS W. KUVSHINOFF

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1. *Introduction*

An experiment was undertaken to test the Computer-Assisted Technique for Numerical Index Preparation (CATNIP), an indexing method that was developed collaboratively by the Library Group and the Computing Center of the Applied Physics Laboratory of the Johns Hopkins University. The experiment was conducted on a sample of 22 abstracts taken from Volume 10, No. 3, 1968, of *Fire Research Abstracts and Reviews* (FRAR) with the kind permission of its Editor, Dr. Robert M. Fristrom. The test material was prepared for input to an IBM 360/91 or an IBM 2741 typewriter terminal to take advantage of the upper and lower case printing capabilities of the machine.

The complete description of CATNIP is being written in a separate report. This paper covers only the application of CATNIP specifically to FRAR, and describes CATNIP features only to the extent necessary to understand the experiment in general terms. The object of this experiment is to ease the indexing burden, for once an abstract is indexed in CATNIP, it never need be reworked for a volume index or a cumulative multivolume index. Moreover, CATNIP provides excellent techniques for maintaining indexing consistency and allows great freedom in cross-referencing.

2. *Form and Content of FRAR*

FRAR is prepared by the Committee on Fire Research, Division of Engineering, National Research Council. It is published by the National Academy of Sciences—National Research Council, Washington, D. C.

An annual volume of FRAR, consisting of three issues, contains approximately 300 pages, around a thousand abstracts. Pagination in each volume is consecutive. Each issue includes, in addition to abstracts, one or more review articles, an editor's foreword, and meeting notes. There may also be an obituary; notes on books, bulletins, translations, and organizations; as well as a letter to the editor. All of these are referred to here as special features, to distinguish them from the abstracts, which make up the bulk of each issue. Finally, there is a table of contents and a list of contributing abstracters in each issue.

Currently, the abstracts are grouped under fifteen broad subject headings:

A. Prevention of Fires and Fire Safety Measures
B. Ignition of Fires
C. Detection of Fires
D. Propagation of Fires
E. Suppression of Fires
F. Fire Damage and Salvage
G. Combustion Engineering

H. Chemical Aspects of Fires
I. Physical Aspects of Fires
J. Meteorological Aspects of Fires
K. Physiological and Psychological Problems from Fires
L. Operations Research, Mathematical Methods, and Statistics
M. Model Studies and Scaling Laws
N. Instrumentation and Fire Equipment
O. Miscellaneous

3. *Current Indexes to FRAR*

Prior to 1969, each issue of FRAR included an author index and a subject index. Now, a cumulated index appears only in the last issue of each volume. A cumulative index was published following Volume 9, covering Volumes 1 through 9, 1958–1967. This is the second multivolume cumulation: the first was published following Volume 5.

4. *Application of CATNIP Coding to FRAR*

As a rule, information retrieval from a collection of literature is a direct function of the quality and depth of item identification and subject-content description. Multiple-access retrievability is provided to items in a collection in these two ways: through bibliographic elements and through subject descriptors, or index terms.

CATNIP provides a coding system for each purpose: one for identification of bibliographic elements of items in a literature collection and the other for organizing subject terms in structured form. Bibliographic elements are identified by two-digit codes ranging from 01 through 99. The subject index is structured by codes ranging from -1 through -9 (the hyphen should not be mistaken for a minus sign; it is merely a convenient symbol for distinguishing these digits as descriptor tags). The CATNIP system, designed to print back-of-a-book type indexes, thus provides nine babilarchic levels. [Babilarchy is index structure downward; the converse of hierarchy, which is index structure upward. In the indexing process the indexer generally selects the principal terms first, then works downward, selecting appropriate modifying subordinate (babilarchic) terms.] In practice, even four-level indexes are rarely seen, and five-level to nine-level indexes may not exist except in extremely special cases. The nine levels are simply there to use should the need arise.

a. Bibliographic Element Coding

Each of the 99 bibliographic element codes can be assigned and used arbitrarily by an indexer, who must, however, always assign the identical code to the same type of element. For example, if code 01 has been designated to indicate the primary author, all primary authors of all other items in the file must be coded 01. A list of bibliographic element codes used for the FRAR experiment is given in the Appendix.

Codes need not be used in sequence. In practice, it has been found that certain codes can be deliberately selected for logical value (e.g., 01 for primary author, 02 for secondary author, 03 for author's affiliation, and so on).

b. Subject Index Coding

The range of babilarchic levels from -1 through -9 (highest to lowest) yields a structured printed index with each level indented a desired number of spaces to the right of its governing hierarchical term, exactly as it would appear in the familiar back-of-a-book index. Samples from the FRAR test are included later in this paper. In the present experiment, only the principal (-1 level) terms and proper names are typed with initial capital letters.

c. Computer Codes and Typing (Keypunching) Conventions

Bibliographic elements and subject terms alike are delimited by slashes (or virgules, as some like to call them). The strings of slashes, codes, elements, and terms run together without spaces. Spaces between individual words which make up multiword elements or compound subject term entries are, however, allowed. For example, a title is typed (or keypunched) with spaces and punctuation exactly as it appears in its original form (of course, with the reservation that slashes cannot be used because the computer will assume them to be delimiters). However, a hyphen, a hyphen and digit, or two digits can be used in any combination freely everywhere, provided they are not immediately preceded by a slash. In the examples that follow, some lines, which represent images of tab cards, terminate with the code &2- or - (hyphen). The first code merely indicates to the computer to double space before printing the next line. This spacing serves as an aid for checking the edit printout from the computer. The hyphen indicates that the record is continuing, and the computer drops the hyphen and closes up the space to the next card or line (hereafter called image, meaning typed line or tab card, as applicable). If an image terminates with a true hyphen, two hyphens are typed. The computer saves one, drops the second, and closes up the space to the next image. If an image terminates at a space between words, nothing is required. The image simply stops at that point, and the next image is ready to be typed. The computer will automatically leave a space between the last word of the first image and the first word of the second.

d. Locator Codes

Index locators are usually page or paragraph numbers. In the case of FRAR, a special problem was encountered because we wished to print a simple page locator for an individual issue index; an issue number and page number for an annual index; and a volume number, issue number, and page number for a multivolume cumulative index. This problem was resolved by assigning code 99 to the volume number, 98 to the issue number, and 97 to the page number. Thus, we have a choice of any one or any combination of these as index locators.

In Section 2, above, it was mentioned that FRAR contains reviews and special features, and that the abstracts are arranged by subject category. These bits of information are meaningful to users of FRAR indexes. It was therefore decided that an indication of the nature of the item or the general subject area should be included in the locator. This is done so easily in CATNIP that it can hardly be termed a luxury.

Let us use the cited issue of FRAR as a source of an example to demonstrate the locator coding method. For the Editor's Foreword, on page iii, the locator is coded thus:

/9910,/983,/97Edit iii/

Fittes, D. W. (Joint Fire Research Organization, Boreham Wood, England) "Some Notes on the Properties of Foams Produced by a Gas Turbine Operated Foam Generator," *Joint Fire Research Organization Fire Research Note No. 668* (June 1967)

This report gives details of the physical properties of the protein-based foams produced by an experimental gas-turbine operated foam generator at different rates of delivery of foaming solution. The relation between critical shear stress and foam drainage is also shown. Some experiments using a detergent-based foam are reported.

Subject Headings: *Foam generator; Foam, properties of; Gas turbine foam generator.*

Author's Summary

FIG. 1. Sample FRAR abstract.

which translates into Volume 10, No. 3, Editorial, page iii, and is printed by the computer as the locator Edit iii for an individual issue, as 3,Edit iii for the annual index, and as 10,3,Edit iii in a multivolume index. A double-printing feature is available for simulating boldface for the volume number, but this seems unnecessary in this case. In any event, if this refinement is found to be desirable in the future, it can be added at any time. The locator code for the review beginning on page 217 and ending on 234 is typed:

/9910,/983,/97Rev217-234/

which prints exactly as described above, except that the span of pages for the review is indicated.

Abbreviations can be used as necessary; e.g., Conf for conference, Trans for translation, etc.

The broad subject area assigned to an abstract is indicated straightforwardly by the appropriate subject category letter given in the list in Section 2. For example, the locator for the first abstract on page 235 is coded:

/9910,/983,/97A235/

All locators in the index, therefore, contain a clue to the general nature or subject area of the item being referred to. A researcher specializing in "Detection of Fires" will soon learn that the letter "C" appearing with a page number in the index is an item of prime interest in his specialty.

5. *Typical Input Preparation for the FRAR Experiment*

For purposes of demonstration, let us take the second abstract on page 254 of the cited FRAR issue and prepare an indexing input record for the computer. The abstract is reproduced as it appears in the journal. The bibliographic elements are taken directly from this material, and the subject terms are selected from the abstract and title of the item. The codes used for the bibliographic elements are listed in the Appendix.

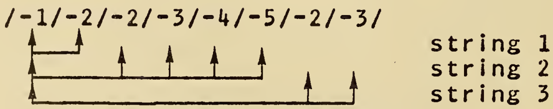

FIG. 2. Sample input for an FRAR abstract.

```
-1
  apples                      }
    -3 + locator              } string 3
  berries
    -3                        }
      -4                      } string 2
        -5 + locator          }
  cherries + locator            string 1
```

FIG. 3. String ordering of index terms.

The locator entered only once, is associated by the CATNIP with each of the coded elements and subject terms in the record is entered first, then by convention, the bibliographic elements are added, and last the subject terms.

Figure 1 is the selected FRAR abstract, and Fig. 2 is the computer input record prepared manually from the abstract.

Note in Fig. 2 how freely the levels follow one another in strings and switch up and down the babilarchic-hierarchic scale. The only rule to remember is that any term n is governed by its closest preceding term $n-1$, regardless of the number of terms on its own level (n) or lower levels ($n+1$, 2, 3,···,) which intervene. Although it may seem complicated at first glance, a few minutes of familiarization with the technique and another few to practice makes any indexer an expert. One especially appealing advantage to the method is that second thoughts need not spoil what has been done already. A new string of subject terms can be tacked on to the end of the sequence which has already been coded and typed.

A term duplicated on the same level in any sequence will be sorted out properly by the computer so that it appears only once with its associated hierarchical and babilarchical terms, and there will be no duplication of locators. Figure 3 illustrates how the computer breaks down a sequence of terms into strings. For the sake of simplicity, the terms are left out and only the level codes are used. The sequence in Fig. 3 will be sorted into three strings.

In CATNIP the -2 terms will be alphabetized, and their subordinate terms will be carried along with them and placed in proper order. Suppose that the first -2 term in Fig. 3 is cherries, the second is berries, and the third is apples. The results will then be alphabetized and ordered in the manner shown in Fig. 4. Note that the locator follows only the last term in each string.

The printout of the indexing terms given in Fig. 2 will appear as shown in Fig. 5.

6. *Syndetics and Articulants in the FRAR Test Index*

Syndetics is an erudite word sometimes used to cover "see" and "see also" references in indexes. Articulants are the syntactic qualifiers such as "of," "by,"

```
/9910/983/97E254/&2

/01Fittes, D. W./03Joint Fire Research Organization/05Boreham
Wood, England/09RPRT/10Some Notes on the Properties of Foams
Produced by a Gas Turbine Operated Foam Generator/25FRN 668/-
171967-06/&2-

/-1Foam/-2properties of/-2protein-based/-2produced by gas tur-
bine/-2generator/-3turbine type/-2detergent-based/-1Turbine/-
-2foam generator/-1Foam generator/-2turbine type/&2-
```

FIG. 4. Alphabetization of subject index terms.

```
Foam
  detergent-based E254
  generator
     turbine type E254
  produced by gas turbine E254
  properties of E254
  protein-based E254
Foam generator
  turbine type E254
Turbine
  foam generator E254
```

FIG. 5. Index ordering of sample shown in Fig. 2.

"for," "and," etc. that add considerable meaning to index entries in the sense of roles. Most simply, roles in indexing are devices which show subject to object relationships of the things named. Typical roles for combustion would be, combustion as a chemical process, the effect of chemicals on combustion, etc. For purposes of the FRAR test, the babilarchic level -9 was used for syndetic entries. In practice, however, it is most convenient to collect them at the end of the file and list them periodically to eliminate repetitions. Once a given "see" or "see also" reference has been entered in the file, it need never be entered again, although no harm is done if it is, except that computer storage space is occupied needlessly. If a given "see" or "see also" reference points to a nonexistent entry in the file, it will not appear in the index. This feature relieves the indexer from an often-forgotten chore.

Articulants in the subject index are not ignored in alphabetization in the present test, but they can be ignored in alphabetization by providing a stop list. Such a stop list is included in the technique described in the next paragraph.

7. *Gutter-Aligned Format for Editing Subject Terms* (*GAFFE*)

The most difficult task in indexing is term selection and maintenance of a consistent thesaurus. Many technical terms have multiple meanings. The word "coupling," for example, has 20 to 30 distinct technical definitions.

The GAFFE feature of CATNIP is designed to help maintain indexing consistency. GAFFE provides a KWIC-type alphabetical listing of index terms. Each term appears in alphabetical order in the center of the page, together with the preceding and following terms in its string. Thus, visual inspection of the listing reveals the different ways in which a given term has been used, and shows the level at which it was used. Terms which might otherwise be lost among the levels, are brought together for comparison and evaluation of usage. Conflicts in usage and requirements for syndetics become readily evident.

8. *KWIC Title Index*

All titles—journal articles, books, reports, etc.—are coded /10 in the FRAR test. One can therefore retrieve all titles by asking for this code and then make a KWIC index of all titles in the file. But CATNIP has other powers as well. Since code /09 identifies the type of publication, it is possible to make a KWIC index of journal article titles only, or book titles only, etc. The power to select specific subsets from an information file is an extremely useful tool for publishers and users alike. A sample of a KWIC title index is shown in Fig. 6.

KWIC INDEX TEST - FRAR TITLES

Pyrolysis Products of Ponderosa Pine at	250 and 350 C=Effect of Fire Retardant and	10,3,A237
is Products of Ponderosa Pine at 250 and	350 C=Effect of Fire Retardant and Other I	10,3,A237
ltraviolet Devices for Fire Detection in	Advanced Flight Vehicles=Solid State U	10,3,C251
Designing for Protection	Against Dust Explosions	10,3,A237
Uses=High Expansion	Air Foam - A Survey of Its Properties and	10,3,E253
dy Burning and Ignitability in Quiescent	Atmospheres=Some Thoughts and Experiments	10,3,Rev217-234
avian Fire Tests on Lining Materials for	Buildings at Copenhagen Fire Test House=Me	10,3,A245
riments on Liquid Fuel Spreading, Steady	Burning and Ignitability in Quiescent Atmo	10,3,Rev217-234
The Rate of	Burning of Wood	10,3,D253
roducts of Ponderosa Pine at 250 and 350	C=Effect of Fire Retardant and Other Inorg	10,3,A237
f Insulating Oil Fires in a Transmission	Cable Tunnel=Experiments of Detection o	10,3,C252
and Pressure Effects on the Ignition of	Cellulosic Fuels by Thermal Radiation=Oxyg	10,3,B249
The Ignition of	Clouds of Particles in Shock-Heated Oxygen	10,3,B249
ulosic Fuels by Thermal Radiation=Oxygen	Concentration and Pressure Effects on the	10,3,B249
dings of Fire Hazards and Extinguishment	Conference=Procee	10,3,D253
The	Cool Flames of Hydrocarbons	10,3,A243
sts on Lining Materials for Buildings at	Copenhagen Fire Test House=Methods of Meas	10,3,A245
osions=	Designing for Protection Against Dust Expl	10,3,A237
Solid State Ultraviolet Devices for Fire	Detection in Advanced Flight Vehicles	10,3,C251
nsmission Cable Tunnel=Experiments of	Detection of Insulating Oil Fires in a Tra	10,3,C252
ght Vehicles=Solid State Ultraviolet	Devices for Fire Detection in Advanced Fli	10,3,C251
Plastic Dusts=Effect of	Diluent Dusts on the Explosibility of Some	10,3,A247
ducing Smokeless Powders=A Study of Safe	Distances in the Planning, Erection, and O	10,3,A235
The Ignition of Wet and	Dry Wood by Radiation	10,3,B250
d Plastic Tanks=The Electrostatic Hazard	During Loading of Petroleum Products into	10,3,A248
Designing for Protection Against	Dust Explosions	10,3,A237
sts on the Explosibility of Some Plastic	Dusts=Effect of Diluent Du	10,3,A247
Dusts=Effect of Diluent	Dusts on the Explosibility of Some Plastic	10,3,A247
ty of Some Plastic Dusts=	Effect of Diluent Dusts on the Explosibili	10,3,A247

Fig. 6. A sample KWIC title index.

9. *Retrieval of Literature Subsets from a CATNIP File*

Although CATNIP is designed to print indexes of literature collections, and is especially suited for such a journal as FRAR and bibliographies in general, it can also be used as a retrieval technique for specific subsets of items in the file which have been uniquely identified by the bibliographic element coding system. For example, one can obtain an alphabetical list of all journals in the file together with the titles of the articles appearing in them. Personal authors can be listed

AUTHOR INDEX TEST

Aerospace Medical Division 10,3,D253

Alvares, N. J. 10,3,A235, 10,3,B249

Banik, E. 10,3,A235

Bray, G. 10,3,A245

Brenden, J. J. 10,3,A237

Buntlin, R. N. 10,3,E253

Burgoyne, J. H. 10,3,A237

Campbell, R. B. 10,3,C251

Chang, H. C. 10,3,C251

Eickner, H. W. 10,3,A238

Fahnstock, G. R. 10,3,A243

Fish, A. 10,3,A243

Fittes, D. W. 10,3,E254

Glassman, I. 10,3,Rev217-234

Gunners, N. E. 10,3,A245

Hansel, J. G. 10,3,Rev217-234

Hoyle, H. 10,3,A245

Lange, A. 10,3,C252

Law, Margaret 10,3,B250, 10,3,D253

McGuire, J. H. 10,3,E254

Nettleton, M. A. 10,3,B249

O'Dogherty, M. J. 10,3,C252

Palmer, K. N. 10,3,A247

Simms, D. L. 10,3,B250, 10,3,D253

Stirling, R. 10,3,B249

Sumi, K. 10,3,E254

Thomas, P. H. 10,3,D253

Tinson, R. 10,3,A248

Tonkin, P. S. 10,3,A247

Wiltshire, L. L. 10,3,A235

Young, R. A. 10,3,C252

Fig. 7. Preliminary author index generated by CATNIP from the FRAR sample of abstracts.

together with their affiliations and the titles of papers, books, and reports they have published. Subject indexes can be produced for any retrieved subset of the file. Such capabilities make it possible to gather statistics and make analyses of the literature in the file.

A certain amount of manipulation is involved in producing such specialized listings, and many of these potential features have not yet been implemented in the CATNIP system for the 360/91. However, if the need is sufficiently great,

INDEXER TEST

```
Air Foam - see Foam  10,3,E253

Building design
  dust explosion protection
   10,3,A237
  explosives factories  10,3,A235

Building materials
  fire resistance testing
   10,3,A245

Burning rate
  of cotton  10,3,A235
  of wood  10,3,D253

Cable tunnels
  detection of oil fires in
   10,3,C252

Cellulose
  ignition of
    by thermal radiation
     10,3,B249
    oxygen concentration effects
     on  10,3,B249
    pressure effects on  10,3,B249

Clothing
  protective
    against fire hazards
     10,3,D253

Cool flame
  of hydrocarbons  10,3,A243

Copenhagen Fire Test House
 10,3,A245

Cotton
  flame propagation on  10,3,A235
  ignitability of  10,3,A235

Dust explosions
  protection against  10,3,A237

Dusts
  diluent
    explosibility of  10,3,A247

Dusts (cont'd)
  plastics
    diluent dusts in  10,3,A247
    explosibility of
      effects of diluent dusts on
       10,3,A247

Electrostatic fire hazard
  during tank-loading operations
   10,3,A248
  of petroleum products  10,3,A248

Explosions
  relief systems, dust  10,3,A237

Factories
  explosives manufacturing
    building separation  10,3,A235
    safe distances  10,3,A235

Fire detection
  of insulating oil  10,3,C252
  ultraviolet device  10,3,C251

Fire detector
  silicon carbide  10,3,C251

Fire hazards
  in oxygen-rich atmospheres
   10,3,D253

Fire protection
  sprinkler systems
    design of  10,3,A245

Fire resistance
  of building materials
    testing of  10,3,A245

Fire retardant
  for wood  10,3,A238

Fire retardants
  effect on Ponderosa pine
   10,3,A237

Fire spread - see Flame
 propagation  10,3,A235

Flame propagation
```

FIG. 8. Preliminary subject index generated by CATNIP from the FRAR sample of abstracts

such capabilities can be built into the system. Only imagination limits the number of possibilities that can be made available.

10. *Sample Indexes*

CATNIP has been operational at the Applied Physics Laboratory on the IBM 7094 for approximately two years, and is being used to index internal documenta-

INDEXER TEST

FIG. 8 (*Concluded*)

tion. As mentioned, it is currently being converted to the 360/91. Author and subject indexes have been successfully produced on the sample of 22 FRAR abstracts, and the preliminary results are shown in Figs. 7 and 8. Note the two-column format, the page number (which can be located at any corner of the page, alternated from corner to corner for versos and rectos, or centered top or bottom), and the running heads which continue from page to page and from column to column. Note also that extra space is provided in the author and subject indexes at the letter breaks (e.g., between the A's and the B's). This extra space is provided to paste in large boldface letters before publication. The printing on these samples appears somewhat sparse, but this is due mainly to the smallness of the sample. The spacing between the locators and the index terms can be varied.

11. *Conclusions*

Results to date clearly indicate that CATNIP is a powerful indexing technique for bibliographies and is admirably suited for indexing journals such as FRAR.

Acknowledgment

The assistance of Gordon Trotter, Systems Analyst, in managing the computer aspects of this test is acknowledged.

APPENDIX

Master Bibliographic Code List for the FRAR Indexing Experiment

01 Primary author (last name, comma, initials with periods and spaces)
02 Secondary author (enter same as for primary author)
03 Author's immediate affiliation
04 Author's major affiliation
05 Author's affiliation address or location
06–08 Unassigned
09 Type of publication
(/09BOOK/, /09REVW/, /09RPRT/, /09JRNL/, /09RPNT/, etc.)
10 Title of item (do not use slashes within title)
11–14 Unassigned
15 Name of journal
16 Volume, number, pages of article (e.g., Vol. 10, No. 3, P. 234–5)
17 Year, month, day of publication
(e.g., /171961-08-25/; use zeros for unknowns)
18–19 Unassigned
20 Book publisher's imprint
21–24 Unassigned
25 Report number (e.g., /25FRN669/)
26 Corporate author
27 Contractor
29 Contract number
29 Contractor's address or location
30–34 Unassigned
35 Conference title (Note: Conference includes meeting, symposia, conferences, colloquia, etc.)
36 Conference location

37	Conference dates	
38	Conference sponsor (if more than one, enter each separately)	
39–44	Unassigned	
45	Abstractor (enter same as author)	
46	Translator (enter same as author)	
47	Editor (enter same as author)	
48	Unassigned	
49	Language of original (if different from English; e.g., /49GERMAN/)	
50–74	Unassigned	
75	Notation of bibliography if extensive in specific subject area; e.g., /75BIB/	
76	Subject of bibliography (e.g., /76Cool Flames/)	
77–96	Unassigned	
97	Page number	locators for index terms
98	Issue number	locators for index terms
99	Volume number	locators for index terms

Review of Latest Developments in Fire Protection

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Related Sections: **A**, *E*, *N*

Subject Heading: **Fire protection.**

Introduction

In this review an attempt is made to see in perspective the various methods of providing protection against industrial fires and explosions, not only comparing one with another, but also with the fire problem as a whole. This will help pinpoint where there are deficiencies and drawbacks in these methods and where there is room for future development.

The important aim for any interested party is that the total cost of fire per annum should be kept to a minimum. Of course, the individual Factory Manager who is concerned with running his plant at a profit and the Insurance Manager, making a profit on the business of servicing the fire risk cover, will see the problem differently from the Government, who should be concerned with keeping down the total cost of fire to the nation. However, all these parties require similar information on the cost and effectiveness of various approaches to the fire problem to allow a sound judgment to be formulated.

Intrinsic Value of Fire Protection Measures

In order to assess the value of fire protection measures it is necessary to compare the cost of the measures with the potential reduction in fire losses that they might bring about. The major part of the cost of fire is due to large fires. It has been estimated[1] that, taking a mean value for all buildings in a built-up area, the expected loss in large fires per annum per square foot of floor area is well under 0.5d. per annum. The present cost of installing detectors or sprinklers including maintenance costs when amortized over a period of twelve years, varies from 2d. per square foot per annum upwards. Even if it is assumed that the wholesale installation of these devices would wipe out completely all large fire losses, including an ample allowance for losses in small fires and consequential losses, the above figures suggest that such a universal installation would not pay for itself at present prices. For this reason it is necessary that protective installations should be concentrated in high risk areas, and indeed many, if not most industrial premises may be classified in this way. Nevertheless, there is a wide variation in fire risk in industry, for example, there is a factor of 70 in the probability of the more hazardous industries having a fire compared with the least hazardous industries.[2]

To achieve the widespread use of fire protective installations there is little doubt that they need to be considerably cheaper than they are at present. While this is of dominant importance for non-industrial premises, it is likely that certain sections of industry of low fire risk or of fire risk comparable to commercial, office, or domestic premises may stand to benefit by the development of such systems. It is relevant, therefore, to give some consideration here to possible ways of reducing the cost of protective installations.

Reducing the Cost of Protective Installations

To achieve this aim may require certain reductions in the standards of the detection and extinction of fire, but such requirements may well be less onerous in comparatively low hazard premises under consideration. Moreover, a reduction in technical performance to achieve simplicity and cheapness may well be balanced by a reduction in the necessity for maintenance. A reduction in costs may also be obtained by improved standardization and the production of increased numbers, but the contribution in this direction is limited, since the labour costs of installation would not be affected. Here, the main way of reducing costs is to reduce the amount of piping needed in the installation of sprinklers, and the amount of wiring needed for detectors.

As far as sprinklers are concerned normal sprinkler systems operate at a mean flow of about 5–10 kg m^{-2} min^{-1} (0.1 to 0.2 gal ft^{-2} min^{-1}) of floor area. The amount of water, however, required to extinguish a square foot of fire in wood is far less than one-tenth of this figure,[3] as long as the spray can be made to reach the burning surface. Therefore, any situation where the fire load is not too great and the surfaces at which burning can take place are easily exposed to water from the sprinkler, a cheaper system may be justified. As far as detectors are concerned, wiring may in many cases be reduced or eliminated by using an infrared detector or a light beam such as a laser[4] to monitor a large area or by using a single conducting wire with a number of fusible links at intervals.

Another possible way of reducing costs is for a number of factories to share high cost capital items, e.g., pumps and detector monitoring equipment. These could well form part of a common service on an industrial estate. However, it is important to state that before encouragement can be given to the widespread installation of cheaper systems than at present exist, more operational information on the fire risks will be needed to give a clear definition where such systems are likely to be beneficial. Moreover the standards for any cheaper systems must be as rigidly controlled as those for more expensive systems.

Necessity for More Advanced Protection Systems

While it is possible that for a number of applications it may be desirable to cheapen fire protection systems with a possible acceptable reduction in performance in order to bring about the optimum use of these systems, there is, on the other hand, an increasing requirement for installations which need to manifest the fullest degree of technical sophistication. The whole tendency of modern technology is to cheapen production and handling processes by the use of expensive automatic equipment, operating in one single concentration of capital goods. The traditional principle of compartmentation is resisted as it interferes with the efficiency of the process. Once fire gets out of control in a situation of this kind—and particularly when highly flammable materials are involved—the losses can run into several million pounds. One tends not to have just large fires, but small fires and enormous fires, and the margin between the two is dangerously reduced. Over the last few years, there have been large fires in petroleum and chemical processes and in high-stacked extensive storage warehouses, which bear out this point. In this type of fire too, the consequential losses may be even more painful to bear than the direct fire losses. In these instances an even larger proportion of the burden in preventing these high losses must fall upon the efficiency of the protective equipment than in traditional risks, and it is worth investing a great deal to ensure that protective equipment is rapid in action and very effective. The problem is difficult, since often in this field the experience gained over the years in protective installations is of limited value; one is not dealing with old problems writ large, but with new problems. Great care is needed in extrapolating empirical information from past experience, particularly when the basic understanding of the laws which govern the operation of the system, is only sketchily comprehended. Perhaps in this context it is relevant to look at some of the criteria by which the effectiveness of protective installations may be judged.

Critical Factors in Protective Installations

To protect a plant or a building against fire or explosion, an installation must either

(1) detect a fire at an early stage and follow the detection by some action, which either directly or indirectly brings the fire under control before it gets out of hand, e.g., informs the fire brigade, brings in an extinguishing agent automatically, instructs computer to divert flammable material in an automatic process up a flare stack, or,
(2) be an inbuilt part of the plant or building which limits the damage caused by a fire or explosion, e.g., fire-resistance between compartments, separation between buildings and storage tanks, flame arresters between items of plant, explosion relief on items of plant.

Detection of Fire

There is no difficulty about the detection of fire in its very early stages. Current smoke detectors and infrared methods are very sensitive, and even these do not represent the limits of sensitivity that are technically possible. The scientific background on fire detection is also reasonably well understood, although more information is needed on the movement and composition of smoke, particularly of the limiting conditions when the buoyancy forces resulting from a small fire are too small to counteract extraneous influences due to draught, etc. There is a definite tendency at present for the fire detection systems to give false alarms, which can be a very undesirable feature, particularly when the detector is harnessed automatically to an extinguishing system. This drawback should be capable of removal with careful design of the system and definition of ambient levels of the parameter that is being detected.

The large majority of automatic installations used indoors, and particularly almost all sprinkler systems, are operated by detecting the smoke and hot gases rising and spreading under the ceiling. For any complete flooding system, for example carbon dioxide or high-expansion foam, there is no reason why this type of detection should not be made as sensitive as possible, subject of course to obtaining no false alarm. However, with a localized system such as sprinklers, while their rapid operation near the fire is an advantage, their operation remote from the fire by the spread of hot gases under the ceiling is not, not only because of the possibility of unwanted water damage, but the disastrous effects it might have on the efficiency of the system. These factors have, over the years, resulted in a development of relatively insensitive detectors for sprinklers and the trend now is to make them even less sensitive still by uprating the sprinklers.[5] As a result, a gap is tending to build up between the time when a fire can be reliably detected and the time when sprinklers operate, so that the fire can be of a large size even before sprinklers operate. This difficulty can be overcome to some extent by having a sensitive fire detection system in addition to sprinklers. On the other hand, there is reason to develop a fire detection system which is not operated by the hot gases at the ceiling, but rather by real flame in the area covered by the extinguishing devices which the detector actuates. It is quite feasible that infrared systems can be made to fulfil this purpose. A positive detector of this kind could not only, for example, bring in the appropriate local extinguishing system at the earliest practicable moment in a fire, but could also prevent a remote part of the system being actuated superfluously, in the absence of a local fire, merely by the presence of the smoke and hot gases.

