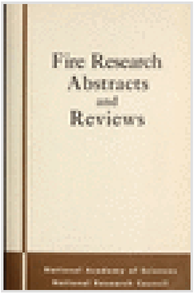
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Volume 2 Number 1

ABSTRACTS

Fire Under Influence of Natural Convection

G. I. Taylor
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The natural convective movements of the atmosphere above fires is responsible for the inflow of cool gas into the fire. The total problem involving a turbulent plume and inflow is very complex. However, progress is made by studying the two parts separately. The rising column problem was first attacked by Schmidt * using Prandtl's mixing length theory of turbulence. He found that the jet spread linearly with height and that the temperature and velocity profiles are similar at all heights. Schmidt's experimental measurements with a small heated coil source verified his calculations. Independent of Schmidt's work, Hunter Rouse,† by assuming velocity and temperature profiles to be independent of height, showed that heated jets would expand linearly. Further experimental results again verified the predictions and resulted in empirical formulas for the velocity and buoyancy distribution for both line and point sources.

The second part of the convection problem, that of the inflow of air, is caused by the removal of air upward. The actual amount removed is proportional to the change of vertical velocity and plume cross section area. Thus, the solution of the first part of the convection problem supplies information for the solution of the second part. The inflow field is found by adding the effects of the sinks of fluid along the vertical convection column. In this way the streamlines of the inflow air have been found for line and point sources. Only for the line source of heat along the ground are the streamlines horizontal. For a line source in unbounded space, there is no steady inflow solution at all.

For natural convection from a line heat source in a wind, there are several competing effects. The convective turbulence may be caused by the wind or by the buoyancy. It is shown that these two effects lead to a method of correlating experimental results in such a way that the convection from large fires is accurately predicted by tests with small fires, and suggests that both sources of turbulence are present.

Finally, the paper discusses the effect of a variable atmospheric density on the convection. Several authors have developed solutions. In a stable atmosphere the rising column spreads out more and more rapidly, slows down, and finally stops. Since it is difficult to carry out such experiments in air, tests have been made in a stratified liquid. In this way good agreement is obtained between the simplified theoretical model and the experiments. The theory is then used to predict the height of rise of the hot gases from various size fires.

In every case the discussion of the convection problem is accompanied by a model analysis in dimensional terms.

Subject Headings: *Convection, natural, fires under the influence of; Fires, influence of natural convection on.*

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* Schmidt, Wilhelm "Turbulente Ausbreitung eines Stromes erhitzter Luft," *Zeitschrift für Angewandte Mathematik und Mechanik* 21, 265–278 and 351–363 (1941)

† Rouse, Hunter, Yih, C. S., and Humphreys, H. W. "Gravitational Convection from a Boundary Source," *Tellus* 4, 201–210 (1952)

Modeling Principles in Relation to Fire

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The general principles of similarity and modeling are discussed. It is suggested that, of the various methods of identifying the dimensionless groups which must be specified to produce similarity between a prototype and its model, the most helpful is the listing of the various kinds of forces, energy rates, and mass rates which are expected to be significant to the problem at hand, and the forming of ratios within each of the three categories. Tables are presented giving representative forces, energy rates, and mass rates of importance in fire modeling.

Radiation Modeling

The radiation terms of the energy-rate table are discussed in sufficient detail to indicate how they may affect fire-modeling laws. The natural-convection fire problem discussed by Taylor (first paper of this symposium series) is used to illustrate how allowance for radiation modifies the model laws. In the absence of radiation, the convection column above a fire and its model are described by the functions

$$\frac{q}{\rho c_p z^{5/2}}\sqrt{\frac{T_0}{g(T-T_0)^3}}=f_1(r/z);\quad \frac{qg}{\rho c_p z u^3 T_0}=f_2(r/z)$$

wherein q is the rate of energy liberation by burning; z and r are the vertical and radial distances, measured from the flame base to the point where the velocity and temperature are u and T; g is the gravitational force per unit mass; and ρ and c_p are the density and specific heat of air (the model is valid only for the same flame temperature as the prototype, for which case ρ scales properly through the flame).

There are two meanings to the term radiation modeling as applied to the above natural-convection fire: (1) complete modeling, allowing for interaction between radiation and flow, and (2) modeling of the reception of flame radiation by the surroundings, on the assumption that the radiation is so small as not to affect the jet temperature and flow pattern. If complete modeling is to be accomplished the ratio of flame radiation to convective heat transfer is

$$\frac{\sigma(T^4-T_0^4)f(\kappa L,\text{shape})}{u\rho c_p(T-T_0)}$$

where κ is the Beer's-law absorption coefficient of the flame, equal to $\kappa'\rho$. Since there is no prospect of success in modeling the temperature field other than by maintaining identical values in the prototype and model, the dimensional groups to be kept constant if modeling is to be achieved are, with ρ measured by atmospheric pressure P and with u eliminated by combination with the other group containing it,

$$\frac{q}{Pz^{5/2}},\ \frac{f(Pz)}{(q/z)^{1/3}P^{2/3}}.$$

Since f(Pz) is not proportional to Pz, the last group above calls for constancy of both Pz and the denominator. Setting $P\propto z^{-1}$ into the first group gives $q\propto z^{3/2}$; setting it into the denominator of the second gives $q\propto z^3$. Complete modeling is thus impossible.

If instead of attempting complete radiation modeling one abandons allowance for interaction—often a good assumption—the second of the above two ratios disappears, and it is only necessary to retain $\kappa' Pz$ or Pz to assure the same intensity of radiation at corresponding points in model and prototype. The dimensional groups to be kept are then

$$\frac{q}{Pz^{5/2}},\ Pz$$

From this, one establishes the scale relations for modeling:

1) Pressure proportional to z^{-1}
2) Burning rate proportional to $z^{3/2}$

i.e., one uses pressure above atmospheric, burns less fuel, and makes a smaller flame. But the necessity for varying atmospheric pressure is most unattractive.

A limiting case occurs if the flame is opaque ($\kappa' Pz \doteq \infty$). The use of atmospheric pressure variation as a modeling tool can be dropped, and one returns to the relation, $q \propto z^{5/2}$, discussed by Taylor. Instead of dropping pressure one may introduce allowance for the chemical reaction rate, on the ground that the production of luminosity may be chemically limited. This introduces the new dimensionless group $zk\rho^{n-1}/u$ or, with u eliminated and the group expressed dimensionally, Z^4P^{3n-2}/q, where n is the chemical reaction order. When this is combined with $q/Pz^{5/2}$, one obtains the modeling criteria:

$$q \propto z^{1/2\left(5-\frac{1}{n-1}\right)};\quad P \propto z^{-\frac{1}{2(n-1)}}$$

Using $n=2$, one finds

$$q \propto z^2;\quad P \propto z^{-1/2}$$

Modeling Driven Jet Flames

The last section of the paper is based on the M.I.T. Sc.D. thesis of Mr. C. A. Homsy (to be published). Propane was burned in a free jet issuing from a 1/32, 1/16, or 1/8 in. nozzle into air in a large ventilated tank operating at pressures from one-third to six atmospheres; and the flame length was measured by chemical analysis of the combustion products along the axis. A model analysis indicated that flame jet modeling should be achieved by holding constant the ratios, turbulent shear: viscous forces (Reynolds number); momentum: buoyancy forces; and the chemical rate: turbulent transport ratio (called here the chemical loading group). The dimensional parts of these ratios under experimental control are

$$Du_0P,\ u_0^3DP/q \text{ or } \frac{u_0^2}{D},\ DP^{n-1}/u_0$$

D is here the nozzle diameter, u_0 the nozzle velocity, and q the energy-equivalent of the fuel firing rate. A little consideration shows that modeling is not possible unless one of these groups is of minor significance. Earlier work had indicated that the flame length depended greatly on Re up to high values of that parameter, then rose very slowly in a manner later interpreted as indicating a possible effect of chemical kinetics as nozzle velocities approached sonic. This viewpoint was reinforced by studies of gaseous combustion inside perforated spheres, where the mixing achievable by sonic-jet feed was so rapid as plainly to make chemical kinetics controlling. Accordingly attention was focused on the first and last of the above three groups. The experiments were planned on the basis of $n=2$, pressure being doubled when D was halved. The data did not correlate as expected; and it was noted that if the reaction order n was assumed nearer 1 than 2 the correlation was much improved. It will be noted that the Reynolds number and buoyancy group can be so combined ($Re^{1/3}/(\text{buoyancy group})^{2/3}$) as to obtain $DP^{1/3}/u_0$, which is identical with the chemical loading group if a reaction order of 4/3 is assumed. Re-examination of the old data and acquisition of additional data confirmed the growing suspicion, reinforced by a jet-structure analysis, that the modeled flame length depends on the Reynolds number and buoyancy group and decreases as the buoyancy/initial momentum ratio increases; and is apparently independent of the chemical loading group. A smaller amount of data on the carbon-luminous length of the flame, however, indicated that at constant Re an approximate correlation is obtained by using the chemical loading group, with an n somewhat above 2; this is not unreasonable.

Subject Headings: ***Models, relation to fire; Fires, model; Model fires; Radiation modeling; Flame, jet, modeling of; Jet flames, modeling of.***

Some Observations on Pool Burning

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The phenomena of uncontrolled fire are rather complex because of the large number of different physical, chemical, and thermal effects which are involved. The minimum essential elements of an uncontrolled fire are (1) a fuel structure, (2) a heat transfer mechanism from flames or combustion products to the fuel structure, and (3) a natural convection mechanism. The chemical combustion mechanism, while essential to the fire, is of such overwhelming complexity that no experimental simplification appears possible and hence no direct modeling appears possible.

The burning pool of liquid represents a simple system because of the simple geometry. The burning still contains the various mechanisms of heat transfer from gases to liquid in order to evaporate the liquid and thus control burning rate. While the experimental reproducibility is high and the geometric questions are reasonably simple, the analysis of data does not yield in a simple way to a correlation approach. A dimensional analysis shows many variables with little prospect of disentanglement.

In this report it is proposed that the burning rate can be divided into contributions arising separately from conduction, convection, and radiation. Each of the separate pieces can then be correlated with a lesser number of dimensionless parameters.

Experimental data on the burning of liquids with simple boiling points (acetone, methyl alcohol) were obtained in apparatus especially developed to suppress room drafts (*Figure 1*). The new data is compared with that of Blinov and Khudiakov in *Figure 2*. It is seen here that conduction of heat through the pan rim is responsible for the high burning rates for small pan sizes. The heat flow path for the heat conduction was: flame to ground by radiation, ground to inducted air by convection, inducted air to pan rim by convection, pan rim to liquid by conduction.

A second effect of radiation to ground was found to be the instability of the hot layer of inducted air near the ground. Additional natural convection columns of this hot air produced large flame disturbances as they were carried into the fire. To control these instabilities required a cooled ground.

The energy equation for the liquid in the pool shows that the burning rate can be split into $v_l^0 = v_{rad} + v_{cv} + v_{cd} - v_0 - v_{int}$ where v_l^0 is the observed burning rate of the liquid

v_{rad}	rate caused by direct radiation
v_{cv}	rate caused by direct convection
v_{cd}	rate caused by rim conduction
v_0	loss of rate by heat loss through bottom
v_{int}	loss of rate by heat required to warm fuel to boiling point

Although insufficient data are available to make an extensive test of the idea of separate contribution, an initial success is indicated in *Figure 3*, where the lower curves show the experimental burning rate data, while the upper curves have been corrected for the energy absorbed by the pan in being heated up to the boiling point