Extinguishing Agents

Turning now to actual materials used for extinguishing purposes, there are certain basic requirements by which their performance may be judged. These may be summarized as follows:

1. High extinguishing power per unit weight, cost or availability.
2. Capability of use under a wide range of fire conditions so that multiplicity in the number of agents used is avoided.
3. Capability of being delivered quickly onto the fire and its immediate vicinity.
4. No undesirable extraneous effects, such as toxicity or extra damage.

Water

There is no doubt that, per unit cost and availability and probably per unit weight as well, water reigns supreme as an extinguishing agent. Its drawback is that in order to manifest its full extinguishing power it must be distributed sufficiently evenly onto surfaces which are actually burning, so that it can be vaporized.[6] Under these conditions a little water can go a long way, indeed. However, when water is not vaporized at a burning surface, there is a triple penalization. Firstly, the latent heat of vaporization is not used to reduce the burning rate of fuel. Secondly, the vapour which might have been evolved is not available to extinguish the flames, and thirdly, the water that runs away may well cause water damage. There is a compensation, however, in that the wetting down of the material in the vicinity of the fire, allows the rate of spread to be reduced and even stopped; the fire is thus isolated and burns out. Indeed, this is the dominant action of sprinklers in controlling fires. Here again, as far as ordinary combustible materials are concerned, little water is needed to prevent this lateral spread of fire. Although information on precisely how much water is required and how it depends on the size of the fuel and the size of the fire is scanty indeed; experiments carried out by O'Dogherty[7] have shown that for wood cribs this flow rate is of the order of 0.06 kg m^{-2} min^{-1} (the area referred to is the actual area of the fuel surfaces). This figure may be compared with the flow rate used for normal sprinkler systems per unit floor area, which is about 5–10 kg m^{-2} min^{-1}. Indeed, one tolerates water in many protective installations because it is so cheap and generally harmless that one can afford to waste the bulk of the agent even when applied for long periods, provided just enough remains on all the surfaces of the fuel near the fire to prevent its spread. If one could be certain of complete extinction in the first minute of application, there would be a substantial argument for using a much more expensive agent even for cellulosic materials. For a fuel like a light hydrocarbon, in which the surface of the burning material has a low temperature, then water cannot be vaporized at the fuel under the best conditions and it becomes a poor extinguishing agent. However, under the right conditions, it is still effective as a method of reducing fire spread, particularly by cooling metal surfaces in the fire.

Again, with high-stacked storage, and with water application from sprinklers at the top of the store, the sheer inaccessibility of fire in the lower part of the store prevents water reaching uniformly all channels through which fire may spread horizontally, and providing them with the necessary degree of wetting needed to stop the lateral progress of the fire. Moreover, the upward draught of the flames which can develop in an uninterrupted canyon between stacked goods, can push the water from the sprinklers completely aside and prevent water getting near the actual source of fire. These difficulties can be overcome to some extent by the installation of sprinklers at intermediate levels. Great care is needed in the siting of such sprinklers, since they are generally responsive only to the direct impact of flame, and powerful fires may develop in a neighbouring canyon or vertical chimney, in or between stacked goods without being detected. Moreover, the obstruction effect of the packed goods round the sprinkler head may prevent the adequate wetting of all the horizontal channels within the region nominally covered by the sprinkler head.

High-expansion foam

Some of the problems outlined above in the use of water can be overcome by using high-expansion foam. This is a versatile agent which extinguishes petrol fires and is able to flow into the larger channels between stacks of goods and prevent access of air to the smaller channels. However, this agent suffers from the disadvantage that it cannot be directed onto the seat of the fire. The foam needs to flow through a whole compartment which happens to include the region where there is fire. This takes time during which the fire might spread well beyond the place where it began. Although residual damage caused by high-expansion foam is substantially less than that caused by water, it is still not known to what extent it is acceptable, particularly where food is stored. These limitations tend to make high-expansion foam less acceptable for very large compartments. There are also certain development problems outstanding with this agent, particularly reliability in cold weather.

Carbon dioxide and vaporizing liquids

Carbon dioxide is also mainly used for filling a whole space and has limited directional effects; its use is also limited by its toxicity. The efficiency of liquid carbon dioxide is hindered by the fact that when it is discharged as a jet into the atmosphere, more than 50 percent of the agent immediately flashes into a gas, the remainder changing into a fine solid. The gas stream then entrains air into itself, bringing about some evaporation of the fine solid. A great deal of the cooling effect which the agent could have on a burning surface, is therefore eliminated. Vaporizing liquid agents such as halogenated methanes do not suffer from this disadvantage, but their inherent cooling capacity is relatively low compared with that of liquid carbon dioxide or water.[8] Recently, some work has been carried out at the Fire Research Station on the use of liquid nitrogen and also on slurries of solid carbon dioxide in vaporizing liquids.[9] These slurries can extract a significant amount of heat from surfaces in and in the immediate vicinity of the fire and during vaporization produce a useful inerting gas. It may be that such agents can achieve some of the desirable properties of water, particularly its ability to be projected directly onto a burning surface and cool it as well as those of carbon dioxide and bromochlorodifluoromethane, i.e., ability not to cause water damage and to surround the burning material with an extinguishing vapour in the event of the agent not scoring a direct hit on the fire. Such slurries would also be effective agents against liquid fires as they appear to be capable of flowing and vaporizing smoothly over the surface of burning liquids. However, halogenated agents when involved in an intense fire might produce gases which, under favorable conditions, bring about corrosion effects.

Dry powder

Dry powder, owing to its greater fineness has perhaps a greater ability than water spray to penetrate flame zones behind obstacles. However, the powder which falls outside the fire zone is generally wasted. It is, therefore, essential that dry powder should be accurately projected on to the flame and the burning material. This restriction limits its widespread use. A promising variant of dry powder is the production of a highly active powder that owes its effectiveness to the fact that it decrepitates and thus becomes very fine in the flame.[10] Another varient is the use of micro-encapsulated materials as extinguishing agents.[11] In this way some harmful or noxious materials may be made acceptable since they manifest their properties only when the encapsulation is destroyed by fire.

Dual Protection

The above comments indicate that for some applications there are certain disadvantages in most types of protective installation. However there are ways of providing two-pronged protection where the two individual prongs are not only compatible, but might reinforce each other to such an extent as to provide a complete answer to a risk, for which either one or the other would not be very effective. The combination of sensitive detectors with insensitive sprinklers has already been mentioned. Sprinklers which control fire from the top of a building downwards could also be used in conjunction with high-expansion foam which controls fire from the floor upwards. The use of roof vents is compatible with the use of high-expansion foam and will tend to reduce the spread of flame under the ceiling in the time taken to fill the compartment. They are not quite so compatible with sprinklers, as the latter tend to push smoke downwards into the room where there is fire, whereas roof vents rely on the buoyancy effect of smoke and hot gases taking them through the vent in the roof. However, the use of roof vents in this context is still likely to be advantageous.

Another possibility is the stratified introduction of a light inert gas, e.g., produced by a jet engine near the upper part of a building, combined with a stratified introduction of heavy gas, e.g., carbon dioxide or high-expansion foam in the lower part of the building. The light inert gas can contribute by extinguishing the flame under the ceiling which is the mechanism of fire spread in buildings and also the major influence tending to cause ceilings to collapse. Methods for subdividing a large building in the event of fire, by using curtains, could also be used in conjunction with high-expansion foam.[12] However, doubling the system in the above manner will, in general, increase the cost of installation, and one must be certain that there is a real improvement in order to warrant the extra cost.

Control of Automatic Processes

Little experience is available on the detection and control of fire that may involve automatic processes. In this situation the computer which controls the process must have special consideration. Although the computer itself may be a comparatively low fire risk, its failure to operate because of fire may bring a whole process to a halt and may even cause hazard in the process itself. For this type of risk, therefore, a computer would merit a protective installation in its own right.

A more complicated problem is the way in which a computer may instruct emergency procedure to a process in a situation where it is possible a fire might occur, or in which it has actually occurred. Decisions need to be made as to whether the process should be shut down and if it is to be shut down, the sequence in which the shut down should take place. If a fire has occurred, it may be necessary to decide whether an automatic extinguishing agent should be brought in, (e.g., when there is a spillage of liquid fuel) or whether it is best to deflect the fuel from the fire, (with a fire in a gas leak which, if extinguished, may lead to explosion). These problems are in their infancy, but it is likely that in the next few years we shall see a great many more of them.

Resistance to Fire and Explosion

The above comments have dealt mainly with protective installations in which fire and explosions are detected and positive action engendered. A different form of protection is to have resistance to fire and explosion actually built in. The object of this protection is to minimize the damage which occurs even if a fire or explosion were to develop to serious proportions. Protection of this kind against fire usually takes the form of thermal resistance, and for explosions of explosion relief. These may be designed to protect either a plant or a building, but there is a dearth of information which would allow proper design for the large (linear) scale application that is coming into use. This is particularly so for the design of explosion relief, since the onset of turbulence and the transition to detonation are factors which increase the tendency for explosions to become more violent as the scale is increased.

Here a point of cross reference exists between fire resistance and protective installations. Undoubtedly a great deal more can be done in using water to help provide what is the equivalent of fire resistance. Indeed, wherever fire protection difficulties are envisaged in the protection of metalwork in fire, then the spraying or the passage of water over or through the metalwork could be a feasible method of protection. This principle is used extensively for protection of tanks containing flammable liquids. There is no real reason why this should not be extended at least to shutter doors, possibly to structural steelwork, and even to temporary metal compartment walls. The reason is that provided the water is sufficiently well distributed over the surface concerned (which could be an interior surface for certain forms of structural steelwork), then it is difficult for the structure to exceed substantially a temperature of 100°C without making use of the considerable cooling capacity of the water. One can use this, therefore, as a simple basic design concept, combined with the fact that if the maximum area of metalwork which must not exceed a certain critical temperature is known, the extent to which non-uniformity of wetting may be tolerated can also be estimated.

Conclusions

The expected loss due to fires in different risks varies greatly, and to this extent the degree of protection which is prudent also varies. High hazard industries such as capital intensive process industries handling highly flammable material and those involving flammable materials of almost any kind in high-stacked storage of flammable goods merit a high degree indeed in sophistication in their fire protection engineering, but a number of practical scaling problems in these fields still remain to be solved. On the other hand, there may be scope in certain instances for simplifying protective installations in order to cheapen them and encourage their more widespread use. Some possible new developments to improve fire protection are suggested. These include the possibilities of double method installations (e.g., the combined use of high-expansion foam and insert gas); sprinkler installations which become active more rapidly and yet do not operate away from the seat of the fire; the use of cold slurries of solid carbon dioxide in a vaporizing liquid as an extinguishing fluid; the possibility of using micro-encapsulation to reduce the noxious and damaging properties of extinguishing materials; and the more widespread use of water cooling as an alternative to fire-resistance.

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Acknowledgment

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ABSTRACTS

A. Prevention of Fires and Fire Safety Measures

Fire Aspects of Civil Defense. Office of Civil Defense TR-25 (July 1968).

Section: **A**

Subject Heading: **Civil Defense.**

Summary

This report describes the general dimensions of the fire threat resulting from nuclear attack, particularly as a result of ignition of thin materials by the thermal (heat) flash.

A review of the best available information on the thermal ignition capabilities of air-burst nuclear weapons with yields from 1 megaton to 100 megatons indicates that thermal ignitions may occur, under average to good visibility conditions, at ranges where the blast overpressure is between 1 and 3 pounds per square inch (psi), with perhaps 2 psi as a reasonable estimator of the region within which ignitions may occur.

The severity of resulting fires and the likelihood of fire spread depend on the amount and spacing of combustibles within the ignition area. Mass fires are likely only in built-up urban areas rather than in suburban or rural areas. Thus the potential ignition areas cannot be considered as a single fire area "engulfed in flame" since the controlling factors are the occurrence and size of the combustible areas rather than the ignition range of the weapon.

Experience with large fires of the past shows that only a small portion of the population at risk is killed as a result of the fire. The rate of development of large fires has been sufficiently low to permit control or movement of people to areas of relative safety. The most serious complication introduced by modern weapons is the threat of fallout that could hamper firefighting or remedial movement.

In planning a fire defense program against the threat of nuclear attack, the reduction of fire vulnerability by removing or covering ignitable materials and by reducing the concentration of combustibles in cities is equally important as the development of a capability to control and extinguish fires.

Bryson, J. O. and Gross, D. (National Bureau of Standards, Washington, D. C.) "Techniques for the Survey and Evaluation of Live Floor Loads and Fire Loads in Modern Office Buildings," *National Bureau of Standards Building Sciences Series No. 16*, 1–30 (December 1968).

Section: **A**

Subject Heading: **Fire loads.**

Authors' Summary

The procedures and techniques developed for measuring and evaluating the live floor loads and fire loads in modern office buildings are summarized. The main

features of a computer program for analyzing the data are outlined. This program provides a tabulation of the data, some statistical properties, and selected graphical relationships between the measured loads and the characteristics and usage of the structure. A rationale is developed which is intended to achieve the ultimate goal—easier and less expensive means of surveying live loads in buildings and their combustible content.

Two office buildings have been surveyed in a pilot evaluation of the survey techniques—the National Bureau of Standards Administration Building in Gaithersburg, Maryland, and the U.S. Civil Service Commission Building in downtown Washington, D. C. Typical results are presented to illustrate the computer output.

Forshey, D. R., Cooper, J. C., Martindill, G. H., and Kuchta, J. M. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Potential Hazards of Propargyl Halides and Allene," *Fire Technology* **5,** 100–111 (1969).

Related Sections: **A,** *B*

Subject Heading: **Propargyl halides and allene.**

Authors' Abstract

The combustion characteristics and detonability of propargyl bromide, propargyl chloride, and allene were investigated as a means to evaluate their hazard in storage, use, and transportation. All three will undergo monopropellant burning, but their ignitibility and tendency toward monopropellant burning were reduced by dilution with toluene.

Palmer, K. N. (Joint Fire Research Organization, Borehamwood, England) "Use of Mechanical Ventilation to Reduce Explosion Hazards in High Flats," *Joint Fire Research Organization Fire Research Note No. 760* (March, 1969).

Section: **A**

Subject Heading: **Ventilation.**

Author's Summary

The use of mechanical ventilation to protect high flats against explosions involving flammable gases or liquids is discussed in general terms. The relevant properties of the gases and vapours are considered, the extraction ventilation requirements are suggested, and application is made to a specific example (Flat 90, Ronan Point).

The advantages of mechanical ventilation are that it would control the time for which a dangerous explosive volume of gas or vapour would be present, reduce the size of the volume, prevent an escape of gas from spreading to other rooms, and would prevent a slow leak from accumulating.

The proposed mechanical ventilation should not cause discomfort to the occupants and should give good protection against explosions caused by leakage of town gas, likely leakage of L.P. gas, and moderate spillages (a few pints) of flammable liquids such as petrol. Some discussion is made of the problem of large spillages.

The desirability of full-scale tests on actual structures is stressed, particularly as regards the extent of mixing of flammable gas or vapour with air and the probability of forming a hazardous pocket in ventilated rooms. Also the extraction rates of unmixed layers and the mixing effect of heating systems should be investigated.

Palmer, K. N. and Rogowski, Z. W. (Joint Fire Research Organization, Borehamwood, England) "The Use of Flame Arresters for Protection of Enclosed Equipment in Propane-Air Atmospheres," *I. Chem. E. Symposium Series No. 25* (1968).

Section: **A**

Subject Heading: **Flame arresters.**

Authors' Synopsis

Flame arresters have been applied to the protection of industrial equipment which may contain a source of ignition and which may cause an explosion hazard in a flammable atmosphere. The arresters release pressure resulting from ignition of gas in the equipment, but prevent flame emerging through the vents. Cubical vessels up to 3 ft^3 in volume have been tested in a propane–air mixture and were safely protected with crimped-ribbon arresters.

The vent area required depended on the volume of the vessel and the distribution of the vents and was a small fraction of the area of one side of the vessel.

The maximum explosion pressure was related by theory to the vent area and the dimensions of the flame arresters.

Rasbash, D. J. (Joint Fire Research Organization, Borehamwood, England) "The Relief of Gas and Vapour Explosions in Domestic Structures," *Joint Fire Research Organization Fire Research Note No. 759* (April, 1969).

Section: **A**

Subject Heading: **Explosion relief.**

Author's Summary

The influence of potential explosion relief such as external windows, doors, etc., in domestic structures on the pressures that may develop during gas and vapour explosions is indicated. A quantitative approach to estimating these pressures is suggested and is applied to a structure similar to that of the Ronan Point Flat.

Saito, Y. and Ishigaki, M. "Danger of Electrostatics Charges on PVC Tubes for Underground Use and Preventive Measures. II. Electrostatic Charges under Various Conditions," *Mining and Safety* **14** (11), 573–581 (1968). In Japanese.*

Section: **A**

Subject Heading: **Electrostatic charge.**

Authors' English Summary

Electrostatic charges generated on the surface of PVC tubes were measured under various conditions in our laboratory. The main features of the results observed are summarised as follows: (a) When limestone powder rubs against vinyl material, frictional electricity is measured even 40 cm from the rubbing point. (b) Residual electrostatic voltage, generated by friction between the vinyl tube and limestone powder, was nearly a quarter of the initial charge after 10 minutes, at a moisture content of 43%. (c) The greater the rubbing distance between vinyl tube and powder, the higher is the generated voltage. The electrostatic charge is rapidly increased on the surface of the tube within 50 cm from the exhaust nozzle. (d) The electrostatic charge decreases linearly against the increase in atmospheric humidity. It is next to impossible to generate electrostatic charges in more than 95% atmospheric humidity. (e) The electrostatic charge varies inversely as moisture content in compressed air mixed with rock dust. (f) Polarity of charge varies with the type of rock dust.

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Widginton, D. W. (Safety in Mines Research Establishment, Sheffield, England) "Some Aspects of the Design of Intrinsically Safe Circuits," *SMRE Research Report No. 256* (1968).*

Section: **A**

Subject Heading: **Safe circuits.**

This report reviews the basic information usually available to the circuit designer, and then discusses the problems involved in the design of intrinsically-safe circuits. Topics covered include the design of voltage-stabilized D.C. and A.C. supplies; the design of inductive circuits, with and without protective shunts; and methods for assessing the effects of long interconnecting cables. A useful method of assessing the safety of certain circuits is to show that the circuit under consideration is less dangerous than another circuit, whose safety can be assessed in terms of the basic information available.

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B. Ignition of Fires

Belyaev, A. F., Frolov, Yu. V., and Korotkov, A. I. "Combustion and Ignition of Particles of Finely Dispersed Aluminum," *Physics of Combustion and Explosions* 4 (3), 323–329 (1968). In Russian.

Related Sections: **B**, *G*

Subject Headings: **Aluminum**; *Metal powder.*

Authors' Summary—Translated by L. J. Holtschlag

Considered is the problem of the combustion and ignition of single particles of finely dispersed aluminum in a high-temperature gas flow. Experimental data were obtained on the effect of the temperature and composition of the gas medium, of the pressure and of the particle size on the ignition and combustion times of aluminum. It was found that the combustion time is independent of the pressure ($P > 20$ atm) and temperature of the medium ($T > 2{,}000°K$), but is strongly dependent on the oxidizing properties of the flow relative to the concentration of active oxygen-containing products (H_2O, CO_2, etc.). A formula is proposed for calculation of the particle burning time. The ignition time of aluminum particles is not especially sensitive to the composition of the oxidizing medium or the pressure, but is strongly dependent on the gas flow temperature. It increases proportional to d^2 with increasing particle diameter.

Gurevich, M. A. and Stepanov, A. M. "Ignition of a Metal Particle," *Physics of Combustion and Explosions* 4 (3), 334–342 (1968). In Russian.

Section: **B**

Subject Heading: **Ignition.**

Authors' Summary—Translated by L. J. Holtschlag

The heat-up of a particle in an oxygen-containing medium is examined. The metal oxide formed as a result of the reaction is disregarded. It is assumed that the processes of heat and mass transfer between the particle and the medium are quasi-stationary within a given film, that homogeneous and heterogeneous reactions are of the first order with respect to oxygen and obey an Arrhenius temperature dependence. In addition, the reaction in the vapor phase is of first order with respect to the metal vapors, while the surface reaction is of zero order. The distributions of the temperature and concentrations of metal vapors and oxygen near a particle are described by a system of sixth-order differential equations.

The temperature curves of the heating and the vaporization rates of magnesium particles in an oxynitrogen medium are calculated on a Ural-2 computer. Particles for which the ignition conditions are fulfilled must go over from the regime of vaporization to an inert medium to the regime of diffusion burning. Such a transition can be observed from the change with time of the temperature distribution in the reduced film. But if the particle ignition conditions are not fulfilled (tempera-

ture of the medium lower than the limit), the above-mentioned transition is not observed. The instant the metal particle goes into the diffusion combustion regime was taken as the instant of ignition. On this basis of this indicator of ignition, the induction times of magnesium particles in an oxynitrogen medium were computed as a function of the particle size, the temperature of the medium, and the oxygen content in the medium.

Rae, D. (Safety in Mines Research Establishment, Sheffield, England) "Experimental Coal-Dust Explosions in the Buxton Full-Scale Surface Gallery. 1. The Characteristics of Coal-Dust Explosions Initiated by Captive Rockets," *SMRE Research Report No. 255* (1968).*

Related Sections: **B**, *D*, *G*

Subject Heading: **Coal-dust explosion.**

The preliminary experiments (the first 56) in the new 366-m long reinforced-concrete explosion gallery at Buxton are described. To start the explosions from dust on the floor, an ignition zone 37 m long containing, usually, six rocket igniters at 6-m intervals from the closed end was needed to obtain explosions in which flame travelled as slowly as possible yet reached the open end. The dust deposits contained up to 50 percent inert with a coal content of 0.2 kg m^{-3} of air in the gallery (cross section 5.6 m^2). The initial pressure rise generated by the ignition arrangement, and its subsequent reflections, determined the behaviour of the flame in its early stages: pressure rises due to the flame itself were less than the changes due to the ignition and this is called the region of weak explosion (which may, however, extend throughout the gallery and during which a number of flame oscillations may occur). For stronger initiations the pressures generated by the flame exceed those due to the ignition, after a time, and then increase rapidly: this is called the region of strong explosion (which, in these experiments, was carefully limited).

Wiltshire, L. L. and Parker, W. J. (Naval Radiological Defense Laboratory, San Francisco, California) "Ignition of Retardant-Treated Cloth by Nuclear Weapon Thermal Pulses," *NRDL-TR-68-139, OCD Work Unit 2542A* (February 10, 1969).

Section: B

Subject Headings: **Ignition, of cloth**; *Ignition; Flame retardants; Nuclear weapons; Thermal pulse; Fire.*

Authors' Summary

The ignition responses of fire-retardant treated black cotton cloth and black rayon cloth to the simulated thermal pulses from nuclear weapons were investi-

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gated. The temporal and spectral characteristics of the main thermal pulse from air bursts ranging from 300 kilotons to 100 megatons were reproduced using a cored carbon arc along with a specially shaped rotating disk shutter. The treatments applied to the cloths were a combination of borax, boric acid, ammonium phosphate, diammonium phosphate, and ammonium sulfate which were recommended for home administered treatment of fabrics by the Department of Agriculture.

The data are presented as graphs of ignition distances versus weapon yield for fire-retardant treated and untreated cloths. While the range of flaming ignition is significantly reduced by these treatments, flaming ignition would still occur well beyond the 5 psi blast overpressure range. The largest reduction in the area over which flaming ignitions would occur with the fire retardants tested amounts to about 50% over that of the untreated cloth.

The effect of the retardants on the glowing ignition of the cloth varied from no effect to a somewhat greater susceptibility to glowing in the case of cotton. However, for rayon, the recommended treatment eliminated glowing ignition altogether.

Both glowing and flaming ignition were transient in the case of the treated fabrics. Flaming and glowing died out rapidly after the conclusion of the thermal pulse.

Some large area treated and untreated black cotton fabrics simulating household draperies were exposed to a 4×4 ft tungsten lamp bank. Under some circumstances the mode of ignition of the large area treated fabrics was changed from transient glowing to transient flaming because of increased concentration of distilled gases near the upper part of the specimen.

The effectiveness of the transient flaming and glowing ignition of these fabrics in the spread of fire to other combustible materials coming in contact with them was tested and found to be very low. Fire retardants formed an increased amount of char in the burned material which allowed it to support its own weight and become a thermal radiation shield.

Wraight, H. (Joint Fire Research Organization, Borehamwood, England) "The Ignition of Motor Tyre Samples," *Joint Fire Research Organization Fire Research Note No. 742* (January 1969).

Section: **B**

Subject Headings: **Tyre ignition;** *Fire hazard; Ignition; Radiation; Rubber.*

Author's Summary

Samples of rubber cut from a used motor tyre have been exposed to thermal radiation in order to examine the behavior of this type of material and in particular to determine the lowest intensity of radiation at which it would ignite. The results show rubber is perhaps somewhat more difficult to ignite than a common species of softwood.

D. Propagation of Fires

Gussak, L. A., Sprintsin, E. N., and Shchelkin, K. I. "Study of Normal Flame Front Stability," *Physics of Combustion and Explosions* **4** (3), 358–366 (1968). In Russian.

Related Sections: **D**, *G*

Subject Heading: **Flame stability.**

Author's Summary—Translated by L. J. Holtschlag

Normal flame stability in a propane–air mixture in a small-volume chamber at initial pressures of 1–9 atm was studied by high-speed Toepler cinematography. The pressure was recorded simultaneously. The value of the Reynolds number of the flame at which instability of the order of 10^3 begins was obtained; it was of the order of $(1–4)\times10^2$, which is in approximate agreement with the theory allowing for viscosity. The characteristic flame dimension was the cross-sectional size of the cells. As the flame front propagates under increasing pressure in the chamber, the average size of the flame cells generated by instability decreases, so that the Reynolds number at which the cell size was taken as the characteristic dimension remains approximately constant. Upon the appearance of instability in a spherical flame, the criterion K, which is equal to the ratio of the time of motion of a perturbation through the combustion products to the characteristic normal flame time, passes through unity.

Hinkley, P. L. and Wraight, H. (Joint Fire Research Organization, Borehamwood, England) "The Contribution of Flames under Ceilings to Fire Spread in Compartments. Part II. Combustible Ceiling Linings," *Joint Fire Research Organization Fire Research Note No. 743* (January 1969).

Section: **D**

Subject Headings: **Fire spread;** *Linings; Heat transfer; Burning rate.*

Authors' Summary and Abstract

Summary

Part 1 of this report described flames originating from a fire on a floor of a corridor and deflected horizontally by an incombustible ceiling. The present report described further experiments with a combustible ceiling lining of combustible cellulose-based building boards. A combustible ceiling results in longer flames,

higher intensities of radiation to the floor and a faster rate of increase of radiation than an incombustible one with similar thermal constants. However, with most linings flames will not spread indefinitely from a limited floor fire; in this respect the indefinite spread of stove enamelled hardboard was exceptional.

The rate of increase of radiation was related to the performance of the material in the Fire Propagation Test; the maximum intensity of radiation was not so related but did not differ greatly between materials except for stove-enamelled hardboard.

The rate of spread of fire along a narrow strip of wood on the floor beneath a burning ceiling lining has been calculated and the results related to the index of performance on the Fire Propagation Test.

Abstract

In order to devise rational tests and performance requirements for combustible linings in various positions in buildings it is necessary to have some quantitative design criteria either from direct experience or from research. There are still many difficulties in presenting a clear description of the processes of fire growth and the contribution of the many factors involved. In parallel with an international study covering the factors in fire growth, certain fundamental features are being studied in detail, and this report is one of a series investigating the characteristics of flames beneath various kinds of ceiling.

At some stage in the growth of a fire in an enclosed space the flames from materials on the floor are deflected by the ceiling and extend horizontally. It was shown in part 1 that, even when the ceiling is incombustible, the horizontal flames dramatically increase the radiation to unburnt fuel away from the fire and this alone leads to fire spread irrespective of other influences.

This report shows that a combustible lining will cause an increase in the length of the horizontal flames and a more rapid increase in the intensity of downward radiation than an incombustible one. The types of lining investigated were all cellulose-based building boards and with most of these (including untreated fibre insulating board) the lengths of horizontal flames depended on the size of the fire on the floor; when this was restricted fire would spread indefinitely beneath only one of the boards tested, a stove-enamelled hardboard. Apart from this material, differences between linings lay in the rate of increase of downward radiation much more than in the intensity finally attained.

The measurements of downward radiation were used to estimate the spread of fire over a narrow strip of combustible material on the floor, the assumption was made that the flames from a narrow strip would be small so that they would not affect the ceiling fire and it was found that the initial rate of spread varied with performance of the material on the Fire Propagation Test. The final rate of spread with the exception of stove-enamelled hardboard did not depend on the type of lining.

The importance of the initial rate of spread would be greatly increased where "feedback" from a larger floor fire to the ceiling fire could occur because the spread would in effect then be an accumulation of successive initial rates of spread and would accelerate until other factors such as a shortage of oxygen intervened. It appears that under these circumstances the performance of a cellulose based board in the Fire Propagation Test is a good measure of its hazard when used as a ceiling lining.

Kurkov, A. P. (Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio) and **Mirsky, W.** (University of Michigan, Ann Arbor, Michigan) "An Analysis of the Mechanism of Flame Extinction by a Cold Wall," *Twelfth Symposium (International) on Combustion*, Pittsburgh, The Combustion Institute, 615–624 (1967).

Related Sections: **D,** *E*

Subject Heading: **Flame extinction.**

Authors' Abstract

The process of laminar flame extinction by a cold wall is studied because of its relation to the wall-quenching phenomenon in the internal combustion engine. The theoretical analysis is performed assuming a one-dimensional transient process and a simple one-step chemical reaction.

A series solution valid in a limited time domain is obtained employing the method of inner and outer expansions. The results are further extended in time by means of numerical integration of the governing equations. It is found that the amount of unreacted fuel near the wall depends significantly on the value of the Lewis number and only weakly on the value of the activation energy.

The comparison with experimental results is made on the basis of several characteristic quantities defined in terms of steady-state burning velocity. The estimated amounts of unreacted fuel and the quench zone thickness in an engine are found to be several times lower than the corresponding experimental values. It appears that the present idealized model gives a lower limit for the amount of unreacted fuel at the wall.

Wilde, D. G. (Safety in Mines Research Establishment, Buxton, England) "Combustion of Rigid Polyurethane Foam in Ventilated Ducts," *The Heating and Ventilating Engineer* (December 1968) and "Polyurethane Foam," *Colliery Guardian* (August 1968).

Section: **D**

Subject Headings: **Polyurethane foam;** *Ventilated ducts.*

J. E. Malcolm, Abstracter

Rigid polyurethane foam is extensively used as thermal and acoustical insulation. For this purpose the foam density varies from 30 to 40 kgm m^{-3} (2 to 2.5 lb/cu ft). The author's investigation concerned the flammability of this material and was inspired by the observation that the degree of flammability is enhanced when the flammable material surfaces are arranged in the configuration of a "duct." As a demonstration, the flame spread on a vertical sheet of 1.25 cm (0.5 in.) thick beechwood was compared with that in a vertical duct of 5×5 cm (2×2 in.) square cross section fabricated from the same size sheet as the plain vertical section. In the former case the specimen was self-extinguishing after removal of the igniting source. In the latter case the wood sheeting burned after the igniting source had been removed until destruction of the duct.

The experimental program reported made use for the most part of a tunnel 2.1 m (7 ft) by 2.1 m (7 ft) in cross section and over 21 m (70 ft) long. A smaller duct of 30×30 cm (12×12 in.) in cross section was also used in experimental fires to provide for combustion gas sampling and analysis. The larger duct was ventilated with air at a velocity of about 1.02 m sec^{-1} (200 ft/min^{-1}). A 50.8 mm (2 in.) layer of polyurethane comprised the test duct (tunnel) lining. An igniter power output of 20,000 or more watts was required to ignite the foam layer. The flame only of the igniter was permitted to contact the foam surface.

Figure 1 shows typical test results in terms of combustion temperature and combustion gas composition. Hydrogen cyanide was also produced in the test

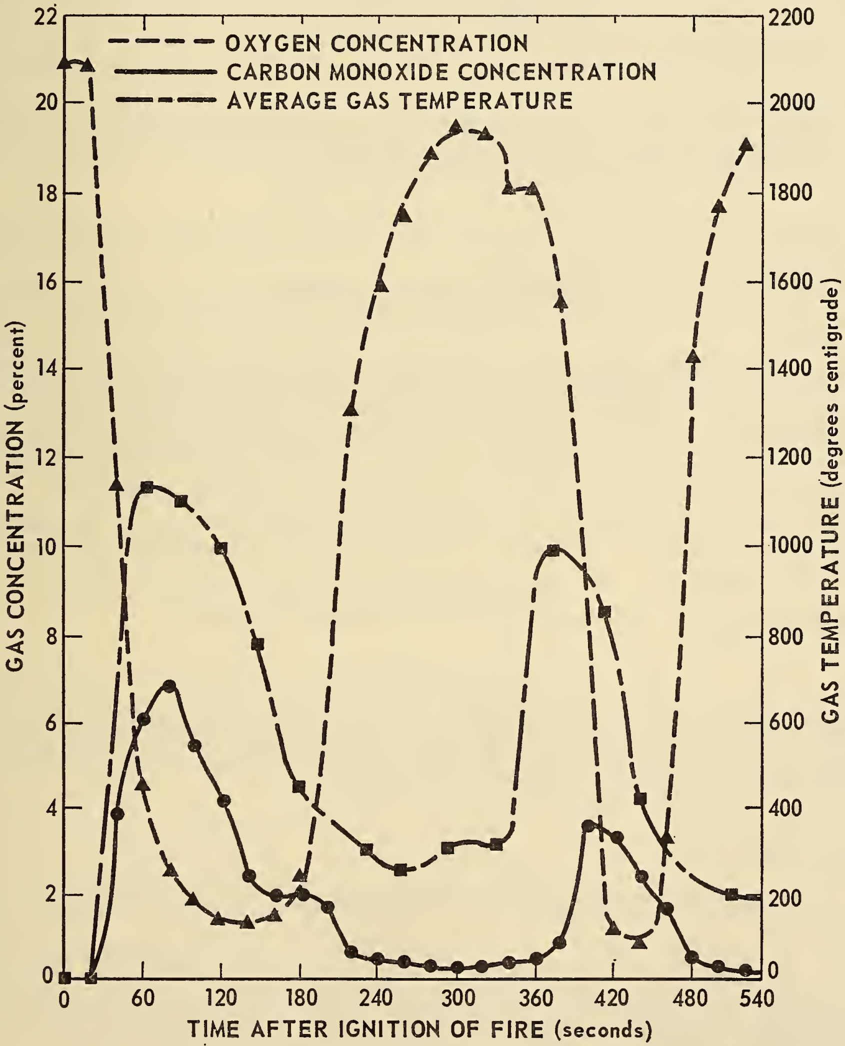

FIGURE 1

configuration fires at about 0.5 percent gas concentration. At this concentration the toxic effect was reported as being about the same as that of the carbon monoxide concentration at peak values noted in Fig. 1.

One test was conducted using a proprietary asbestos cement coating 21 mm (0.75 in.) thick over the foam layer. This overcoating was effective in preventing foam ignition at igniter powers of from 1.8 to 7 megawatts. Other tunnel lining configurations involving partial coatings over the polyurethane foam layer were also investigated.

Figure 1 shows that periods of extreme oxygen deficiency occurred in the test configuration fire. Dense black smoke was produced, and the foam lining was reduced to a thin black ash in the course of combustion. In one test, wherein the igniter was placed half-way along the length of foam lining, the author notes that the flame spread in the direction of ventilation was steady at about 24 m min^{-1} (80 ft min^{-1}), whereas the rate against ventilation was spasmodic, and at times as high as 27 meters per minute (90 ft min^{-1}). In this test virtually all the foam (i.e., 21 m (70 ft) length of duct lining or 228 kgm (518 lb) of foam was destroyed in four minutes.

Photocells, thermistors, 16 mm color motion pictures and closed circuit television were used to observe the fire characteristics.

From the tests conducted, the author concludes that:

(a) Small-scale tests made in free air do not indicate the fire risk in polyurethane foam linings of ventilated ducts.
(b) Polyurethane foam lining in ducts is easily ignited, and the position and type of igniter is not important provided that the igniter flames contact the foam surface.
(c) Fumes in polyurethane-lined duct fires contain low oxygen concentrations, heavy concentrations of oxides of carbon, toxic concentrations of hydrogen cyanide, and average gas temperatures at times in excess of 1,000°C.
(d) The fume toxicity in foam-lined duct fires results largely from polyurethane pyrolysis in the absence of sufficient oxygen for complete combustion.
(e) Fires with polyurethane foam linings in ventilated ducts are particularly dangerous because of the combination of the fire intensity and the high rate of flame spread.

In the two articles on these fire tests, four references are cited.

Woolliscroft, M. J. (Joint Fire Research Organization, Borehamwood, England) "Notes on Forest Fire Fieldwork (New Forest, 1967)," *Joint Fire Research Organization Fire Research Note No. 740* (1967).

Related Sections: **D**, *G*

Subject Headings: **Forest fire**; *Woodland; Fire; Wildland; Fire spread; Flame.*

Author's Summary

This report describes fieldwork carried out in March 1967, to study forest and heathland fires. The main emphasis was on head fires as these are the most serious and difficult to understand.

Results suggest that radiation from the flames contributes appreciably to the spread of head fires.

Woolliscroft, M. J. (Joint Fire Research Organization, Borehamwood, England) "A Report on Forest Fire Fieldwork (New Forest, 1968)," *Joint Fire Research Organization Fire Research Note No. 744* (January 1969).

Related Sections: **D**, *G*

Subject Headings: **Forest fire**; *Fire spread; Wildland; Radiation.*

Author's Summary

This report describes some field measurements on fires in heathland fuels. Flame radiation appears to be the factor controlling head fires in the field. Fires in mixed fuels containing dry grass spread as fast as they would if only grass were present.

E. Suppression of Fires

Hough, R. L. (Hough Laboratory, Springfield, Ohio) "Investigation of Unique Organometallic Compounds as Potential Fire Extinguishants," *Report under Air Force Contract F33615-69-C-1315, administered by Air Force Aero Propulsion Laboratory for period, 2 December 1968 to 31 March 1969, AFAPL-TR-69-42* (March 1969).

Section: **E**

Subject Heading: **Organometallic fire extinguishants.**

Author's Abstract

This study was performed to determine the feasibility of using volatile halogenated organoöxymetallic compounds for extinguishing diffusion flames. Because these compounds decompose thermally, yielding halogenated liquids and gases as well as the respective metal oxides, it was postulated that they would function as fire extinguishing agents when deployed into a region filled with flames. A rapidly moving cloud of gas phase nucleated particulates, having a very high surface to mass ratio, together with the attending halogenated species would have a degree of flame penetration not available in gaseous or liquid agents alone.

Organooxymetallics having branched fluorinated ligands are more volatile than straight chain or unfluorinated analogs. The 1,1,1,3,3,3-hexafluoro-2-propoxy ligand was investigated utilizing a special diffusion burner designed for this research. Experimental difficulties were encountered in burner design and operation. Considering this, it appears that compounds as tetrakis 1,1,1,3,3,3-hexafluoro-2-propoxy silicon and 1,1,1,3,3,3-hexafluoro-2-propanol are as effective as bromotrifluoromethane in extinguishing small propane-air diffusion flames.

More research is needed, however, to establish flame inhibition rank for this interesting class of compounds.

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Kida, H. (Fire Research Institute, Tokyo, Japan) "Extinction of Fires of Liquid Fuel with Sprays of Salt Solutions," *Bulletin of the Fire Prevention Society of Japan* **18** (2), 1–8 (1969).

Section: **E**

Subject Heading: **Salt solution sprays.**

Tosiro Kinbara, Abstracter

Water and aqueous solutions of KBr, KCl, NH_4Cl, Na_2CO_3, $NaHCO_3$, K_2CO_3, $KHCO_3$, HCOOK, etc., of various concentrations were sprayed vertically downward upon a flame of burning layer of hexane of 5 mm thickness lying on the water contained in a cup 8 cm in diameter, and the times required for extinction were measured. The nozzle producing the spray was mounted 70 cm above the cup and the discharge pressure was kept at 3.5 $kgwt/cm^2$.

When pure water was used, the mean diameter of spray drops was 0.1 mm and the water reached the cup at the rate of 0.027 $cm^3/sec\ cm^2$. No appreciable difference was observed for these values when salt solutions were used.

The results for the extinction time scattered widely, and as the concentration of salt solution was made smaller, the extinction time was not only elongated in its mean value but was scattered in a wider range.

Thus, when pure water was used, the frequency of extinction time was distributed over 1 to 30 sec and it could only be concluded that its maximum was located somewhere between 6 to 20 sec, the mean being 13 sec. However, with 20% $KHCO_3$ solution for instance, 70% of the frequency concentrated between 2 to 5 sec, the peak being 26 at 4 sec for the repeat of 100 times.

The author insists that, for evaluating the extinction capability of sprays, the characteristic of the frequency-extinction time is as important as its mean value.

Matsuguma, M., Umezu, M., and Yamao, S. "On High-Expansion Foam for Use in Underground Firefighting. Foaming Agents and Extinguishing Effect," *Mining and Safety* **15** (1), 3–13 (1969). In Japanese.*

Section: **E**

Subject Heading: **Foam.**

Authors' English Summary

About 50 foaming agents were examined in order to develop the most suitable foam-forming solution for the high-expansion foam-plug method. In practice it is desirable that high-expansion foam should have a long life, low drainage, and resistance to high temperature and flame. The foaming capacity of a foaming agent is

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reduced by great hardness and low temperature of the diluent water. A softening agent, e.g., ethylene diamine tetra-acetic acid, has then to be used, or the concentration has to be higher than the usual value of 0.5%. Addition of carboxy methyl cellulose to the solution is effective in increasing the viscosity of the foam and rendering it more durable. Excessive addition, however, prevents the foam from spreading over the fire area. The primary extinguishing effect of high-expansion foam is sealing and the second effect is cooling. These effects vary with the speed of propagation of the foam plug and the quantity of water contained in the foam. The relation between the extinguishing effect of the foam plug and the speed of propagation of the foam plug and the position of the fire has been investigated.

Lovelace Foundation (Albuquerque, New Mexico) "Fire in a Hyperbaric Chamber," *Fire Journal* (November 1965).

Segal, L. (California State Fire Marshal's Office), **Turner, H. L.** (Los Angeles Fire Prevention Bureau), **Yanda, R. L. and Moore, C.** (Hyperbaric Research Center, Hospital of the Good Samaritan, Los Angeles) "Fire Suppression in Hyperbaric Chambers," *Fire Journal* (May 1966).

Turner, H. L. (Los Angeles Fire Prevention Bureau) and **Segal, L.** (California State Fire Marshal's Office) "Fire Behavior and Protection in Hyperbaric Chambers," *Fire Journal* (November 1965).

Botteri, B. P. (Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio) "Fire Protection for Oxygen-Enriched-Atmosphere Applications," *Fire Journal* (January 1968).

Denison, D. M., Ernsting, J., Tonkins, W. J., and Cresswell, A. W. (Royal Air Force Institute of Aviation Medicine, Farnborough, Hampshire, England) "Problem of Fire in Oxygen-Rich Surroundings," *Nature* **218,** 1110–1113, (1968).

Johnston, R. and Radnofsky, M. I. (Manned Spacecraft Center, Houston, Texas) "Nonflammable Clothing Development Program," *Fire Technology* **4,** 88–102, (1968).

The following abstract, based on these six articles, is written under the title of "The Hazard and Suppression of Fires in the Oxygen-Enriched Operation of Hyperbaric Chambers."

Related Sections: E, *A*

Subject Heading: **Oxygen enriched fires.**

P. Breisacher, Abstracter

On three occasions during the past five years fatal accidents have occurred during routine operations of hyperbaric chambers. The high risks involved have often been overlooked despite the fact that preventative measures are reasonably well understood. The subject has been variously attacked by different researchers.

The death of two Navy divers on February 16, 1965 in the Washington Experimental Diving School illustrates the severe limitations placed upon operation of hyperbaric chambers in an O_2-rich environment. The chamber in question was filled with a mixture of 28% O_2, 37% N_2 and 35% He at 40 psig.

Initial warning of fire occurred shortly after the two men had sealed the lock to their diving capsule. Observation posts showed that flames rapidly engulfed the whole cabin after a tongue of flame was seen emanating from the CO_2 scrubber motor. Pressure rose rapidly to 110 psig in the fixed volume chamber. This corresponded to a temperature of 800°F. Rescue operations failed due to inability to equalize external pressures rapidly enough to open the entry portal. It was also observed that final entry was accompanied by a momentary rekindling of the fire as O_2 was again fed to the oxidant-depleted chamber atmosphere. This accident illustrates the need to study carefully the (1) operation of the chamber itself, (2) the need to remove sources of accidental ignition, (3) the maximum usage of noncombustible materials, (4) evaluating the composition of the gas mixtures employed, and most importantly the best approaches toward (5) rapid extinguishment of fires once initiated.

The problem of fire suppression was studied by Segal in a large (20 ft long, 10 ft wide) hyperbaric chamber. An overhead water spray augmented by hand-held units was tested under burning conditions with special regard toward water pressure, nozzle size, nozzle spacing, and delivery rate. The hand-held extinguisheres were equipped with quick opening valves. Typical fires were out in 2 sec with hand units as opposed to 25 sec for the overhead system.

Both methods are necessary since it is possible that the occupants of the cabin become incapacitated. Another modification proposed is to divide the cabin into two chambers at identical pressures but separate extinguishment systems. This would provide isolation of crew members while fire suppression is occurring. It also precludes the need to proceed through the impossibly slow decompression cycle needed to facilitate escape from the chamber. The chamber pressure was instrumental in determining the degree of coverage. The free fall of droplets at higher chamber pressures becomes constricted or held up as pressure rises. The water-chamber differential pressure had little effect in altering the pattern. It is therefore necessary to install many more nozzles to cover the most extreme situation.

Turner studied the use of medically useful hyperbaric chambers operating at pressures up to 7 atm. Special consideration is given toward the observable variation of water spray coverage as the chamber pressure is increased. Test of burning time and char length were conducted using cotton, flammable liquids, and rayon–modacryclic materials. Flame retarded samples of the fabrics were also tested. Burning rates do not rise linearly with pressure. Oxygen enrichment always increases the burning rates. Flameproofing does not significantly alter or reduce burning rates.

Botteri studied the properties of various ignition sources when employed at pressures and O_2 concentrations. Initiation sources included (a) electrical, (b) hot surfaces, and (c) hot gases. The electrical energy needed to autoignite a gas mixture varies according to the oxygen enrichment. Inert gases, such as He, tend to suppress the ignition temperature. An average man's charged potential can reach 4 kV with an average capacitance of 204 microfarads. This equals an electrostatic charge of 1.63 millijoules per person. This was shown to be large enough to ignite combustible gases and powders as well as 100% O_2.

When the O_2 concentration is increased it is noted that the final pressure, flame temperature, and heat release reach a maximum. Time to attain this maximized state was determined for hydrocarbon–O_2 and hydrocarbon–air mixtures.

Detection of fire cannot be left to thermal alarms. They are much too slow. Flame radiation detectors are showing some promise. Smoke detectors are of little value.

Dennison surveyed the ignitability of many fabrics in pure O_2 atmospheres. Conviction determines the rapidity of fire spread in most materials. Radiation and conduction control burning rates in the case of fibrous piles such as denim and brushed nylon.

Any electrical source capable of producing spark energies greater than 10 millijoules should be regarded as a potential ignition source (we have noted earlier the capability of a man's 1–2 millijoules action as a spark source). It is advisable to maintain a relative humidity of at least 50% in order to reduce the possibility of electrical breakdown. Any surface temperature of greater than 150°C should be eliminated. Any fire extinguishment technique must be rapid enough to attain maximum delivery within 2 sec and be able to contain the blaze in 5 sec. Materials used include CH_3Br, CO_2, H_2O, and Freon 1301. Rate of application must be 5 ml/cm^2/sec. Toxicity effects of any fire suppressor must be determined before use. Precautions must be taken to cope with the artificial sudden O_2 enrichment occurring if an O_2 leak should develop.

Johnston has studied the need to select materials of internal construction which maximize the flame-retardant properties of the whole chamber. All combustible materials must be removed from the main compartment. Attempts are being made to find direct substitutes for all fire prone materials in the spacecraft interior. The problem of useability of these new materials is often quite a problem. The actual use of the material will often determine its net combustion toward total cabin safety. All materials must first meet the necessary requirement that they be emitters of nontoxic gases when heated. They must be capable of static properties in atmospheres ranging from 6.2 to 16.5 psia O_2. Stainless steel fiber will ignite at high O_2 pressure when exposed to spark or flame. In extravehicular flight they must be stable at 10^{-14} mm pressure. Other important criteria include resistance to micrometeorite impact and ultraviolet and infrared transmission curves. The visors used in the recent moon-landing mission employed a material that possessed high transmittance on the visible and low transparency to uv or ir. This visor also had to withstand a temperature range of +300°F to −300°F. As every part of the space capsule is tested and examined for fire resistance it is immediately replenished with a new material as soon as some of its aforementioned properties have been assayed.

The distinct tests are performed. One is for flammability properties, the other two for materials degradation under exposure to simulated lunar thermal vacuum and radiation environments. The flammability test pays special attention to possible autoignition when heated. The flame propagation test places a material sample in a bell jar reset to a small tissue ignitor. Propagation rates are measured for the vertically suspended sample. Ignition tests place the sample in a temperature programmed furnace fitted with sparker at the top. The latter is periodically fired until ignition takes place. The ignition is actually due to evolution of pyrolitic products. Autoignition is the temperature at which ignition occurs without application of the tissue ignitor. If this temperature is >450°F the material is accepted, assuming it meets all other requirements.

Some of the materials tested include metallized asbestos, beta fiber, teflon, and others. Some of these cloths are of undefined composition. Some possess high abrasion resistance and thermal barrier properties. Beta fiber has a useable work range of −250°F to 1200°F, with low porosity and completely nonflammable properties in the temperature range used. Asbestos has poor tensile strength and low abrasion resistance. Blends of asbestos with other fibers to increase fabric strength are being attempted. A particular mixture of beta fiber with metallized chromed-R has generated a highly tensile material. The useable range without degradation is −320° to 2000°F.

F. Fire Damage and Salvage

Bertschy, A. W. and Peterson, H. B. (Naval Research Laboratory, Washington, D. C.) "Corrosion Resistance of Some Common Metals to Concentrated and 6% Solutions of Light Water Fire-Extinguishing Agent," *NRL Report 6932* (August 8, 1969).

Related Sections: **F**, *O*

Subject Heading: **Corrosion.**

Authors' Abstract

A study has been made concerning the corrosion resistance of a group of common construction metals that might come in contact with the fire-extinguishing agent known as Light Water. The metals examined were exposed to concentrated Light Water material and to 6% solutions of Light Water prepared with sea water and with fresh water.

Type 304 stainless steel and titanium were virtually unaffected by any of the liquids. Overall weight losses for type 6061 aluminum alloy were low, on the order of 2 milligrams per square decimeter per day (mdd). However, localized pitting was observed. Monel had losses of 5 mdd with the Light Water concentrate. The copper-base metals immersed in the concentrate exhibited weight losses in the range of 10–13 mdd, while steel, lead, and zinc were in the 18–40 mdd range.

The corrosive effect of 6% solutions prepared with fresh water was generally not different than with fresh water itself, except for the copper-base alloys. The 6% solutions prepared with sea water gave results generally not different than with sea water itself.

A comparison of the Light Water concentrate test results with earlier tests conducted on protein-type foam concentrates shows the latter to be considerably more corrosive. The limits for corrosion as set forth in the proposed military specifica-

tion for Light Water fire-extinguishing concentrate are lower than those in the current federal specification for protein foam concentrate.

This is an interim report. Work on the problem is continuing.

Bowes, P. C. and Field, P. (Joint Fire Research Organization, Borehamwood, England) "The Assessment of Smoke Production by Building Materials in Fires. 2. Test Method Based on Smoke Accumulation in a Compartment," *Joint Fire Research Organization Fire Research Note No. 749* (March 1969).

Section: **F**

Subject Headings: **Smoke;** *Fire propagation test.*

Authors' Abstract

The measurement of the optical density of smoke produced by materials under test in the Fire Propagation Test Apparatus, and allowed to accumulate in a relatively large closed compartment, has been studied as a possible standard test for smoke production by building materials.

It is concluded that the procedure is suitable as a routine adjunct to the Fire Propagation Test without modification to the apparatus.

Shoub, H. and Ingberg, S. H. (National Bureau of Standards, Washington, D. C.) "Fire Resistance of Steel Deck Floor Assemblies," *National Bureau of Standards Building Science Series 11* (December 1967).

Section: **F**

Subject Headings: **Fire resistance, steel plate floors;** *Burnout tests; Floor tests; Fire severity.*

Authors' Abstract

Tests were conducted to determine the resistance to fire of welded steel plate and beam floor assemblies with various conditions of floor covering on the plates, and ceiling protections beneath the beams. The trials included fire exposures from the burnout of combustible materials ranging from 10 to 40 lb/ft^2 on the floor surface as well as standard fire endurance tests in which the ceiling of the structure was exposed to fire.

The results of the tests indicated that the use of steel floor structures was practical from considerations of fire safety. For the test conditions established, fire exposure on top of the floor did not heat the structural steel supporting members sufficiently to cause load failure or collapse, and did not produce untenable conditions in the room below. In tests involving fire exposure to the underside of floors, the fire endurance times, based solely on heat transmission criteria, ranged from 1 hr 24 min to over 4 hr. Temperature levels attained by the structural members and deflection of the floor assemblies are also reported.

G. Combustion Engineering

Anderson, H. E. (Northern Forest Fire Laboratory, U. S. Forest Service, Missoula, Montana) "Sundance Fire—An Analysis of Fire Phenomena," *U. S. Forest Service Research Paper INT-56* (1968).*

Related Sections: **G**, *D*

Subject Heading: **Sundance Fire.**

A. A. Brown, Abstracter

A recent research report on the Sundance Forest Fire which occurred in Northern Idaho in early September, 1967, makes a distinctive contribution to the history of forest fires in the United States.

The Sundance Fire first came to attention on August 23, 1967. It broke out of control on August 30 and on September 1 it made a spectacular run of 16 miles, visiting complete devastation on 50,000 acres (78 square miles) of valuable timber lands. Because of drought conditions at the time and the very heavy volume of fuels typical of forests of this region, the fire developed an awesome rate of energy release. This resulted in a towering convection column which ascended to 35,000 ft, and powerful tornado-like fire whirls which broke off and uprooted trees in great numbers. It also resulted in numerous spot fires, some of which were set as far as 12 miles in advance of the fire front. Such violent behavior is usually associated with the "fire storm." Fire-storm phenomena certainly did occur, yet such effects might be described as localized in the course of the 16 mile run since they represented a series of special situations created by heavy mixed fuels, rugged topography, a brisk prevailing wind, the merging of numerous spot fires, and the violent but intermittent spread of fire through the tree crowns in advance of the surface fire on the ground. Such phenomena were highly complex and varied as the fire's environment varied in terms of fuel, weather, and topography. Nevertheless the general behavior of the fire may be described as simply that of a fast moving forest conflagration.

All the phenomena exhibited by this fire are familiar to the experienced forest fire control officer. The area burned was much smaller than that of several historic fires of the past in this region, and no homes were burned, and no lives were lost to the flames. Nevertheless, in several respects the Sundance Fire was a unique combination and its documentation by a research team headed by Hal E. Anderson of the U.S. Forest Service's Northern Forest Fire Laboratory is equally so. It was the costliest fire in forest fire fighting history, and it burned with blowtorch intensity, for most of its turbulent run. At 8:00 p.m., September 1, it reached a peak heat output of nearly one-half billion Btu per sec (Fig. 1) and a fire intensity of 22,500 Btu per sec per ft of fire front. Consequently, it created an unusually large contiguous area of total devastation.

It is customary for forest fire control agencies to review the natural history of each large fire and of the action taken to control it. Such reviews have several purposes. But because a large fire is always regarded as the acid test of the performance of personnel, the tendency is always to place primary emphasis on exactly what men did rather than on what the fire did. Anderson reversed this

* See also *FRAR 10*, 127 (1968).

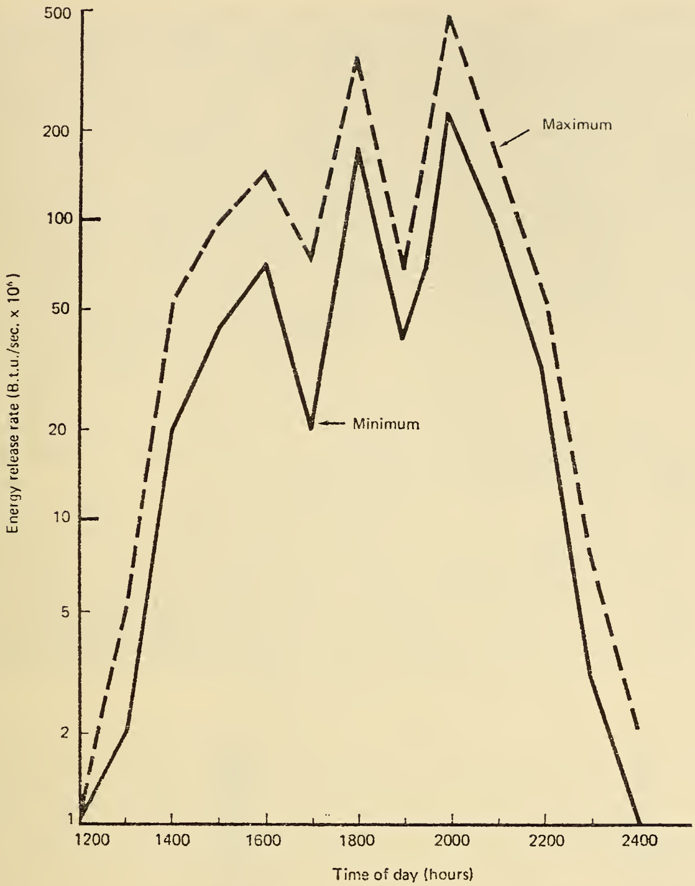

FIG. 1. Rate of energy release at fire front over a 12-hour period on September 1.

emphasis and undertook the difficult task of correctly establishing the conditions of the fire's environment and of documenting its behavior in some detail. Neglecting any effect of fire-fighting activities on the behavior of the fire was completely valid during its main run.

As recounted by Brackebusch, Chief of the Northern Forest Fire Laboratory in the Preface, an unusual number of observers in the vicinity of the fire made it possible for the team to draw heavily on eyewitness accounts to reconstruct the chronology of events in the fire's progress. By this process they developed a detailed map of the burned area, showing the position of the fire front at hourly intervals throughout the period of active spread. This was the source, too, of data for the general description of the movement and behavior of the fire front which was entitled "The Fire Story."

This is followed by a more detailed treatment of specific fire phenomena to which further field study contributed. This is presented as an hourly log of the fire's main run on September 1. Included in this log are five aspects of the fire's history consisting of hour-to-hour changes in the location of the fire front, changes in local weather conditions, in computed rate of spread of the fire (Fig. 2), in the specific fuels being consumed, and in the computed levels of fire intensity that prevailed.

Only a few general conclusions were drawn. These were that the spectacular run of the fire was the result of the combination of unusually dry fuels which were in quantities averaging close to 20 tons per acre and which had been subjected to severe drought conditions, of low humidities for over 72 hr, of increasing winds sustained for a period of 9 hr, and of the presence of a live four-mile fire front on the morning of September 1. It was also concluded that fire-storm characteristics induced by spot fires, which greatly stimulated the burning rate early in the day, also broke up the front and slowed further movement late in the day.

In terms of quantitative data the average rate of spread was determined to be from 1 to 6 miles per hr, the fire intensity built up to 22,500 Btu per sec per ft of fire front and the total energy release built up to 500 million Btu per sec. The convection column rose to 35,000 ft, winds induced by fire whirls exceeded 95 mph, and the numerous firebrands that set new fires were either lifted to 18,000 ft and transported by the prevailing wind or were carried by vortices produced by the wind blowing around the convection column.

The author concludes also that firsthand analysis of wildfire phenomena is profitable to the laboratory scientist in two ways. First, by providing an opportunity to apply laboratory findings to field situations by which their validity can be tested; second, to identify the poorly understood aspects of the various phenomena, which are in need of further research. In this context he specifically identified vortex generation, firebrand propagation, and spot fire ignition characteristics.