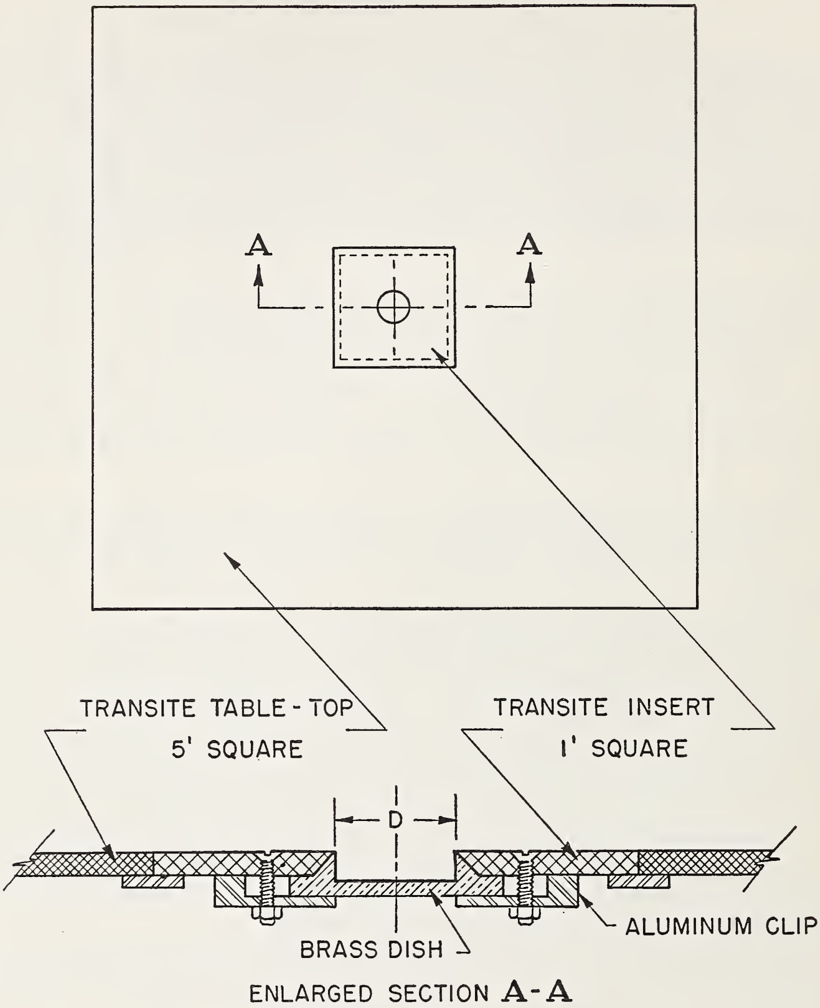

Figure 1. Installation of brass dish

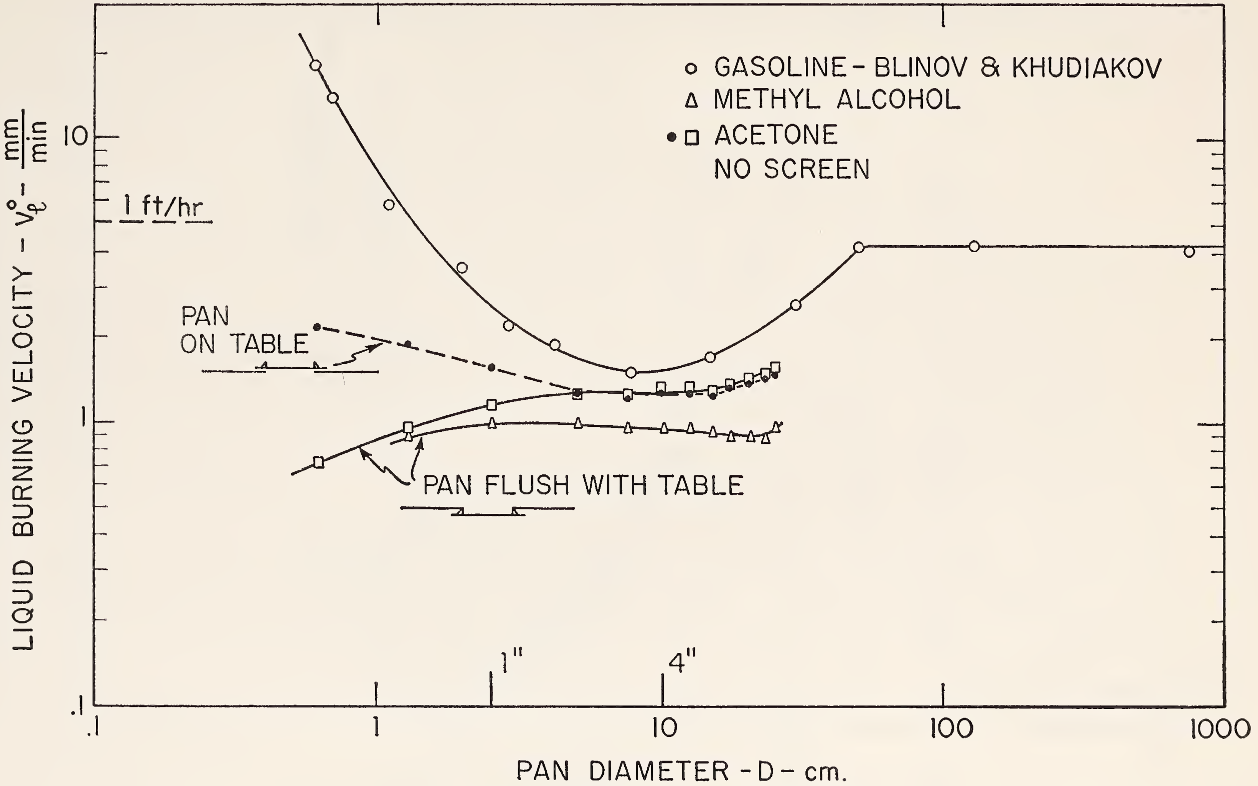

Figure 2. Liquid burning velocity

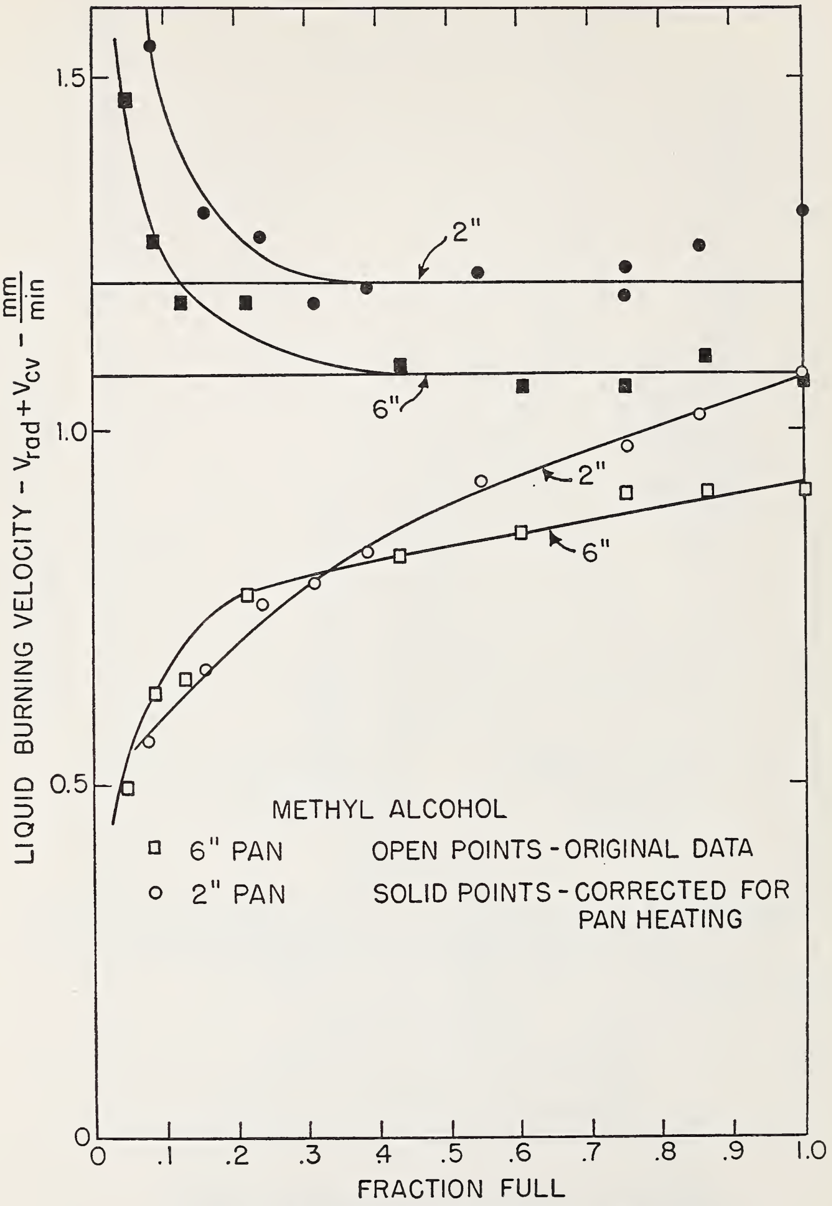

Figure 3. Effect of partial filling on burning velocity

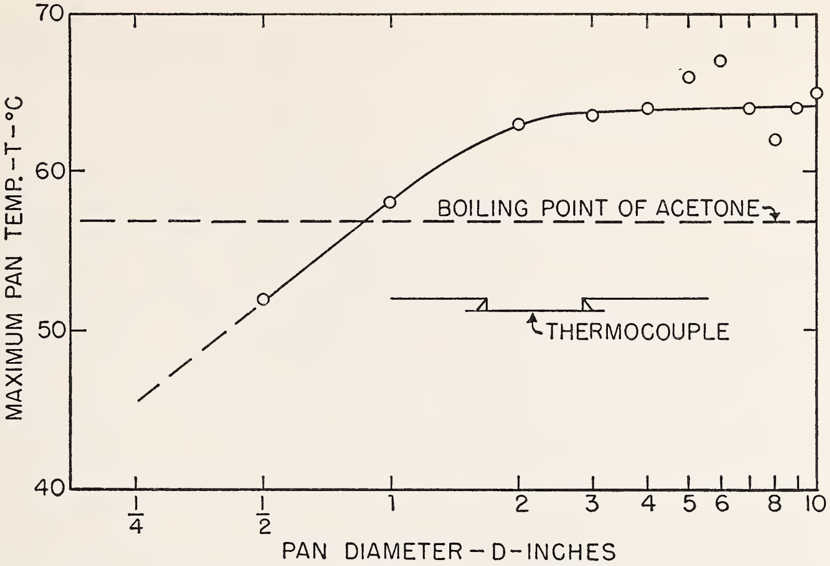

Figure 4. Pan temperatures when burning acetone

of the liquid. The reason for the sharp rise of the curves at low fuel levels is seen in *Figure 4.* The pans of large size (heat capacity small compared to the total heating value of the fuel) heat up to a temperature some 8°C above the boiling point of the fuel, while small pans heat up much less. While the available pan temperature data cannot be directly applied to the data of *Figure 3,* it is clear that for small initial fuel depths, the pan would not heat up to the boiling point as was assumed in computing $v_{rad}+v_{cv}$ from the measured burning rate v_l^0.

Subject Headings: ***Pool burning; Diffusion flames, in pool burning; Flame, diffusion, in pool burning; Tray burning.***

Burning Rates of Liquid Fuels in Large and Small Open Trays

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U. S. Bureau of Mines, Pittsburgh, Pennsylvania

Interest in this area was prompted by recognition of the hazards created by the accidental spillage and ignition of volatile liquid fuels. Spill fires were simulated in the laboratory by burning such fuels in shallow trays. A paper by Blinov and Khudiakov,[†] together with a commentary by Professor Hottel,[‡] were directly applicable to the study. The present paper represents an extension of the work of Blinov and Khudiakov to six single-component fuels, namely methanol, unsymmetrical dimethylhydrazine, benzene, hexane, butane, and liquid hydrogen, in the order of increasing rate of burning. Using these new data, we infer burning rates at large tray diameters. These burning rates support a semiempirical law connecting the burning rate with the heat of combustion and the heat of vaporization of the fuel.

The measurements reported by Blinov and Khudiakov are discussed. The appropriate experimental conditions are that the tray should be flush-filled with the liquid fuel, that wind should be absent or negligible (these two conditions are primarily important at small tray diameters), and that the burning rates should be measured only after the fuel has attained a steady state of burning. The constant value of burning rate, or the value approached asymptotically with increasing diameter, is of first importance. This carries the implication that significant work can be done with tray diameters of the order of 3 feet. Such trays can be handled without a special installation.

Blinov and Khudiakov discussed heat transfer from flame to liquid surface by the expected modes of conduction, convection, and radiation, and their conclusions were put into semiquantitative form by H. C. Hottel. Radiation flux per unit of liquid surface, expressed as $\sigma F(T_F^4 - T_B^4)(1 - e^{-\kappa d})$, was assumed to dominate the heat-transfer picture at large tray diameters.

The above expression conforms to our measured burning rates under the following simple assumptions: The flame temperature T_F, shape factor F, and extinction coefficient κ, are constant for diameters beyond 12 inches, and conduction and convection are negligible. With each of six fuels, a value was compared with the burning rate at the 1 foot diameter, and the ratio of these rates equated to $(1 - e^{-\kappa d})$, thus defining κ. Variation of d, the tray diameter, then gave a curve representing evaporation rates from the tray due exclusively to radiative heat transfer. The calculated curves and experimental measurements were generally in good agreement.

There is an obvious exception in the case of benzene, which is unusually susceptible in burning rate to any casual environmental disturbance that ruffles the flame and increases its opacity. Particular study of this fuel leads to conclusions that are held applicable to all fuels: Slight drafts accelerate burning by increasing the opacity factor $(1 - e^{-\kappa d})$ in the Hottel equation; however, as long as the flame remains full (unbroken) this acceleration can be important only when d is small.

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[†] Blinov, V. I. and Khudiakov, G. N. (Institute of Energetics of the Academy of Sciences, USSR) "Certain Laws Governing Diffusive Burning of Liquids," Academiia Nauk, SSSR Doklady, 113, 1094–1098 (1957)

[‡] FIRE RESEARCH ABSTRACTS AND REVIEWS 1, 41–44 (1959)

Stronger drafts, ordinarily of greater than 10 ft/sec velocity, can tear the flame, and this introduces a premixing of fuel vapor with air which results in a higher T_F, and consequently in higher fuel-evaporation rates, than the "limiting" values associated with diffusive burning.

Concerning the other fuels, butane flames tend to "walk" or spread to cover a larger area than that represented by the fuel tray. This brings about transitory increases in burning rate, presumably the result of increasing the shape factor. The reason that butane flames can spread in this way must be due to the fact that the vapors are particularly dense. Thermocouple measurements in the vapor zone close to the liquid phase showed that the vapor is only at the boiling point or very little above it, whereas in benzene or methanol flames, for example, the vapor zone in close proximity to the liquid is very hot. The vapor zone in liquid-hydrogen flames was also cool. Therefore, in liquid-hydrogen and butane fires, convective and conductive heat transfer appears to be negligible at burner diameters smaller than 1 foot. Concerning the burning rates in methanol, the trend with increasing tray diameter is so flat that small satisfaction can be taken from the agreement between experimental points and the curve calculated for radiative heat transfer. This leaves open the possibility that heat transfer in methanol may be largely convective. An attempt was made to resolve this point by using a differential thermocouple at the liquid surface in a 1 foot tray. The best estimate is that about 30 per cent of heat transfer is radiative at this tray diameter; the remainder is presumably conductive and convective. The shapes and periodic movements of the largest methanol flames suggest that convection is still important.

It is shown that the percentages of heat radiated to the surroundings are nearly equal for all fuels. These percentages are based on a spherical symmetry of radiation and complete burning of the fuel to carbon dioxide and water. Since the percentages of heat radiated outward are so nearly equal, it was assumed that the percentages of heat radiated to the liquid surface were also comparable in all flames and that the burning rate was therefore proportional to the heat of combustion, ΔH_{comb}. A few measurements at low ambient temperature also showed that the burning rate was inversely proportional to ΔH_{vap}, the effective heat of vaporization, which is the heat of vaporization at the boiling point plus the integrated heat capacity of the fuel from ambient temperature to the boiling point. This being the case, burning rates should be inversely proportional to $\Delta H_{vap}/\Delta H_{comb}$. The available data with pure fuels are in remarkable agreement with this old concept. However, the situation with respect to blended fuels requires further investigation.

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

Subject Headings: *Tray burning; Pool burning; Burning rates, of liquid fuels; Fuels, burning rates in trays.*

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

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The objectives of these tests were to measure the temperature distribution in the flames of tank fires (open vessels) in relation to the burning surface and the height of the liquid surface in the tank. It appears self-evident that the area of a burning surface stands in a direct relation to the burning rate of a fuel and to the energy of an uncontrolled fire. This relation, however, is influenced by various factors such as air flow to the burning surface, heat radiation from the flame to the burning surface, the radiation to and from the surroundings, the composition of the fuel, etc.

We tried to separate the various factors by using tank fire models of various diameters and ratios of height/diameter and by using different liquid fuels. Also studied was the heat transport by back radiation from neighboring objects, the influence of humidity and barometric pressure of the air.

Conclusions of the tests are as follows: The natural draft and the wind velocity across the burning surface has a major influence on the burning velocity while humidity and the temperature of the incoming air stream is of minor importance to the burning velocity and temperature distribution. The radiation from any objects to the burning surface should be avoided, or if inevitable, calculated. The burning velocity of various fuels depends on the exposed surface of the liquid. The relation can be determined from the results obtained with various models.

The burning rate and the temperature distribution in the flames is greatly influenced by the distance between burning surface and tank rim. This influence is similar with all fuels and depends on the theoretical amount of combustion air of the respective fuel.

The temperature readings show that the radiated heat from the flames is absorbed in a relatively thin layer of the liquid fuel near the burning surface. With non-homogeneous fuels such as hydrocarbons heat transfer into the liquid occurs by a secondary circulation which is caused by the differential evaporation of the various components with different boiling points.

The temperature maximum in the flame maintains an almost constant distance from the burning surface. This distance is influenced by the shape of the tank.

Tests with various models seem to show some correlation, but the different factors have still to be studied separately, and do not follow the same model law.

Subject Headings: *Tank fires; Fires, tank; Burning rates, in tank fires.*

Extinguishment Effectiveness of Some Powdered Materials on Hydrocarbon Fires

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The National Bureau of Standards has conducted studies of the manner in which dry chemical powders are effective in controlling flammable liquid fires. One problem was to develop a method for evaluating the relative effectiveness of different powders. Another, was to find a correlation between the extinction effectiveness of a powder and the size of the fire model. These studies were expected to shed some light on the way in which extinguishment is achieved as well as to provide information on the applicability of laboratory results to full-scale fires.

The extinguishment effectiveness of various powders was measured with the use of model heptane fires of 1⅛, 6, and 23 inch diameters. The powders used were sodium bicarbonate, potassium bicarbonate, potassium iodide, potassium oxalate monohydrate, and glass beads. The chemicals chosen were, initially, in crystalline forms. To improve their flow properties, 2 per cent stearate (by weight) was added to the material before grinding in a ball mill. Sieving and air elutriation methods were used to separate the pulverized powders into samples of narrow particle size ranges between 5 and 40 microns. Samples of these graded powders were then applied to model fires at controlled rates to determine their fire extinction effectiveness. Effectiveness was defined as the minimum powder application rate required for flame extinction.

The initial laboratory test equipment developed and used is shown in *Figure 1.* The powder was contained in a salt-shaker type dispenser. It was sifted from this container through the screen bottom by means of an electromagnetic vibrator. One of the cups shown was used to measure powder application rate. The second cup contained the burning heptane fire. Both cups were of 1 inch diameter and were placed on a platform which moved them at a uniform rate through the powder cloud. The powder cloud either did or did not extinguish the flame, depending on the conditions of the experiment. The equipment was enclosed in a box which permitted close control of ambient variables.

Experiments were performed with this equipment to determine the weight rate of powder application for effective extinction as a function of the particle size. The data reported were the results of at least twenty individual runs for each powder size sample. The results were analyzed statistically to provide the best determination of the application rate required for extinction. Potassium oxalate was found to be more effective than potassium iodide which, in turn, was more effective than potassium bicarbonate, etc. The relatively high application rates required for glass beads suggest that a thermal mechanism alone is not sufficient to explain flame extinction of these powders. It appears that both the chemical nature and particle size of the powders influence the application rate required for extinguishment.

Questions might be raised on whether the results from a 1 inch cup fire model are applicable to large fires. Accordingly, equipment was developed for powder application to much larger fires. The powder contained in a hopper was carried by a serrated rotor to a port fed with compressed air. This air stripped off and mixed with the powder. The resulting mixture was fed to a nozzle which produced a fan-shaped discharge. The discharge rate was governed by a variable speed motor. An infrared detector measured the time rate of extinguishment. Actually, two dispensers of this type were constructed, one being used for a 6 inch diameter fire model and another larger unit for fire models of 23 inch diameter.

In each of these experiments, the fuel was heptane floated on water. The circular fuel tubs were filled close to the brim so that very little freeboard existed.

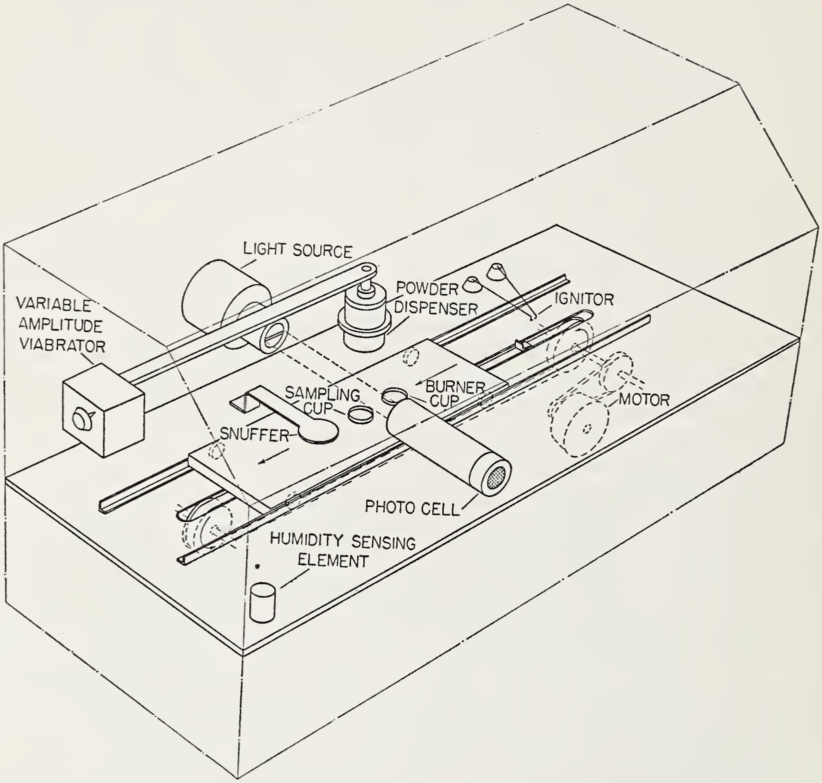

Figure 1. Apparatus for evaluating the fire extinction efficiency of powders using the $1\frac{1}{8}$ inch fire model

A circular collar of roughly twice the diameter of the fuel tub was placed around its upper edge. This was found to assist in stabilizing the burning process. The use of this equipment permitted measurement of the time required for extinguishment as well as the effective rate of powder application.

Data were presented of extinction time as a function of powder application rate expressed in terms of powder surface area per unit time. Within a limited range of particle sizes, powder surface area seemed to be the best means for correlation of the data for a given chemical. The surface area per unit weight of powder sample or specific surface, was determined from air permeability measurements. Again, potassium oxalate was found to be the most effective of all the powders. These data make it evident that chemical composition, powder particle size, and application rate, are all important in influencing the effectiveness of these extinguishing agents. The results for the 23 inch diameter fire model were similar.