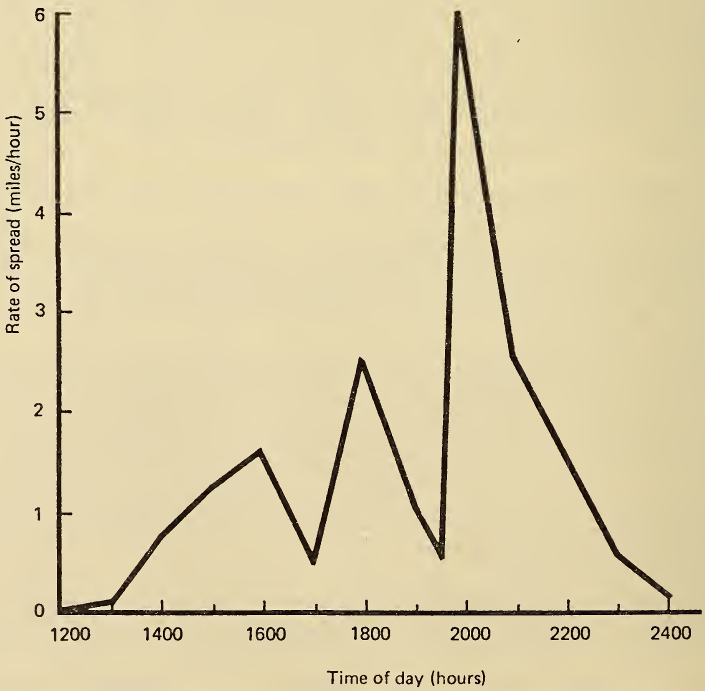

FIG. 2. Rate of fire spread during a 12-hour period on September 1.

To the practitioner and the fire scientist in other fields the value and need of case studies of this kind may have additional aspects. Interested public officials and administrators have already highly commended this report as a source of authentic information for many uses. Other scientists are likely to view a case study as an exercise in applied research with too little control or measurement of variables to produce worthwhile information. Actually, the most important scientific value of studying a once-in-fifty-year phenomenum such as the Sundance Fire has already been touched on by the author. It is in the opportunity it gives to test theories, to identify the unknowns, and to clarify the degree to which the phenomenum in question is understood. Even more dramatically it demonstrates the lack of any effect on fire behavior of conventional methods of fire control during the main run of a high intensity fire.

Baev, V. K. and Tret'yakov, P. K. "Characteristic Burning Times of Fuel-Air Mixtures," *Physics of Combustion and Explosions* 4(3), 367–376 (1968). In Russian.

Section: **G**

Subject Heading: **Burning times.**

Authors' Summary—Translated by L. J. Holtschlag

In the case of a fully-developed flow the flame of a homogeneous mixture can be described by a single criterion (for the given geometric system) containing the characteristic burning time, which is a quantity proportional to the ratio of the coefficient of thermal diffusion to the square of the normal flame propagation rate. The experimental arrangement and the method of determining the characteristic burning times of the fuel–air mixtures are described. The measurement results are given and tables are compiled for five fuels (methane, technical-grade propane and carbon monoxide, hydrogen, and B-70 gasoline) at atmospheric pressure in the temperature range of 20–300°C and at a variation of the excess air coefficient of from 0.65 to 1.70.

Baldwin, R. (Joint Fire Research Organization, Borehamwood, England) "Flame Merging in Multiple Fires," *Combustion and Flame* **12,** 318–324 (1968).

Section: **G**

Subject Heading: **Flame merging.**

F. R. Steward, Abstracter

This paper is concerned with determining a criteria for the merging of a number of individual flames into a single conflagration.

A simple theoretical consideration of a number of equally spaced fuel sources of equal size and strength is analyzed in terms of the entrainment requirements of each layer of flames as one proceeds inward. Merging of the individual flames into a single conflagration is assumed to occur when the inward directed pressure forces determined from Bernoulli's equation just balance the upward directed buoyancy forces produced by the hot burning gases. Merging will occur when one row of flames lean into those of the next inner row. The critical condition for such an occurrence was found to be given by the rather simple relation

$$S/D=f(L/D),$$

where S=the distance between sources, D=a characteristic dimension of an individual source, and L=the heighth of an individual flame. The function of L/D is not yielded by the analysis.

Experimental data from several sources in which a number of fires were observed to merge into a single conflagration are presented along with data taken in the author's laboratory using 1 ft^2 town gas burners of various configurations and separations.

It was found possible to correlate the various data according to the above relation. The boundary between merged and unmerged flames was found to be well represented by a straight line

$$S/D=0.22(L/D)^{0.96}$$

over the range of the data presented. However, all the data fall within the rather limited region of $2<S/D<9$.

Using the above relation it was shown that in order for merging of flames to occur in a situation where houses or blocks of buildings are the individual fuel sources the building density must be greater than 64 percent.

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de Ris, J. N. (National Bureau of Standards, Washington, D. C.) "Spread of a Laminar Diffusion Flame," *Twelfth Symposium* (*International*) *on Combustion*, Pittsburgh, The Combustion Institute, 241–252 (1969).

Section: **G**

Subject Heading: **Diffusion flame spread.**

F. A. Williams, Abstracter

In this paper two fire spread problems are formulated mathematically. Results of the mathematical analysis are given in the form of simple theoretical equations for the rate of flame spread. Discussions of the physical meaning of the results and qualitative comparisons with experiment are included.

The problems are both two-dimensional and concern a stationary condensed fuel which vaporizes and reacts with oxygen in the gas phase. A flame front is established in the gas and propagates along the surface by transferring heat to the nonvaporizing fuel ahead of the flame. The theory predicts the steady rate of flame propagation along a plane surface under the assumption that there exists a surface vaporization temperature below which no vaporization occurs and above which the vaporization rate would increase so rapidly with increasing surface temperature that the difference between the true surface temperature and the vaporization temperature can be neglected. The rate of the gas-phase reaction is assumed to be infinite so that the flame-sheet approximation can be employed.

Buoyancy is neglected, but a specifiable gas velocity parallel to the fuel surface is included, so that convective gas flow or buoyancy-induced entrainment can be considered in an approximate way. To facilitate solution, in addition to "constant-property" assumptions, it is postulated that this gas velocity is constant and that the convective flux of fuel normal to the vaporizing surface is negligible in comparison with the diffusive flux.

In the first problem (A), it is assumed that the condensed fuel bed is very thin and insulated on its nonvaporizing side, so that its temperature is constant across its thickness. Radiative heat transfer is neglected in this problem. The approximate formula obtained for the rate of flame spread is

$$V=[\sqrt{2}\lambda_1/(\rho_2c_2t)](T_f-T_v)/(T_v-T_0), \tag{1}$$

where λ is the thermal conductivity, ρ the density, and c the specific heat. The subscript 1 refers to gas and 2 to condensed fuel. The thickness of the fuel bed is t. The subscripts f, v, and 0 on the temperature T identify flame vaporizing surface and ambient conditions. There is some experimental confirmation of the prediction that V varies inversely with t and that V is independent of pressure and of gas velocity.

In the second problem (B), it is assumed that the thickness of the condensed fuel bed is infinite. Radiative heat transfer from the flame to the fuel surface is included in this problem, under the approximations that along the flame the radiant flux emitted is a constant fraction of the heat of reaction, that downstream from the flame the constant radiant flux R_2 is absorbed by the fuel surface, and that upstream from the flame the radiant flux absorbed by the fuel surface is $R_1 \exp(-x/l)$, where x is the upstream distance from the point of flame attachment and where R_1 and l are constants. If l is large compared with the heat conduction distance in the gas, then the formula obtained for the rate of flame spread reduces to

$$V=[V_1\rho_1c_1\lambda_1/\rho_2c_2\lambda_2(T_v-T_\infty)^2][T_f-T_v+R_1(l/V_1\rho_1c_1\lambda_1)^{1/2}+(2R_2/\pi V_1\rho_1c_1)]^2, \tag{2}$$

where V_1 is the specified gas velocity relative to the flame. In Eq. (2), λ_2 is the conductivity in the direction perpendicular to the fuel surface; V was found to be independent of the value of the fuel conductivity in the direction parallel to the fuel surface. As λ_1 approaches zero, Eq. (2) approaches a formula derived earlier for flame spread by radiant energy transfer. If correlations on buoyant fire plumes are used to relate V_1 to pressure, then the pressure dependence of V predicted by Eq. (2) in the absence of radiative transfer roughly agrees with some experimental observations.

The reviewer believes that these new results will be of interest to researchers engaged in studying fire spread. Also, the way in which the formulation was designed to reduce the system of equations to a Weiner–Hopf problem appears to be neat. For example, although convective and diffusive fuel fluxes are typically of the same order in this type of flow, the removal of the convective flux to maintain linearity should still provide results that are correct qualitatively. For the benefit of readers who are interested in following in detail the derivation given in the paper, it may be helpful to point out an error in transcription in Eq. (5); according to this equation, α_2 is the fuel–oxygen coupling function, but throughout the rest of the paper α_2 represents the fuel-temperature coupling function. It is stated that problem A is reduced to two simultaneous Weiner–Hopf integral equations which are solved using a substitute kernel, while problem B is reduced to three simultaneous Weiner–Hopf integral equations which are solved exactly. It is unfortunate that space limitations necessitated a four-sentence description of the derivation of the integral equations and their solution, since it is surprising that the more complex problem, with three equations and radiation included, can be solved exactly while the simpler problem, with two equations and no radiation, cannot. Apparently, the reason for this peculiarity can be ascertained only by consulting the author's 1968 Harvard University Ph.D. thesis. It would have been helpful if only the exact kernels and the substitute kernel had been given in the paper.

There is one aspect of the solution to problem B which the reviewer finds confusing. Physically, it would seem that one should obtain a well-posed problem if, instead of specifying the gas velocity V_1 in advance, one simply set $V_1 = V$. This merely states that the gas is at rest with respect to the solid. It is an attractive assumption because, under this condition, the assumption of constant V_1 would be most nearly valid. Under the constant-property assumptions, the condition $V_1 = V$ should be exact for flame spread in a quiescent zero-gravity environment. And since there is plenty of oxygen in the atmosphere for flame propagation to occur under these conditions, a solution should exist. Yet, if radiation is neglected and V_1 is replaced by V in Eq. (2), the propagation speed drops out of the formula and the equation reduces to a generally unsatisfied identity between properties that are presumed known. The physical reason for this is not clear to the reviewer.

A final general point, recognized by the author, concerns the validity of the flame-sheet approximation for flame spread. The theory possesses an infinitesimally thick flame which extends to an attachment point on the fuel surface. For situations in which radiant heat transfer is negligible, the gas-phase region that influences flame propagation is a volume with dimension of the order of the characteristic gas-phase heat-conduction length, centered at the point of flame attachment. Rates of heat transfer beyond this region are small and affect the propagation rate very little. But throughout this region the heat conduction will also cause flame quenching and reduce the reaction rate to such an extent that the flame-sheet approximation breaks down. Thus, a basic assumption of the theory is of questionable validity throughout the entire region of relevance to flame spread. Of course, the true problem is too difficult to solve, and the model problem should certainly yield results that are correct qualitatively in many ways. However, it would be interesting to study the effect of finite-rate gas-phase kinetics on flame-spread rates.

Lommasson, T. E., Miller, R. K., Kirkpatrick, R. G., and Keller, J. A. (The Dikewood Corporation, Albuquerque, New Mexico) "A 'Firestorm' Existence and Buildup Hypothesis," *Report to Defense Atomic Support Agency under Contract No. DASA 01-67-C-0008* (September 10, 1968).

Related Sections: **G**, *I*, *J*, *L*

Subject Heading: **Firestorm.**

Authors' Abstract

A hypothesis is developed relating the velocity of the radial inflow winds generated by large fires to the area and the energy release rate of the fires. The hy-

pothesis is applied to data from the Flambeau series of experimental fires. The wind velocities predicted by the hypothesis agree well with observed velocities.

A fire-induced-wind-aided-spread hypothesis is developed which indicates the existence of a critical value of the fire-induced wind velocity (for specific target area characteristics), above which the rate of spread is great enough that the severity of the fires increases with time. If the violent burning period of the structures is long enough such a situation may develop into a classical "firestorm."

Through the use of an initial fire model, bombing raid data, and information on builtupness, the initial fire-induced wind velocities are computed for certain German cities subjected to incendiary raids during World War II. The computed velocities clearly separate those German cities which developed into "firestorms" from those which remained "group fires," implying the existence of a critical velocity for the fire-induced inflow.

The effects of nonuniform distributions of fire power densities on the hypotheses are investigated, preparatory to eventual application of the existence and buildup hypothesis to fires caused by nuclear attack on target areas of varying characteristics.

The hypothesis, in its present stage of development, appears to provide a useful method for predicting "firestorm" occurrences with higher confidence than earlier estimating procedures.

Plant, J. and Barbero, L. P. (Safety in Mines Research Establishment, Sheffield, England) "Deflagration and the Transmission of Detonation in Certain British Mining Safety Explosives," *SMRE Research Report No. 258* (1969).*

Related Sections: **G**, *D*

Subject Heading: **Deflagration.**

Authors' Summary

Five British permitted explosives have been examined to assess the part played by some of their properties in determining the likelihood of deflagration occurring under practical conditions. The properties investigated were: readiness to transmit detonation across an air gap or dust barrier; propensity to deflagrate under various degrees of confinement when detonation has not been transmitted; and readiness to be initiated to detonation and the velocity of detonation when the density of the explosive has been increased. The ease with which increases in density can be produced by impact was also investigated. Readiness to transmit detonation from one cartridge to another across an air gap was found to be adequate in all the explosives provided that the explosive had not previously been compressed. In similar tests, when the donor and receptor cartridges were separated by a coal-dust barrier, there was no significant difference between the explosives. When the explosives were subjected to impact their densities were increased to values at which their transmission properties were seriously impaired. It was concluded, therefore, that under practical conditions the explosives would not differ signifi-

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cantly in their readiness to transmit detonation. Since a small amount of strata movement could prevent transmission of detonation under experimental conditions, the most significant factor in determining the likelihood of deflagration occurring in practice would be the explosive's inherent propensity to deflagrate. In the case of the five explosives examined, this was greater in the explosives with larger cellulose content.

Tyul'panov, R. S. and Alimpiev, A. I. "Experimental Investigation of the Combustion Stability of Fuel Droplets in a Turbulent Flow," *Physics of Combustion and Explosions* 4(3), 377–382 (1968). In Russian.

Section: **G**

Subject Heading: **Droplet combustion stability.**

Authors' Abstract—Translated by L. J. Holtschlag

The results of experimental investigations of the influence of various flow parameters (pressure, temperature, oxygen concentration) on the conditions of flame-out on fuel droplets moving at average flow velocity are outlined. It is shown that when the above-mentioned parameters and the droplet size are constant, the flame-out conditions are governed by the magnitude of the pulsation velocity. By generalizing the experimental data it was possible to obtain a relationship determining the possibility of combustion around a droplet in a turbulent flow which is analogous in form to Spaulding's relation for the flame-out condition on a sphere in a laminar flow. It was established that the value of the coefficient K depends to a great extent on the oxygen concentration and increases as the latter does. The results agree qualitatively with the conclusions of the diffusion theory of droplet combustion.

Edmondson, H. and Heat, M. P. (University of Salford, Lancashire, England) "A Precise Test of the Flame-Stretch Theory of Blow-Off," *Twelfth Symposium (International) on Combustion*, Pittsburgh, The Combustion Institute, 1007–1014 (1969).

Section: **G**

Subject Heading: **Flame-stretch theory.**

J. B. Levy, Abstracter

This paper is concerned with testing Reed's[1] proposal that the blow-off of aerated burner flames can be explained in terms of flame stretch in the stabilization region. The authors have carried out careful measurements of burning velocities of methane–air flames containing 0, 1%, 2%, and 3% methyl bromide. Blow-off rates were determined in a series of six burner pipes of copper, iron, and stainless steel having diameters ranging from 0.62 cm to 1.30 cm, by keeping the methane–methyl bromide ratios constant and increasing the air flow until blow-off occurred.

It was found that the boundary-velocity gradient at blow-off, $g_b = 4Q/\pi R^3$, where Q is the volumetric rate at blow-off and R the burner radius, varied in a smooth manner with the percent of methane and gave an individual curve for the uninhibited mixture and for each of the inhibited mixtures. According to Reed, blow-off occurs at a critical value of the Karlovitz flame-stretch factor K

$$K = (n_0 U)(du/dy),$$

where U = velocity of the unburned gas, and du/dy = velocity gradient, and n_0 measures the flame front thickness. When the experimental data were plotted it was found that blow-off did occur at a constant K value regardless of the inhibitor content. For lean flames, K was fairly constant. For rich flames, K increased rapidly. The increase of K for rich flames is discussed in terms of enhancement of the local burning velocity in the stabilization zone by secondary combustion.

References

1. Reed, S. B.: *Combust. Flame 11*, 177 (1967); Reed, S. B.: *J. Inst. Gas Engr. 8*, 157 (1968).

H. Chemical Aspects of Fires

Burgoyne, J. H., Cullis, C. F., and Lieberman, M. J. (Imperial College, London, England) "The Influence of Additives on the Reactions in Hydrogen-Chlorine Flames," *Twelfth Symposium (International) on Combustion*, Pittsburgh, The Combustion Institute, 943–955 (1969).

Related Sections: **H**, *D*

Subject Heading: **Hydrogen-chlorine flame additives.**

G. S. Pearson, Abstracter

The effects of a wide range of additives on the burning velocity of hydrogen–chlorine–nitrogen mixtures, burning both in air and in nitrogen, have been examined. As the additive may have a pronounced effect on stoichiometry, the results have been expressed in terms of the way in which the maximum burning velocity varies. This maximum burning velocity was obtained by optimizing the hydrogen to chlorine ratio to get the maximum value for a given amount of additive.

With flames burning in air all the additives showed inhibiting effects and shifted the position of maximum burning velocity from fuel-rich toward stoichiometric mixtures. The order of the inhibiting influence of the various additives studied was: n-butane > isobutane > ethane > methane > ethylene > acetylene > chloromethane > dimethylether > bromoethane. However, with flames burning in nitrogen, certain additives showed quite large promotional effects in the following order: bromomethane > deuteromethane-d_4 > chloromethane > methane > acetylene. The

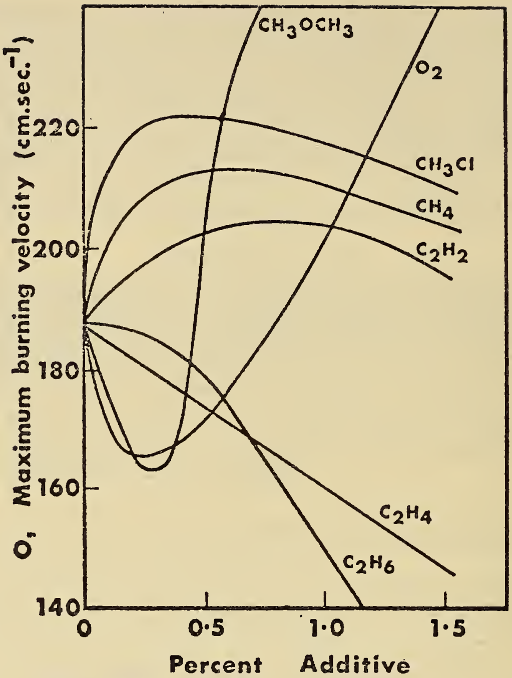

FIG. 1. Comparison of the effects of some additives on the maximum burning velocity for hydrogen–chlorine–nitrogen flames in a nitrogen surround.

position of the maximum burning velocity moved towards fuel-rich mixtures. Other additives (*n*-butane, isobutane, ethane, and ethylene) had only inhibiting effects and moved the position of the maximum burning velocity towards fuel-lean mixtures. The effects of some additives are shown in Fig. 1.

Additions of oxygen and of dimethyl ether caused initial inhibition followed by rapid promotion; the position of the maximum eventually showed a large shift toward fuel-rich compositions. The strong promotional effects are stated to be too great to result simply from an increase in flame temperature, although no temperatures are quoted, and it is suggested that the promotion is the result of the breakdown of the additives to yield chain-propagating radicals or the formation of chloro compounds which break down in a like manner. The observed reductions are regarded as being consistent with the fall in flame temperature (again no values are given) as a result of carbon radiation heat losses, since the addition of carbon containing additives is to produce initially a red tip and then soot formation.

Burning velocity data for a number of additives are presented graphically. Tabular presentation shows the percentage additive required for red or yellow tip and smoke formation.

The effect of air entrainment is shown to be pronounced—the maximum burning velocity for a hydrogen-chlorine flame with 30% nitrogen surrounded by air is 271 cm sec^{-1} (maximum at 67% H_2, 33% Cl_2) and, while surrounded by nitrogen, the maximum burning velocity is 186.5 cm sec^{-1} (maximum at 54% H_2, 46% Cl_2).

Fenimore, C. P. (General Electric Research and Development Center, Schenectady, New York) "Destruction of Methane in Water Gas by Reaction of CH_3 with OH Radicals," *Twelfth Symposium (International) on Combustion*, Pittsburgh, The Combustion Institute, 463–467 (1969).

Related Sections: **H**, *D*

Subject Heading: **Methane reaction.**

G. S. Pearson, Abstracter

The burned gases issuing from the primary reaction zone of fuel-rich hydrocarbon–oxygen flames often contain a little methane and acetylene and—if the mixture is rich enough—other hydrocarbons. This paper examines the rate of reaction of residual methane in the burned gas from fuel-rich methane oxygen flames. The flames were stabilized on a double, concentric, water-cooled, flat flame burner and were obtained by combustion of a mixture of composition X $CH_4+O_2+0.12$ Ar, where $0.9 \leqslant X \leqslant 1.1$. The burned gas was analyzed using a mass spectrometer and it was found that 1% to 3% of the fuel survived the reaction zone and decayed in the burned gas by a process first order in methane and with an activation energy (for the range 1970° to 2190°K) of about 115 kcal mole^{-1}. The decay could be expressed by

$$-d[CH_4]/dt = k\,K[CH_4][H_2O]/[H_2]$$

where k is a rate constant for the reaction of the actual reactants, and the term $K[CH_4][H_2O]/[H_2]$ is taken to represent the product of the concentrations of the actual reactants.

From consideration of rival mechanisms it is concluded that the most probable is that CH_3 and OH react with a rate constant of $2.6(\pm 0.3)\times 10^{12}$ cm^3 mole^{-1} sec^{-1} which is insensitive to temperature over the temperature range studied. The methane decays are a result of a shift in the equilibria

$$H+CH_4 \rightleftharpoons CH_3+H_2$$
$$H+H_2O \rightleftharpoons OH+H_2.$$

These results are shown to be in general accord with unpublished results previously obtained by Jones and Fenimore in which a greater range of $[H_2O]/[H_2]$ was obtained by adding carbon oxides to the reactant mixture.

Geyer, G. B. (Federal Aviation Administration, Atlantic City, New Jersey) "Extinguishing Agents for Hydrocarbon Fuel Fires," *Fire Technology* **5**, 151–159 (1969).

Related Sections: **H**, *E*, *A*

Subject Headings: **Extinguishing agents**; *Hydrocarbon; Fuel; Fires.*

G. S. Pearson, Abstracter

The extinguishing agents currently available for combating hydrocarbon fuel fires are reviewed prior to laboratory evaluation and subdivided into three groups, depending on their principal function in causing the extinguishing of aircraft fuel fires. No comparative data are presented in this paper. These groups are:

I. Foam vapor-securing and blanketing agents.
   (1) Chemical foam; bubbles filled with carbon dioxide from bicarbonate and acid in a foam stabilizer.
   (2) Mechanical foam; bubbles filled with mechanically entrained air in a dilute solution of foaming agent.

II. Auxiliary agents, used in conjunction with foam to accomplish various functions.
   (1) Dry chemical powders.
   (2) Liquid vaporizing agents.

III. New types of agents.

In Group I, chemical foam has only limited use for large aircraft fires, mainly because of the mechanical and logistics problems. Mechanical foam, however, is widely used and various types are considered:

(a) Protein base agents: Six percent type.
Federal specification O–F–555b. This will be used as a standard in the laboratory trials.

(b) Protein base agents: Three percent type.
No federal specification but currently used by U.S. commercial airports. Both of these are "low expansion" types with expansion ratios of 8:1 to 10:1.

(c) Fluorocarbon modified protein base agents. Six percent type (also three percent type).
Developed to achieve acceptable compatibility between protein foam agents and potassium bicarbonate base (Purple-K) powder conforming to MIL-F-2287A (WEP). The difference in compatability as determined by U.S. Naval Applied Science Laboratory and the Underwriters' Laboratories Inc. is discussed. Increased compatability results from gentle application, thus allowing the fluoro-carbon surfactants to aid development of the protective film. Gentle application is particularly recommended in crash fire fighting in all situations where potassium bicarbonate and fluoro-protein-type foams are used and this is achieved by using a fully dispersed foam pattern.

(d) High expansion synthetic foams.
These synthetic detergent (Syndet) agents have expansion ratios of 20:1. They have low radiant heat stability and drainage time compared to protein base agents.

(e) Ultra-high expansion foam.
Expansion ratios of 100:1 to 1000:1 can be obtained. It has spectacular fire extinguishing performance under certain fire test conditions but general use requires further study.

(f) Light Water.
25 percent, MIL–F–23905A (now obsolete).
6 percent, MIL–F–23905B (AS).
Light water foam acts by the aqueous fluorocarbon solution which drains from the foam having a lower surface tension than the fuel and thus spontaneously spreading and floating on the fuel surface.

In Group II there are five dry chemical powders used in large Class B fires:

(a) Sodium bicarbonate base (Foam Compatible CDC). MIL–F–19563 (AER).
(b) Potassium bicarbonate base (Purple-K). MIL–F–22287A (WEP).
(c) Monammonium phosphate base (All Purpose Type). MIL–F–23555 (WEP).
This is the only powder recommended for both Class A and Class B fires.
(d) Potassium chloride base (Super K).
Aimed to get maximum powder compatibility with regular protein base foams. It is currently being evaluated.
(e) Potassium sulfate base.
Currently in use in Europe but not in the U.S. Will not be included in laboratory program.

The liquid vaporizing agents have previously been assessed as to their relative efficiency in breaking the chain reaction responsible for hydrocarbon fuel combustion (Wright Air Development Center Technical Report 59-463, "A Study of Vaporizable Extinguishants"). These will be evaluated for compatibility with new types of foam.

Finally the new types of agents to be evaluated will be:

(a) Particulated gel foam.
This is a simple surfactant foam whose efficiency in extinguishing hot fuel fires is achieved by addition of a polymer which forms a particulate gel in the presence of water.
(b) Thin water by the manufacturer.
This is stated to be a Syndet base product similar to high expansion foams.
(c) Organ-O-Sil.
A combination of 90 percent water dispersed in a fog and 10 percent Aerosel R-972 (water absorbing silicone dioxide) produces an unwettable white powder (dry water).

All the above materials are to be evaluated using new or existing tests representative of full-scale conditions.

Halstead, C. J. and Jenkins, D. R. ("Shell" Research Limited, Thornton Research Centre, Chester, England) "Radical Recombination in Rich Premixed Hydrogen/Oxygen Flames," *Twelfth Symposium (International) on Combustion*, Pittsburgh, 979–987 (1969).

Section: **H**

Subject Heading: **Radical recombination.**

G. A. Agoston, Abstracter

This is a report of an experimental study of recombination rates of the radicals H and OH in the post-reaction zone of laminar rich premixed hydrogen/oxygen flames at atmospheric pressure. The data were interpreted in terms of the reactions

$$H+H+M \rightarrow H_2+M \quad (1)$$

$$H+OH+M \rightarrow H_2O+M \quad (2)$$

where M represents a third body such as H_2 or H_2O or a diluent X (i.e., N_2, Ar, He, and CO_2).

Consideration of the rates of disappearance of H and OH leads to the expression[1]

$$k_0([H_2]+K_6[H_2O])/2=A[H_2]^2+B[H_2]+C \quad (3)$$

where

k_0 is the observed recombination rate constant defined by

$$d[H]/dt=-k_0[H]^2;$$

K_6 is the equilibrium constant for $H+H_2O \rightleftharpoons H_2+OH$;

$A=k_{H,H_2}-k_{H,X}$;

$B=(k_{H,H_2O}+K_6k_{OH,H_2})[H_2O]+k_{H,X}(1-[H_2O])-k_{OH,X}K_6[H_2O]$;

$C=K_6[H_2O]^2k_{OH,H_2O}+K_6[H_2O]k_{OH,X}(1-[H_2O])$;

$k_{H,M}$ is the rate constant for Reaction (1):

$$-d[H]/dt=2k_{H,M}[H]^2[M];$$

$k_{OH,M}$ is the reaction rate constant for Reaction (2):

$$-d[H]/dt=-d[OH]/dt=k_{OH,M}[H][OH][M].$$

When dry steam is employed as a diluent, A, B, and C in Eq. (3) take the following forms:

$A'=(k_{H,H_2}+K_6k_{OH,H_2O})-(k_{H,H_2O}+K_6k_{OH,H_2})$

$B'=(k_{H,H_2O}+K_6k_{OH,H_2})-2K_6k_{OH,H_2O}$

$C'=K_6k_{OH,H_2O}$

One of the aims of this study was to determine the values of $k_{H,X}$ and $k_{OH,X}$ at three temperature levels. Measurements of k_0 as a function of $[H_2]$ lead to values of A, B, and C which, in principle, should permit evaluation of all the rate constants except k_{H,H_2O} and k_{OH,H_2} which appear in composite form. However, since $[H_2O]$ varies only slightly in flames diluted by X, this approach alone is inadequate. With dry steam as a diluent sufficient variation in $[H_2O]$ may be obtained, yielding values for A', B', and C' from which the values for k_{H,H_2}, k_{OH,H_2O}, and $(k_{H,H_2O}+K_6k_{OH,H_2})$ can be calculated. Once these three values are known, then an analysis can be made of flames with diluents X. Actually, when CO_2 is used, part is reduced to CO and, hence, a more complex expression applies. The equation is not presented because a complete analysis of these flames was not possible owing to the limited accuracy and reproducibility of the data.

In the study, a laminar-flow flat-flame burner was used having wall heating for additive steam applications and a motor-driven carriage for uniform vertical movement. The lithium/lithium hydroxide technique was used for determining [H]. Atomic absorption spectroscopy was used to obtain a continuous record of transmitted intensity of lithium resonance radiation as a function of distance from the reaction zone. The system was calibrated permitting the determination of [H] as a function of time in each flame.

Flames were studied containing the diluents N_2, Ar, He, and CO_2. Each diluent was employed in sets of 10 to 12 flames varying from slightly fuel-rich to very rich ($H_2/O_2 \sim 7$) and having flame temperatures of 1600°, 1800°, and 2000°K (±40°K). The diluent concentration in each set was varied along with that of the incoming hydrogen clearly in order to maintain isothermal flame conditions. Sets of steam flames were set up at 1840° and 1990°K.

The determination of the recombination rate constant k_0 requires that the plot of $[H]^{-1}$ versus time after leaving the reaction zone be linear. Close to the reaction zone there is distinct curvature suggesting the influence of hydrogen atom diffusion. For flames at 1600°K diffusion appears to be a prominent factor; these data were not studied further because of the complexity of the phenomena. Among the sets studied the differences in observed recombination rates of hydrogen atoms are fairly small. It is felt that there are no marked differences between H_2 and diluent gas molecules in their efficiencies as third bodies.

In the analysis of the steam flames no significant differences were found between the results at the two temperatures. The plot of $k_0([H_2]+K_6[H_2O])$ versus $[H_2]$ yields a poorly defined value for the curvature term A'. However, by using the value for k_{H,H_2} of 0.20×10^{-32} ml^2 molecule^{-2} sec^{-1} at 1915°K found by Hurle, Jones, and Rosenfeld,[2,3] the authors could fix a point at $[H_2]=1$ and thereby obtain a more precise value for A'. Thus they were able to calculate the following at the mean temperature of 1915°K:

$$k_{OH,H_2O}=2.4\times10^{-32}\ \text{ml}^2\ \text{molecule}^{-2}\ \text{sec}^{-1}$$

$$(k_{H,H_2O}+K_6k_{OH,H_2})=2.1\times10^{-32}\ \text{ml}^2\ \text{molecule}^{-2}\ \text{sec}^{-1}.$$

The data obtained from the sets of flames with diluents yielded corresponding sets of values for A, B, and C. The rate constant $k_{H,X}$ was calculated using the values for A and the adopted value for k_{H,H_2}. All eight results obtained, including the effective values for CO_2, fall within the range 0.38×10^{-32} to 1.7×10^{-32} ml^2 molecule^{-2} sec^{-1}. The rate constant $k_{OH,X}$ was evaluated from values for C and for k_{OH,H_2O} at 1915°K. These results fall within the range 1.2×10^{-32} to 2.4×10^{-32} ml^2 molecule^{-2} sec^{-1} except in the case of CO_2 where the value is less than $\sim0.5\times10^{-32}$. The results show a rather small temperature dependence, most differences falling within the factor-of-2 error estimate.

In a note added in proof, the authors report that their more recent work has shown that some of their measured recombination rates are too low because of neglect of the reverse dissociation reaction. Preliminary recalculation indicates that the result for k_{OH,H_2O} given above is too low. They promise to publish revised values for all rate constants.

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2. HURLE, I. R.: *Eleventh Symposium (International) on Combustion*, The Combustion Institute, p. 827, 1967.
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Hilado, C. J. (Union Carbide Corporation) "Smoke from Cellular Polymers," *Fire Technology* **5**, 130–139 (1969).

Section: **H**

Subject Heading: **Smoke.**

G. A. Agoston, Abstracter

This paper summarizes an experimental study of the Rohm and Haas XP2 Test (light absorption) for rating the density of smoke from burning (flaming) cellular polymers. In review, the author compares critically this test with the National Bureau of Standards smoke test, which provides measurement for both flaming and nonflaming (smoldering) conditions.

Tables are presented listing published smoke density ratings obtained in these tests and also in two other tests (not described), viz., Method of Test of Surface Burning Characteristics of Building Materials NFPA No. 255 (ASTM–E–84) and Standard Method for Surface Flammability of Materials Using a Radiant Heat Energy Source (ASTM–E–162).

The Rohm and Haas Test was chosen for study because of its relative simplicity and ease of operation. The test employs a cabinet measuring 30 in. high, 12 in. wide, and 12 in. deep, completely enclosed except for 1-in.-high openings around the bottom. The specimen is exposed to a propane–air flame from a Bernz-O-Matic TX-1 pencil-tip burner, applied at a 45° angle for a maximum of 4 min.

An initial series of tests was conducted to enable standardization of the procedure. Rigid urethane forms having different densities (3.9, 5.7, 8.5, 14.7, 22.3, and 31.5 pcf) were tested as were three types of wood (red oak, white pine, and fir) included for reference. Specimen size was varied for each material ($1\times1\times0.25$ in., $1\times1\times0.5$ in., $1\times1\times1$ in., $2\times2\times\frac{1}{2}$ in., $2\times2\times1$ in., and $2\times2\times2$ in.).

Measurements were made of the fraction of light absorbed by the smoke in the photometer path and the time required after ignition to reach maximum absorption. During a test, smoke particles often deposit on the lenses of the photoelectric system. Therefore, each time after the smoke had cleared, a measure of "residual light absorption" was made. In some cases the specimen did not burn completely. The degree of completion is reported as "percent weight loss".

The data show that the maximum light absorption, the residual light absorption, and the time to reach maximum absorption all increase with increase in foam density and in volume of the specimen of wood or polymer; whereas, the weight loss for the wood specimens tends to decrease. The weight-loss data for foam samples of 2 cu. in. and larger were not reproducible, owing to localized burn-through and haphazard fall of the remaining portions. The smaller foam specimens burned completely.

The 1-in.-cube specimen size was selected as standard for the following reasons:

1. This size is not too large for research materials in limited supply or for samples from small thickness applications; yet it is large enough to ensure adequate discrimination in maximum light absorption.
2. This volume permits adequate exposure to the burner flame and, hence, good reproducibility.
3. The cubic configuration eliminates possible differences in sample orientation.

Earlier work had shown that propane burner pressure variation over the range 20 to 60 psi yields no significant difference in temperature at the specimen location. In the present work, 40 psi was chosen as standard.

The author introduced a pan of water beneath the specimen support screen because certain polymer materials produce burning drops. This practice was followed in all the tests in order to reproduce the humidity conditions.

Using the above conditions, the author then tested a series of different cellular polymers, viz., polyethylene, phenolic, flexible and rigid urethane, flame-retardant flexible and rigid urethane, isocyanurate, polystyrene flame-retardant polystyrene, polyvinyl chloride, styrene–butadiene rubber, neoprene rubber, and flame-retardant neoprene rubber. In agreement with published work involving other procedures, the data show that the smokiest materials (e.g., cellular rubbers and polyvinyl chloride, and highly flame-retardant foams) produce higher smoke densities than untreated wood, while less smoky materials (phenolic and polyethylene cellular polymers) produce less.

The author points out that the smoke density for nonflaming (smoldering) wood is considerably greater than for flaming wood and that marked differences among flaming cellular polymers can even disappear under nonflaming conditions. Since both flaming and nonflaming conditions occur in actual fires, building codes should specify precisely which tests are to be followed.

Karim, G. A. (Imperial College, London, England) and **Singh, Ritinder** (Rols Royce, Ltd., Derby, England) "A Thermodynamic Investigation of the Combustion of Methane," *Journal of the Institute of Fuel* **40,** (321), 447–455 (1967).

Section: **H**

Subject Heading: **Methane combustion.**

P. Breisacher, Abstracter

One of the uses of natural gas is the production of "synthesis" gas ($CO+H_2$) from the properly controlled partial oxidation of methane. The final product concentrations will depend largely upon pressures and temperatures employed. This work has centered upon a computer study designed to isolate the optimum conditions of the conversion reaction. The assumption was made that thermodynamic equilibrium is attained, temperatures and pressures covered are 1200° to 2300°K and 1→100 atmospheres. Reactant concentrations (CH_4, N_2, CO_2, and H_2O quenchant additions) were also determined.

Results show that, at low temperatures and high initial CH_4 concentrations, very little CH_4 is found in the products. The effect is even more pronounced at high pressures. The percentage of CO_2 and H_2O in the products decrease as the temperature is raised. The proportion of CO and H_2 will rise under these conditions. The H_2/CO ratio will decrease as temperature rises.

When carbon is a product of oxidation (rich limit) the amount of synthesis gas produced is not a function of temperature. If the amount of CH_4 remaining after oxidation is very small, then the equilibrium compositions are a function of the water–gas shift reaction. The presence of a large amount of inert N_2 does not affect the product distribution when CH_4 is small. The actual flame temperature would, of course, be vastly different. The hydrogen to carbon ratio in the products can be altered by using different hydrocarbons. The ratio $H_2/H{\cdot}C{\cdot}$ can be altered by adding H_2O, H_2, CO, or CO_2 to the reactant mixture. The equilibrium composition will depend only on the hydrogen to carbon ratio and not on the compounds which make up the feed gas. Increasing the proportion of H_2 and H_2O on the products reduces the CO and CO_2 concentrations. The quantity of synthesis gas produced is increased.

The data on temperature rise following combustion of CH_4 were computed from a program devised by National Aeronautics and Space Administration.[1] Each temperature change was noted for different initial temperatures, pressures, and initial composition.

Reference

1. Zeleznik, F. J. and Gordon, S.: A General IBM 704 or 7090 Computer Program for Computation of Chemical Equilibrium Compositions, Rocket Performance and Chapman-Jouguet Detonations, NASA-TN-D-1454, October 1962.

Saito, Fumiharu (Building Research Institute, Tokyo, Japan) "Smoke Generation from Building Materials of Organic Substances," *Bulletin of the Fire Prevention Society of Japan* 18(2), 9 (1969).

Related Sections: **H**, *I*

Subject Heading: **Smoke generation.**

Tosiro Kinbara, Abstracter

The paper consists of two parts, the first concerned with the smoke generation ability of various organic building materials heated in an electric furnace, and the second with the intensity of smoke rising from the internal combustible lining of a box having an open window on one side.

In the first study, smoke emitted from a burning material was conducted to a room of volume V and the attenuation coefficient of light C_s through the room was measured. The smoke quantity C in this room was defined as the product C_sV.

On the other hand, C was found to be proportional to the weight loss W of the sample, the proportional constant K being related with the ambient temperature (absolute scale) as follows:

$$K = A - BT^n,$$

where A, B, and n are constants depending not only on the material, but on the mode of combustion, i.e., the smoldering or the flaming.

Much importance was attached to the rate of C increase dC/dt from the viewpoint of fire fighting and the constants in the following equation were numerically obtained for various kinds of materials.

$$dC/dt = (A - BT^n)(dW/dt) = (A - BT^n)W_0k_0 \exp(-E/RT),$$

where k_0 is the rate constant, W_0 the initial weight, and E the activation energy.

In the second study, a box 1.0×2.0×1.0 m, 0.5×1.0×0.5 m, or 0.5×0.5×1.0 m in size, having an opening (area A, height H) on a side was used. The inside walls and ceiling were made of combustible materials. It was ignited by a crib burning in it, and the smoke quantity and the weight loss were measured as before. The total area of walls and ceiling was denoted by A_s, that of the surfaces of crib elements A_c, and A_c/A_s was so chosen that it kept constant for various A_s.

Since it has been well known that the burning velocity is proportional to $A(H^{1/2})$, the relation between the burning rate (kg/min. m²) and $A(H^{1/2})/A_s$ was studied. When $A(H^{1/2})/A_s>0.5(m^{1/2})$, R and accordingly the smoke generation coefficient K keeps constant, but when $A(H^{1/2})/A_s<0.5(m^{1/2})$, R decreases with $A(H^{1/2})/A_s$. This was explained as the transformation of combustion mode from flaming to smoldering.

I. Physical Aspects of Fires

Atallah, S. (Arthur D. Little, Boston, Massachusetts) **and de Ris, J. N.** (Factory Mutual Research Corporation, Norwood, Massachusetts) "Pressure Rise due to a Fire in an Enclosure," *Fire Technology* **5,** 112–121 (1969).

Section: **I**

Subject Heading: **Enclosure fires.**

H. M. Cassel, Abstracter

Equations for the time-dependence of temperature rise and pressure rise due to the reaction of pure oxygen with cellulose in a closed system are derived under the following simplifying assumptions:

1. The enclosure is impermeable to heat.
2. No heat is lost to incombustible contents.
3. CO_2 and H_2O are the only combustion products.
4. Water vapor does not condense.
5. The volume of the fuel is negligible in comparison to that of the enclosure.
6. The fuel is uniformly distributed so that oxygen gains easy access to all combustible material.

The deductions as presented suffer from confusing statements. According to

$$H=C_v(N+5m/162)(T-T_0)/m, \quad (1)$$

where C_v = average molar specific heat at constant volume, m = mass of burned fuel, T = temperature of gas mixture at any time t, N = number of moles of O_2 at zero time. Thus, H appears as the enthalpy of the gas at time t. On the other hand, according to the "Nomenclature," H = the heat of combustion of cellulose at T_0 in cal/g. Obviously, the latent heats of vaporization and pyrolysis have not been taken into account.

Several suggestions are brought forward to support an exponential time-dependence of the rate of reaction:

$$\dot{m}=k_4 \exp(k_5 t) \quad (10)$$

Consequently,

$$m=(k_4/k_5)(\exp(k_5 t)+1)+m_0.$$

However, the authors arrive at

$$m=m_0 \exp(k_5 t) \quad (11)$$

Unfortunately, they are not familiar with Semenov's[1] more reasonable treatment of thermal explosions, which is based upon the equivalence of $\dot{m}=k_0 \exp(k_1 t)$ and $\dot{m}=k_0+k_1 m$, where k_0 refers to a process preceding the explosion and continuing during its development.

In comparing available experimental data with the exponential rate law the authors find encouragement (1) in the result of Botteri[2] whose data for the pressure rise in a closed chamber due to the combustion of cotton in oxygen can be represented by the equation $m=0.3 \exp(0.35t)$, and (2) by the *Report of the Apollo Accident*[3] which indicates $m=3.1 \exp(0.39t)$.

References

1. Semenov, N. N.: *Some Problems in Chemical Kinetics and Reactivity*, Vol. 2, p. 106, Princeton University Press, 1959.
2. Botteri, B. P.: Fire Protection or Oxygen-Enriched Atmosphere Application, *Fire Journal 62*, 48–55 (January 1968).
3. "Origin and Propagation of Fire," *Report of Apollo 204 Review Board, Panel 5, Appendix D-5, Enclosure 5-8*, U.S. Government Printing Office.

Butcher, E. G. and Fardell, P. J. (Joint Fire Research Organization, Borehamwood, England) **and Jackmann, P. J.** (Heating and Ventilating Research Association, England) "The Prediction of the Behavior of Smoke in a Building Using Computer Techniques," *Joint Fire Research Organization Fire Research Note 754* (February 1969)

Section: **I**

Subject Heading: **Smoke behavior, movement, spread.**

Authors' Abstract

A method is described for calculating the movement of smoke in a building caused by a fire in one or more rooms, using a digital computer. The density of the smoke, as well as the smoke spread, can be estimated

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Lee, Shao-Lin and Garris, C. A. (State University of New York at Stony Brook, Stony Brook, New York) "Formation of Multiple Fire Whirls," *Twelfth Symposium (International) on Combustion*, Pittsburgh, The Combustion Institute, 265–273 (1969).

Related Sections: **I**, *J*

Subject Heading: **Fire whirls, multiple.**

S. J. Ying, Abstracter

This paper presents interesting results of the study of the formation of multiple fire whirls. Multiple fire whirls were formed through experiments and a critical dimensionless parameter was obtained through theoretical consideration.

The experiments were done carefully in a room with least ambient disturbance. Multiple fire whirls were formed from a controlled propane gas line fire which was placed between two parallel metal screen belts. During the transient period of the formation of multiple fire whirls, it was found that a fairly steady continuous flame must be established before the screen can be set in motion at a very low speed; under these conditions very little effect on the flame is observed. As the screen speed gradually reaches a certain critical value, the line fire breaks up into approximately equally-spaced fire whirls. The experiments were done for different propane flow rates ranging in steps from 0.042 1 bm/min to 0.169 1 bm/min and for screen speeds ranging from 0.8 ft/sec to about 4 ft/sec.

To understand factors controlling the phenomena, a theory was developed through stability consideration. The set of momentum and continuity equations were linearized by the perturbation method. A major parameter was obtained in the form of

$$\mathrm{Re}/B^{1/5},$$

where $\mathrm{Re} = U_s L/\nu$ is Reynolds number, B is the dimensionless buoyancy parameter, U_s the screen speed, L the half distance between screens, and ν the kinematic viscosity. From the experiments, it can be easily seen that the phenomena are controlled by two important factors: the screen speed and the fuel burning rate. Since Re is related to the motion of the screen and B is related to the burning rate of fuel, the parameter found from the theory is certainly very reasonable. However, the exact power of B has only been established through this theoretical study.

From this study a few interesting points may be drawn:

1. Since $(\mathrm{Re})_c/B^{1/5}$ keeps almost constant as $B^{1/5}$ varies from 200 to 280, the vorticity required for developing fire whirls increases with buoyancy.
2. The space of the fire whirls increases with vorticity but decreases with increased buoyancy.
3. The behavior of the visible whirl height depends upon the vortex strength and the fuel available to an individual whirl:
   a. With a small fuel supply, whirl height is determined by the effectiveness of the fuel–air mixing, which is governed by the whirl vortex strength. The whirl height then increases with available vorticity, but decreases with increased fuel supply due to reduced circulation associated with a reduction in the characteristic spacing.
   b. With a large fuel supply, whirl height is governed by the quantity of fuel available to it. The whirl height, then, increases with both increased vorticity and with increased fuel supply.

J. Meteorological Aspects of Fires

Sando, R. W. (North Central Forest Experiment Station, U. S. Forest Service, St. Paul, Minnesota) "Prescribed Burning Weather in Minnesota," *Forest Service Research Paper NC-28* (1969).

Related Sections: **J**, *D*

Subject Heading: **Prescribed burning.**

Author's Conclusions

Some conclusions about the weather patterns affecting a program of prescribed burning in Minnesota are:

1. Northwest winds are the most common winds on days suitable for prescribed burning.

2. The average windspeed that can be expected at 1:00 p.m. is highest during April and May and lowest during July and August.
3. Northeasterly winds are the most variable and northwesterly winds the most persistent.
4. Low-velocity winds (less than 8 mph) are much more likely to change direction than are high-velocity winds.
5. There is a 70 percent probability that the windspeed on suitable days will be less than 15 mph and a 90 percent probability it will be less than 20 mph.
6. The probability of the occurrence of acceptable wind conditions is high, and unfavorable winds will generally not be the limiting factor in a successful burn.
7. From 25 to 40 acceptable burning days can be expected to occur in Minnesota each year; however, specific requirements may significantly reduce this number.
8. The months of July, August, and October are probably the best months for prescribed burning.
9. Suitable burning conditions occur most frequently in midsummer, and prescribed burning activity at this time will conflict the least with wildfire control activities.

K. Physiological and Psychological Aspects of Fires

Butler, C. P. (Naval Radiological Defense Laboratory, San Francisco, California) "Operation Flambeau—Civil Defense Experiment and Support," *Naval Radiological Defense Laboratory Report NRDL-TR-68-143, Office of Civil Defense Task Order DAHC20-67-C-0149, Work Unit 2536F* (18 February 1969).

Related Sections: **K,** *D*

Subject Headings: **Operation Flambeau;** *Escape Restraint Time (ERT); Fire tests; Life hazards.*

Excerpts from the Report

The Findings

Operation Flambeau, a series of large instrumented fires, has been initiated to solve this problem. Each of these fires is an array of fuel units, composed of 20 tons of pinyon trees, laid out in a geometrical pattern simulating the fuel distribution in a typical urban residential development. Intensity–time data were measured at street level for the principal causes of life hazards, i.e., oxygen depletion, carbon dioxide concentration, carbon monoxide concentration, air temperature, thermal radiation, street visibility and lachrymating gases.

The Escape Restraint Time (ERT) is the time interval during which a life hazard equals or exceeds some fixed threshold for deleterious effects on the human body. These effects are anoxia due to oxygen depletion, carbon dioxide asphyxia, carbon monoxide poisoning, intolerable thermal radiation, heat prostration due to high temperatures, loss of visual contact with the local environment due to low street visibility and temporary blindness due to lachrymating gases.

Two ERTs have been calculated for each hazard, one based on a threshold value for one hour survival and the second at a threshold value for one day survival, both at a continuous exposure. The hazards are listed in order of increasing severity.

Summary of Escape Restraint Times for Life Hazards in Flambeau Fire 760-12

	One Hour Threshold	One Day Threshold
Oxygen depletion	0 minutes	0 minutes
Carbon dioxide	0 minutes	5 minutes
Street visibility	60+ minutes	60+ minutes
Carbon monoxide	80 minutes	4+ hours
Air temperature	90 minutes	2 hours
Thermal radiation	3+ hours	3+ hours
Lachrymator gases	6+ hours	6+ hours

Measurements were made of street level life hazards in a 44 acre mass fire of burning pinyon trees laid out in a geometrical pattern simulating the fuel loading of a typical residential area.

The life hazards of anoxia due to oxygen depletion, carbon dioxide asphyxia, carbon monoxide poisoning, intolerable thermal radiation, heat prostration, loss of street visibility and temporary blindness from lachrymating gases were calculated on the basis of the Escape Restraint Time for one-hour and one-day threshold for survival.

The principal conclusion of this work is that the ERT's for the one-hour thresholds are all equal except for oxygen depletion and carbon dioxide. For the one-day threshold, the ERT's extend to 6+ hours, with carbon monoxide the most serious.

Brouillette, J. R. (The Ohio State University, Columbus, Ohio) "The Department of Public Works—A Community Emergency Organization," *Report under Office of Civil Defense Contract OCDOPS-64-66, Work Unit 2651-A* (December 1968).

Section: **K**

Subject Heading: **Public works departments.**

Author's Abstract

The typical department of public works is a highly bureaucratic, public organization responsible for designing, constructing, and maintaining city property and certain services to the general public. It possesses specialized disaster-relevant engineering and maintenance skills, extensive physical resources including large mobile equipment, and a fairly well-developed radio communication system. Its two major categories of personnel, maintenance and engineering, are geared for emergency as well as normal operation. Except in floods and hurricanes, most departments are not active in community warning and pre-impact activity. Rather, they become most heavily involved after impact and remain so until well into the rehabilitation phase. In all but the most stressful community emergencies, the department carries out its predefined emergency tasks with its normal structure. The pre-emergency links which the public works department maintains with other organizations serve as an important basis for the efficient passage of information, personnel, and resources crucial for the solution of disaster generated problems.

Finally, the department often assumes the role of "community coordinator" when the major demands on the community require engineering skills for their solution.

Gross, D., Loftus, J. J., Lees, T. G., and Gray, V. E. (National Bureau of Standards, Washington, D. C.) "Smoke and Gases Produced by Burning Aircraft Interior Materials," *National Bureau of Standards Building Science Series 11* (February (1969).*

Related Sections: **K**, *F*

Subject Headings: **Aircraft materials**; *Combustion products; Fire tests; Interior finish; Toxic gases.*

Authors' Abstract

Measurements are reported of the smoke produced during both flaming and smoldering exposures on 141 aircraft interior materials. Smoke is reported in terms of specific optical density, a dimensionless attenuation coefficient which defines the photometric obscuration produced by a quantity of smoke accumulated from a specimen of given thickness and unit surface area within a chamber of unit volume. A very wide range in the maximum specific optical density was observed. For the majority of materials, more smoke was produced during the flaming exposure test. However, certain materials produced significantly more smoke in the absence of open flaming.

During the smoke chamber tests, indications of the maximum concentrations of CO, HCl, HCN, and other selected potentially toxic combustion products were obtained using commercial colorimetric detector tubes. A study was made of the operation, accuracy, and limitations of the detector tubes used. Measurements of the concentrations of HCl were also made using specific ion electrode techniques.

Qualitative identification of the major components of the original test materials was accomplished primarily by infrared absorption spectrophotometry.

Pryor, A. J. (Southwest Research Institute, San Antonio, Texas) "Full-Scale Fire Tests of Interior Wall Finish Assemblies," *Fire Journal* **63**(2), 14–20 (1969).

Section: **K**

Subject Heading: Fire tests.

P. Breisacher, Abstracter

Investigations of several fires in homes located in the San Francisco Bay area showed several fatal conflagrations had occurred in houses where prefinished

* The work reported in this was sponsored by the Federal Aviation Administration, Washington, D. C. under Contract No. FA66NF-AP-7, Project No. 510-001-11X.

plywood had been nailed directly to the wall studs. As a result a proposal was made to require that the plywood material be backed by 0.5 in. noncombustible gypsum wallboard. The tests described were performed to determine whether this requirement really increased the safety level to the occupants of the structure.

Test structures were built of the two types of wall material. Furnishings, size, and initial conditions prior to ignition were identical. Temperatures and gas compositions were measured at various times. Thermocouples were located in all rooms at elevations 1 in., 1 ft, 5 ft, and 7 ft off the floor. Gas probes were at 1 ft and 5 ft elevations. One gas probe was placed 6 in. above the bed pillows.

In test No. 1, the interior wall was 0.25 in. prefinished select hardwood nailed over 0.5 in. gypsum wallboard. In test No. 2 the 0.25 in. hardwood was nailed directly to the studs.

Before testing, both temperature and wind velocity were checked in an attempt to have them as close as possible during each test. The relative humidity was not deemed significant. All furnishings were placed in identical positions and windows were opened to similar distances. The ignition crib of Douglas fir was lighted and the test-time start was noted upon full involvement of the crib. The end-point or limiting condition of the test was determined by the following: Temperature, 300°F; CO, 1%; CO_2, 12%; O_2, 7%.

Results showed both tests had a similar pattern with respect to temperature (limit-value). The peak was reached at about 7 to 9 min after ignition. The fire progressed to the bedroom with limiting value temperatures in 24 min. All data were taken with the bedroom door closed. An open bedroom door would probably have yielded similar buildup of limiting conditions. A series of flame-spread tests were separately performed with the two wall materials. The Standard ASTM E-84 surface burning test was performed. Results correlated with the full-structure test. The spread was nearly identical when plain plywood and backed plywood were used. The conclusion to be drawn is that gypsum backing to plywood wall materials does not alter the flame-spread conditions or contribute to enhanced safety. The 20 min delay in reaching life ending conditions in the bedroom (with door closed) seems to dictate that the need for an escape mechanism from this area of a structure is most important.

Stark, G. W. V., Evans, Wendy, and Field, P. (Joint Fire Research Organization, Borehamwood, England) "Toxic Gases from Rigid Poly (Vinyl Chloride) in Fires," *Joint Fire Research Organization Fire Research Note No. 752* (March 1969).

Related Sections: **K**, *H*

Subject Headings: **Toxic gases**; *HCl; Plastics.*

Authors' Summary and Conclusions

Tests have been made in a small compartment to examine the effect of the presence of PVC with a cellulosic fuel fire on the toxic gases evolved under different degrees of ventilation.

When the ventilation was small, as might be provided by a fanlight, hydrogen chloride was evolved from the PVC at a low rate, 30 min or more after the evolution of carbon monoxide from the cellulosic fuel, which occurred a few minutes after ignition. When the ventilation was larger, as might be provided by an open door, hydrogen chloride was evolved almost as quickly as carbon monoxide and in comparable amounts. When combustion of the PVC was complete, the hydrogen chloride evolved was equivalent to the chlorine content.

However, the amount of hydrogen chloride produced by the combustion of, say, a PVC wallpaper, would not add much to the toxic risk due to the carbon monoxide formed by the combustion of the cellulosic content of a furnished room.

Further tests are in progress to examine the effect of scale on the combustion processes and to test the feasibility of determining the rate of evolution of hydrogen chloride from the temperatures of surfaces within the compartment on fire.

The results of the tests reported herein suggest that, when a fire starts in a compartment of a building, the risk due to the evolution of carbon monoxide is an immediate one, but the delay in the evolution of hydrogen chloride from a compartment containing both cellulosic materials and PVC is significant only if the ventilation is low, for example, that provided by an open fanlight. If the ventilation is higher, for example, an open door, then the risk due to hydrogen chloride evolved from the plastic occurs soon after the emission of carbon monoxide, and the total quantity released is a proportion of the weight of the plastic present. For amounts of PVC as may be presented by a coated wallpaper, the amount of hydrogen chloride released should not materially increase the risk above that already presented by the carbon monoxide produced from the cellulosic contents of the compartment.

L. Operations Research, Mathematical Methods, and Statistics

Eggleston, L. A. (Southwest Research Institute, San Antonio, Texas) "Fire Defense Systems Analysis," *Report under Office of Civil Defense Contract N0022867-Cs787, Work Unit 2526B* (February 1969).

Section: **L**

Subject Heading: **Fire defense.**

Author's Abstract

Systems analysis principles are used to develop a hypothetical but not infeasible fire defense of a metropolitan area under nuclear attack conditions. This is defined as being equivalent to the Urbanized Area listed by the Bureau of the Census. The peacetime defense elements are reviewed together with their normal requirements and constraints. The system is then examined under nuclear attack conditions, with new requirements and constraints. It is concluded that, with citizen participation in thermal hardening, adequate commands, and appropriate procedures, there is a reasonable degree of fire defense possible in an attack situation.

Fry, J. F. (Joint Fire Research Organization, Borehamwood, England) "Fires in Post-War Multi-Storey Flats in London, 1966," *Joint Fire Research Organization Fire Research Note No. 751* (February 1969).

Section: **L**

Subject Headings: **Fires, in flats;** *Building, multi-storey; Fire statistics.*

Author's Abstract

As part of a continuing series of analyses reports of fires in post-war multi-storey flats in inner London have been studied. They show that the rates of incidence of these fires are lower than those in dwellings in general if fires in rubbish chutes are discounted; that fires start most frequently in kitchens (again discounting those in rubbish chutes); that fires in common service areas are frequently associated with accumulations of rubbish; and that most fires which spread beyond the room of origin are confined to the flat or maisonette in which they start.

There is little evidence of special escape or fire-fighting problems although two persons were rescued from one fire by turn-table ladder.

Hogg, Jane M. (Home Office Scientific Advisers' Branch, London, England) "The Siting of Fire Stations," *Operational Research Quarterly* **19**(3), 275–287 (1968).

Section: **L**

Subject Headings: **Siting of fire stations.**

A. W. McMasters, Abstracter

A computer solution procedure is described for selecting an optimal set of r fire station sites from a set of n possible sites ($n>r$) for a given geographical area where the frequency of fire calls does not change from year to year. The optimality criterion is the minimization of the sum of travel times to all fires by all engines over a specified period of time in the past. [The author used the word "pump" instead of "engine" in the paper when referring to the British fire-fighting equipment. The definition of a "pump," beyond meaning a pumper truck, must be deferred to the Home Office Fire Service.]