Data on minimum application rate required for extinguishment were obtained for fire sizes of 1⅛, 6, and 23 inch diameters fire models. *Table 1* presents these data in summary form. It shows the minimum application rate of sodium bicarbonate in terms of powder surface area required for extinguishment. It also shows the ratio of minimum application rate required for extinction between sodium bicarbonate and other materials. For example, in the 1⅛ inch fire, 2.1 times the surface area application rate was required for sodium bicarbonate as for potassium bicarbonate. Neglecting experimental errors, this ratio for a given chemical should remain a constant for all fires, if the mechanism of extinguishment remains the same over the range of the fire sizes. The table shows that, with the exception of potassium iodide, such an effect was in fact observed. This material, when applied to the 1⅛ inch fire model, showed almost twice the effectiveness in comparison with the two larger models. The exact reason for this is not clear. Perhaps, in this model, the higher density and momentum of potassium iodide changes the effectiveness with which it could be applied and retained in the combustion reaction zone. The last column of this table presents the ratio of powder surface area application rate to fuel volume consumption rate. While this ratio varies by a factor of about two, it does seem to indicate that no major change takes place in the mechanism with which the powder was active in controlling the fires.

TABLE 1

MINIMUM EFFECTIVE RATES OF POWDER APPLICATION FOR VARIOUS FIRE SIZES AND POWDER TYPES

	Minimum Effective Powder Application Rate				Ratio of Powder Application Rate to Fuel Consumption Rate
		NaHCO₃ required as multiple of that for:			
Fire Diameter	$NaHCO_3$	$KHCO_3$	KI	$K_2C_2O_4H_2O$	
in.	cm²/sec				cm²/ml
1.12	68	2.1	4.5	4.9	8.7×10^3
6.0	2,100	2.6	2.3	4.2	9.1×10^3
22.8	25,500	2.7	2.7	4.6	4.2×10^3
40.6 *	200,000	—	—	—	6.2×10^3

* From data by Hird and Gregsten

Figure 2 shows this data in slightly different fashion. Two different ordinate scales are used. Powder application rate and fuel consumption rate are presented as functions of model fire diameter on a logarithmic scale. Data for sodium and potassium bicarbonate powders on large outdoor fires of 13 x 13 ft. square, obtained by Neill at the Naval Research Laboratory, as well as British data by Hird and Gregsten, are included. In plotting their results, which were obtained with the use of square-shaped fuel areas, the diameter of the equivalent circular area was used.

The general agreement of the data from these experimental groups is surprising, even more so when differences in powder application techniques are considered. NBS data were obtained with fixed dispensing equipment which produced a fan-shaped discharge covering the whole surface of the flammable liquid. The NRL data were obtained by manual operation of a portable extinguisher specially fitted

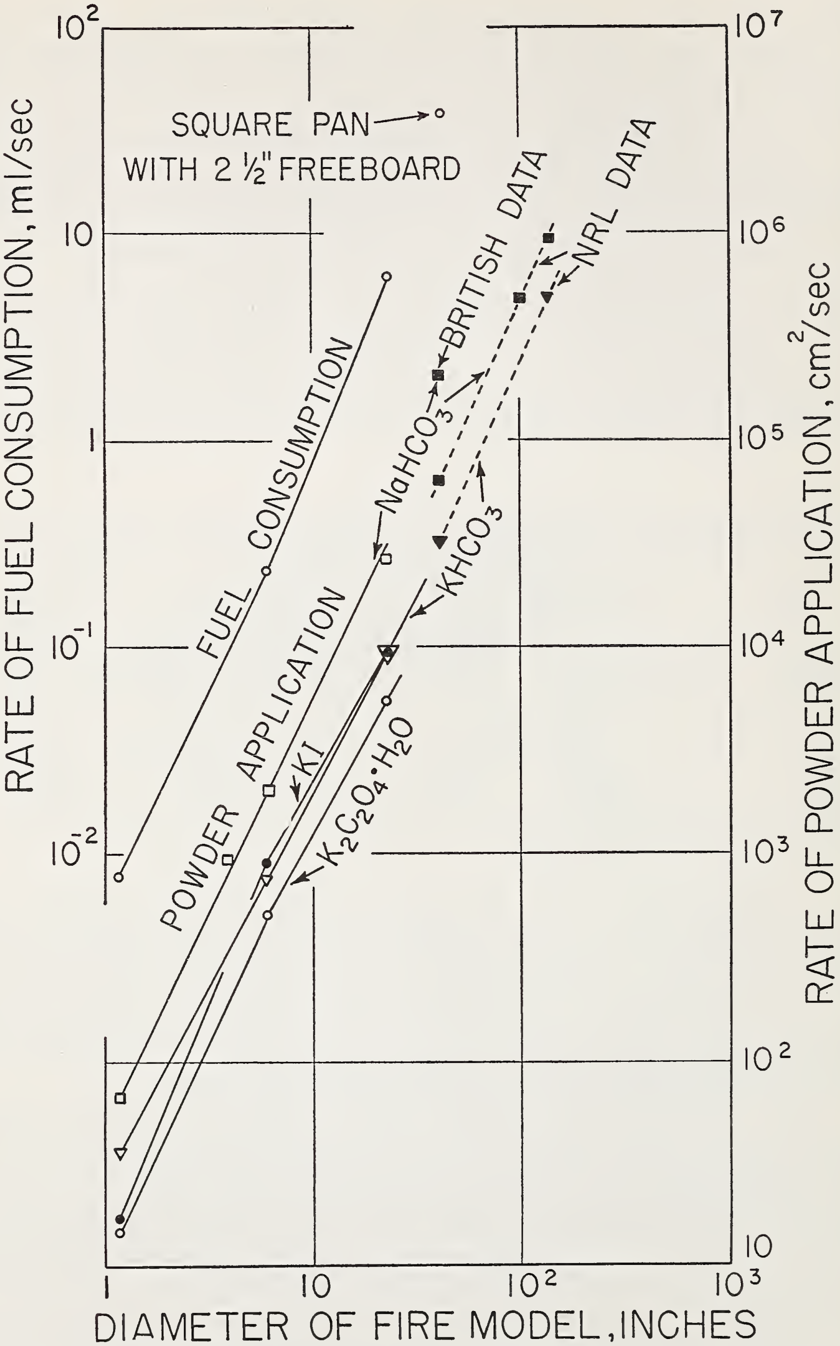

Figure 2. Rate of fuel consumption and minimum rate of powder application for extinguishment of fires of different diameters

for the studies. The nozzle of this unit was oscillated in such a manner as to cause the powder to involve the whole fire area. The British data were based upon square fuel fires with 2½ inch freeboard and a longer preburn period.

These results encourage confidence in the use of small fires for studying the extinction effectiveness of different powder materials to diffusion fires involving flammable liquid hydrocarbon fuels. The results also seem to give rather strong evidence that the mechanism by which these fires are extinguished is not greatly dependent on the size of the fire, at least within the range of fire sizes explored.

Subject Headings: ***Fires, model, extinguishment of; Extinguishment of model fires, by powders; Powders, extinguishing effect, on fire models.***

Study of Convection Currents Created by Fires of Large Area

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The investigations undertaken at the National Hydraulics Laboratory have been concerned with fluid dynamic behavior of convection currents caused by widespread fires with the objective of devising effective fire control procedures.

The complexity of the problems considered has led to simple field methods of experimentation and abbreviated calculations, the last stage always involving the study of an actual fire. The principal techniques have consisted of the establishment of the steady-state in which convection results from two primary causes—the source of heat and the draft—which were studied separately on different models, namely heated plates and fuel burning in tanks. The experimental study was preceded by a theoretical survey in order to separate the fundamental parameters and to make evident the laws of similarity that can be verified on models of different dimensions.

The first part of the investigation was concerned with the study of convection currents above the heated plates. The numerous references * in this field are concerned mainly with convection between two plane surfaces at different temperatures, which corresponds, for the problem in question, to the case of stratified atmosphere. A very important study by Yih † deals with convection currents created within an infinite medium by a point source of heat, a linear heat source, and a heat source composed of two linear sources. In the case of laminar and turbulent discharges, this reference permits calculation of velocity and density and, therefore, of temperature.

The majority of model studies have dealt with models of small size (several millimeters or centimeters) which makes extrapolation to large phenomena somewhat risky. This has led the National Hydraulics Laboratory to make new tests on heated surfaces of 50 to 100 centimeters diameter, which were either aluminum (50 centimeters) or steel (1 meter) and at temperatures up to 600°C. Measurements were made of pressures (with the help of a special micromanometer) and temperatures. Velocity measurements were made by photographic techniques. The experiments indicated that the temperature gradients conformed to the prediction of Yih and that the pressure variations at the center of the surfaces were very small, with a tendency to show a slight depression.

These incomplete tests will be resumed on a larger scale with more detailed instrumentation to determine more precisely the values of pressure, temperature, and velocity. However, the results presently available have shown that the presence of a cold front accentuates the formation of lateral convection. The second part of the study deals with convection currents during combustion.

Studies were performed with vessels of 1 and 5 meters diameter, with alcohol, benzene, and gasoline for the 1 meter vessel, gasoline and oil for the 5 meter vessel.

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* Ostroch, S. "Convection Phenomena in Fluids Heated from Below," *Transactions of ASME* 79, 299–305 (1957)

† Yih, C. S. "Free Convection Due to Boundary Sources," *Proceedings of the First Symposium on the Use of Models in Geophysical Fluid Dynamics," The Johns Hopkins University,* 117–133 (September 1–4 1953)

Measurements were mainly directed toward pressure observations at the center of the vessels where a slight depression had been noticed.

Photographs and films taken while the experiments were proceeding have shown the formation of laterally unstable whirlpools and vortexes with rotational direction altering during the course of the experiment. The few tests undertaken do not permit the drawing of general conclusions. In the program of tests planned, it is expected not only to determine velocity, temperature, and pressure, but also to measure the composition of smoke and, in particular, to study the effect of several types of fires occurring close to each other.

These experiments were preceded by a large-scale experimental fire in the Landes (southwest France) where in the course of the incineration of the Lande de Transacq of 325 hectares the development of the fire was observed. With an ambient temperature of 25°C and a wind of 5 to 8 meters per second, the flames reached a height of 10 to 12 meters and the smoke mushroomed to a height of 500 to 600 meters. The velocity of air on the ground about 100 meters away from the foot of the fire was 10 to 15 meters per second. The presence of a cold front at higher altitude gave the column of smoke the appearance of a mushroom, and smoke on the boundary subsequently turned down towards the ground apparently as a result of a convection current of cellular nature. A second conflagration experiment was unsuccessful.

In the program of proposed tests, the burning of 100 hectares of wasteland is planned.

Subject Headings: *Convection, currents, created by fires; Fires, creation of convection currents.*

Some Studies of Building Fires Using Models

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The ignition of cellulosic materials by radiation is described and the concept that a constant ignition temperature can be used over a limited range of heating conditions is discussed. Because the size of the irradiated area affects the mixing of the plume of volatiles with the surrounding air, it determines the minimum intensity and, to a lesser extent, the time at which ignition occurs. At very high rates of heating, the ignition temperature tends to rise with an increase in the heating rate owing, presumably, to the smaller amount of volatile material formed as a result of the smaller depth to which the heat penetrates. At very low rates of heating, the ignition depends more on internal self-heating and under these conditions the ignition temperature depends on the size of the specimen heated.

Thus, there are scale effects in ignition and these vary between the regimes mentioned. The same is true in general for the burning of fires in rooms but to date the relative importance of the rate controlling factors for the different regimes has not been fully established. Therefore, the studies describe the use of models to investigate what happens in a fire and compare the behaviour of small and large fires. From this work, it is hoped that a predictive model theory can be derived.

Usually a fire in a room starts from a small source and spreads throughout the compartment involving all the combustible surfaces. After this stage, often called "flash-over" has been reached, the burning becomes more steady, though the temperature continues to rise slowly because of the gradual decrease in the heat loss through the walls as they become heated. Eventually, the rate of supply of volatile material falls, the flames subside, and the temperature falls, and the final period of the fire consists mainly of the burning of solid carbonaceous residue.

Some ad hoc small-scale experiments were made to study the growth period up to flash-over and it has been possible to reproduce the main differences between fires involving two different types of wall linings. However, there are considerable complexities in this transient period of a building fire and recently small-scale work has been done to study the relatively steady period after flash-over. The severity of the fire in this period determines the fire resistance required of the structure of the building and mean burning rates and temperatures were measured for various sizes of compartments and windows and for various amounts of wood fuel. At relatively small window openings the rate of burning as measured by the rate of weight loss is proportional to the air flow entering the window.

The burning rates do not show any scale effect apart from that caused by the variation of air velocity with scale, due to the relatively greater buoyancy effect of larger fires. The relatively smaller burning rate of small-scale fires due to the lower air velocity is associated with a lower temperature.

In experiments made on fires with restricted ventilation, both in the United Kingdom and Japan, the fuel quantity was varied, but no systematic control was kept on the variation of the surface area of fuel exposed to the heat within the enclosure and the experiments show that increasing the quantity of fuel prolongs the fire in proportion. As windows become larger in relation to the size of compartment, the burning rate tends to a limiting value, independent of window size, but proportional to the quantity of fuel of given stick size. The few experiments made suggest that the burning rate for fires in enclosures with large openings is proportional to the area of wood exposed, but this is only true for certain arrangements of wood sticks in the crib.

Measurements have been made of the radiation from the flames and from the window for fires in cubical compartments with one side completely open. Empirical correlations are given for three sizes of compartments where the intensity of radiation is related to the rate of burning per unit area of floor or window.

The heights of flames emerging from the opening were visually estimated and those from small fires were relatively larger. On the assumption that air is entrained into flames at a velocity proportional to the velocity of the upward moving gases in the flame, and that this upward velocity is proportional to the square root of the height above the base of the flame, a method of correlating the data obtained for the three sizes of fires has been devised.

If one assumes a constant air-fuel ratio for the burning of wood, one cannot conclude that the burning rate is proportional to the air flow into the window, because it is in principle possible for part of the combustion to occur outside the room utilizing air entrained into the flame outside the window.

The heat balance of a room fire and the relation between the decomposition rate of wood and heat transfer rate are both necessary to determine the thermal conditions in the room and the rate of loss in weight, but the behaviour of wood under heat is not known sufficiently well to make a quantitative theory. The ratio of gaseous fuel production and air flow rate will affect the position of the reaction zone and thereby influence the heat transfer rate from the flames to the fuel. This may reduce the decomposition rate per unit area when the total fuel surface area is increased so that increasing the amount of fuel does not necessarily raise the total burning rate in proportion. The heat loss to the walls becomes relatively more important as the air flow decreases.

These considerations although formulated only qualitatively suggest further studies in building fires and the possibility of improvement in the design of models.

Subject Headings: ***Models, study of building fires by means of; Building fires, use of models in study of; Fires, in buildings, use of models in.***

Upward Convection Current from a Burning Wooden House

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The purpose of this study is first, to find the approximate similarity law on temperature distribution along the central axis of upward current from a rectangular heat source, and secondly, to calculate the temperature above a burning wooden house in a calm condition, based on this similarity law.

Dimensional Analysis

Let us take the origin of coordinates at the center of the heat source, the Ƶ axis in the upward vertical direction and the r axis in the radial direction. Equations of momentum and heat continuity are represented as follows:

$$\frac{d}{d\text{Ƶ}}\int_0^\infty \rho w^2 2\pi r dr = g\int_0^\infty \rho\,\frac{\Delta\theta}{\theta_0}\,2\pi r dr \qquad (1)$$

$$\int_0^\infty c_p\rho w(\Delta\theta)2\pi r dr = Q \qquad (2)$$

where w is the upward velocity, $\Delta\theta$ is the excess temperature at any point in the current, θ_0 is the absolute temperature of the surrounding air, and c_p and ρ are the specific heat and density of the gas in the current, g is the acceleration due to gravity and Q is a heat quantity conveyed by the current per unit time.

Suppose that the radius of heat source is r_0, and replace the coordinates r and Ƶ with the non-dimensional ones r/r_0 and Ƶ$/r_0$, then by dimensional analysis, we obtain the two following non-dimensional quantities $\overline{W}$ and Ⓗ considering equations (1) and (2).

$$\overline{W} = \frac{W r_0^{1/3}}{\sqrt[3]{\dfrac{Qg}{c_p\rho\theta_0}}} \qquad (3)$$

$$\textcircled{H} = \frac{\Delta\theta r_0^{5/3}}{\sqrt[3]{\dfrac{Q^2\theta_0}{c_p^2\rho^2 g}}} \qquad (4)$$

Let us call these two, the non-dimensional upward velocity and non-dimensional excess temperature and use them hereafter in expressing the results of experiment.

Experiment and Its Results

Two types of heat sources were employed. In the case of the first type, alcohol was burnt in seven circular vessels with radii of 3.3, 6, 9.9, 14.3, 18.75, 23.75, 37.5 cm. This type of heat source is called "continuous heat source." In the case of the second type, many little wicks of alcohol lamps were placed within a circle of a certain radius. This is called "discontinuous heat source."