The solution procedure requires that a set of data on all fires over some specified period of time for the area in question be available. These data must have times and locations of fires as well as the length of time and the number of engines needed to suppress each fire.

Using these data the area in question is then divided into subareas in some manner with minimum size being one square kilometer. The details of how this might be accomplished are vague enough to let anyone use his own judgment. Topographical features and frequency of fires were suggested as influencing factors. The geographical location of a center of gravity based on the locations of all the fires which occurred within a subarea during the specified time period is then determined and all fires are assumed to occur at that point in the solution procedure.

A matrix of average minimum travel times between possible station sites and the centers of gravity of the subareas is then developed and includes the effect of daily traffic conditions on travel speeds.

Each possible station site is assumed to have a given fixed capacity in terms of the number of engines it can house. If a site is selected a requirement is imposed that the station be filled to capacity. The capacity of a particular site is to be determined by either the size of the existing facilities at a site or the largest sized station which could be built on sites having no existing facilities.

The solution procedure involves a computer replay of the fire demands which actually occurred over the specified time period. For a given set of r selected sites, equipment is sent from the selected site nearest a fire if it is not being used on another fire; otherwise equipment from the next nearest site is sent if it is available, and so on. The determination of the best combinations of r sites is apparently made by exhaustive enumeration of all possible ways of selecting r sites from the n possible. The description of the solution process is so obscure that it is not possible to determine if a more efficient procedure than exhaustive enumeration was developed.

In the paper, the solution procedure is applied to the County Borough of Bristol, England, and a list of optimal sites for $r=1$ to $r=9$ is presented. There were 19 possible sites with capacities varying from 2 to 9 engines. The time period used was the seven years from 1958 through 1964. The solution procedure was written in Algol for an Altas computer.

The Home Office Fire Service standards of fire cover were used to determine feasible r combinations from the optimal list. These standards are:

(a) Any fire call in an urban area should receive a response of three or four engines, with the first engine reaching the fire within five minutes;
(b) Any fire call in a rural area should receive a response of one engine within twenty minutes.

The optimal solutions given for $r \geq 3$ were feasible for the Borough of Bristol. For $r<3$ help from other counties would be needed.

The discussion section of the paper was devoted mostly to showing how the total trend time is reduced by increasing the value of r. No comment was made about the importance of the number of engines at a site. It was also interesting to see that there was no constraint on the total number of engines available to the Borough. It is hard to believe that no budget constraint exists limiting the total number of engines. The inclusion of such a constraint or the relaxation of the full-station requirement would result in possible alternatives such as one engine at each of the 19 sites.

Mention is made of the fact that minimizing total travel times subject to the fire standards of the Home Office is not the best optimality criterion and that if cost data were available a better criterion is the minimization of the total damage plus equipment and station maintenance costs.

The paper is quite vague about the whole solution procedure. Most readers will find it difficult to understand much more about the process than is described above. In addition, little annoyances such as a matrix product involving a $n \times m$ matrix and an $m \times n$ matrix ($n>1$) resulting in a scalar and an obscure statistical test regarding the time-varying pattern of fire incidence in subareas of Bristol (no null hypothesis is stated and no literature source is given) tend to discourage the reader from trying to ferret out what is hidden between the lines. Finally, no reference is made to possible useful existing theories and methods; for example, the papers by Hakimi[1] and Maranzana[2] on vertex medians of graphs should provide ideas for solution procedures which are more efficient than exhaustive enumeration.

References

1. Hakimi, S. L.: "Optimum Distribution of Switching Centers in a Communication Network and Some Related Graph Theoretic Problems," *Operations Research 13* (3), 462–475 (1965).
2. Maranzane, F. E.: "On the Location of Supply Points to Minimize Transportation Costs," *Operational Research Quarterly 15* (3), 261–270 (1964).

Martin, S. B., Ramstad, R., and Colvin, C. B. (URS Research Company, Burlingame, California) "Development and Application of an Interim Fire-Behavior Model," *Report under Office of Civil Defense Contract N00228-67-C-0710 through the Naval Radiological Defense Laboratory, Report NRDL-TRC-68-29* (April 1968).

Related Sections: L, *I*, *D*

Subject Heading: **Fire model.**

Authors' Abstract

This study involved the development of interim techniques for evaluating the incendiary damage to urban targets following a nuclear attack. The techniques were applied to two cities (San Jose and New Orleans). Following a survey of selected areas of these target cities, the distributions of initial fires resulting from specified, hypothetical attack were predicted and—on an hourly basis—the subsequent spread of fire throughout the cities was estimated.

It was found that the distribution of initial fires depends strongly on whether or not window coverings are drawn, whether or not the detonation is a surface burst, and the number of rooms exposed. Conditions following the hypothetical attack were compared with existing criteria for mass fire development and although a moving-front fire appears unlikely, firestorm conditions may be approached in the CBD.

Simard, A. J. and Valenzuela, J. M. (Forest Fire Research Institute, Ottawa, Canada) "A Computer Program to Analyze Differences in Simultaneous Wind Speed and Direction Measurements at Several Stations," *Forest Fire Information Report FF-X-18* (April 1969).

Related Sections: L, *J*

Subject Heading: **Wind measurements.**

Authors' Discussion

The computer program "WIND" was developed to statistically compare wind observations at a number of different stations. The basic assumption is that airport winds are a valid measure of the overall surface winds. There are provisions, however, for comparing observations at up to five airports at one time.

In fact, ideally the airport observations should first be compared with geostrophic wind measurements at 2000 to 5000 ft above the surface. This will determine whether or not measurements made at an individual airport are in fact representative of the general wind flow patterns. To do this, simply substitute the geostrophic winds for airport winds and airport winds for sheltered stations and follow the procedures described in this paper for comparing surface stations. This two-step procedure will allow the comparison of sheltered station winds with a true standard value.

Using airport winds as a base, the program compares the wind speed and direction as measured at any number of non-airport stations. The average wind speed and wind speed ratios of the two stations are computed individually in eight directions. The standard deviation, standard error of the mean and significance of the difference between the average wind speeds at the two stations is also computed for each direction.

With the data provided by the program, one can adjust wind observations at the sheltered station so that they are comparable to the observations at the airport.

The program is written in Fortran IVG language and requires 96K of core storage.

The approximate execution time on the IBM 360-65 may be determined by the following formula:

$$T=0.08(N-1)!+0.08n+0.02(n-1+0.07),$$

where T is the time in minutes, N the number of open stations, and n the number of sheltered stations.

As a rule of thumb, it requires about 0.1 min per comparison. Note that all open stations are compared with each other—hence, the need for a limit of five.

Takata, A. N. (IIT Research Institute, Chicago, Illinois) "Mathematical Modelling of Fire Defenses," *Report under Office of Civil Defense Contract N0022867C2081 through the Naval Radiological Defense Laboratory* (March 1969).

Related Sections: **L**, *G*

Subject Heading: **Fire defenses.**

Author's Abstract

This study involves the development of techniques to evaluate the effect of fire defenses on building fires caused by a nuclear burst and the incorporation of the fire-defense techniques in a fire-spread model. The resultant computer program allows evaluation of the effectiveness of various number of self-help teams, brigades and fire department units in suppressing and containing building fires scattered throughout a tract of several thousand buildings. Preliminary computations indicate that within a few hours about one-fourth of the manpower available in a tract can suppress all fires created by the initial ignition of one-half or less of the buildings. Most of the manpower, particularly those in the self-help teams, can be diverted to other activities after several minutes of effort. The preliminary results show that ordinary citizens with minimal instruction and training can bring about very pronounced reductions in the total fire damage.

Tolin, E. T., Davis, J. B., and Mandt, C. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Automated Forest Fire Dispatching—A Progress Report," *Fire Technology* **5,** 122–129 (1969).

Related Sections: **L,** *M, N*

Subject Headings: **Fire fighting;** *Automated systems; Computer technology; Systems analysis.*

K. M. Foreman, Abstracter

This paper concerns a prototype computerized dispatch system for combating forest fires. The system was employed during the summer of 1968 in the San Bernardino (California) County Ranger Unit area, with the objectives of determining the feasibility of the operating principles, better defining requirements, and developing a more sophisticated system.

The basic automated system requirements are to provide estimates of the time of arrival of fire fighters and recommend travel routes for the initial attack on a conflagration. In addition, the storage capacity and rapid data retrieval of computers should make possible instantaneous situation reports on the deployment and availability of active fire-fighting elements as well as direct tactical reserve units and those of cooperative organizations.

The prototype system utilized a commercial time-sharing service in which a large computer was connected by teletype lines to the dispatcher, who was located 70 miles away. Programming was developed prior to deployment of the system so as to permit normal language inputs and outputs at the dispatch terminal. The computational procedure is based on network theory in which forest roads or trails become links and each road intersection a node. Each node and fire-fighting crew or equipment has a code number which is referenced in the computer's output.

Where incomplete linkage exists to close out a path from a node back to itself, the network is a "tree." When all nodes in such a network can be reached by a linkage grouping, it is called a "spanning tree." The computer calculates and displays the minimum spanning tree for the most rapid and efficient routing of fire-fighting resources within a forest area comprising the network. Experience indicated that the average elapsed time from inquiry to computer print-out was almost $1\frac{1}{2}$ min; the desired time is about 5 sec. Much of the actual time was spent in contacting and typing input data to the computer. The prototype system also was used for updating fire-fighting inventories and scheduling equipment return. Thus, while more use was made of the prototype system than initially expected, the program became more costly than anticipated. At a cost of $100 per dispatch for a 15 to 20 acre fire, the unrefined prototype system was considered impractical although the automated dispatch concept was proven feasible.

Future directions for this effort are:

a. Improved computer programming;
b. Use of cheaper and more efficient computers;
c. Development of better output displays;
d. Improvement of models for fire spread, control and dispatch including economic factors;
e. Application of the system to a different type control area.

As a result of this demonstration program, a new application for automated systems has become apparent. This added use is for support dispatching in large forested regions where travel times for crews become relatively long and dispatchers cannot achieve intimate familiarity with the area.

N. Instrumentation and Fire Equipment

Heselden, A. J. M. and Griffiths, Lynda G. (Joint Fire Research Organization, Borehamwood, England) "Further Experiments with Wood Block Radiometers Including the Response to a Skewed Pulse of Radiation," *Joint Fire Research Organization Fire Research Note No. 747* (January 1969).

Related Sections: **N**, *I*

Subject Headings: **Wood block radiometer**; *Correlation; Damage; Radiation; Conflagration.*

Authors' Summary

Wood blocks of the kind used to make measurements at the Flambeau test fire 760–12–67 have been calibrated using a skewed pulse of radiation approximating to that measured in similar previous fires. The relation between damage sustained by the blocks and peak intensity were broadly similar to those for a constant intensity pulse except that with a skewed pulse having a peak intensity of about 2 W/cm^2 the behavior of the block was more variable.

The data obtained at the recent Flambeau fire 760–12–67 have been re-examined in the light of these new calibrations. The variation of peak intensity over the fire area was closely similar to that previously obtained when the incident intensity was assumed to be constant for a period of 20 min. Correlations were found, as before, between the peak intensities at various positions in the "streets" between the fuel piles.

Salzberg, F. (IIT Research Institute, Chicago, Illinois) "Feasibility and Representativeness of Large-Scale Boxcar Burns," *Report under Office of Civil Defense Contract N0022867C2716 through the Naval Radiological Defense Laboratory* (October 1968).

Section: **N**

Subject Headings: **Boxcar fires**; *Burning rates; Fire spread; Mass fires.*

Author's Abstract

This study deals with the feasibility of using retired boxcars for simulating urban area fires. Considerations are given to the representativeness of boxcars fires, development of an experimental plan, and a cost analysis.

It is shown that with some additional fuel, two wood-lined boxcars are adequate for simulating structural fires involving one story. Depending on the experimental site, the total related costs range from \$700 to \$1850 per boxcar.

An outline is given of experimental series designed to study various aspects of

urban area fires by means of boxcar fires. Included are studies of fire spread, development of group fires, and behavior of mass fires.

Senkevich, O. V., Grebtsove, A. S., and Goldovska, M. K. "A Portable Chromatograph for Use during the Extinction of Underground Fires," *Ugol' Ukr* **12**(10), 43–45 (October 1968). *SMRE Translation No. 5679.**

Section: **N**

Subject Heading: **Chromatograph.**

The instrument is a self-acting volumetric chromatographic gas analyser developed by the Central Scientific Research Laboratory of the Militarised Mine Rescue Service of the Donbass. With this it is possible to determine eight gas components entering into the composition of gases from an underground fire. The apparatus and its method of working are described. It is claimed that tests performed during rescue work have proved it to be effective and its performance is favourably compared with the standard OOG–2 interferometer.

O. Miscellaneous

King, N. K. and Vines, R. G. (Commonwealth Scientific and Industrial Organization, Australia) "Variation in the Flammability of the Leaves of Some Australian Forest Species," *Division of Applied Chemistry Paper* (July 1969).

Section: **O**

Subject Heading: **Leaf flammability.**

Authors' Summary with Appendix

Summary

We have tested the nonflammability of oven-dried leaves of a selection of species, and have sought to relate the nonflammability to leaf composition. It is not closely related to the concentration of any one element in the leaves but is related to the sum of the concentrations of all the mineral elements, especially to the sum of potassium, sodium, calcium, magnesium, phosphorus, and silicon. The effect of volatile essential oils on leaf flammability is discussed below.

The Effect of Volatile Oils

The effect of volatile oils was further checked in the flow calorimeter previously described by Pompe and Vines (1966).

Samples of oven-dried *Phytolacca octandra* would hardly burn at all in the calorimeter. However, if the same leaves were placed in a vacuum disiccator and stored in an atmosphere of eucalypt vapor (a mixture of cineole and fenchone), a small uptake of oil by the leaves was evident—approximately 3% by weight: these same leaves were then found to burn readily in the calorimeter. It is clear that their characteristics had been drastically changed by the presence of even very small

* Reprint of Safety in Mines Research Establishment Abstract. By permission.

quantities of oil. In the absence of oil, the oven-dried leaves merely smoldered slowly, but when oil was present flaming was pronounced and much more heat was evolved than could be accounted for by the burning of the oil alone: in fact, though the leaves of *Phytolacca octandra* did not burn completely, they behaved much more like leaves from a eucalypt.

Similar experiments with leaves of *Solanum auriculatum* and *Coprosma* also gave interesting results. The oven-dried leaves burned readily, and the heat evolved was comparable with that given out by a eucalypt; however, the presence of a small amount of oil led to more pronounced burning in the early stages of combustion even though the total heat output was not significantly increased.

The explanation of the effect of essential oils on burning, as put forward previously by Pompe and Vines, would therefore seem correct. The argument may be summarized thus:

1. (a) The heat of combustion of most oven-dried fuels (leaves, etc.) is a little more than 5000 cal/g when these are completely burned in a bomb.
   (b) Nevertheless, under natural conditions, the corresponding heat of combustion of even the most flammable fuels is reduced to $\simeq$4000 cal/g because burning is only partial—unconsumed carbon is left behind and smoke is produced.
   (c) Moisture in a forest fuel reduces the heat of combustion by a small amount; however, the presence of moisture has a far greater effect on the *rate* of burning, which is substantially decreased.
   (d) The heat of combustion of essential oils is about 9000 to 10,000 cal/g, but, since these are present in such small quantity, the heat of combustion of oil-containing fuels is still about 4000 cal/g under natural conditions.
2. The presence of water in leaves prolongs the burning time* and there is therefore a distinct difference in behaviour between "wet burning" and "dry burning." On the other hand, the presence of essential oils seems to cause a wet burning situation to become much more like a dry burning one: the amount of heat released is not significantly greater, but the rate of heat release is substantially more, just because much heat is given out in the early stages of combustion as the volatile oils are consumed. This then promotes combustion in even moist foliage which, in the absence of essential oils, could scarcely be made to burn at all.

If this is an accurate description of the effect of essential oils, daily ambient temperatures could have a greater influence on fire behavior in a eucalypt forest than might be expected from consideration of variations in fuel moisture content alone (cf. Pompe and Vines). On hot days, more oil vapor should be present in the atmosphere, and this could well produce *slight* changes in the burning properties of leafy fuels in tree crowns.

One further effect of ambient temperature is, of course, its influence on convective activity above a fire. Increased solar insolation plays an important part in the establishment of super-adiabatic lapse rates in the air over a fire, and the formation of a convective column is largely dependent upon this effect. In exactly the same way, the onset of a nocturnal inversion often damps down convective activity and leads to a reduction in fire intensity and flame height.

* Before flaming combustion is possible, the fuel must be heated beyond its ignition temperature: presumably one effect of the presence of moisture is to prevent rapid heating of the fuel while evaporation proceeds.

TRANSLATIONS

Kuznetsov, I. L. and Ignateuko, Yu. "Photometric Analysis and Calculation of a Plane Homogeneous Turbulent Flamejet," *The Physics of Combustion and Explosion* 3(1) 157 (March 1967).

Related Sections: G, *I*

Subject Heading: **Photometric analyses of turbulent flame.**

Translated by L. J. Holtschlag

In flames of homogenous hydrocarbon–air mixtures, the luminescence of the combustion products is negligibly small as compared with that of the reaction zone. It is possible in any case to use the difference in radiation spectra to record only the radiation that is characteristic of the reaction zone. For a plane turbulent flamejet, then, if the size of the reaction zone is small relative to the dimensions of the jet (a surface or microvolumetric model of burning), the luminosity of a certain point of the jet will be proportional to the probability density of the presence of a laminar front (surface model) or of a reaction zone (microvolumetric model).

Consequently, if normally exposed flame negatives as well as averaged streamlines in the combustion zone are available, it is possible to construct the probability density of the presence of reaction along the streamline, $p=p(L)$ (Fig. 1), providing the dependence of the density of negative blackening on the luminosity of the specimen is known. Averaged streamlines are relatively easy to obtain by tracing. Note that the dependence of the density of negative blackening on the luminosity of the specimen must be obtained using the flame to be studied as the source of illumination.

The physical completeness of combustion along a streamline will be determined by the expression

$$P(L)=\int_0^L p(L)\,aL.$$

This integral is defined by the area beneath the curve $p=p(L)$ (see Fig. 1) and varies from 0 (fresh mixture) to 1 (combustion products). By physical completeness of combustion is meant the fraction of mixture burned. Such a definition of the completeness of combustion differs from the time-averaged probability of the presence of combustion products at a given point if the expansion of the combustion products is taken into account.

Of course, the qualitatively obvious relation (1) was given as an experimental check. In doing so it cannot be considered sufficient to calculate P from the data of an inertial thermocouple, since the time-averaged heat content of the gas must be measured for the definition of P given above. But we do not know to what extent the indication of the thermocouple corresponds to this quantity. In our opinion the gas-analysis method is more reliable if, on one hand, the sample is extracted in such a way that the water-cooled gas sampler introduces minimum possible aerodynamic perturbations and if, on the other hand, a correction is

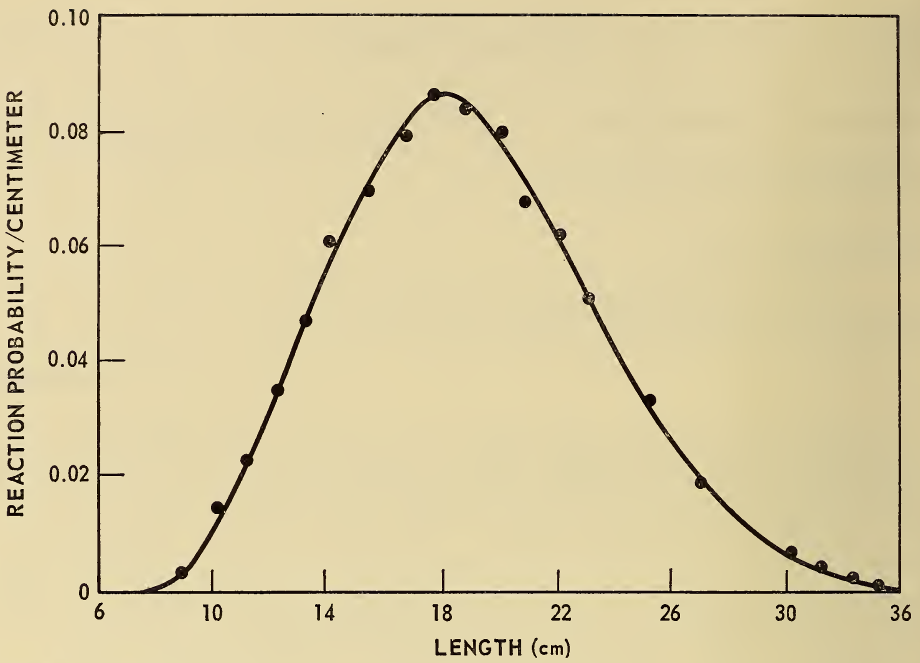

FIG. 1. Probability density of the presence of reaction along the streamline from the results of photometry.

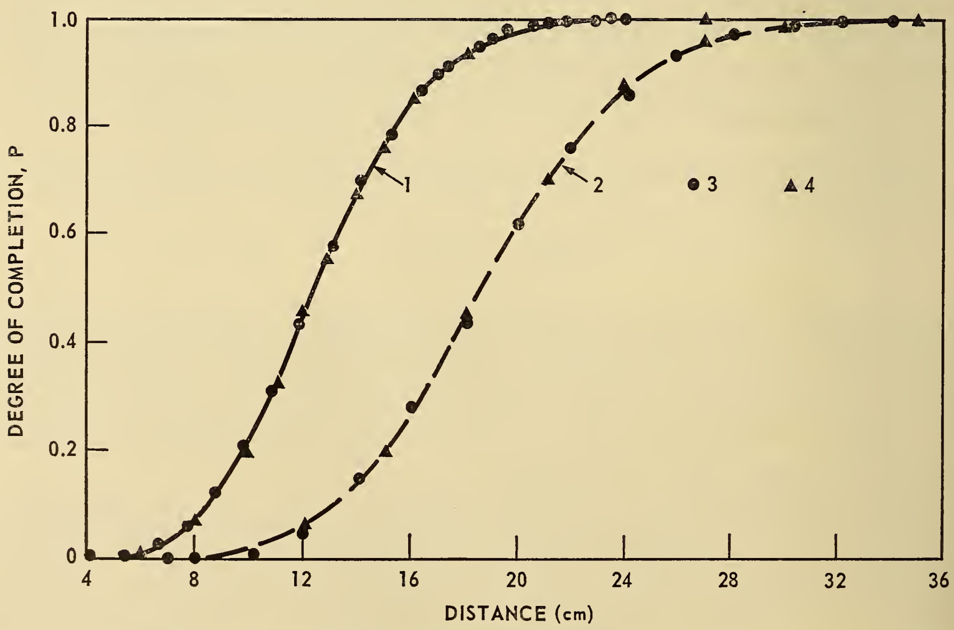

FIG. 2. Physical completeness of burning along the axis of the flame jet. 1—turbulizer, $\phi=5$ mm, 3.5% C_3H_8, $W=1.25$ m/sec; 2—ditto, $W=25$ m/sec; 3—photometry; 4—gas analysis.

introduced for the difference in rate pumping rates of the fresh mixture and the combustion products.

In our experiments the extraction rate was kept equal to the product of the mean velocity and the cross section of the gas sampler ($\phi=6$ mm), insofar as possible, and the correction for the difference in extraction rates was determined experimentally, amounting to about 87. The good agreement between these methods of calculating the physical completeness of combustion is evident from Fig. 2, where the values of P as computed by relation (1) and by the data of gas analysis for the two burning regimes are compared. Thus, calculation of P by photometric data is sufficiently accurate and is incomparably less laborious than by gas analysis.

By photometric analysis of the negatives of different flames with averaged streamlines traced on the negatives we computed the physical completeness of combustion along the streamlines and then drew up the boundaries of equal burnings. The experiments were conducted using a plane burner, 40-mm square, with various turbulence-generating screens; the turbulent characteristics of the cold flow (except for the turbulent scale) were studied in advance.[1] As the fuel we used propane–butane mixed with air of 3.5–5.5% per volume (stoichiometry$\approx$4%). The boundaries of even burnup for one of the regimes are given in Fig. 3.

By analyzing the boundaries of equal burnup we can see that, in all the experiments, the line $p=0.5$ differs but little from the straight parallel flow axis until appreciable combustion has occurred along the axis. On the other hand, analysis of the Toepler photographs shows that the outflow of combustion products from the combustion zone is so intense that the zone of mixing with the ambient air is sufficiently far away to neglect the probability that the ambient air reaches the combustion zone. If, to calculate P, use is made of a relation analogous in measuring to relation (22) of Ref. 2, it takes the form

$$P(x,\,y)=1-\tfrac{1}{2}\left\{\Phi\left[\frac{(a_0-b)-y}{\sigma(x)}\right]+\Phi\left[\frac{(a_0-b)+y}{\sigma(x)}\right]\right\}, \qquad (2)$$

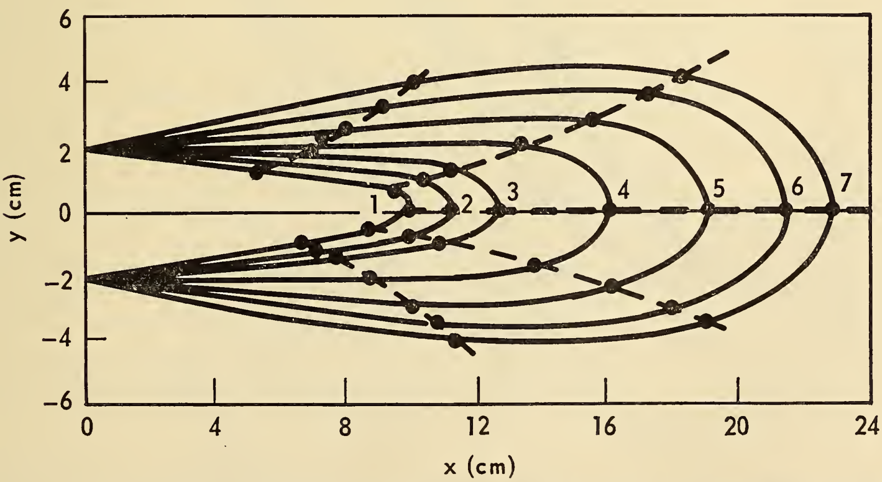

FIG. 3. Typical limits of uniform burning. Turbulizer, $\phi=2$ mm, 4% C_3H_8, $W=12.5$ m/sec. Degree of completion P: 0.02 (1); 0.05 (2); 0.12 (3); 0.50 (4); 0.82 (5); 0.95 (6); 0.98 (7).

where $\sigma^2(x)$ is the scatter of the distribution $p(x)$ in the transverse direction; a_0 is half the burner width; and $\Phi(\xi)$ is the tabulated probability interval.

The quantity $b=b(x)$, taking into account what was stated above, is close to zero until combustion has proceeded to an appreciable extent on the axis, equalling a_0 at the end of the combustion zone.

An attempt to compute the distribution of b in the combustion zone by the inverse procedure, on the basis of the experimental results (the dots in Fig. 4), led to a curious result: the distribution of G is very close to that of $a_0P(x, 0)$. Knowing the physical completeness of combustion on the axis of the jet, it is easy to find $b(x)$. Moreover, it can be seen that the distributions of these two quantities are seemingly shifted relative to each other by a certain quantity Δx, which is approximately the same in all experiments with the same turbulent generating screen. For a screen of rods of $\phi=2$ mm we have $\Delta x=1.9$ mm; of $\phi=5$ mm, $\Delta x=8$ mm; of $\phi=8$ mm, $\Delta x=14.4$ mm. This circumstance leads to a relation for computing $b(x)$ and $P(x, 0)$ at a known value of $\sigma(x)$;

$$P(x, 0)=1-\Phi\{[a_0-a_0P(x-\Delta x)]/\sigma(x)]\}. \tag{3}$$

By beginning the calculation with sufficiently small values of x, when combustion on the axis and, consequently, b are obviously very close to zero, it is possible to compute $P(x, 0)$ and $b(x)$ stepwise by relation (3) with a step of Δx.

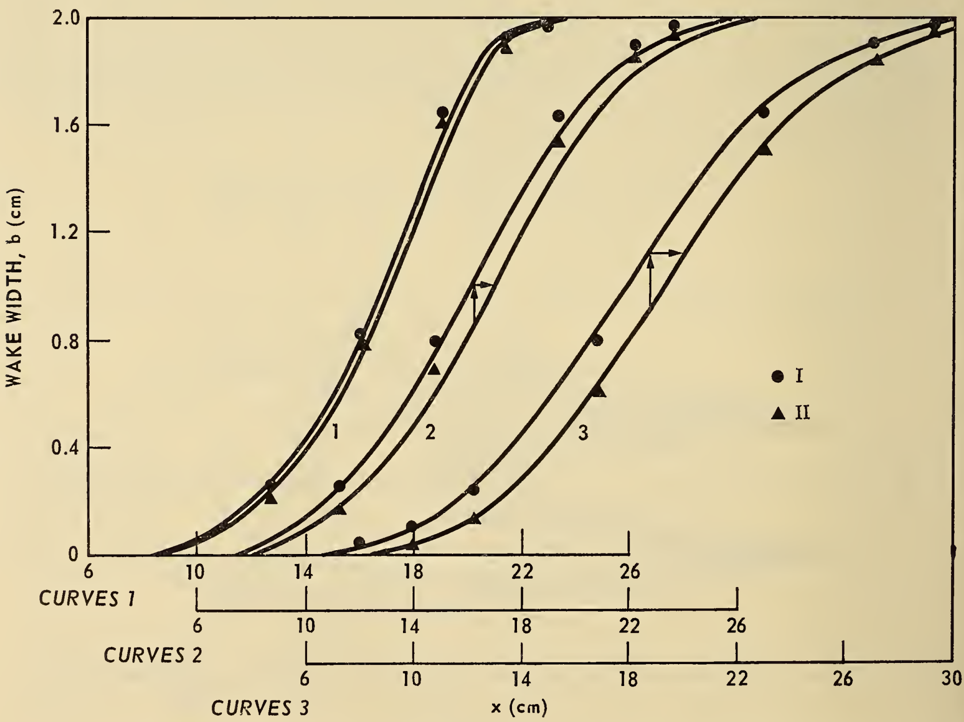

FIG. 4. Comparison of the distributions a_0P and b calculated from the experimental data [I, $a_0P(x)$; II, $b(x)$] and by formula (3). 1—turbulizer, $\phi=2$ mm, 4% C_3H_8, $W=12.5$ m/sec; 2—ditto, $W=19.6$ m/sec; 3—turbulizer, $\phi=8$ mm, 3.5% C_3H_8, $W=27.8$ m/sec.