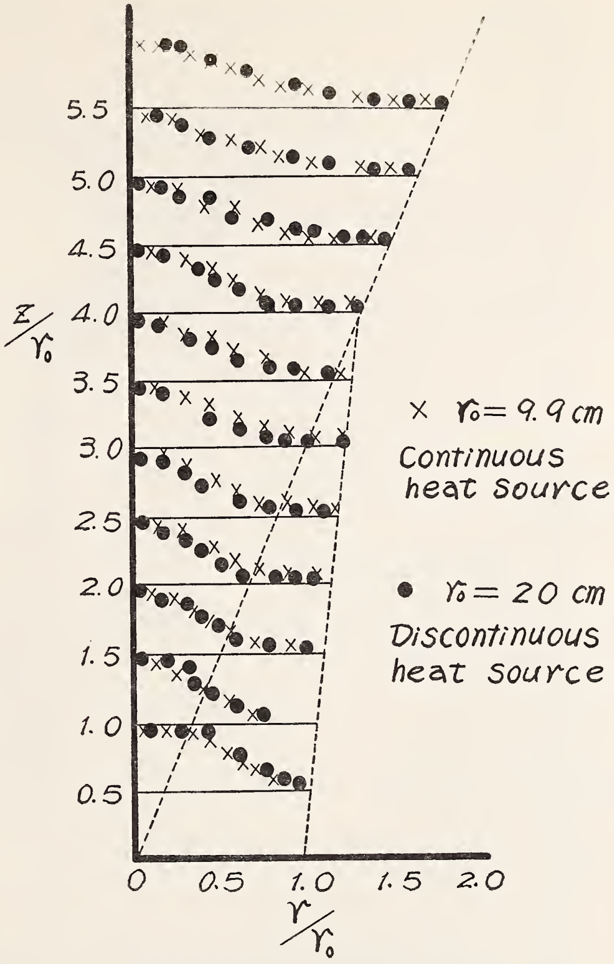
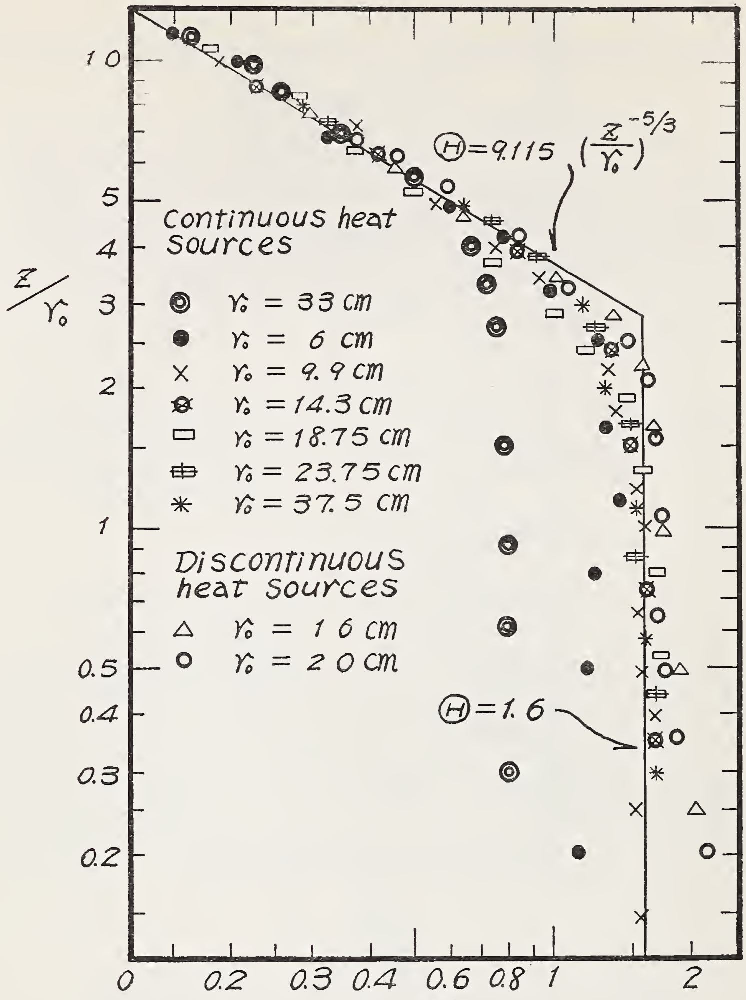


Figure 1. Horizontal distributions of temperature above circular heat source

Figure 1 indicates the horizontal distributions of temperatures of the upward current from a continuous heat source of 9.9 cm. in radius and a discontinuous heat source of 20 cm. in radius. They are expressed in the non-dimensional coordinate system. From this figure, we observe the following two facts:

1) The horizontal temperature distributions at any height in the upward currents from the circular heat sources of various radii can be represented by one curve in these non-dimensional coordinates.
2) There are two kinds of domains as to the horizontal temperature distribution. In the domain near to the heat source ($Z/r_0 < 2.5$), horizontal distribution of the temperature takes the shape of a plateau and hot current does not spread so widely in horizontal direction as it rises, whereas in the domain far from the heat source ($Z/r_0 > 2.5$), horizontal temperature distri-



$$Ⓗ = \frac{\Delta\theta\, r_0^{5/3}}{\sqrt[3]{\dfrac{Q^2\theta_0}{C_p^2\rho^2 g}}}$$

Figure 2. Temperature distributions along the central axis of upward currents from circular heat sources, expressed in non-dimensional coordinate system

bution is like the one of the upward current from a point heat source and the hot current spreads sidewise as if it started from a point heat source placed at the center of the circular one.

Figure 2 indicates the vertical distributions of temperatures of the upward current from the circular heat sources of various radii. In this figure, too, we can divide the distribution into two domains and all the vertical temperature distributions from the sources of various radii can be represented by one curve, although there are some exceptions in the cases of sources whose radii are $r_0 = 3.3$ cm. and 6 cm. In these cases no similarity law holds, as is shown in *Figure 2.* This may be due to the following fact; the flames rising from heat sources of $r_0 = 9.9$ cm. and larger are turbulent flames, and alcohol burns nearly over the whole surface of sources, whereas the flames from heat sources of $r_0 = 3.3$ cm. and 6 cm. may be considered to be laminar flames in which alcohol burns chiefly on the boundaries of the containers. We exclude these laminar flames for the purpose of wooden house fire research.

Figure 3 shows the diagrammatical temperature distribution near a heat source. Near a heat source, hot gas and surrounding air mix at the boundary and temperature drops there. The higher the gas rises, the deeper the air penetrates from the surroundings into the hot gas and at last the boundary between the mixed and unmixed gases disappears at A in *Figure 3.*

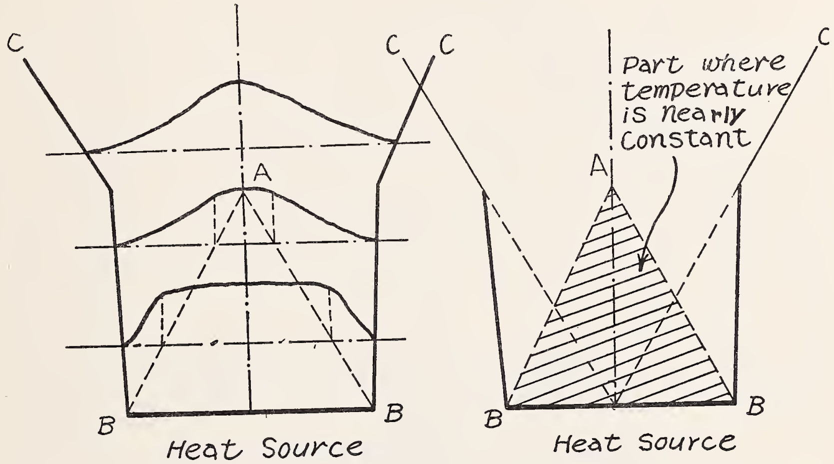


Figure 3. Diagrammatical temperature distributions near a circular heat source

In the domain BAB, the temperature of the gas is nearly constant, but above A, the central temperature decreases with height because the mixing is performed even on the central axis. This accounts for the two different parts in this upward current.

In the case of rectangular heat source, we can imagine two kinds of boundary lines: A_1B_1 and A_2B_2, the boundaries due to the shorter side of the rectangle and the longer one respectively. *Figure 4* shows the diagrammatical picture of these boundaries. At point A_1 the boundary line due to the shorter side disappears, while the one due to the longer side still remains. So in the domain between A_1 and A_2, the temperature remains constant in the direction of B_2B_2 and the temperature distribution is similar to the one produced by a line heat source. In the domain above a point A_2, hot gas and surrounding air are mixed in all directions, and so the temperature distribution must show a similar distribution to the one when a point heat source exists at the center of the rectangle.

Figure 2 shows the results of experiments for the circular heat sources. By calculation we derive the following equations:

$$\textcircled{H}=1.6$$

$$\textcircled{H}=9.115\left(\frac{Z}{r_0}\right)^{-5/3}$$

as the non-dimensional equations for vertical temperature distribution of the upward current from a circular heat source in the domains near and far from the heat source respectively.

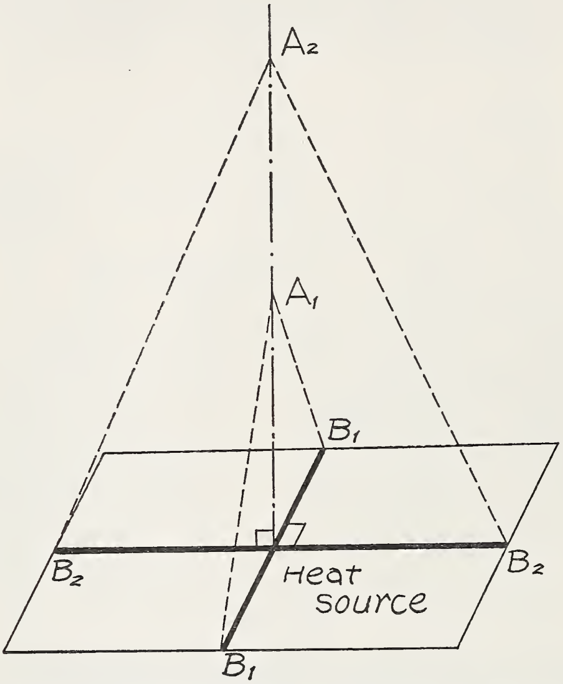


Figure 4. Front lines in the case of a rectangular heat source

Figure 5 shows the results of experiments for the rectangular heat sources, where r_0 is equal to the value of the radius of a circle having the same area as the original rectangle. Non-dimensional equations of the vertical temperature distribution for each domain can be derived by calculation as follows:

$$\text{1st domain}\quad \textcircled{H}=1.6$$

$$\text{2nd domain}\quad \textcircled{H}=\frac{1.764}{\sqrt[3]{n}}\left(\frac{Z}{r_0}\right)^{-1}$$

$$\text{3rd domain}\quad \textcircled{H}=9.115\left(\frac{Z}{r_0}\right)^{-5/3}$$

where n is the ratio of length of adjacent sides of rectangles.

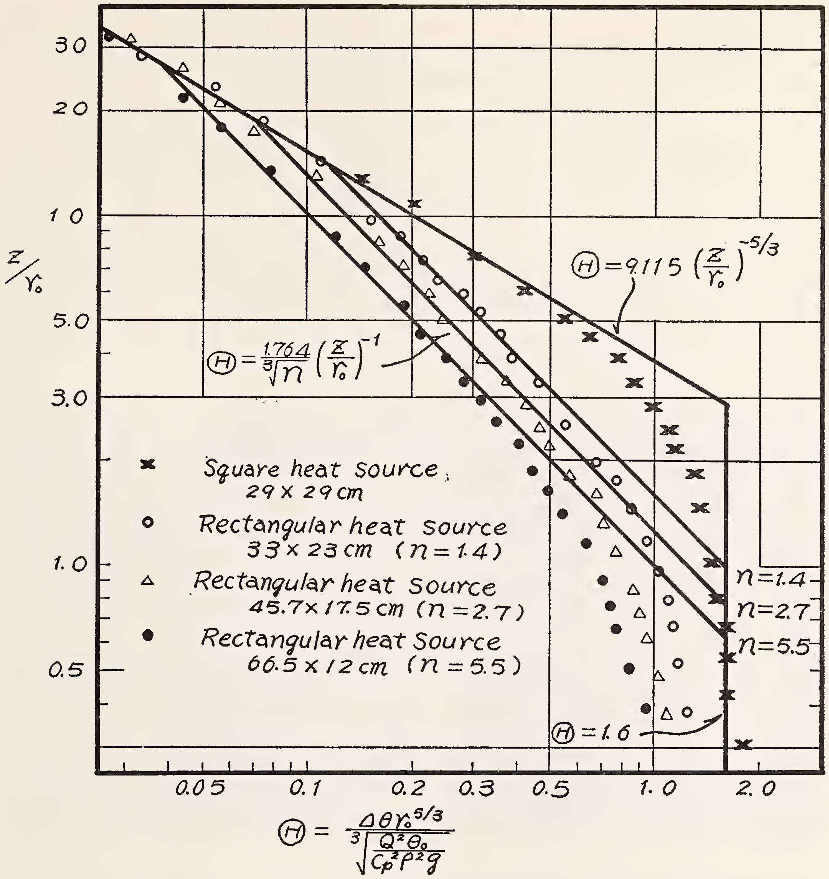


Figure 5. Temperature distributions along the central axis of the upward currents from rectangular heat sources

We can apply this similarity law to the case of the wooden house fire if the plan of the house is assumed to be a rectangle and if we make some corrections of the heat loss by radiation, which is considerable in the case of wooden house fire. Examples of numerical calculations are given in the full report. Considerable differences of temperature exist between the square-shaped house and oblong-shaped one.

Subject Headings: ***Convection, currents, in house fire; Fires, convection currents in.***

A Steady-State Technique for Studying the Properties of Free-Burning Wood Fires

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The U.S. Forest Service started a laboratory study with the ultimate objective of determining model laws governing properties of wood fires. The first phase of this study was devoted to the development of a steady-state aerothermodynamic system, burning solid fuels, in which parameters governing the combustion are examined over an extended period of time.

The essential elements for the fire system are: a wood fuel bed, a combustion table equipped to transport the fuel bed at a controlled rate, a base of known thermal properties on which the fuel rests, and instruments to measure specified variables.

The fuel bed is a crib of wood sticks of square cross section bonded at each joint with a small drop of thermo-setting resin glue. The physical features of such a crib are controlled, such as the species of wood, the density of the wood, the dimensions of the sticks, the moisture content, the spacing, and the width and height of the crib.

The crib is ignited at one end with 10 to 20 cc. of n-hexane poured into a shallow trough containing an asbestos wick. As the fire gradually spreads to the other end of the crib a chain-belt mechanism in the combustion table moves the crib and its base so that the column of flame is held stationary in space (*Figure 1*). The mechanism also draws two heavy asbestos sheets, one on each side of the fire, in synchronism with the flame to simulate the relative movement of ground and fire front.

Several separate slabs make up the base for the test cribs. In tests thus far conducted, preformed concrete slabs with a density of about 90 lb/cu ft have been used.

Temperatures in the convection column are measured with a grid of 36 chromel-alumel thermocouples placed above the combustion table, crosswise and lengthwise of the crib, from 1 inch above the crib to 10 feet above the level of the table. All of the thermocouples are connected to multipoint recording potentiometers.

A continuous record of the lapse rate within the testing room during each test is made with a series of thermocouples suspended from ceiling to floor and connected to a multipoint recording potentiometer. The rate of heat transfer through the walls and ceiling during each test is measured by thermopile heat meters fastened to the walls and ceilings.

Venting of the convective gases is accomplished through a hood 11 feet square and a 13 inch diameter stack. A motor driven blower in the stack is used to remove the exhaust. Temperatures of the combustion gas flowing into the stack are measured with a thermocouple, and the velocity of the stack gas is measured with a Pitot tube connected to an ionization-type pressure transducer. A technique of collecting samples of combustion gas in glass sampling bottles has been developed for analysis either in an Orsat apparatus or by gas chromatography.

A thermopile radiometer mounted so that it can be pointed toward the fire at various angular elevations from the horizontal and at a radial distance of 14 feet from a selected point in the fire is used to measure the radiation from the crib fires. The stand on which the radiometer is mounted is movable so that measurements can be taken from the front, rear and either side of the fire.

To measure the heat transmitted from the fire to the base, the center slab of the base is removed soon after each fire and immersed in water in a sealed and insulated calorimeter box. The heat content of the slab is calculated from the temperature rise of the water.

The residue left after each fire, which consists of ash, carbon, and partially carbonized wood, is collected, weighed, and pulverized. Samples of the pulverized material are burned to an ash in a muffle furnace to determine their carbon content, and other samples are tested for their heat value in a bomb calorimeter.

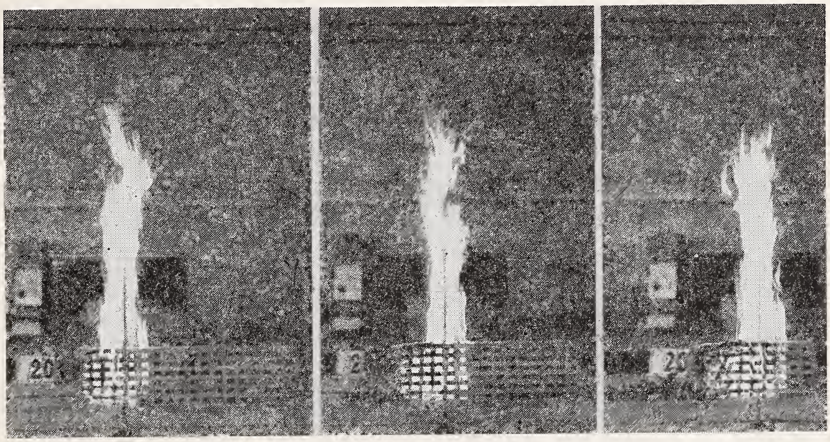

Figure 1. Flame from a test fire at three different times, illustrating the fixed position of the flame as the crib moves

Time-lapse movies taken from the side and rear of the fire are made with two motion-picture cameras. From these movies the width and height of the flame can be measured and any unusual behavior can be detected. Shadowgraphs of the flame and convection column are also photographed.

There are two important features of the procedure. (1) The crib is made relatively long, and the zone or band of fire travels the length of the crib. After an initial period of build up, the fire reaches a steady state; this condition is held until near the end of the fire. It is the behavior of the fire in the steady state that is currently being investigated. (2) The flame is held in a fixed position in space by moving the fuel into the fire. This technique permits stationary instrumentation. The rate of fire spread is the rate the fuel is fed to the fire to maintain the flame in a fixed position.