The results of such a computation for three different combustion modes are also given in Fig. 4 (the arrows indicate the direction of calculation).

The quantity Δx, which has a strong effect on the extent and width of the combustion zone, is obviously a function of the turbulence scale. Since we do not have exact calculations of the latter, the form of this function remains unknown. Besides, on the basis of our experiments, it is not possible to deny categorically the existence of a weak dependence of Δx on the normal velocity, since the ranges of u_H in our experiments are not large (from 21 to 33 cm/sec).

In all the preceding calculations, σ was taken to vary linearly with distance from the burner exit plane:

$$\sigma = mx. \tag{4}$$

To compute the coefficient m we make use of the fact that b in relation (2) is close to zero for small values of the completeness of combustion along the axis. If, e.g., the coordinate $x_{0.02}$ is known, for which $P(x, 0)=0.02$, we get from (2)

$$\sigma_{0.02} = a_0/2.32, \tag{5}$$

where the number 2.32 is the argument of the tabulated probabilty integral, equalling 0.98. Accordingly, expressions (4) and (5) yield

$$m = a_0/2.32x_{0.02}. \tag{6}$$

On the other hand, the coordinate $x_{0.02}$ can be computed using the results of experiments on the rate of propagation of the forward edge of a turbulent jet,[1] in which the following relation was obtained:

$$u_T = ku' + [(E-1)/\sqrt{3}]u_H \cos\alpha + u_H, \tag{7}$$

where $\cos\alpha$ equals unity for sufficiently developed turbulence ($u' \gtrsim 2u_H$), and the coefficient k depends on which forward edge is recorded (from the combustion). The value of k turned out to be 1.6 for $P=0.02$. An approximate expression (accurate to within about 3%) is obtained for $x_{0.02}$ from simple geometrical considerations:

$$x_{0.02} = a_0[(W/u_{T0.02})^2]^{1/2} - 1. \tag{8}$$

Finally,

$$m = 1/2.32\left[\left(\frac{W}{1.60u' + [(E-1)/\sqrt{3}]u_H + u_H}\right)^2 - 1\right]^{1/2}, \tag{9}$$

where W is the mean flow rate; u' is the rms velocity pulsation over the length $x_{0.02}$; E is the expansion factor; and u_H is the normal velocity.

To compute the average value of u', it is necessary to have a graph of the dependence of the degree of turbulence on x, $\epsilon = \epsilon(x)$ (assuming that ϵ does not vary in the transverse direction in the core of the cold flow). Using the relation $\epsilon = \epsilon(x)$, as well as relations (7) and (8), it is easy to find $x_{0.02}$ and u' by the method of successive approximation.

Thus, the proposed calculation of a plane homogeneous turbulent flamejet consists of the following operations:

1. Calculation of the coefficient m from relation (9) using a graph of $\epsilon = \epsilon(x)$ and formulas (7) and (8):
2. Stepwise calculation of $P(x, 0)$ and b by (3);
3. Plot of $P(x_k, y)$ at various distances x_k from the exit plane by formula (2);
4. Construction of the boundaries of uniform combustion.

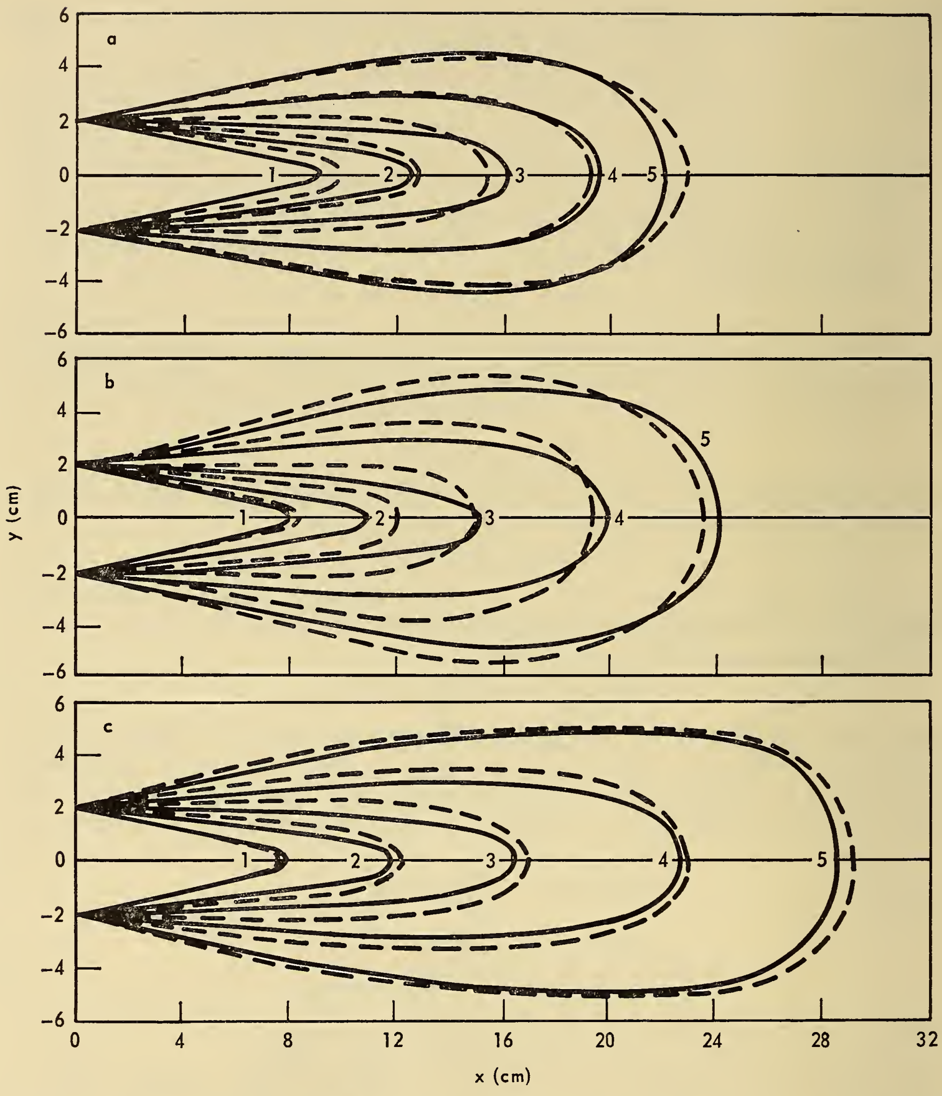

FIG. 5. Limits of uniform burning for the three different regimes (solid line—theoretical; dashed line—photometry). a—turbulizer, $\phi=2$ mm, 4% C_3H_8, $W=12.5$ m/sec; b—turbulizer, $\phi=5$ mm, 4% C_3H_8, $W=19.5$ m/sec; c—turbulizer, $\phi=8$ mm, 3.5% C_3H_8, $W=27.8$ m/sec. Degree of completion P: 0.02 (1), 0.12 (2), 0.40 (3), 0.82 (4), 0.98 (5).

Comparison of the computational results and the experimental data given in Fig. 5 shows completely satisfactory agreement for both the length of the jet and the shape of the boundaries of uniform combustion.

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2. PRUDNIKOV, A. G.: Izv. AN SSSR, OTN, Energetika i Avtomatika; No. 1 (1960).

Tyulpanov, R. S. and Sobolev, O. P. "Burning of a Polydisperse Jet of Liquid Fuel," *The Physics of Combustion and Explosion* **3**(1) 94 (March 1967).

Related Sections: **G**, *H*, *I*

Subject Headings: **Burning jet**; *Diffusion flames.*

Translated by L. J. Holtschlag

The process of disperse liquid-fuel combustion is of such complexity that all aspects of the actual physical phenomena must be taken into account in describing it. To determine a number of the integral characteristics, however, a simplified model of the combustion can be used, in which it is proposed that the burnup of a two-phase stream in injection heaters is governed by the process of vaporization of fuel droplets.[1,2] Given in these references are methods of analyzing combustion for various engineering applications either in the approximation of a monodisperse jet or in a more accurate approximation involving the consideration of several groups of droplets of a specific size.

As experimental investigations show, when a fuel is dispersed by centrifugal injectors the initial spectrum of the droplet diameter obeys a normal Gaussian distribution, usually written for such cases in the form of the Ragin–Ramlew law[3]

$$w=\exp[-m(r/r_{cp})^n\simeq\exp-(r/-r)^n,$$

where

$$\bar{r}=r_{cp}/(m)^{1/n}\sim r_{cp}.$$

Here, w is the weight of droplets of diameter greater than r; r is the diameter of the droplets; r_{cp} is the average weight diameter of the droplets; n is a coefficient characterizing the dispersion of the droplets (the greater the n the more uniform the size of the droplets); and m is a numerical coefficient, $m\sim0.7$.

By differentiating the distribution with respect to r, we get the number of droplets in the interval from r to $r+dr$:

$$dN=-dw/(\pi r^3/6)=-(6n/\pi)(r^{n-4}/r^{-n})\exp[-(r/\bar{r})^n]\,dr.$$

At the instant τ_i, the portion of droplets less than a certain r_i is completely vaporized, while the number of droplets of size greater than r_i remains constant. This condition is valid for the value of the Weber criterion at which the droplets are not broken up by the stream during the process of vaporization—that is, when the droplets travel in a subsonic stream at small values of the mean relative droplet velocity. Then we can write that the number of droplets greater than r_i will be constant:

$$N=\int_{r_i}^{\infty}(dN/dr)dr=\text{const.}$$

The amount of fuel that does not vaporize up to the given instant will be

$$S=\int_{r_i}^{\infty}(6n/\pi)(r^{n-4}/r^{-4})\exp[-(r/\bar{r})^n](\pi r_\tau^3/6)dr,$$

where r_τ is the radius of a droplet having the initial size $r>r_i$ at the instant τ.

To determine r_τ we make use of a solution for vaporization of droplets of a specific size which takes into account both the aerodynamic characteristics of the stream and the physical–chemical properties of the fuel[2]:

$$\tau = \frac{2}{a^4 b}\left[\frac{y^3}{3} - \frac{3}{2}y^2 + 3y - \ln y\right]_{y_\tau = 1 + a(r_\tau)^{1/2}}^{y = 1 + a(r^{1/2})}$$

where τ is the time it takes a droplet to vaporize from the size r to r_τ; $a = 2\sqrt{\epsilon w/\nu}$ is a parameter characterizing the aerodynamic properties of the flow. The parameter a multiplied by $r^{1/2}$ yields the running R_k (ϵ is the intensity of the turbulence, *an* is the velocity of the stream, and ν is the coefficient of kinematic viscosity); $b = \lambda(T_{\text{med}} T_k)/\rho$ liq.Q is a parameter similar in meaning to the coefficient of thermal diffusibility (λ is the coefficient of thermal diffusivity of the gas phase, ρ liq. is the density of the liquid, Q is the heat necessary to heat the fuel from the droplet temperature T_k to the temperature of the medium T_{med}).

The value of this parameter will vary weakly in a broad range of T_{med}. The value of $r_\tau = b(r, \tau)$ can be found by means of a graphic plot of the family of curves

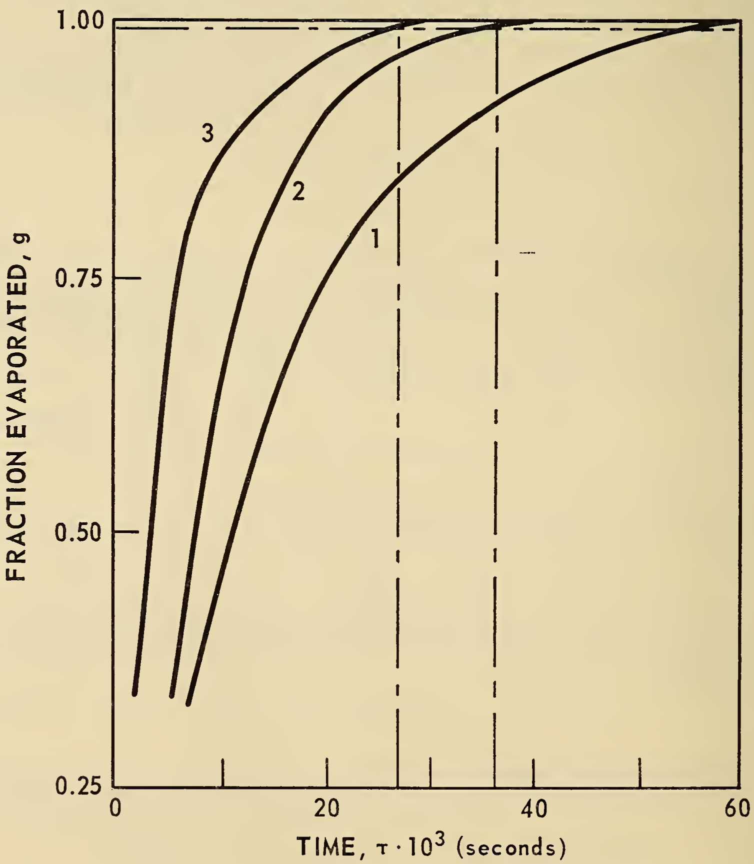

FIG. 1. Curves of the variation of $g = b(\tau)$ for $a = 300$ (1), 600 (2), and 1000 (3); $b = 0.35 \times 10^{-7}$, $n = 3$.

for a given value of a and b. The value S, which is a double integral in r from r_i to ∞ and in τ from 0 to τ, can be determined numerically.

Considering $r_\tau=0$ at the instant τ_i for particles with an initial diameter of $r<r_i$, the integration limits with respect to r can be varied from 0 to ∞ and the quantity of fuel vaporized up to the time τ_i is written as

$$g=1-S=1-\int_0^\infty \int_0^{t_i} n(r^{n-4}/\bar{r}^n)[f(r,\tau)]^3 \exp[-(r/\bar{r})^n]dr\, d\tau.$$

This relation is valid under the assumption that the principal limiting stage in the combustion of a polydisperse jet of liquid fuel is the process of droplet vaporization.

Calculations were made of the burnup, that is, $g=b(\tau)$ was determined for several values of $a=300$, 600, and 1000 ($m^{-1/2}$) for a value of $b=0.35\times10^{-1}$ m^2/sec, and $n=3$, and for several values of $n=2$, 2.5, and 3 with $a=300$ ($m^{-1/2}$) and $b=0.35\times10^{-7}$ m²/sec. The results of these calculations are given in Figs. 1 and 2. As is evident from these figures, the vaporization time is considerably reduced with increasing numerical value of the parameters a and n, which is, of course, obvious for physical reasons. The time of total vaporization (taken to be $g=0.99$) for various values of a, corresponding to various operating modes of stationary gas-turbine plants, is given in Fig. 3.

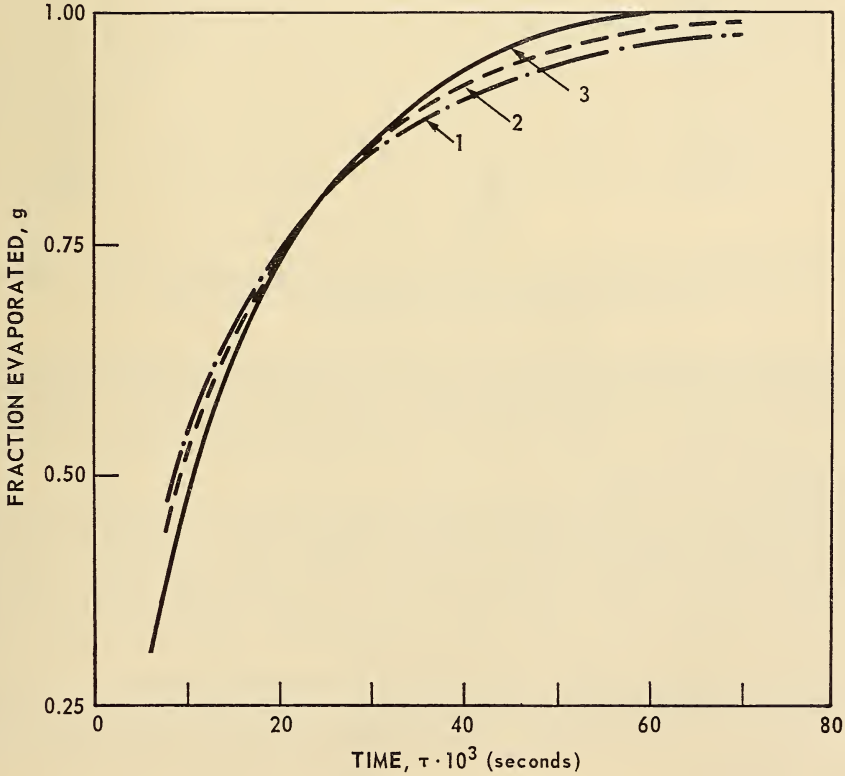

FIG. 2. Curves of the variation of $g=b(\tau)$ for $n=2$ (1), 2.5 (2), and 3(3); $b=0.35\times10^{-7}$, $a=300$.

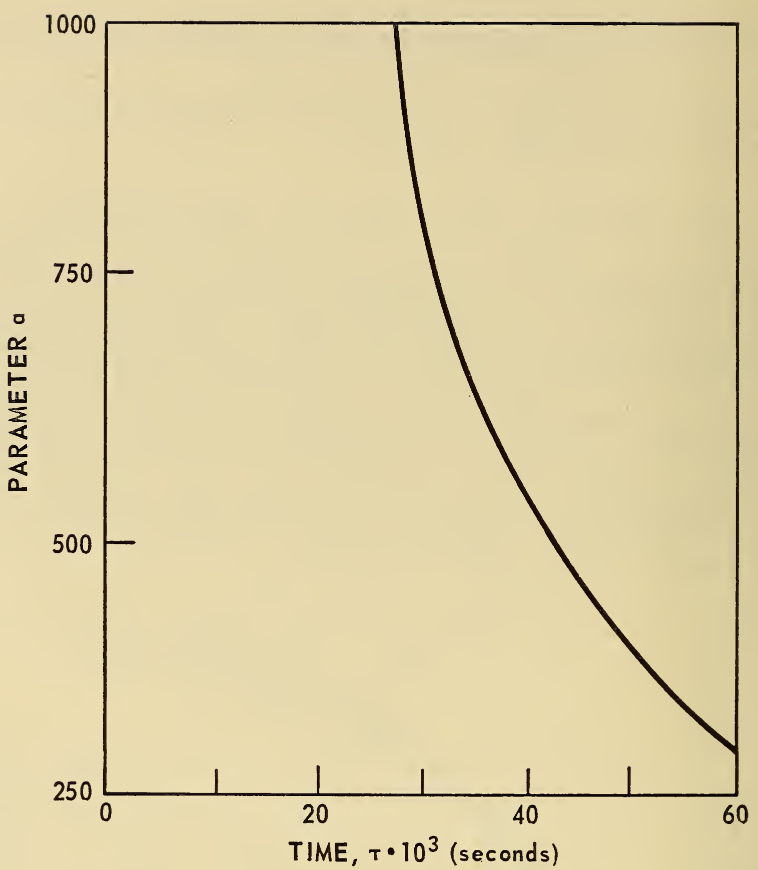

FIG. 3. Variation of the time of the complete evaporation of a polydisperse jet upon variation of the parameter a for values of $b=0.35\times10^{-7}$ and $n=3$.

Curve families can be plotted for other cases in the same way; from these curves it is possible to find the total combustion (vaporization) time for a polydisperse jet if the values of n, a, b, and $\bar{r}$ are known—that is, those quantities which govern the initial conditions, as well as the physical and physical–chemical properties of the medium and the fuel.

To make a check of this scheme for the total combustion of a polydisperse jet experiments were developed by the method of Ref. 2 on the combustion of several fuel jets in combustion chambers of various devices. Observed in Ref. 2 was a noticeable deviation of the experimental data for the theoretical curve obtained under the assumption of a torch with monodispersive properties. These experiments and a number of recent ones were developed in conformity with the arguments presented above for the calculation of the polydisperse nature of a jet in the form of the relationships $g=b(\tau/\tau_{rp})$ and were compared with the theoretical curve obtained for values of a, b, n, and $\bar{r}$, which are typical for this group of experiments (Fig. 4).

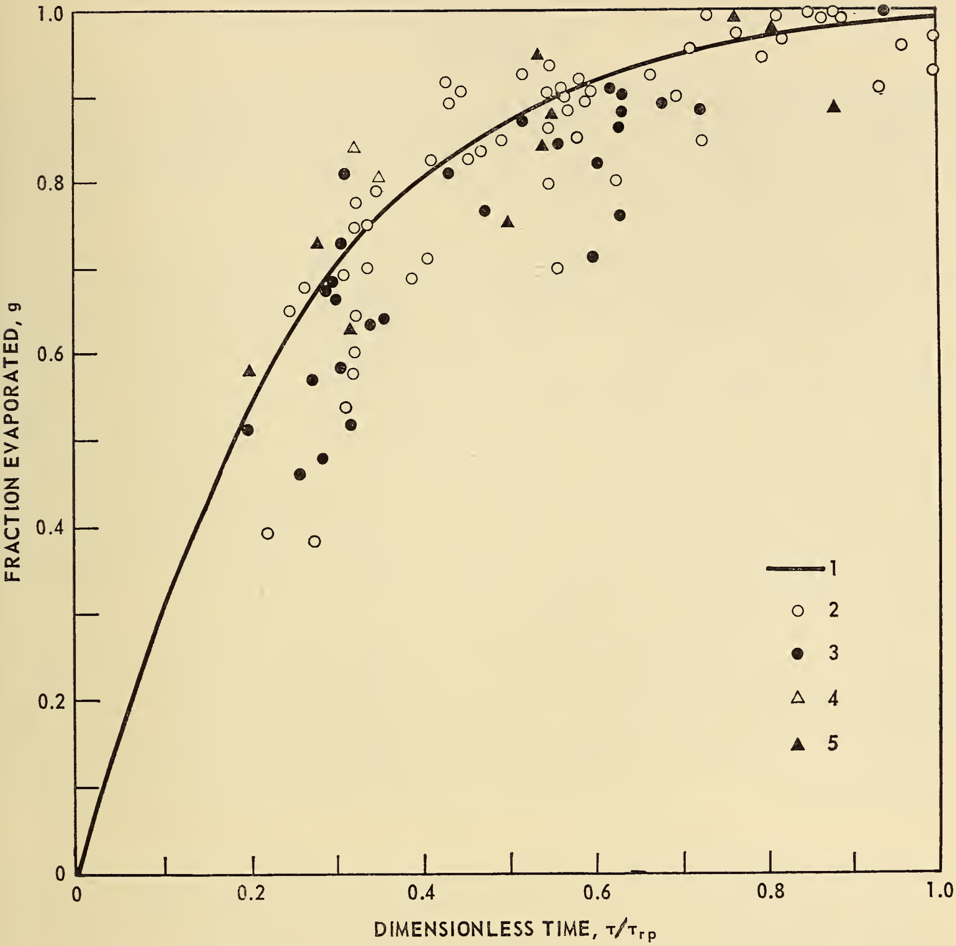

FIG. 4. Comparison of the theoretical relation of $g=b(\tau)$ with the experimental data: 1—theoretical curve ($a=600$, $b=0.35\times10^{-7}$, $n=3$); 2, 3, 4—recording chamber: $a=450$–750, $b=(0.26$ to $0.39)\times10^{-7}$; 5—turbulizing-grid chamber: $a=340$ to 550, $b=(0.28$ to $0.4)\times10^{-7}$.

As is evident from Fig. 4, good agreement is observed between the calculation and the experimental data. The scatter of the experimental points is explained by the errors incurred in measuring and averaging the quantities contained in the expressions for g and τ_{rp}, as well as by the scatter of a and b for the experiments compared with the calculation.

References

1. BURSTEIN, S. Z., HAMMER, S. S., AND AGOSTA, V. D.: *Detonation and Two-Phase Flow*, p. 243, Academic Press, N.Y.–London, 1962.
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3. LEONARD, A. S.: J. ARS *68*, 12–16 (1947).

BOOKS

Manual of Firefighting. Part III. Hydraulics and Water Supplies. (3rd ed., completely revised). Issued under the Authority of the Home Office, Her Majesty's Stationery Office, London, 1968. Available in the U.S. from Sales Section, British Information Services, 845 Third Avenue, New York, N.Y. 10022. Hard Cover: $3.40; Soft Cover: $1.30.

"To the student of fire engineering, a basic knowledge of hydraulics is of paramount importance in mastering the many problems involved in the use of water for firefighting. In this, the third edition of Part III of the *Manual of Firefighting*, the text has been completely revised and the chapter on hydraulics has been set out in a more logical sequence, including all formulae that a fireman may need when studying for promotion or to pass technical fire engineering examinations. At fires, simplified methods of calculation are required that will enable a fireman to estimate roughly, but very quickly, flows or pressures, or to say whether a water supply is sufficient to enable further jets to be supplied. Every effort, therefore, has been made to include as many as possible of such "fireground calculations." Appendices have now been included on graphs, logarithms, involution and evolution, and these have been conveniently grouped with all other formulae at the end of the book for easy reference."

[The Manual quoted above is an excellent elementary test, covering the essentials of fluid flow and details on hoses, pumps, and auxiliaries for the practical fireman. It includes an excellent summary of rules of thumb for field use. The material on hydraulics would be useful to any fireman and is presented in an elementary succinct manner. The material on water works and water relating applies specifically to British practice, but it still would provide a useful guide to an American reader.]

R. M. Fristrom, *Editor*

Fire Service Drill Book. (4th ed., completely revised). Issued under the Authority of the Home Office, Her Majesty's Stationery Office, London, 1968. Available in the U.S. from Sales Section, British Information Services, 845 Third Avenue, New York, N.Y. 10022. ($1.40).

This book is intended as a text for training fire officers and men. Coverage includes: squad drill and saluting; appliance drills on the use of hoses, pumps, water tenders, trailer pumps, and foam equipment; escape drills, various ladder drills, and fire boat drills. Tests are suggested for the various pieces of equipment and recommendations on the disposition of faulty gear. A short section on physical training is included. The book is completed by a miscellany including the tying of knots, signals, a list of abbreviations, and a glossary of 150 terms used in the fire service. The book is an excellent test. The treatment is elementary, but explicit and thorough. The illustrations are extensive and well chosen. The inclusion of a glossary and list of abbreviations should be most helpful for the novice. Although British and American equipment varies substantially in details, this outline of British practice is to be recommended for the many practical suggestions it contains and for serious comparison between American and British practice and training.

R. M. Fristrom, *Editor*

Fire Investigation by Paul L. Kirk. John Wiley and Sons, Inc., 605 Third Avenue, New York, N.Y. 10016 (1969) $8.95 255 pages.

This is a book written for the fire investigator and attorney interested in potential arson cases. Coverage is indicated by the chapter headings: 1. Introduction; 2. Elementary Chemistry of Combustion; 3. Nature and Behavior of Fire; 4. Combustion Properties of Non-Solid Fuels; 5. Combustion Properties of Solid Fuels; 6. Role of Pyrolysis; 7. Fire Patterns of Structural Fires; 8. Fire Patterns of Outdoor Fires; 9. Sources of Ignition; 10. Automobile and Boat Fires; 11. Clothing and Fabric Fires; 12. Practical Investigation of Structural Fires; 13. Arson; 14. The Legal Aspects of Arson; 15. Carbon-Monoxide Asphyxiation; 16. Explosions Associated with Fires; 17. Building Construction Materials. Appendixes: 1. Fire Experimentation; 2. Illustrations of Fire Origins.

The technical level is elementary, but the coverage and treatment is excellent and well adapted to the audience. Many fire research workers will find interesting material in the latter chapters on fire investigation and arson.

The author states: "It is the purpose of this volume to fill in some of these gaps—to explain the elementary technical considerations of the combustion processes, of fuels and of the investigative technique in simple enough terms so that the relatively untrained investigator or the attorney who must understand the implications of the investigation will be aided significantly. We cannot, as yet, expect all investigators to be sufficiently conversant with chemical principles so as to be able to apply them effectively nor can we expect all investigators to be expert in their operation. We can, however, hope to upgrade markedly the average performance as well as to increase the percentage of expert investigators. It is the author's hope that the information carried in this volume will assist in achieving these desirable goals."

The author has been reasonably successful in this objective. The book can be recommended as a well written introduction to the field.

R. M. Fristrom, *Editor*

JOURNALS

Combustion Science and Technology—Gordon and Breach, Science Publishers, Inc. 150 Fifth Avenue, New York, N.J. 10011

Irvin Glassman, Editor and William A. Sirignano, Associate Editor (Guggenheim Laboratories, Princeton University, Princeton, N.J. 08540)

"*Combustion Science and Technology* will provide for open discussion and prompt publication of new results, discoveries and developments in the various disciplines which constitute the field of combustion. The editors invite original contributions dealing with flame and fire research, flame radiation, chemical fuels and propellants, reacting flows, thermochemistry, atmospheric chemistry and combustion phenomena related to aircraft gas turbines, chemical rockets, ramjets, automotive engines, furnaces and environmental studies. In so doing, the editors hope to establish a central vehicle for the rapid exchange of ideas and results emanating from the many diverse areas associated with combustion. Included in CST will be full-length articles and short communications, unsolicited and solicited comments on published matter, and a yearly index. Several features formerly carried in *Pyrodynamics*, the *Journal of Applied Thermal Processes*, will be incorporated as well."

Publication Details: First issue: June 1969. Publication: bi-monthly. There will be no page charges to authors or institutions. Publication time for all material offered will be of the order of 8 weeks.

Subscription: Individuals: $19.50 yr. Libraries: $38.00 yr.

[We welcome a new or perhaps more precisely a revived member to the combustion literature. The coverage makes it of considerable interest to the fire research worker and the ideal of prompt regular publication is a very worthy one. We will follow the progress of *Combustion Science and Technology* with interest.]

R. M. Fristrom, *Editor*

MEETINGS

Conference on the Safe Use of Electrical Energy in Spaces where the Risk of Explosion Exists—Gottwaldov, Che. Scheduled 8–10 October 1968. Postponed to June 1969.

Some Aspects of the Design of Intrinsically Safe Circuits—D. W. Widginton

This report reviews the basic information usually available to the circuit designer, and then discusses the problems involved in the design of intrinsically safe circuits. Topics covered include the design of voltage-established dc and ac supplies; the design of inductive circuits, with and without protective shunts; and methods for assessing the effects of long interconnecting cables. A useful method of assessing the safety of certain circuits is to show that the circuit under consideration is less dangerous than another circuit, whose safety can be assessed in terms of the basic information available. Paper 26 (preprint, also published as SMRE Research Report No. 256). 6 refs., 7 figs., 1 table.