In the course of developing the system, data have been obtained which illustrate its diagnostic usefulness. In the experimental fires, steady-state conditions have been maintained for 15 to 30 minutes, the duration depending on the length of the crib. During the steady-state burning, rate of fire spread through the crib was linear.

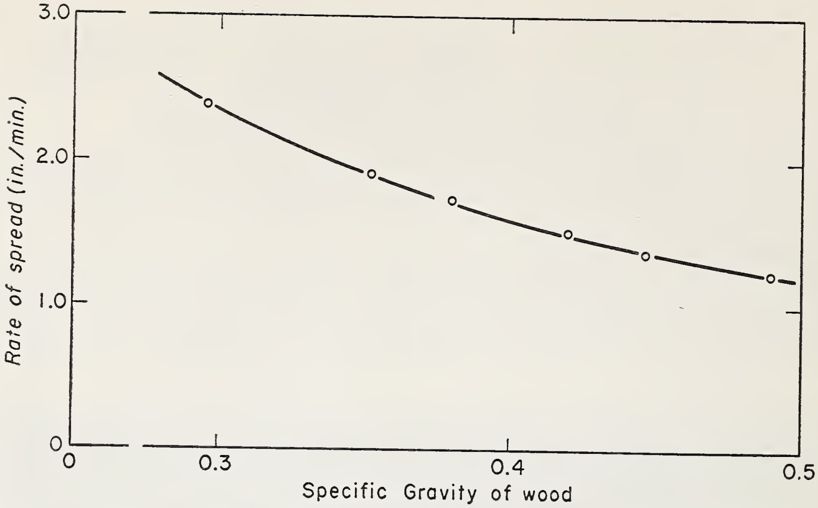

Figure 2. Rate of fire spread through cribs of white fir of different specific gravity

The effect of density of the wood on the rate of spread of the fire was investigated early. This information was essential to the selection of wood for subsequent crib tests. An increase in specific gravity was found to decrease the rate of spread of fire through the crib (*Figure 2*).

The horizontal distribution of temperature in a convection column at several heights, and the change in temperature up the central axis of a convection column are presented in the report. The irradiance to the side of the fire at an angle of 20 degrees from the horizontal is also presented.

The quantity of the heat of combustion that went into the concrete slabs on which the cribs rested varied from 2.3 to 7.1 per cent depending on the size of the crib. The heat remaining in the charcoal averaged 1.21 per cent of the total heat of the fuel.

Subject Headings: *Model fires, of wood; Wood, fires, steady-state model.*

Experiments with Model Mine Fires

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The burning of wood in a ventilated duct was studied in two separate series of experiments. The duct was made of an outer casing of steel, lined with refractory material. It was 48 ft. long and its internal dimensions were 6.5 in. x 4.75 in.; it may be considered as a 1:15 representation of a 240 yd. length of a typical mine roadway 8 ft. wide and 6 ft. high. The duct was ventilated by forge-type blowers and the linear air speed could be controlled and measured. When the duct was lined with fuel, speeds in excess of 60 ft/min could be obtained. It was fitted with 18 unshielded chrome-alumel thermocouples mounted centrally in the cross section; the outputs were switched in turn to a recording milliameter by a thyratron circuit through a D.C. amplifier and a reference unit. Sampling of the duct atmosphere was continuous during an experiment and the samples, after dying and cooling, were passed to carbon monoxide and carbon dioxide infrared gas analyzers. Viewing ports with mica windows were fitted at 3 ft. intervals along the length of the duct.

The first series of tests was made to determine a suitable type and arrangement of fuel. Hardwood, softwood, and fiberboard were tried and the effects of varying the fuel density and arrangement of the fuel in the duct were studied. The effect of "supporting radiation" was easily apparent and only when the wood lagging covered both roof and sides did the fire propagate along the whole of the fire zone.

It was concluded that a lining of hardwood 0.5 in. thick on the roof and sides should be adopted as standard for the next series of experiments, which were planned to show the effect of air speeds between 45 and 615 ft/min on the progress of the fires. The rate of progress of the fire and the length of the active fire zone were assessed both by direct observation through the viewing ports and by the temperatures of the thermocouples. The rate of fuel consumption was calculated from the carbon monoxide and carbon dioxide contents of the products of combustion.

A total of 17 experiments were made and it was found that the fires were of three types:

1) *Self-stifling fires* At low air speeds, fires did not propagate. When oxygen vitiation was almost complete, active flaming ceased and production of oxides of carbon decreased rapidly. Smouldering continued for some time but eventually ceased when the fire had travelled only a short distance.

2) *Spasmodic fires* At medium air speeds, fires propagated along the whole length of the duct, though not at a steady rate. A period of high activity was followed by one of slow smouldering which might last as long as 25 minutes. Flaming combustion then recommenced but died again and a second period of smouldering began. The cycle was repeated several times.

3) *Continuous fires* At high air speeds, fires propagated continuously without check.

When the duration of the fires was plotted against air speed, a marked discontinuity was apparent at about 150 ft/min when there is a transition from the self-stifling to the spasmodic type. This point may correspond to a transition from laminar to turbulent flow as calculation shows that the Reynolds number may be in the critical range near 3000.

The duration of the fires, their maximum lengths, and the average burning rates were all found to approach limiting values at high air speeds. Whether this is due to the fact that the duct was of limited length can be tested only by experiments with a longer one. In general, the results obtained are chiefly useful in indicating the limits of a model duct as small as the one used.

Subject Headings: *Fires, coal-mine, model study of; Model fires, coal-mine.*

On the Self-Ignition of Wood Materials

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When combustible materials are piled on the ground, they often ignite spontaneously. Whether they ignite by themselves or not depends not only upon the chemical and physical properties of the materials, but also upon their quantities and the ambient temperature. When wood materials are piled in the open air, self-ignition takes place only if the materials are piled mountain high. This is because the accumulation of heat from the chemical reaction inside the pile is very slow. Therefore, it is practically impossible to carry out experiments on self-ignition of this kind.

If the differential equation for self-ignition could be solved analytically, experimental investigations for this phenomenon would be unnecessary but actually it is impossible to solve the equation completely. Thus, to study the self-ignition of slow heat-producing materials, it becomes necessary, first, to find an approximate solution which does not depend on the size of the sample, and secondly, to ascertain if that solution is consistent with the experimental results obtained using a sample of small size.

The equation for self-ignition containing a term of heat production of the Arrhenius type is as follows:

$$c\rho \frac{\partial T}{\partial t} = k\nabla^2 T + Ae^{\frac{-E}{RT}} \qquad (1)$$

where $Ae^{\frac{-E}{RT}}$ = Arrhenius heat generation
T = absolute temperature
c = specific heat of the material
ρ = density of the material
k = thermal conductivity of the material
E = activation energy
R = gas constant

We considered the case in which a specimen of uniform material in the form of a slab, cylinder, or sphere is placed in a region of temperature T_a. The above equation is transformed into the following well-known equation of dimensionless quantities:

$$\frac{\partial\theta}{\partial\tau} = \frac{\partial^2\theta}{\partial\xi^2} + \frac{m}{\xi}\frac{\partial\theta}{\partial\xi} + \delta e^{\theta} \qquad (2)$$

where δ = discriminant $= \frac{A}{\kappa} r^2 \frac{E}{RT_a^2} e^{\frac{-E}{RT_a}}$

θ = reduced temperature $= \frac{E}{RT_a^2}(T - T_a)$

ξ = reduced distance $= \frac{x}{r}$

τ = reduced time $= \frac{\kappa}{c\rho r^2} t$

m = 0 for a slab, m = 1 for a cylinder and m = 2 for a sphere

r = radius for cylinder and sphere, half thickness for a slab

x = distance from the center (for m = 2), from the central line (for m = 1) or from the central plan (for m = 0)

Equation (2) for the case of a steady state, *i.e.* for $\frac{\partial\theta}{\partial\tau} = 0$, has been extensively studied and solved by several authors. However, the equation in its complete form is unsolvable, and therefore we tried to arrive at an approximate solution for it.

Since the difficulty in solving equation (2) arises from the inclusion of the term e^θ, we assumed the approximation

$$e^\theta = 1 + \beta\theta \quad (3)$$

where β is a constant with respect to θ and ξ. If one assumes β to be constant, equation (3) would be too rough an approximation. Therefore, we assumed β to be a function of θ_0, that is, the temperature in the center of the specimen and the highest one of the temperatures at all points of the specimen at that time. Thus—

$$\beta = 1 + a_1\theta_0 + a_2\theta_0^2 \quad (4)$$

If the temperature in the center at time t is θ_0, we consider that equation (4) holds throughout the time interval 0∼t. The constants a_1 and a_2 depend on the shape of the specimen.

For the steady state, we obtain

$$\frac{d^2\theta}{d\xi^2} + \frac{m}{\xi}\frac{d\theta}{d\xi} + \delta(1 + \beta\theta) = 0$$

We can easily solve this approximate equation and its solution should coincide with the one which has already been obtained by many authors. β should be chosen to meet this requirement. Thus, for example, if the specimen is spherical *

$$\beta = 1 + 0.3691\,\theta_0 + 0.0908\,\theta_0^2 \quad (5)$$

This is the answer obtained for the stationary state. Nevertheless, if we assume that equation (5) can be extended to the non-steady state, the fundamental equation

$$\frac{\partial\theta}{\partial\tau} = \frac{\partial^2\theta}{\partial\xi^2} + \frac{2}{\xi}\frac{\partial\theta}{\partial\xi} + \delta(1 + \beta\theta)$$

is solved, and the time τ, necessary for the temperature at the center to increase

---

* Kinbara, Tosiro and Akita, K. "An Approximate Solution of the Equation for Self-ignition," *Combustion and Flame* (To be published)

from 0 to θ_0, when the surface temperature is kept equal to T_a, is expressed as follows:

$$\tau=\frac{1}{\pi^2-q^2}\log\frac{2q_0^2}{(\pi^2-q_0^2)\left\{\frac{q_0}{\sin q_0}-(1+\beta\theta_0)\right\}}\qquad(6)$$

where

$$q_0^2=\delta\beta$$

Relating to this theory, experiments were conducted using sawdust contained in a sphere of wire gauze.

The experimental and the theoretical results showed close agreement with respect to the qualitative pattern of the temperature rise with time, that is to say, temperature rises slowly at first but after a certain time (*i.e.* ignition time) it rises very rapidly. However, from the quantitative point of view, the agreement is far from perfect and the theoretical ignition time seemed to fall short of the experimental one.

To account for this discrepancy, we considered the consumption of material before ignition. Then A and accordingly the discriminant δ should be considered to decrease with the reaction.

Thus, for the sake of simplicity, we assumed

$$\delta=\delta_0 e^{-\lambda\theta}\qquad(7)$$

The fundamental equation (2) transforms into

$$\frac{\partial\theta}{\partial\tau}=\frac{\partial^2\theta}{\partial\xi^2}+\frac{m}{\xi}\frac{\partial\theta}{\partial\xi}+\delta_0 e^{(1-\lambda)\theta}\qquad(8)$$

and it can be solved in the same way as (2). When suitable values are given to δ_0 and λ, the calculated θ from (8) showed close agreement with the experimental θ.

Thus, assuming consumption of materials during the process of heating, our solution seems to be applicable to the self-ignition of spherical samples of any size.

Subject Headings: ***Wood, self-ignition of; Ignition, of wood.***

Summary of Session on Full-scale Case Studies and Tests

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Applied Physics Laboratory, The Johns Hopkins University
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An evening session dealt with three full-scale case studies and tests, viz., Natural Phenomena Exhibited by Forest Fires (J. S. Barrows, Intermountain Forest and Range Experiment Station), The St. Lawrence Burns (G. W. Shorter, National Research Council, Canada), and Operation School Burning (R. M. Hill, Fire Marshall, City of Los Angeles).

All three papers demonstrated the complexity of the details of fire behavior, particularly when there is no steady state during the course of the conflagration (*i.e.*, fires in buildings). Such full-scale observations have a considerable value in pointing out possible improvement in building design, particularly from the viewpoint of gas flow and ventilation, and the testing of protection devices under realistic conditions. In the case of forest fires they identify large-scale interactions between the fire and the atmosphere. Their very complexity and dependence on uncontrollable external conditions make such tests unsuitable, however, as a basis for suggesting modeling principles.

The results of the two building-fire experiments emphasized the rapid spread of smoke and hot gases, deficient in oxygen and rich in carbon monoxide, throughout the structure, particularly when no effective partitions are available. The discussion of forest fires stressed the complex interaction between fires, fuel type, wind conditions, and terrain. Much current work is concerned with accumulating phenomenological evidence on the effect of variables on burning rates.

Natural Phenomena Exhibited by Forest Fires

By means of time-lapse movies the influence of fuel type, weather factors, and topography on fire behavior was described. Examples were given of fires when both ground and aerial fuels were burning (Dudley Lake Fire, Arizona), where the fuel consisted primarily of small-size brush (Topanga Canyon Fire, California) and of a fire composed of large-size material (Intermountain Lumber Fire, Montana). Test fires in fuel beds containing large amounts of finely divided particles indicated that fire propagation rate is nearly proportional to the concentration of fuel.

The importance of weather factors was shown in the Coal Creek Fire, Montana, when during a three-day fire well-developed convection columns formed in the afternoons, accompanied by high fuel consumption. At night and early morning the fire intensity died down considerably. On inclined terrains changes in wind directions between morning and afternoon will influence the fire propagation rates. Test fires in fuel beds of different humidity demonstrated a qualitative relation between fire spread and moisture content of the fuel.

Convection columns were investigated in a variety of fires. Convection column heights of 5 miles or more were measured. Occasional violent whirls with velocities in excess of 200 miles per hour were observed.

The St. Lawrence Burns

During the construction of the St. Lawrence Power Project six two-storied dwellings and two larger buildings became available for full-scale fire tests. Three of the dwellings were lined with combustible materials and three with noncombustible materials.

Measurements were made of carbon monoxide and oxygen concentration, smoke-density, sound, temperature, black-body temperature, and radiation intensity. The critical times for survival of occupants in upstairs bedrooms are given in the Table based on criteria of excessive carbon monoxide content (1.28%) or gas temperature (300°F) and on visibility (four feet).

Type of Wall Lining	Closed Bedroom		Open Bedroom	
	Gas or Temp.	Visibility	Gas or Temp.	Visibility
Noncombustible	11.7 min. (300°F)	6.4 min.	2.5 (300°F)	2.1 min.
Combustible	5.6 min. (1.28% CO)	3.4 min.	1.8 (300°F)	1.6 min.

Radiation measurements showed that buildings lined with combustible materials gave rise to radiation levels (40 cal/cm^2/sec) about twice those produced by noncombustible-lined buildings. The black-body temperature never exceeded 1000°C, corresponding to a radiation level of 3.6 cal/cm^2/sec. Thus, the greatest radiation contribution was from the volume of flame surrounding the window openings rather than from the window openings themselves.

Operation School Burning

Extensive fire tests were carried out on the Robert Louis Stevenson Junior High School, Los Angeles, California, prior to its demolition. The purpose of the tests was to investigate methods of protecting multi-storied open stairway school buildings. The tests included studies of the effectiveness of fire curtains, roof vents, and complete or partial automatic sprinkler protection. Data were also tabulated on the operation of automatic fire and smoke detection equipment, fusible links, and automatic door closers.

The test results are described in detail in the official report "Operation School Burning," published by the National Fire Protection Association (1959). Among the more important results were the following:

> Smoke (specifically as it pertains to visibility and irritant effects) was the principal safety hazard. Untenable smoke conditions preceded untenable temperature conditions in nearly every test.
>
> Natural or forced draft vents up to the capacity tested failed to produce satisfactory venting action.
>
> A complete system of automatic sprinklers will maintain low temperatures throughout the building, reducing build-up of smoke.
>
> Partial automatic sprinklers (in corridors, but not over the test fire) did not prevent smoke spread.

Subject Headings: ***Forest fires, natural phenomena exhibited by; St. Lawrence Burns; Fires, school.***

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ABSTRACTS

I. Ignition Phenomena

Zabetakis, M. G. and Burgess, D. (U.S. Bureau of Mines, Pittsburgh, Pennsylvania) "Research on the Fire and Explosion Hazards Associated with New Liquid Propellants," *Office of Naval Research, Bureau of Ships, N Aonr-48-59 Progress Report No. 1* (April 24, 1959—July 31, 1959)

This is the first of a series of reports on the subject. The work is divided into three phases: I. Ignition; II. Flame Propagation; and III. Flame Spreading and Extinguishment. Tests were conducted on unsymmetrical dimethyl hydrazine (UDMH) and aniline. The oxidants included air, oxygen, nitrogen dioxide, red fuming nitric acid (RFNA), and white fuming nitric acid (WFNA). In addition, similar tests were conducted in helium-oxygen and carbon dioxide-oxygen atmospheres. Initial pressures were one atmosphere.

Using a modified Bureau of Mines I-8 ignition temperature apparatus, the minimum spontaneous ignition temperatures (S.I.T.) of aniline-RFNA-air mixtures are presented graphically as a function of total NO_2 concentration. Values vary from a high of 617°C (0% NO_2-100% air) to a low of 200°C (24% NO_2-76% air). Data on the systems UDMH in RFNA-air, WFNA-air, 70% HNO_3-air, and NO_2-air are also graphically represented as a function of the total NO_2 concentration. Values vary from a high of 250°C (0% NO_2), common to all oxidants investigated, to lows of 100°C (RFNA-air, 8.5% NO_2), 100°C (WFNA-air, 14% NO_2), 120°C (70% HNO_3-air, 38% NO_2), and 10°C (NO_2-air with 25% NO_2). The S.I.T. of UDMH in He-O_2 and CO_2-O_2 atmospheres is presented graphically as a function of oxygen concentration; in pure helium atmosphere decomposition occurs at about 400°C, while only 280°C is required to induce decomposition in pure CO_2; the lowest S.I.T. for both kinds of atmospheres is 225°C at a 50 to 55% oxygen concentration.

The minimum energy concept is applicable to initiation by shock wave, by hot wire, by break spark, and electrostatic spark. Minimum energy and optimum electrode separations are given for UDMH-air mixtures. A minimum ignition energy of 0.36 millijoules occurs well on the fuel-rich side of stoichiometric at about 8% UDMH; optimum electrode separation is 0.075–0.080 inches. These values are shown to be comparable to those for saturated hydrocarbons such as methane and ethane.

The flammability limits of aniline in air-water mixtures at one atmosphere pressure and 141°C using a Bureau of Mines F-11 apparatus are presented graphically. The data indicate that a minimum of 16 volumes of water vapor are required per volume of aniline to produce a nonflammable mixture with all proportions of air; that flame propagation can occur with as little as 13.7 volume per cent oxygen; and that all mixtures containing in excess of approximately 32.5 volume per cent water vapor are nonflammable at the above temperature and pressure.

The information presented regarding flashover rates above a pool of propellant, and burning rates of open fires supported by liquid propellants was of a preliminary and exploratory nature, and will therefore be included in a future report when the results are more conclusive.

Subject Headings: ***Ignition of propellants; Propellants, ignition of; Flame, propagation of propellants; Dimethyl hydrazine, ignition of.***

W. G. Labes

Zabetakis, M. G. and Grumer, J. (U.S. Bureau of Mines, Pittsburgh, Pennsylvania) "Research on the Fire and Explosion Hazards Associated with New Liquid Propellants," *Office of Naval Research, Bureau of Ships, N Aonr-48-59 Progress Report No. 2* (August 1, 1959—October 31, 1959)

This is the second of a series of reports on the subject. The work is divided into three phases: I. Ignition; II. Flame Propagation; III. Flame Spreading and Extinguishment. Unsymmetrical dimethyl hydrazine (UDMH) was the fuel tested during this period.

The spontaneous ignition temperature (S.I.T.) of UDMH in NO_2-O_2, NO_2-He, and NO_2-air atmospheres at 15 p.s.i.a. pressure in an open 277 cc. pyrex chamber is graphically represented as a function of NO_2 concentration. Values for NO_2-air and NO_2-O_2 are almost identical, ranging from about 240°C (0% NO_2) to 20°C (10% NO_2). For the NO_2-He atmosphere above 22% NO_2 dual S.I.T. values exhibited are attributed to the sharp decline in the compressibility factor of NO_2 over the temperature range 50 to 100°C. This same effect is exhibited by the NO_2-O_2 and NO_2-air curves to a lesser extent.

Additional S.I.T. tests of UDMH in NO_2-air atmospheres at 30 p.s.i.a. pressure in a closed 458 cc. pyrex-lined bomb were conducted and results graphically represented and compared with the same curve for 15 p.s.i.a. pressure. Values under the two conditions do not vary widely; above about 8% NO_2 S.I.T. values are consistently lower for the higher pressure, after which the curves cross and the values at 30 p.s.i.a. pressure increase over those at 15 p.s.i.a. pressure. The S.I.T. value common to both curves is about 80°C.

The results of tests conducted to determine the extent of thermal decomposition of vaporized (70%) HNO_3 as a function of time and temperature are also graphically presented. They show that the 10-minute heating period used in the S.I.T. tests with UDMH in vaporized fuming nitric acid-air mixtures (described in

Progress Report No. 1) was not sufficiently long to permit complete thermal decomposition of the nitric acid into NO_2, O_2, and H_2O. It is suggested that these experiments be extended to include longer mixing times.

The results of exploratory tests of flame propagation for UDMH-air mixtures in a 1-liter spherical bomb with central ignition and in a tube of stainless steel and aluminum construction with I.D. of 1.26 inches and length-diameter ratio of 60 are reported. Using the spherical bomb, a single test with 6.8 per cent UDMH and two with 5.1 per cent UDMH gives results similar to those with conventional fuels, indicating flame speeds of 240 and 90–95 cm/sec, maximum pressures of 115 and about 100 p.s.i. and pressure rise rates of about 12,000 and 4000–7000 p.s.i./sec, each with the respective mixtures.

Work with the tube gave results totally unexpected in the light of experience with conventional fuels. While the lean limit (0.9–1.9% UDMH) is consistent with previous data, the rich limit is unexpectedly low in the range 9.4–10.7% UDMH. As a check on the ignition and pressure sensing systems, combined limits of ignition and flame propagation were determined for ethylene-air mixtures and were found to agree with accepted data. Further studies on the effect of confinement on UDMH-air explosions are recommended as the result of what is thought to be erratic data.

Flashover rates of flame across UDMH liquid pools in air were measured at temperatures between 12 and 55°C. No significant temperature dependence of flashover rates was found. The average UDMH flashover rate of 162 cm/sec compares with that of hexane (114 cm/sec ± 10%) and methanol (250 cm/sec), leading to the conclusion that the initial spurt of fire due to ignition of a spill of UDMH in open air should be about as rapid as with standard fuels under like conditions.

Observations of burning rates of UDMH liquid pools indicate the same trends as for standard fuels. In large trays (about 30 inches diameter), the burning rates of butane, hexane, benzene, and methanol are reported to be 0.8, 0.7, 0.6, and 0.13 cm/min, respectively. Two measurements with UDMH, one in a tray 20 inches square and the second in a 30 inch diameter tray, resulted in burning rates of 0.32 and 0.31 cm/min, respectively. Correlation of the burning rate with the ratio (heat of combustion)/(heat of vaporization) is shown to include UDMH as well as the other fuels mentioned above.

It is reported in the literature that about two volumes of water to one of UDMH will extinguish fires of the latter. As supplemental information it is reported that, when the heat of mixing is not abstracted, small pools of a mixture containing 48 parts UDMH to 52 parts water can be burned; one containing 46 parts UDMH cannot. When cooled after mixing, a mixture of 55 parts UDMH and 45 parts water at 23°C can be burned; equal volumes of the two liquids cannot be ignited. At about 60°C, a 40–60 mixture burns, while a 35–65 mixture does not burn; at 80°C it was found that a 30–70 mixture burns and a 25–75 mixture does not burn.

In regard to the composition of combustion products of UDMH in air, it is reported that, if the supply of air is unlimited, the atmosphere close to the burning liquid is free of cyanides; if the air supply is limited, then toxic cyanides and carbon monoxide in the combustion gases should be anticipated by fire fighters.

It was found that the temperatures in diffusion flames of UDMH in air are similar to those of alcohol, benzol, petrol, and kerosene burning in air. Values measured were about 600°C in the unburned gas immediately above the liquid UDMH; the maximum temperature at the flame front was about 1100°C.

Radiation from large flames of UDMH was measured with a calibrated thermopile. Assuming complete combustion, and the radiation distributed uniformly on a sphere whose surface contacts the thermopile, the energy radiated was 24 per cent of the heat of combustion. This value compares well with those of butane, benzene, hexane, methane, and carbon monoxide.

Subject Headings: *Ignition of propellants; Propellants, ignition of; Flame, propagation of propellants; Dimethyl hydrazine, ignition of.*

W. G. Labes

McGuire, J. H. and Law, M. (Joint Fire Research Organization, Boreham Wood, England) "The Performance of Spark Guards," *British Journal of Applied Physics* 9, 470–474 (1958)

Annually in the United Kingdom domestic fireplaces cause about 6000 fires in materials other than structural timbers. Some spark guards were found to reduce satisfactorily the probability of such ignitions with little decrease in radiative room heating. This paper deals with the fire risk created by flying coals and sparks and its reduction by the use of spark guards.

Bits of a bituminous, high-volatile, noncoking coal were ignited in a bunsen flame and dropped about 3 inches directly onto dried cotton, viscose rayon net, Hessian scrim, newspaper, Belgian cotton carpet, and surgical cotton wool. Firebrands weighing only .005 gm. readily ignited the surgical cotton wool in any disposition. At the opposite extreme, coals 0.5 inch in diameter failed to start lasting fires in Belgian carpet.

The probability that a spherical coal could pass through a mesh spark guard without striking the wires was calculated to be

$$P=\{1-[(D+t)/d]\}^2$$

in which D was the diameter of the coal, t the diameter of the mesh material, and d the distance between centers of adjacent openings. For cylindrical coals of random orientation and direction of flight normal to the mesh, the probability of free passage was found to be

$$P=(d-t-a)/2\pi\ n^2a^2d^2$$

in which a is the particle diameter, and n the ratio of length to diameter.

The maximum probabilities that spherical particles or cylindrical particles (with a length-diameter ratio of 8) would pass through various mesh spark guards and start fires were found to be as follows for the four materials (excluding cotton wool and Belgian carpet):

Guard	*Probability* (parts per million)
8-mesh wire	40
6-mesh wire	340
4-mesh wire	24,000
45 denier nylon	3.3
150 denier nylon	34

Obviously only the 6- and 8-mesh wire and the nylon mesh were effective guards.

Subject Headings: *Ignition by hot particles; Spark guards, performance of.*

G. R. Fahnestock

Zabetakis, M. G., Stahl, R. W., and Watson, H. A. (U.S. Bureau of Mines, Pittsburgh, Pennsylvania) "Determining the Explosibility of Mine Atmospheres," *U.S. Bureau of Mines Information Circular 7901* (1959)

This article presents a simplified graphic method for determining the explosibility of mine atmospheres under mine-fire conditions. At times it is necessary to seal part of a mine during a fire in order to extinguish the fire. Before unsealing, it is necessary to determine whether or not the mine atmosphere is explosive or may become explosive when air is admitted. There are various experimental methods for determining the explosibility of a particular atmosphere but they are generally impracticable in the field.

The method is based upon the use of an explosibility diagram which is actually a composition diagram with per cent of effective inert gases plotted on the horizontal axis and per cent effective combustible gases on the vertical axis. Areas of explosive mixtures, nonexplosive mixtures, and mixtures explosive when mixed with air are defined by a family of explosibility curves which are specific for a given atmosphere in terms of R, the ratio of methane to total combustibles. The parent diagram given is that for methane-nitrogen-air mixtures at 80°F and atmospheric pressure. Since mine-fire atmospheres often contain hydrogen and carbon monoxide as well as methane, air, carbon dioxide, and excess nitrogen (i.e., nitrogen in excess of that in air), the diagram was expanded to include these gases, but at a maximum of five per cent hydrogen and three per cent carbon monoxide.

The first step in the procedure is to measure the volume per cent of each of these gases present in the mine atmosphere. The quantity Effective Inert is then calculated.

$$\text{Effective Inert} = \%\ \text{excess}\ N_2 + 1.5 \times (\%\ CO_2)$$

Since carbon dioxide and nitrogen are not equally effective in producing nonflammable mixtures, the factor 1.5 is necessary as an equalization factor. Methane, hydrogen, and carbon monoxide do not have the same lower limits of flammability. They are corrected to give the same effective lower limit for each gas in calculating the second concentration required, the Effective Combustible.

$$\text{Effective Combustible} = \%CH_4 + 1.25 \times (\%H_2) + 0.4 \times (\%CO)$$

R, the ratio of methane to total combustibles, is then calculated to determine the explosibility curve to be used. With these compositions, the composition point is located on the explosibility diagram and the character of the mine atmosphere, at ordinary temperatures, is thus defined. In practice, the composition of a sealed area may vary with time but one may judge these effects by recalling that the addition of combustible alone, for example, would shift the composition point along the line joining this point to that representing 100 per cent combustible, 0 per cent inert, 0 per cent air.

The authors also present a short-cut for assessing the explosibility of a mixture. The quantity of oxygen required for flame propagation, i.e., the maximum allowable oxygen, depends on the relative quantities of methane, carbon monoxide, and hydrogen present.

$$\text{Maximum } O_2 = 5.0 + 7 \times R$$

If the maximum O_2 value is not exceeded for a given mixture, that atmosphere cannot be ignited "as is," but will fall within regions either nonexplosive or explosive when mixed with air. However, this method will not apply if the maximum O_2 value is exceeded.

Subject Headings: ***Mines, explosibility of; Methane, explosive limits of; Hydrogen, explosive limits of; Carbon monoxide, explosive limits of.***

G. M. Steffan

Eggert, J. (Federal Institute of Technology, Zürich, Switzerland) "The Ignition of Explosives by Radiation," *The Journal of Physical Chemistry* 63, 11–15 (1959)

The author discusses investigations into the nature of detonations initiated in explosive solids by intense radiation. Preliminary experiments showed that NH_3NI_3 and other compounds studied require a certain minimum incident energy for detonation. It was found also that dark compounds were more sensitive than light-colored compounds and that a correlation existed between the detonation energy and the ignition temperature.

The decomposition of NH_3NI_3 at levels of radiation not sufficient for detonation was investigated. The decomposition was expected to occur as follows:

$$NH_3NI_3 + h\nu \rightarrow N_2 + 3HI$$
$$3HI + 3NH_3NI_3 \rightarrow 3NH_4I + 1.5N_2 + 4.5I_2$$

giving a minimum quantum yield of $\varphi = 4$. It was found, however, that the yield ranged only from $\varphi = 0.06$ to $\varphi = 0.6$. The lower values were obtained under conditions which suppress the second reaction. This, coupled with a temperature coefficient greater than unity (2.3 between 18.5 and 25°C) for the decomposition on irradiation, indicated that the decomposition was mainly photothermal and not photochemical in nature.

The detonation of the other substances investigated was purely photothermal. This was demonstrated by the determination of the temperature dependence of the minimum ignition energy. Extrapolation to zero energy coincided with the ignition temperature. The connection between ignition temperature and minimum detonation energy for the various compounds was rather loose. This was explained by the influence of spectral absorptivities, thermal capacities, and heat conductivities. However, the temperature effect seemed dominant.

These results refer to a certain duration of the radiation (0.8 ms.) and a fixed layer thickness. The effect of thickness was investigated with deposits of Ag_3N on glass. The minimum energy was found to increase gradually at first with decreasing thickness and then very rapidly as the thickness became less than 0.1μ, but it was found to decrease with decreasing duration of the radiation. It was also found, however, from high speed cinematographic analysis, that the detonation is initiated long before the end of the light flash.

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

R. H. Atalla

Cassel, H. M. and Liebman, I. (U.S. Bureau of Mines, Pittsburgh, Pennsylvania) "Cooperative Mechanism in Ignition of Dust Dispersions," *Combustion and Flame* 3, 467–475 (1959)

This paper reports an experimental investigation of ignition temperature and time to ignition of single dust particles in air and oxygen, and also of dust clouds in air. Theoretical relations were presented which agreed qualitatively with the experimentally determined dependence of ignition time and temperature on particle size for ignition of individual particles. The experimentally determined ignition temperature dependence on dust cloud concentration was explained on the basis of a cooperative mechanism between particles in dust dispersions. The sequence of events relative to ignition of a fuel particle in a hot oxidizer gas was pictured as follows: heating of the initially cold fuel particle by the ambient gas to a temperature near that of the bulk gas where the heat evolution by chemical reaction at the surface of the particle heats it to temperatures above ambient. Ignition will occur if the rate of increase of heat evolution is greater than the rate of increase of heat loss to the surroundings with respect to increase in particle temperature.

A mathematical relation was derived for calculating the rate of conductive heating of a single particle by a hot ambient gas prior to ignition. In addition to the assumption stated in the paper that heat transfer is solely by conduction, it should be realized that the assumption of steady state was also made in order to calculate the temperature gradient (and hence the heat transfer rate) in the gas at the particle surface. The time required for the temperature difference between particle and bulk gas to diminish to 1 per cent of the initial difference was calculated to be 0.04 seconds for a magnesium particle 2×10^{-3} cm. in diameter in air. Other factors affecting the actual heating time were also discussed.

In the temperature region prior to ignition where heat evolution by chemical reaction is significant the rate of increase of particle temperature was expressed mathematically in terms of heat capacity of the particle, heat release by chemical reaction, and heat loss by conduction to the surrounding gas. From this relation it was shown that the dependence of ignition temperature on particle size is quasi-hyperbolic. The ignition temperature (minimum ambient temperature required for ignition) decreases with increase in particle size.

Spherical particles of magnesium and 50–50 magnesium-aluminum alloy were studied experimentally. Particle sizes between 5 and 75 microns in diameter obtained by elutriation were used. The particles were fed into the top of a vertical furnace and kept floating in the hot zone by a rising stream of hot air or oxygen. The time required to heat single particles to ignition was found to increase from less than 0.1 to 0.3 seconds as the particle diameter was varied between 10 and 75 microns. The ignition temperatures (on the order of 600 to 900°C) for single particles were found to decrease with increase in particle size in air. For a given particle size the ignition temperature was nearly the same in pure oxygen as that for air indicating that the reaction rate during the ignition stage was not controlled by diffusion but by the rate of heterogeneous reaction at the particle surface.

The ignition temperature of monodisperse clouds of fuel particles was found to be considerably lower than for single particles and to decrease considerably with increase in dust concentration. The reduced ignition temperature was caused by a cooperative mechanism. In the cloud each particle is close to heat-generating particles and therefore loses less heat than an isolated particle. For a given mass concentration of dust the distance between adjacent particles is less for small particles than for large particles and therefore at sufficient dust concentration the ignition temperature of clouds of fine particles can be even lower than for clouds of coarse particles due to the cooperative mechanism.

At low concentration of particles it was observed that ignition was not initiated uniformly throughout the cloud but originated from sporadically distributed flamelets which subsequently engulfed the entire cloud. This observation was explained as the natural consequence of statistical density fluctuations within the otherwise uniform cloud.