High Power Electric Arc in Flameproof Enclosures—M. Vidlička

The author discusses the electric arc as a source of hot particles for test purposes and compares various set-ups described in the literature as to their efficiency in igniting an explosive mixture. He further considers the igniting efficiency of particles after passing through clearances of different types. Paper 23 (preprint). In Czech and German. 14 refs., 16 figs., 2 tables. (From author's English summary.)

Overvoltage Measurements on Inductive Intrinsically Safe Circuits—B. Kolodzejski

The current tendency is to place more emphasis on methods for assessing intrinsic safety which do not require the use of special apparatus. This involves the measurement of electrical parameters (current, voltage, capacitance, inductance). Such procedures lead to a clearer understanding of the mechanism of ignition and provide a means of determining true factors of safety. In predominantly inductive circuits the arc voltage at the moment of circuit break is an important factor. A method for measuring the over-voltage produced at a circuit-break is described; this method can be used to assess the inductance of both air- and iron-cored inductors. This new method is compared with other methods of over-voltage measurement. Paper 9 (preprint). In Russian. 3 refs., 12 figs., 1 table.

Research in the Field of Intrinsic Safety and Automatic Protection in Gassy Atmospheres—V. S. Kravchenko, E. F. Karpov, and V. I. Serov

The relative stability of the ignition energy of discharges during the breaking of inductive and nonreactive circuits, and also the model produced based on the linear reduction of current in such discharges permit the calculation of an inductance of equivalent igniting capacity for complex inductive circuits (with iron cores or rectifier, linear and nonlinear shunts with shading rings) and their use for the evaluation of the intrinsic safety of complex circuits in accordance with the known characteristics of simple intrinsically safe inductive circuits. A mathematical method of evaluation is used for the design and testing of complex electrical circuits. The useful output of intrinsically safe sources of voltage, limited by short-circuit current, can be increased by means of a special shape of the load curve of the voltage source. An increase in the performance of i.s. systems can be achieved also by means of an artificial shortening of the period of discharge and the use of impulsive systems with a reservoir of energy. Explosive atmospheres are classified in the U.S.S.R. according to the size of the safe gap within the limits of four classes (CH_4, petroleum ether, $C_2H_4H_2$) which ensures uniformity of i.s. equipment and contributes to its wider use. New testing and research equipment in the U.S.S.R. includes a portable explosion chamber which is filled by an electrolytic apparatus producing a universal oxygen–hydrogen atmosphere with adjustable composition. A thermo-catalytic, low-temperature, platinum–palladium element, developed in the U.S.S.R., sensitive to methane, has made it possible to produce automatic continuous fixed methane analysers, type AMT–2, portable methane alarms, type SMP–1 and SS2, and to develop the combined methane relay TMPK–2. Paper 11 (preprint) In Russian. (From authors' English summary.)

The Use of Aluminium Alloys in Flameproof Apparatus—M. Trochta

A history is given of the use of aluminium alloys in flameproof equipment for mines, following the increased mechanization and consequent call for a reduction in weight and dimensions of such equipment. Some alterations to the design of various types of electrical apparatus which proved necessary as a result of the introduction of these new materials are described. Paper 22 (preprint) In Czech and German. 20 figs., 2 tables.

Report on Experiments and Results Achieved in Poland, Drawn Up on the Basis of First Experiences with an Increase of Voltage in One Section of the "Lenin" Mine at Wesola—A. Peretiatkowica and T. Trzcina

The supply in one section of the "Lenin" Mine is at 865 V and another section is being adjusted to this voltage. The opinion of the Central Mining Institute at Katovice on this problem is set out. Some comments are made on accident prevention and intrinsic safety. The apparatus and electrical equipment used in the experimental installation are described. The authors state the results of investigations of a number of electrical appliances and equipment. They discuss the conditions of operation of electric motors and the voltage losses during starting-up. Finally, the authors analyse the economic aspects of the problem and consider the prospects for increasing the voltage in Polish mines. Paper 27 (preprint) In French. 13 figs., 4 tables.

Investigation Under Load Using Model 1000V *Electrical Equipment for a Cutter-Loader Face*—V. Gluzinski and H. Pudelko

The increase in both the total power requirements of machinery at the face and those of individual machines, due to the concentration of coalmining operations in Polish mines, is affected mainly by the development of coal cutters and drag conveyors. The supply voltage of 500 V used hitherto permits the use of electrical motors with a maximum power of 135 kW at the face. Hydraulic coal cutters with electrical motors of 250 kW are being designed and in order to ensure suitable conditions of operation and optimum supply parameters for the future it was decided to go over to a voltage of 1000 V, the upper limit permitted by the regulations in the low-voltage range. The authors discuss the conditions for the protection against short-circuits at this voltage and the improvement of the working conditions of electrical motors. A device for checking the state of the insulation, and the starting circuit are described in greater detail. Directions for the adjustment of the electrical equipment to the 1000 V voltage are included. The most suitable method of supply appears to be a block system with separate supply to the cutter-loader, multi-motor drag conveyor, and transport system in the section. Paper 6 (preprint) In Russian. 12 figs. (authors' English summary)

Safeguarding Against Dangers Arising From Contact, Ignition, and Fire in the Electrical Supply Network in Underground Mines—R. Streich

In order to be able to judge which of the designs of the supply mains for mines ensures the greatest safety, the physiological and physical limits of contact dangers of persons, of the danger of ignition of explosive gases, and of the danger of fire were defined. The author investigated to what extent different designs of supply networks (earthed or insulated) allow these limits to be observed and what effects this has on safety. Finally, various designs of protective measures and their efficiency are discussed. It seems that an insulated or high-resistance earthed network incorporating a device for monitoring the insulation and with provision for selective disconnection at approximately 50–60 mA earth current best ensures safety and keeps undesirable interruptions of operations to a minimum. Paper 20 (preprint) In German. 18 figs. (author's English summary)

Scientific Bases for Reliable and Safe Power Supply for Mines—N. F. Shishkin

The author discusses the problems involved in achieving reliable arc-free and contactless switching of power circuits. Rapid circuit interruption in the event of a fault is considered more important than the actual values of energy, power, voltage or current that are present. Systems are described for rapid circuit interruption, for system voltages from 127 V to 10 kV, with a total tripping time of 0.5–3.5 msec. Paper 21 (preprint). In Russian. 7 figs.

New Technique for the Protection of 3-Phase Power Systems Underground—S. J. Szpilka

In this paper, the problem of phase-to-phase short circuit tripping is discussed. It is shown that overcurrent protection cannot meet all the economic and safety requirements. The effect of the supply distance on the conductor cross section for different protective devices is illustrated. Two new protective devices are described which solve this problem and introduce some extra advantages. The new protective devices are described which solve this problem and introduce some extra advantages. The new protective devices respond to the current asymmetry. A new filter is described which has been used in one of the prototypes. Paper 28 (preprint) In English. 15 figs. (Author's summary).

Topical Problems in the Protection of Electrical Motors for the Mining Industry—S. Nitka and S. Czyja

The operation of electric motors driving underground mining machinery is briefly analysed and the causes of failures occurring are discussed. The general requirements are stated which the protection has to satisfy to achieve optimum protection of the electric motor. As an example, the filter protection, type UZS is described which was designed by the Institute for the Design and Mechanisation of the Coal Industry at Gliwice. Here, special attention was given to the design of the overload protection actuator which makes it possible to modify readily the timing of the current characteristics of the protection device. Paper 15 (preprint) In Russian. 7 refs., 5 figs. (Authors' English abstract)

Indirect and Direct Monitoring of Temperature in Low Voltage and High Voltage Motors—H. Dreier

Information is given, especially for users, of the results of research on temperature protection of motors, particularly those of "increased safety" construction. The most widely used method involves indirect temperature control which is provided by protective motor switches used in conjunction with a thermal relay which is heated by the motor current. More modern techniques using thermistors and temperature-dependent resistors for direct temperature measurement are also described. Paper 4 (preprint) In German. 19 refs., 7 figs.

The Danger Caused by Voltages Induced in Earth Conductors—Z. Hudeček

The author discusses the problem of induction of voltage/current in the earth conductor in a 3-phase system when the phases are not symmetrically located with respect to the earth conductor. The possible ignition of firedamp by sparking produced as a result of induction is considered; the author concludes that there is probably no danger of ignition, but suggests an empirical check on the values he has estimated theoretically. Paper 12 (preprint) In Czech and German. 7 refs., 5 figs., 2 tables.

Ignition of Explosive Mixtures by High Frequency Energy—K. H. Gehm

The limiting conditions for ignition by electrical discharges are discussed, together with the field strength in the surroundings of a transmitter. The influence of the receiver on possible values of induced currents and voltages is also taken into account. Finally, the possibility of the occurrence of incendive sparks in the neighbourhood of transmitters is discussed; a diagram of safe working distances is included. Paper 7 (preprint) In German. 6 figs., 2 tables.

Ignition of Explosive Mixtures by Static Electricity—E. Heidelberg

The author discusses the ignition energy liberated by spark discharges, and corona discharges, nonconductive layers on earthed conductors, and sliding discharges. Paper 8 (preprint) In German.

Rural Fires Conference—Canberra, Australia. July 15–17, 1969 (Fire Research in the Division of Applied Chemistry, CSIRO—Record of Work since the 1966 Conference in Adelaide).

Fire Behavior

Combustion of Forest Fuels

Effect of Water

The effect of moisture on forest fuels is now well understood. Previously it had been thought that water simply cools the flames by abstracting heat during evaporation. However, the processes involved are more complex. Water acts in three ways:

It decreases the rate of combustion of a fuel so that the resultant fire is less intense,

It increases the formation of smoke and carbonaceous ash whereby the evolution of heat is reduced, and

It affects the radiation characteristics of the flames, and so retards drying of unburned fuel ahead of the flame front.

Effect of Essential Oils

Essential oils which are found in the leaves of eucalypts produce more or less opposite effects. Contrary to popular belief, essential oils do not substantially increase the amount of heat produced by a fire; this is because they are present in such small quantities. However, they do promote rapid combustion so that even moist leaves behave much more like dry ones. These findings can be used to explain many of the crown-fire phenomena which are observed during Australian forest fires.

Variation in the Flammability of Leaves

The comparative "nonflammability" of oven-dried leaves of a number of species has been measured by a simple laboratory test. The nonflammability correlates well with the total mineral content of the leaves, and especially with the sulphated ash which is a readily determined characteristic. Leaves from a eucalypt are more flammable than those of any other species tested, even after all essential oils have been removed by oven drying.

Extraction of leaves with water, followed by oven drying, reduces both the sulphated ash and the nonflammability; it is found that the fall in nonflammability is close to that predicted from the fall in sulphated ash. The reverse effect (addition of minerals to the leaves by impregnation with aqueous solutions of various salts, followed by rinsing and oven drying) is complicated by changes in the leaves brought about by the chemicals used; but, on the whole, the experiments confirm the thesis that nonflammability correlates positively with sulphated ash.

This work may be of use in the search for species suitable for wind-breaks (and possibly green fire-breaks) around farms, roads and plantations.

References

Vines, R. G.: "Influence of Moisture on the Combustion of Leaves," *Australian Forestry 30,* 231 (1966).

King, N. K. and Vines, R. G.: "Variation in the Flammability of the Leaves of Some Australian Forest Species," *CSIRO Chemical Research Labs. Report,* July 1969.

A Survey of Forest Fire Danger in Victoria

An attempt has been made to derive forest Fire Danger Ratings in Victoria, year by year, from a study of past weather records for Melbourne. Comparative estimates obtained using McArthur's Fire Danger Meter agree reasonably well with the known fire records of past seasons. Severe fire years seem to be determined mainly by the incidence of days of "Extreme" Fire Danger.

Reference

Vines, R. G.: A Survey of Forest Fire Danger in Victoria, *Australian For. Res.* (1969), to be published.

Heat Transfer in Fires

The heat from a fire can be dissipated in three ways: by convection, conduction, and radiation. Various studies have been made of the mode of heat transfer in typical situations.

Heat Transfer from an Infinitely Wide Line-fire

A novel technique has been developed for measuring the heat release from a small ground-fire, and the new method greatly simplifies field experiments. A radiometer is supported horizontally and looks down on the fire, which is lit as a wide line and spreads at constant velocity. The total radiation received is a measure of all radiation produced, provided a small correction is made for radiation lost horizontally. Convection is measured with a special "strain-gauge" wind meter and an associated thermocouple to determine air temperatures; thus the total heat emitted from the fire can be compared with the known heat release of the fuel burning on the ground.

In an experiment in a pine forest in Western Australia, the measured heat release from a small fire agreed (to within ~20%) with that calculated from the known fuel consumption. The ratio of convection to radiation, as averaged over the life of the fire, was approximately 3:1.

Reference

Packham, D. R.: "Heat Transfer above a Small Ground Fire," *Australian For. Res.* (1969), to be published.

Heat Transfer through the Bark of Trees and in Soils

Trees

Little is known about the physiological effects of fire on trees. Experiments have therefore been undertaken to measure the cambuim temperatures of representative species under different fire conditions, and so compare their resistance to fires of varying intensity.

Fire resistance depends upon bark thickness, and for this reason only big trees can survive unharmed in a severe fire. When a tree is subjected to fire, the rate of change in cambium temperature depends upon the thermal diffusivity of the bark and is largely independent of bark structure or moisture content. In certain conditions a simple mathematical model can be used to calculate heat transfer, and the estimates obtained agree well with experimental results. Thus, if the thermal output and duration of a fire are known (be it a wild fire or a controlled burn), the approximate cambium temperature of any tree can be predicted theoretically.

The development of devastating wild fires can be prevented by prescribed burning techniques, but there is some controversy as to the effects of prescribed burning on forest species. The results of this and other studies suggest that prescribed burning—properly executed, and with due regard to tree type—does not constitute a threat to forest survival.

Soils

Studies of soil temperatures have been made during prescribed burns and much fiercer fires. The measurements indicate that heat penetrates little beneath the surface layers of the soil. Wet soil conducts heat better than dry soil, but the thermal gradient is not large while water is present, for temperatures below the surface can not rise beyond 100°C until all moisture has been removed.

References

Vines, R. G.: "Heat Transfer through Bark and the Resistance of Trees to Fire," *Australian J. Botany 16*, 499 (1968).

Cromer, R. N. and Vines, R. G.: "Soil Temperatures under a Burning Window," *Australian For. Res. 2* (2), 29 (1966).

Radiation Characteristics of Flames at Low Pressures

Laboratory experiments show that the partial pressure of oxygen around a flame has some effect on radiation properties, for the radiation intensity is reduced when the pressure of the atmosphere surrounding a diffusion flame is decreased. Since the rate of spread of bushfires is affected by radiation from the flames, these observations suggest that fires on a mountain top might behave in a different manner from those burning under similar conditions at lower altitudes.

Reference

MacArthur, D. A.: Work in progress.

Prescribed Burning

Meteorological Effects of Prescribed Burning

Aerial controlled burning has now become a matter of routine in Western Australian forests, and nearly a million acres of karri and jarrah forest were treated in this manner in 1967 and 1968. It is important that control fires, which may cover areas of 30,000 acres or more at any one time, never get out of hand. Studies of the meteorological effects of these large-scale fires have therefore been undertaken, by flying an aircraft through the smoke columns produced.

The fires studied showed no apparent tendency to become uncontrollable, probably because of the limited quantity of fuel available, the low burning rate, and the stable atmospheric conditions. For the five fires investigated, the emergent heat was carried away in the smoke column equally at all levels, up to the base of the atmospheric temperature inversion which was present on each occasion. Measurement of the heat carried down-wind agreed well with the calculated amounts of heat released by each fire. Turbulence records showed clear differences between air motions inside and outside the smoke plume, and the largest effects were found close to the boundary between smoke and clear air.

The results of this work provide meteorologists with data for predicting conditions under which "blow up" fires are likely—and conversely, for predicting conditions appropriate for prescribed burning.

Reference

Taylor, R. J., Bethwaite, F. D., Packham, D. R., and Vines, R. G.: "A Meso-Meteorological Investigation of Five Forest Fires," *CSIRO Division of Meteorological Physics Technical Paper No. 18*, 1968.

Aerial Controlled Burning Techniques

The original method of lighting fires from the air involved the use of a hand operated incendiary device. In 1966 the hand machine was replaced by automatic equipment for distributing incendiaries, and since that time flying techniques have been improved so as to increase the safety of the operation. Mobile radio beacons are now used as ground-markers to guide aircraft on the desired flight paths, and this helps in dropping incendiaries accurately in a predetermined grid pattern. Western Australian foresters have further developed these methods so that it has become possible to treat very large areas in a relatively short time.

References

Baxter, J. R., Packham, D. R., and Peet, G. B.: "Controlled Burning from Aircraft," *CSIRO Chemical Research Labs. Report*, July 1966.
Packham, D. R. and Peet, G. B.: "Developments in Controlled Burning from Aircraft," *CSIRO Chemical Research Labs. Report*, October 1967.

Protection of Crop Trees during Prescribed Burning in Pine Plantations

In Western Australia there is interest in such protection, and for this purpose a cheap water based aluminium paint which reflects heat has been developed. The paint was found to give good protection during a fire which was considerably hotter than any that would be prescribed for controlled burning. It is not at all effective in preventing even a very cool fire from climbing trees which, for any reason, are weeping turpentine.

Reference

King, N. K.: Work in progress.

Mapping Fires from Aircraft

The mapping of fires in inaccessible country is a major fire control problem. By day, aerial observation is often difficult because smoke obscures the flames, and accurate mapping of fire edges sometimes becomes impossible even if the observer is equipped with the Fire Section's infrared viewer. However, at night fire edges and spot fires can be clearly seen even in quite dense smoke—though mapping is again difficult since an aerial observer cannot recognise terrain, and the aircraft's position is uncertain.

Attempts have been made to solve these night-mapping problems by using precision dead-reckoning navigation and a portable radio beacon located at a known position near the fire area. The aircraft flies known tracks from the beacon, and the fire edges are mapped as the observer passes over them. The method has already been successfully employed on a few occasions in mapping wild fires.

With the advent of fast infrared films it is now possible to photograph details of a fire from the air at night, and this technique may prove useful in pinpointing dangerous fire situations. There should be no difficulty in developing more sophisticated equipment for mapping at night if the aircraft can be located accurately, and the Fire Section (with the willing cooperation of the Department of Civil Aviation) has been investigating the possibility of using radio nav-aids such as DME* for this purpose. Calibration tests of DME carried out at Mt. Gambier showed that normal air-navigation ground beacons are accurate enough for almost all fire location work.

The calibration tests should, of course, be repeated in mountainous areas. However it now seems feasible to equip a light aircraft with the appropriate photographic equipment, and multiple DME units for precise location, and to attempt the routine mapping of fires. The only apparent obstacle is the expense of such equipment for use in aircraft.

Reference

Cheney, N. P., Hooper, R., MacArthur, D. A., Packham, D. R., and Vines, R. G.: "Techniques for the Aerial Mapping of Wild Fires," *Australian For. Res. 3* (4), 3 (1968).

Once a fire is out, the path of the fire and the area burnt are often noted for future records. Aerial photographs taken with infrared film have been found useful for this purpose, because they show much more clearly than ordinary photographs the line of demarcation between burnt and unburnt country. This simple and inexpensive technique could be more widely employed to obtain accurate records of the path of a fire.

Reference

CSIRO Annual Report, Chemical Research Labs., 1966–1967.

* Distance Measuring Equipment, which operates by determining the time interval between the transmission of a radio signal from an aircraft and the reply from a distant, fixed radio-beacon which picks up the signal and returns it.

Central States Section of the Combustion Institute—University of Minnesota, March 18–19, 1969.

Meeting Report—Fire Research

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*Atlantic Research Corporation**

The Central States Section of the Combustion Institute sponsored a two-day meeting on Fire Research at the University of Minnesota. Dr. E. A. Fletcher of Minnesota was the Meeting Chairman and Dr. H. J. Nielsen of Illinois Institute of Technology Research Institute was Program Chairman. About 75 people attended the meeting, and 18 papers were given, followed by a tour of the University of Minnesota Mechanical Engineering Department. This was a national meeting, in the sense that half the attendees were from the East or West Coast rather than the central states.

Session I—Flame Spread

1. Energy Absorption Near and Below the Burning Surface of Hydrocarbon Pools. *W. H. Andersen*, R. D. Garfinkle, G. E. Carpenter and R. E. Brown, Shock Hydrodynamics, Inc.
2. Some Thoughts and Experiments on Liquid Fuel Flame Spreading, Steady State Burning and Ignitability in Quiescent Atmospheres. *I. Glassman* and J. G. Hansel, Princeton University.
3. Flame Propagation in Layered Methane–Air Systems. *I. Liebman*, J. Corry and H. E. Perlee, Explosives Research Center, Bureau of Mines.
4. Fires in Spacecraft Environments. *S. Atallah*, U. Bonne and J. de Ris, Arthur D. Little, Inc.

Session II—Flame Spread and Fuel Flame Interaction

5. Combustion of Cellulosic Cylinders. F. J. Kosdon and *F. A. Williams*, University of California.
6. Smoulder Propagation in Cellulosic Fuels. *K. Murty*, University of Minnesota.
7. Flame Spread Model for Cellulosic Materials. *W. J. Parker*, U.S. Naval Radiological Defense Laboratory.
8. A Model for Describing Fire Spread Rate through a Fuel Bed. *B. Fransden*, U.S. Department of Agriculture.
9. Tailoring the Fire Spread Rate to the Field. *R. C. Rothermel*, U.S. Department of Agriculture.

Session III—Fire Modeling

10. Some Observations on the Mode of Burning of a Five Foot Diameter Pan of Fuel. *B. D. Wood* and P. L. Blackshear, Jr., University of Minnesota.
11. Mass Fire Scaling with Small Electrically Heated Models. B. T. Lee, U.S. Naval Radiological Defense Laboratory.
12. Flow Patterns in Large Fires. *H. J. Nielsen*, IITRI.
13. Spotting by Firebrands Connected by a Complex Flow Field. Shao-Lin Lee and *J. Hellman*, State University of New York.

* Present address: Factory Mutual Research Corporation, Norwood, Massachusetts.

14. Some Fundamental Parameters in Fire Research. *A. L. Berlad*, State University of New York.
15. Turbulent Free Convection above a Heated Horizontal Flat Plate. *R. C. Corlett* and T. M. Fu, University of Washington.

Session IV—Miscellaneous

16. Radiative Extinction of Diffusion Flames. *U. Bonne*, Honeywell, Inc.
17. Combustion Intensity as Controlled by Mixing. A. A. Putnam and *R. D. Giammar*, Battelle Memorial Institute.
18. The Influence of Free Convection on the Ignition of Vertical Cellulosic Panels by Thermal Radiation. N. J. A. Alvares, P. L. Blackshear, Jr., and *K. A. Murty*, University of Minnesota.

Some summarizing comments on a few of the papers of particular interest to this reporter are presented below.

Berlad's paper was a timely attempt to identify combustion parameters deriving from statistical properties of fuel bed arrays (as in a forest bed). Once such parameters are understood quantitatively, they may be related by an overall theory. A key parameter is the ignition delay when a firebrand descends into a fuel array. Another parameter is the autoignition temperature of a well-ventilated fuel array. A third is the isothermal gasification kinetics of finely divided fuels.

Glassman and Hansel described their current studies of flame spread across a liquid surface below its flash point, presenting motion pictures which clearly showed that motion of the liquid ahead of the flame front plays a key role in the propagation mechanism. The propagation may be slowed by increasing the liquid viscosity or stopped by a barrier just below the surface. The authors propose that the liquid circulation is not necessarily due to thermal convection currents, but could be attributed to a temperature-induced surface tension gradient. They have not yet proven this.

Parker made detailed studies of the microstructure of a flame propagating downward and consuming a vertical cellulosic card about 0.2 mm thick. He was able to show that the pyrolysis zone begins behind (i.e., above) the flame front. The propagation rate is governed by gaseous conduction from the flame to the pyrolysis zone, rather than by conduction down the card on radiation. The flame zone can be modeled by a methane jet issuing from a slot in a vertical metal plate, and temperature gradient measurements in such a modeled flame yield heat fluxes consistent with the required heat of pyrolysis of cellulose.

Bonne studied small laminar diffusion flames (parallel fuel vapor and oxidant jets) under conditions of negligible free convection, in order to simulate zero-*g* combustion. Finite radiant heat loss occurs from such flames, and they possess a finite height above which fuel and oxidant mix without burning. Theoretical and experimental study emphasizing these facts led to a flame extinction condition in terms of the competing rates of fuel–oxidizer mixing and radiative heat loss.

Office of Civil Defense (OCD) Fire Research Contractors Meeting, June 1–5, 1969, Asilomar, California.

The agenda of the seventh annual OCD Fire Research Contractors Meeting given below reflects the broad interests of the group. Many of the areas are represented by continuing programs. It has been interesting and impressive to see the increase in understanding of these complex problems over the years. This long-term approach is paying dividends in general understanding. The weakest link in this otherwise excellent research program is the lack of overall synthesis of the valuable information which has been produced into a compact useful form. This is a common defect in fire research programs, and the reduction of research information to directly useful material is one of the outstanding challenges to the fire research community.

R. M. Fristrom

Morning Sessions

Introduction		W. E. Strope, OCD J. W. Kerr, OCD

Session 1—Fire Hazards

2537B	Hazards of Smokes and Toxic Gases	Pryor, SwRI
2538D	Power Density Rating for Fire in Urban Areas	Takata, IITRI
1134A	Tests for Effects of Building Fires on Shelter Environment	Vodvarka, IITRI
1135A	Fire Laboratory Tests	

Session 2—Fire Start and Fire Spread Calculations

2538B	IITRI Fire Spread Model Development and Calculations	Takata, IITRI
2538C	URS Fire Spread Model Development and Calculations	Martin, URS
1614B	Blast and Fire Vulnerability of Fallout Shelter Occupants	Crowley, SSI
2538E	Fire Spread Model Adaptations	

Session 3—Fundamental Fire Research

2531A	Fundamental Fire Research	Blackshear, U. Minn.
2431B	Committee on Fire Research	Emmons, Harvard
2531C	Fundamental Research in Limitation and Control of Fires	Lipska, NRDL

Session 4—Fire Defense

2522F	Fire Department Operations Analysis	Christian, IITRI
2522E	Fire Service Capabilities for Damage Control	Martin, URS
2526B	Fire Defense Systems Analysis	Eggleston, SwRI

Session 5—Firebrands

2536E	Laboratory Study of Firebrand Generation	Waterman, IITRI
2539A	Laboratory Study of Ignition of Host Materials by Firebrands	Waterman, IITRI
2539B	Measurements on Firebrand Phenomena at Accidental Fires and Controlled Burns	Salzberg, IITRI

Session 6—Mass Fires, I

2561B	Operation FLAMBEAU—CD Test Design and Support	Butler, NRDL
2536F	Mass Fire Characteristics and Development	Lee, NRDL
2561A	Camp Parks Mass Fire Research	Butler, NRDL

Session 7—Thermal Hardening

2542A	Exploratory Development of Thermal Hardening Measures	Parker, NRDL
2552C	Additives to Improve Smoke Generation	Hawkins, URS
2553C	Hardening of Smoke Generators	Black, URS

Session 8—Blast Effects on Fire Start and Fire Spread

2534B	Fire Start Capabilities of Urban Nuclear Detonations	Bracciaventi, NASL
2534F	Effects of Blast on Fire Starts and Fire Spread from Thermal-Radiation-Caused Ignitions	Martin, URS

Session 9—Mass Fires II

2562A	Urban Burn Program	Vodvarka, IITRI
2561E	Wildland Fires	Palmer, USFS
3124B	Effects of Mass Fires on Fallout Deposition	Miller, URS

Session 10

Status Summary of Research on Fire Hazards and Fire Defense	L. A. Eggleston, SwRI
Status Summary of Research on Fire Buildup and Fire Spread	W. J. Christian, IITRI
Status Summary of Research on Basic Understanding of Fire	S. B. Martin, URS

Afternoon Discussion Sessions

Fire Hazards and Fire Defense

Discussions on topics of Sessions 1, 4, and 7.

Fire Buildup and Fire Spread

Discussions on topics of Sessions 2, 5, and 8.

Basic Understanding of Fire

Discussions on topics of Sessions 3, 6, and 9.

Evening Sessions

First Session

Chairman: J. W. Kerr, OCD.
General Topic: The OCD Fire Research Program.
Subjects included:

a. Present emphasis and future directions in OCD fire research.
b. Relationship of OCD fire research to the overall OCD research program.
c. OCD fire research and the concept of operations under nuclear attack.

Second Session

Chairman: W. J. Parker, NRDL.
General Topic: Fundamental Fire Research.
Subjects included:

a. Survey of recent and ongoing fundamental fire research.
b. Critical problems in fundamental fire research.

Third Session

Chairman: T. E. Waterman, IITRI.
General Topic: Origin, Evolution and Present Definition of Terms Used in Research on the Fire Effects of Nuclear Weapons.
Subjects included:

a. Ignition point, fuel array, incendiary equivalent.
b. Flashover, significant fire.
c. Mass fire, firestorm, uncontrollable fire.

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B. Ignition of Fires

C. Detection of Fires

D. Propagation of Fires

E. Suppression of Fires

F. Fire Damage and Salvage

G. Combustion Engineering

H. Chemical Aspects of Fires

I. Physical Aspects of Fires

J. Meteorological Aspects of Fires

K. Physiological and Psychological Problems from Fires

L. Operations Research, Mathematical Methods, and Statistics

M. Model Studies and Scaling Laws

N. Instrumentation and Fire Equipment

O. Miscellaneous

CUMULATIVE INDEX OF BOOKS, JOURNALS, MEETINGS, TRANSLATIONS

Books

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Under the terms of its Congressional charter, the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and autonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

THE NATIONAL RESEARCH COUNCIL was organized as an agency of the National Academy of Sciences in 1916, at the request of President Wilson, to enable the broad community of U.S. scientists and engineers to associate their efforts with the limited membership of the Academy in service to science and the nation. Its members, who receive their appointments from the President of the National Academy of Sciences, are drawn from academic, industrial and government organizations throughout the country. The National Research Council serves both Academies in the discharge of their responsibilities.

Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

THE COMMITTEE ON FIRE RESEARCH functions within the Division of Engineering to stimulate and advise on research directed toward the development of new knowledge and new techniques that may aid in preventing or controlling wartime and peacetime fires. The Committee was established in December of 1955 at the request of the Federal Civil Defense Administration. It is supported by the Office of Civil Defense of the Department of the Army, the U.S. Department of Agriculture through the Forest Service, the National Science Foundation, and the National Bureau of Standards.