Subject Headings: ***Dusts, ignition of; Ignition of dusts; Powders, ignition of metal.***

C. P. Talley

II. Thermal Decomposition

Madorsky, S. L. (National Bureau of Standards, Washington, D.C.) "Thermal Degradation of Polymers at Low Rates," *Journal of Research of the National Bureau of Standards* **62**, 219–228 (1959)

Previous work on the rates of thermal degradation of polymers in a vacuum by the loss-of-weight method showed that the rate of weight loss was distorted or obscured during the short time necessary to raise the sample to the required pyrolysis temperature. Some vaporization always took place. It is necessary to maintain a constant temperature during the whole pyrolysis in rate studies. The initial weight loss, therefore, masks the true nature of the initiation of the thermal degradation.

In order to overcome this difficulty one available method was to run the pyrolysis over much longer periods while maintaining much lower temperatures. Thus the initial loss of sample due to high heating rates was vastly reduced. However, the cumbersome nature of such long experiments and some doubt as to the equivalence of conditions of time-temperature interchanges led to the construction of an apparatus that will continuously and automatically record temperature and weight. The initial parts of the rate curves could then be accurately and quickly plotted no matter how fast the warmup cycle.

Polymers studied included polystyrene (molecular weight 230,000), poly

(α-methylstyrene) (molecular weight 350,000), polymethylene, a pure grade polyethylene (of high molecular weight 525,000), a polyethylene (molecular weight 20,000), and poly(chlorotrifluoroethylene) (average molecular weight 100,000).

A platinum crucible is suspended in a closely (±0.1°C) controlled high-temperature oven. The crucible is connected to one arm of the balance known as the "Elmic" recording instrument. The temperature of the furnace is measured and in addition the temperature of the bottom of the crucible is obtained. The weight change is measured with the balance. All data are recorded on a three-channel, 10 mv full-scale recorder. Another furnace was added onto the top of the main unit in order to overcome the end cooling previously noted. Varying the power input to both furnaces, showed that the temperature recorded by a thermocouple firmly anchored to the crucible inside bottom and another 2 to 3 mm. below the outside bottom could be made to coincide. All experiments were carried out at 10^{-4} mm. Hg. Average total sample weights used were 4 to 5 grams. Zero time of a run was when operating temperature was reached.

Graphs are presented showing the percentage of sample volatilized *vs.* time at various operating temperatures for all except poly(chlorotrifluoroethylene). No evidence now exists to indicate high rates of weight loss during the initial heating of the samples, which was noted at the previously employed higher temperatures.

Another set of curves shows the rates of degradation as a function of percentage of volatilization. These are plotted either as percentage of sample initially or as a percentage of residue. Initial rates are given in per cent/minute. The extrapolated straight parts of all curves are the apparent initial rates if no warm-up disturbances were present. The shape of the polystyrene rate curves indicates a zero order reaction. The appendage benzene rings apparently lend stability to the chains so that the number of chain ends and, therefore, the rate of monomer, dimer, and trimer fragment formation stays constant. In the case of poly(α-methylstyrene), the presence of quaternary carbons in the chain imparts instability to the chain, consequently the formation of new chain ends takes place at random and the reaction is first order. A similar conclusion can be arrived at in the case of polyethylene and polymethylene.

The activation energies were obtained by plotting the apparent initial rates at various temperatures for any given polymer as a function of the inverse of the absolute temperature. In all cases a 12 to 17°C discrepancy was indicated in the temperature measurement when comparison was made with the previous work. This error does not affect the initial rates or volatilization curves but slightly affects the activation energies obtained from the Arrhenius plot. All values are lowered for polystyrene (55 kcal/mole), poly(α-methylstyrene) (55 kcal/mole), and polymethylene (73) from previously obtained values of 58, 58, and 76 respectively.

Poly(chlorotrifluoroethylene) and a polyethylene of molecular weight 20,000 were also pyrolized. Again the activation energy proved lower by about 3 per cent in both cases.

Comparison with similar pyrolysis experiments of other authors show poor agreement if compared on a plot of the percentage of volatilization *vs.* time. It may be that inherent difficulties in measuring the sample temperature cause this discrepancy. Other problems include the presence of occluded gas in the sample which causes spattering of the sample and spurious weight losses. Another problem is the diffusion-delayed passage of volatile fragments from the bulk material. The inability to maintain a uniform temperature throughout the polymer is due to low heat conductivity. These difficulties have been largely eliminated in this work by keeping the sample sizes down to 5 mg.

Uncertainties in temperature and rate observation during the initial heating up period have been greatly reduced with the automatic recording of temperatures and weights and permitted use of lower pyrolyzing temperatures.

Subject Headings: *Polymers, thermal degradation of; Thermal degradation of polymers.*

P. Breisacher

Gordon, M. (Arthur D. Little Research Institute, Inveresk, Midlothian, Scotland) "Theory of Chain-End Activated Degradation of Heterodisperse Polymers," *Transactions of the Faraday Society* 53, 1662–1675 (1957)

In previous theories of bulk degradation of vinyl polymers in vacuo, constant initial chain lengths (homodisperse model) were assumed even though nearly all experiments were made with heterodisperse polymers. Gordon assumes an exponential initial distribution of chain lengths

$$\Pi_y = q \exp(-qy) \qquad (1)$$

in which Π_y is the number fraction of y-mer and $1/q$ is the mean or number average degree of polymerization DP_n. Such assumption has two advantages. First, it results from polymerizations in which chain growth is arrested by radical disproportionation, by chain transfer, by mixture of the two, or by various polycondensation reactions. For polymers produced under termination by radical combination the distribution of chain lengths is

$$\Pi_y = q^2 y \exp(-qy) \qquad (2)$$

with mean $2/q$, which results from distribution (1) by the process of self-convolution, but a polymer originally obeying (2) approaches (1) during degradation. Second, exponential distribution (1) leads to the simplest mathematical theories because the distribution remains constant under a wide variety of degradation mechanisms, provided initiation is confined to chain ends and the monomer produced in the "zipping" reaction is removed by distillation.

Invariance of the exponential distribution (1) is demonstrated by a probability model in the form of the curve $y = e^{-x}$ in which y represents the relative number of chains of length x. All chains are then shortened by the fixed zip-length x by which the degradation proceeds. Since chains no longer than x vanish by distillation, the portion of the curve respresenting y values less than x is eliminated. On renormalizing the remainder of the curve the original curve is reproduced. The consideration is valid only if both x's and y's are randomly selected, that is, if the rates of activation, propagation, and termination (hence the zip-length) of chain ends are independent of the length of polymer chain to which the ends belong.

From the invariance of the exponential distribution and the common assumption that the nature of the chain ends also is invariant it follows that the mass decay is a first-order reaction. The first-order mass decay observed experimentally with numerous polymers becomes theoretically intelligible once the homodisperse model is abandoned for the more realistic exponential distribution of polymer chains.

An improved theory is developed for steady-state degradation independently of the initial chain length distribution. The theory assumes that (1) monomer radicals form a negligible part of the total radical population, (2) both monomer and polymer radicals reach constancy in the steady state, (3) termination involves monomer and polymer radicals with equal rate constants, (4) the radical initiation reaction is first-order in all chain ends. Termination is treated either as first-order or as second-order.

Previous data on the initial degradation rates of polymethylmethacrylate as a function of DP_n still fit well the new asymptotic solutions for high and low DP_n, but are now seen to diverge largely from the solution for the intermediate region. Because of the simplicity of the solution for exponentially distributed polymer, a small random scission component, superposed on chain-end activated zipping, can be treated with ample accuracy to fit the data in the literature for DP_n-decay during degradation of polystyrene. The data are not sufficiently accurate to distinguish between random splitting, weak-link scission, or scission following chain transfer to polymer. The rate curves on low-molecular-weight polystyrene at high temperature by Madorsky can be fitted to the improved theory assuming termination by disproportionation, another rate curve by Grassie and Kerr for high-molecular-weight polystyrene at low temperature can be fitted assuming first-order termination. In accordance with theory, Madorsky's rate curves at various temperatures can be superposed with suitable scale factors, which obey the appropriate Arrhenius law. Grassie and Kerr's observation of superposition of the DP_n-decay curves at various temperatures can be explained plausibly. Attention is drawn to the importance of bulk degradation studies in tactic polymers.

Subject Headings: ***Polymers, thermal degradation of; Thermal degradation of polymers.***

F. L. Browne

Smith, K. N. (Johns-Manville Corporation, Manville, New Jersey) "Self-Heating of Wood Fiber," TAPPI 42, 869–872 (1959)

Wood fibers were formed into fiberboard for testing. To determine the rate of self-heating, a 3-inch cube of fiberboard was heated to 325°F in an electric furnace. Air was circulated by a blower over the test cube at a controlled rate, usually 41.5 cu. in. per min. As soon as a thermocouple at the center of the cube began to exceed 325°F because of self-heating, the furnace temperature was held steadily 0.5°F below the cube temperature to render negligible any further exchange of heat between cube and furnace. The slope of the temperature-time curve in the region from 10 to 15°F above the original furnace temperature, where the curve was linear, was taken as a measure of self-heating. Preliminary tests showed that temperature was uniform throughout the cube and that change in rate of circulation of air had little effect.

The content of alcohol-benzene extract in the wood fibers was determined according to TAPPI standard T6m-54. Fiberboard was taken from commercial production or was made either on an 8 ft. diameter Oliver forming machine or in a board former complying with TAPPI method T-1001-SM-51. Northern fibers tested were poplar, lodgepole pine, white fir, Douglas fir, ponderosa pine, willow, cottonwood, mixed hardwoods, and newsprint. Southern softwood groundwood pulp was screened, dried, and classified into five size fractions from which boards were made as follows: one board was made with plus 30 mesh fiber; a second, with 70 per cent minus 30 plus 40 and 30 per cent minus 40 plus 50 mesh fiber; a third, with 39 per cent minus 50 plus 60, 46 per cent minus 40 plus 50, and 15 per cent minus 60 plus 100 mesh fiber; and a fourth, with minus 60 mesh fiber. The southern softwood pulp was tested also after drying at different temperatures from room temperature to 400°F, after extraction with alcohol-benzene, and after evacuation at 1.0 mm. of Hg.

The rate of self-heating proved closely proportional to the content of alcohol-benzene extract. For northern woods the reaction rate in °F/min, y, was related to the content of alcohol-benzene extract (per cent of moisture-free fiber), x, by the equation

$$y = 0.094x - 0.004$$

with a correlation coefficient of 0.86. For southern softwood the equation was

$$y = 0.159x + 0.101$$

with a correlation coefficient of 0.76.

Size of fiber proved important because the reaction rate decreased as the fiber size increased even though the content of extract did not follow the same pattern. The other treatments of southern fibers altered the reaction rate only in proportion to the change in extractive content. The component of wood responsible for the exothermic reaction of self-heating seems to be soluble in alcohol-benzene and relatively nonvolatile at either high temperature or low pressure.

Subject Headings: *Wood fibers, self-heating of.*

F. L. Browne

Sandholzer, M. W. (National Bureau of Standards, Washington, D.C.) "Some Properties of Flameproof Fabrics," *American Dyestuff Reporter* 48, 37–41 (1959)

Five cotton and rayon fabrics were treated with seven different flame retardant finishes. The materials used for flameproofing were (1) tetrakis (hydroxymethyl) phosphonium chloride, (2) the preceding constituent combined with bromoform-triallyl phosphate polyester, (3) and (4) proprietary formulas of resins applied by a commercial finisher of fabrics, (5) a proprietary formula containing metallic oxide-chlorinated hydrocarbon, (6) a proprietary formula of urea-phosphate, and (7) a water soluble borax-boric acid mixture. The fabrics tested included sateen, monk's cloth, Byrd cloth, bengaline, and rayon.

The fabrics were tested by three different methods for flame resistance—the vertical bunsen burner test, the match test, and the radiant panel test—before and after laundering up to fourteen launderings. Fabric strength tests were made on treated and untreated fabrics before and after laundering.

The result of flameproof treatment was a tendency to stiffen the fabrics. The results of flame resistance tests indicated that the borax-boric acid was excellent, representing the water soluble flameproofing agents generally, and that commercial applications were successful on fine-woven, medium, and heavy weight fabrics, but that the flame resistance of rayon treated with the metal oxide-chlorinated hydrocarbon deteriorated upon successive launderings. The results of fabric strength tests indicated little or no effect upon breaking strength but an adverse effect upon tearing strength. The conclusion was that considerable progress has been made in achieving laundering durability of flame resistance in fabrics. The report could have been materially improved if essential components of proprietary formulas for flameproofing were published.

Subject Headings: ***Flame retardants, properties of.***

D. Dembrow

III. Heat and Material Transfer

Batchelor, G. K. (Trinity College, Cambridge, England) "Heat Convection and Buoyancy Effects in Fluids," *Quarterly Journal of the Royal Meteorological Society* **80**, 339–359 (1954)

The interdependence of the distributions of velocity and temperature, as well as the nonlinearity of the equations of motion, make precise analytical solutions of problems in free convection very difficult to obtain. The author points out that this difficulty can be overcome to a considerable extent by the use of dimensional analysis which is a powerful research tool. However, he cautiously states "that it is also a blind, undiscriminating weapon and that it is fatally easy to prove too much and to get more out of a problem than was put into it."

The author gives governing equations for continuity, momentum, and heat, but no attempt is made to solve them for the different cases of free convection studied. Similarity solutions are assumed for the distributions of temperature and velocity and are found to exist in most cases. The cases studied are divided into two general groups, (A) problems of free convection due to discrete sources at a horizontal boundary, and (B) problems of free convection due to sources distributed over a surface.

The first case in group A is a maintained point source with laminar flow. The analysis applies to convection over heat sources of very low output and then only up to that height above the source where Reynolds number exceeds the critical value for stability. The second case is a maintained point source with turbulent flow which applies to heat sources of high output. If $\overline{w}$ is the mean vertical velocity at a point a distance r from the center of the convection column and a height z above the source, $\overline{T-T_o}$ the mean difference between the temperature at this point and the ambient temperature, then dimensional analysis gives

$$\overline{w}=\frac{F^{1/3}}{z^{1/3}}\times \text{func}(r/R)$$

$$g\,\frac{(\overline{T-T_o})}{T_o}=\frac{F^{2/3}}{z^{5/3}}\times \text{func}(r/R)$$

$$R=\alpha z$$

where g is the acceleration due to gravity, and F is a quantity proportional to the strength of the heat source for which the rate of output is $(c_p\rho_o T_o/g)F$. The convection column radius R is defined as that value of r for which $\overline{T-T_o}$ falls to 1/e of its value at $r=0$. The constant α has a numerical value of 0.12. The convection column is thus a cone with a half-angle of 7°. Experimental work shows that the distribution functions can be closely approximated with Gaussian curves.

The equations for a maintained line source with turbulent flow are similar to the point source case. The convection cone becomes a convection wedge with a half-angle of 9° and the distributions of $\overline{w}$ and $g\,(\overline{T-T_0})/T_0$ can also be expressed in Gaussian form. The main differences are the relationship of $\overline{w}$ and $g(\overline{T-T_0})/T_0$ to z. The vertical velocity $\overline{w}$ is independent of z as is the inflow velocity at all levels. The mean temperature difference decreases less rapidly with height than in the point source case since it varies inversely as z.

The treatment for a single line source holds fairly well for two parallel line sources because the distribution functions for two parallel sources are not additive but closely resemble the distribution functions for a single source located midway between the two line sources.

The preceding cases apply to neutrally stable or unstratified fluids. Another case in group A is a maintained point source with turbulent flow in a stratified fluid. Similarity solutions exist if the fluid is unstably stratified but not for stable stratification.

The first case in group B deals with cellular and turbulent circulation between two horizontal surfaces in which heat flows upwards through the lower surface. The second case is that of a semi-infinite fluid above a heated horizontal boundary. If a quasi-steady state condition can be assumed in the turbulent region and if the mean temperature of the fluid in this region is determined uniquely by the vertical heat flux, then dimensional analysis shows that

$$g\,\frac{(\overline{T-T_0})}{T_0}\,\alpha\,\frac{f^{2/3}}{z^{1/3}}$$

where T_0 is the temperature at a considerable distance from the boundary. The vertical heat flux per unit area of boundary is $(c_p\rho_0T_0/g)f$.

Convection in the presence of a forced wind is discussed only briefly because the paper is intended to apply primarily to free convection. The application of Batchelor's work to large-scale atmospheric convection would require the introduction of the concept of potential temperature but this would leave the basic treatment unaltered.

Subject Headings: *Buoyancy effects in fluids; Heat convection in fluids.*

G. M. Byram

IV. Diffusion Flames

Nakamura, J. (College of General Education, University of Tokyo, Japan) "Effect of the Electric Field upon the Spectra of the Hydrocarbon Diffusion Flame," *Combustion and Flame* 3, 277–283 (1959)

Previous work [1] by the author, has shown an abundance of ions in hydrocarbon diffusion flames with a maximum concentration in the premixed gas combustion zone P. Spectroscopic investigation of the P zone shows the intensity of C_2 to be greatest in the lower part of the zone, and to decrease further up, while CH is greatest in the middle of the P zone. This has led to an investigation into the relationship between ion production and CH formation or C_2 extinction.

When a hydrocarbon diffusion flame is subjected to an electric field, it shows a change in color of the P zone, and also a change in size depending on the direction of the field. Thus burning droplets of alcohol are extinguished by falling through an electric field.

A diffusion flame of propane was burnt on a slot-type burner and a wire gauze suspended 7 cm. above the burner. The electric potential between the gauze and the burner could be varied from +2 to −7 kv. A quartz spectrograph with a narrow acceptance angle was used to measure the intensity of CH, C_2, OH at different heights up the flame. Measurements of the rotational temperatures of radicals were also attempted. Measurement of ion distribution in the flame was influenced by the applied field, so that only the electric potential in the flame was measured by the probe method.

It is shown that neither the numbers of ions nor the extent of excitation of radicals in a flame is affected by the applied fields; however, the distribution of the radicals seems to be displaced by a kind of Chattock electric wind or pressure.

There is no evidence that the mechanism of combustion is influenced by an external electric field.

Reference

1. Kinbara, T. and Nakamura, J. "Ions in Diffusion Flames," *Fifth Symposium (International) on Combustion,* New York: Reinhold Publishing Corporation, 285–289 (1955)

Subject Headings: ***Diffusion flames, electric field effects on spectra of; Spectra of diffusion flames.***

G. L. Isles

V. Combustion Principles

Hirschfelder, J. O. and McCone, A., Jr. (University of Wisconsin, Madison, Wisconsin) "Theory of Flames Produced by Unimolecular Reactions. I. Accurate Numerical Solutions," *The Physics of Fluids* 2, 551–564 (1959)

In the first part of the paper the general time-dependent flame equations are given including the effects of thermal diffusion, radiation, external forces, and pressure variations. These equations apply to a wide variety of flow problems, each characterized by its own boundary conditions. Solution of these time-dependent equations would provide insight, for example, into flame stability, or into the mechanism of transition of a flame into a detonation. There are, however, many mathematical difficulties.

The remainder of the paper deals with steady-state flame propagation for the one-dimensional case in which the flame is supported by a unimolecular reaction $A \rightarrow B$. The effects of thermal diffusion and external forces are neglected, as also in the first instance are pressure variations through the flame. The reverse reaction B → A is also neglected initially. Assuming a constant Lewis number of unity throughout the flame, i.e., constant total enthalpy, accurate numerical solutions are obtained for the flame velocity and for the composition and temperature profiles within the flame. So-called "quenching" distances (distances from the holder to the position of half-change of the chemical reaction), temperature thicknesses, and reaction thicknesses (corresponding to the middle 80 per cent of the conversion) are quoted for a number of values of the initial parameters.

In subsequent discussion special emphasis is placed on the effect on the flame of heat transfer to the flame holder (cf. flat flames on cooled porous plug burners). This affects the solution to the flame equations by altering the flame temperature. It is found that for a steady-state flame the heat flux at the flame holder can only be between a minimum and a maximum value. Due to the fact that the Arrhenius type of reaction rate does not decrease mathematically to zero at low temperatures, some minute amount of heat transfer to the holder is a necessary prerequisite of a steady-state flame. Such heat transfer can only occur for a finite distance of the flame from the holder, thus allowing only a finite reaction time. The maximum permissible heat transfer on the other hand, is related directly with the reduction in flame temperature as the heat loss to the holder increases. This in turn causes a decrease in the flame velocity which accounts for the phenomenon.

When the heat transfer to the holder is less than the maximum there are two steady-state solutions possible, one corresponding to a flame velocity lower than that at maximum heat transfer and the other at a higher flame velocity. These modes have previously been discussed by Spalding.[1] The higher velocity mode of propagation is the stable one.

Subsequent sections of the paper deal with the effect of diluting the fuel with reaction product, with the effect on the flame of the back reaction B → A, and with the effect of pressure on the unimolecular flames. It is shown that dilution of the fuel with reaction product could be allowed for by means of a proportionate "diluent" effect on the energy liberated in the reaction. The effect of the reverse reaction B → A which is required by thermodynamical considerations may also be allowed for by simple means.

The effect of pressure on the propagation of a unimolecular flame is dealt with under two headings. At high pressure the kinetic energy of the gases can be neglected and both the lowest flame velocity and the flame thickness are inversely proportional to the square root of the ambient pressure. Hence, as the pressure decreases the flame velocity increases, and when the flame velocity becomes an appreciable fraction of the velocity of sound, the kinetic energy of the gases must be considered. The characteristics of the flames are somewhat changed, the whole structure of the flame becoming dependent on the pressure, which decreases on passing from the cold to the hot boundary. Finally a critical ambient pressure p_c is reached at which the velocity of the hot gas in the flame becomes just equal to the velocity of sound at the flame temperature. Below this pressure steady-state flame propagation would not be possible. In fact the low pressure regime is only of academic interest since it involves extremely low pressures (perhaps *ca.* 10^{-4} atm.) where unimolecular chemical reactions exhibit second order reaction kinetics. It was also found in the calculations involving kinetic energy that this energy is only important over a very small range of pressure, and becomes negligible if the flame velocity is below 0.1 times the velocity of sound in the unburnt gas.

Reference

1. Spalding, D. B. "A Theory of Inflammability Limits and Flame-Quenching," *Proceedings of The Royal Society* A 240, 83–100 (1957) (Abstract: *Fire Research Abstracts and Reviews* 1, 123–124 (1959)

Subject Headings: ***Flame, theory of unimolecular.***

G. Dixon-Lewis

Hirschfelder, J. O. (University of Wisconsin, Madison, Wisconsin) "Theory of Flames Produced by Unimolecular Reactions. II. Ignition Temperature and Other Types of Approximations," *The Physics of Fluids* **2**, 565–574 (1959)

Numerous analyses have been published on the theory of flame propagation. In general, they fall into two groups: (1) detailed numerical solutions for various models, and (2) approximate, analytical solutions designed to bring out the functional relationships between the various significant parameters. This is the second paper in a series concerning these problems. In the first paper numerical integration of the flame equations is carried out for the Lewis number equal to unity. In this second paper, the flame system under consideration is composed of a one-dimensional, steady-state, laminar flame undergoing an exothermic, unimolecular reaction. Various types of approximations are introduced. One of them is the ignition temperature T_i. Below this temperature the reaction rate is set equal to zero. Above T_i the rate is assumed to be independent of temperature by selecting an average temperature T_a associated with an average rate constant. In the choice of this average value the author used the solutions of the flame equations obtained by numerical integration in the first paper. Finally, the author compares the results of various other approximations as employed by different investigators. This paper does not introduce any new concepts on the theory of flame propagation; its value is to be found in the comparative aspects of the analysis and in pointing out the significance of approximate solutions in our understanding of this complex problem.

Subject Headings: ***Flame, theory of unimolecular; Ignition temperatures of unimolecular flames.***

H. Wise

Fenimore, C. P. and Jones, G. W. (General Electric Research Laboratory, Schenectady, New York) "Consumption of Oxygen Molecules in Hydrocarbon Flames Chiefly by Reaction with Hydrogen Atoms," *Journal of Physical Chemistry* **63**, 1834–1838 (1959)

The authors have extended their studies of the mechanisms of flame reactions to the reaction $H+O_2 \rightarrow OH+O$ (1) in hydrocarbon-oxygen-argon flames. The technique used was to measure the concentrations of H and O_2 through the flame zone and to compare the rate of the reaction with that calculated from the known rate constant at the measured temperature. In all cases the two rates were in satisfactory agreement, indicating that (1) is the most important route by which O_2 is consumed in these flames. Flame temperatures ranged from 1310–1950° K.

Flames of methane, propane, and acetylene burning in oxygen-argon (1.87:8) were studied at pressures of the order of 7 cm. and with water-cooled flat flame burners. Temperatures were determined with quartz-coated thermocouples and samples were taken with quartz probes. The hydrogen atom concentration was found by adding D_2O or D_2 and observing the rate of HD formation. Results found by these two techniques were in satisfactory agreement.

A moderately rich CH_4-H_2-O_2-A (1:1.07:8:1) flame was studied most extensively. In this flame the rate of oxygen consumption through the flame from 1100–1600° K was in agreement with the rate calculated from (1). In addition, the activation energy found for the oxygen consumption reaction was 17 kcal., in good agreement with the 18 ± 3 kcal. value found for (1) by the authors in earlier work.

Other methane flames studied had CH_4:O_2:A:H_2 ratios of 1:1.12:0.4:0, 1:2.56:10:0, 1:2.31:10:0, and 1:1.68:8:1. In all, the results indicated that reaction (1) was the important route for O_2 consumption. Addition of small amounts of N_2O to the latter two flames indicated that it too was destroyed by reaction with H atoms, i.e., $H + N_2O \rightarrow OH + N_2$.

Studies with propane-oxygen-argon and acetylene-oxygen-argon flames gave similar results.

Subject Headings: ***Flame, free radical reaction in.***

J. B. Levy

Millan, G., Da Riva, I., and Sanz, S. (Instituto Nacional de Tecnica Aeronautica Esteban Terradas, Madrid, Spain) "Combustion of Fuel Sprays," *Air Research and Development Command United States Air Force Contract AF 61(514)–997, AFOSR TN 59–629, ASTIA 217814* (1959)

The combustion of a fuel spray burning in an oxidizing atmosphere is analyzed theoretically by Probert's method. The Rosin-Rammler function used by Probert to describe the droplet size distribution in the fuel spray is here replaced by the Mugele-Evans equation, which sets a maximum size to the droplets (the minimum size is taken to be zero), thereby affording a closer approximation to the actual distribution.

Various typical situations are considered, such as continuous burning, starting and stopping of the fuel injection, and periodic fuel injections of short duration. Expressions are derived for the cumulative size distribution of the droplets present in the combustion chamber, and for the unburned volume of fuel spray as a function of time, for each of these situations. Curves are presented, relating dimensionless unburned volume with dimensionless time, and what appears to be a dimensionless burned volume with dimensionless time. The former curve has the same general shape and the same crossover characteristic shown by Probert's plot of per cent spray unevaporated against his Evaporation Index, $b = \frac{\sqrt{\lambda\tau}}{\bar{\chi}}$, which is equivalent to dimensionless time if the definitions used in this report are substituted.[1]

Some general conclusions are drawn regarding the most desirable characteristics of a fuel spray, and these confirm Probert's findings. A spray with a uniform size distribution (large value of distribution function) burns more completely and in a shorter time than less uniform sprays, even though in the initial stages of combustion it is the less uniform sprays which burn most rapidly.

The report suffers from a lack of proper definition of the terms used in the text and the figures. Some of the undefined quantities are (f F) in *Figure 1;* (g_i), (G), (t_v) in *Figures 2 and 3;* ($\bar{x}_{32}$) in *Table 1.* It is necessary to guess whether t_v is equivalent to t_c, and whether g_i is defined in the same way as g_f; there is no clue to the definition of G, in equation 19.

The lack of experimental data constitutes an important difficulty in judging the validity of the model considered.

Reference

1. Probert, R. P. "The Influence of Spray Particle Size and Distribution in the Combustion of Oil Droplets," *Philosophical Magazine 37,* 94–105 (1946)

Subject Headings: ***Fuel sprays, combustion of; Sprays, combustion of fuel.***

B. Greifer

Popov, V. A. "Development of the Combustion Process of Moving Particles in Nonstationary Hydrodynamic and Thermal Conditions," *Akademiia Nauk SSSR. Otdelenie Tekhnicheskikh Nauk. Izvestiia* (*Academy of Sciences, USSR. Technical Sciences Section. Bulletin No. 12,* 90–95 (1958)). Translated by B. W. Kuvshinoff, Applied Physics Laboratory, The Johns Hopkins University

Elucidation of the combustion and explosion mechanism of dusts requires a clear understanding of the reaction mechanism of single particles. In this work the author chose initially to examine the combustion mechanism of single particles that were moving freely; but then finding that the results were too difficult to interpret, he carried out subsidiary experiments on captive particles to determine essential reaction constants. In the experiments, carbon particles were used of diameters 2.4, 3.2, 4.0, and 4.5 mm., formed from coal with 15 per cent peat tar as a binder and carbonized at 900° C.

In the initial moving-particle experiments, the particles were preheated in nitrogen and dropped through heated air contained in a glass combustion tube. After allowing them to fall fixed distances, they were quenched and weighed. By averaging results from many particles, graphs were built up of particle velocity, temperature, total weight loss, and reaction rate as these varied with distance. While velocity and total weight loss increased steadily, temperature and specific reaction rates showed inclinations to peak, though not coincidentally.

Next, to determine the essential reaction constants, captive particles were continuously weighed and photographed in the classical manner so that reaction rate, temperature, and diameter were determined as these varied with time.

Elements of a theory were quoted from Russian sources, notably from a textbook "Combustion of Carbon"[1] against which the data obtained were tested. The theoretical model used was the standard one of "boundary layer diffusion" to the solid surface, followed by chemical reaction; this led to the standard equation of the specific reaction-rate reciprocal equal to the sum of two resistances. In addition, pore diffusion was also considered theoretically using an interesting relation quoted from reference 1, but in application the whole equation for chemical and for specific internal reaction was assumed to equate to a simple Arrhenius factor. Tested thus, the captive particle data fit the Arrhenius factor tolerably well with an activation energy of 19,400 cal. With these data, burning rates of the moving particles were predicted, and good agreement with theory is claimed for the latter part of the reaction, but not initially.

These results have considerable interest since it is now fairly certain [2] that three temperature regimes exist: (1) at temperature less than 800° C or thereabouts, the reaction is zero order and the activation energy of the process lies between 20,000 and 40,000 cal.; (2) at temperatures above 1200° C, the reaction is first order and obeys a T^2 law if diffusionally controlled, or has an activation energy of about 4000 cal. if chemically controlled; and (3) a transition region between 800 and 1200° C. Popov's results lie right in the transition range of temperatures, but the activation energy of 19,400 cal. clearly indicates low-temperature chemical reaction-control with zero order reaction. The results will not therefore have much relevance to combustion in flames; for this the temperatures of investigation must lie in the high temperature region, in excess of 1200° C.

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1. Predvoditelev, A. S., Khitrin, L. N., *et al. Combustion of Carbon,* Chapter 3, AS USSR (1949)
2. Essenhigh, R. H. and Perry, M. G. Conference on "Science in the Use of Coal," Sheffield Institute of Fuel, p. D1 (1958)

Subject Headings: ***Dusts, combustion of; Particles, combustion of single.***

R. H. Essenhigh

Basov, V. N. and Popov, V. A. "On the Coefficient of Resistance to Motion of Burning Particles," *Akademiia Nauk SSSR. Otdelenie Tekhnicheskikh Nauk. Izvestiia* (*Academy of Sciences, USSR. Technical Sciences Section Bulletin No. 8,* 12–14 (August 1958))

Particles moving in a gas stream are subjected to a dragging force. If the particles are burning, the alteration to the boundary layer conditions might be expected to alter the drag coefficient. The objective of this work was to determine experimentally the change in the drag coefficient, if any, when the particles started to burn. The general conclusion was that there was no change. Experiments were carried out both on captive particles and on free particles.

In the captive particle experiments, the particles of carbon were formed from coal with 15 per cent peat tar as a binder and carbonized at 900° C. The particles (of 15.5 mm. diameter) were fastened to a silica rod that was suspended horizontally and so constrained that it could move horizontally only in the direction of its own axis. After heating the particle in a muffle furnace, it was then subjected to an oxidizing gas stream issuing from a tube of 42 mm. diameter and directed down the axis of the rod, and the force on the particle (and thus the drag coefficient) was determined by displacement of the rod from its equilibrium position. The experiments were repeated with particles both inside and outside the tube carrying the oxidizing gas, which was oxygen enriched air. The drag coefficient varied with (1) Reynolds number for fixed position and (2) distance from the tube mouth between ±1 diameters for fixed Reynolds number; but within the limits of experimental measurement, the drag coefficient was unaffected by surface temperature or by the existence of reaction.

In the free particle experiments, spherical particles of electrode carbon of diameters 2.4, 3.2, 4.0, and 4.5 mm. were used. These were heated to 900° C in nitrogen and then fed individually from a special feeder into a vertical glass combustion tube. The falling particles were photographed with a rotating drum camera but were so illuminated by a careful arrangement of lights and screens that only those near the axis were photographed. From the time-distance traces thus obtained, graphs of velocity against distance could be constructed. Comparison of the results with those for nonburning particles showed complete correspondence; and from this it was deduced that the drag coefficient on the particles was unaffected by their combustion. This is reported as not confirming previously published results obtained by Leont'eva [1] who reported an increase in the drag coefficient on coal particles if the particles were burning. In the reviewer's opinion without having seen the paper by Leont'eva, the discrepancy could be due to the different materials studied, since coal combustion is accompanied by volatile jet flames and by swelling.

The purpose of studying drag coefficients is not stated but presumably is connected with particle motion in burning clouds. In this connection the reviewer would draw attention to the effects of dust concentration found [2] over the flammable concentration range in which it was observed that particulate interaction so affected particle motion that the laws of motion for the single particle could not be used.

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2. Essenhigh, R. H. Conference on *"Science in the Use of Coal," Sheffield Institute of Fuel* B42–43 (1958)
   Brown, K. C. and Essenhigh, R. H. *Safety in Mines Research Establishment Research Report No. 165* (April 1959)

Subject Headings: ***Particles, coefficient of resistance of burning; Drag coefficients of burning particles.***

R. H. Essenhigh

Cooperman, P. (University of Pittsburgh, Pittsburgh, Pennsylvania) "Some Criteria for the *In Situ* Combustion of Crude Oil," *Journal of Applied Physics* **30,** 1376–1380 (1959)

To drive highly viscous crude oil from its reservoir by applying heat to reduce the resistance of viscous and capillary forces is economical if the heat can be applied over a large portion of the reservoir and the cost is low. *In situ* combustion, generating a combustion zone in the reservoir and using the crude oil itself as the fuel, satisfies these conditions. The air or oxygen supplied not only feeds the combustion zone but also heats the crude oil ahead and replaces it from the porous rocks later.

The interrelated chemical, thermal, and hydrodynamic aspects of an ideal model are discussed and the analysis is based on the following assumptions:

1) One-dimensional flow system,
2) No vacuum occurs in the porous space,
3) Viscosity is a known function of temperature only,
4) Chemical reactions and phase changes take place only at boundaries of zones,
5) The whole system is adiabatic.

The general equations are presented as follows:

Conservation of matter:

$$\frac{\partial}{\partial t}(\varphi \rho_i S_i) + \frac{\partial}{\partial x}(\rho_i v_i) = 0 \qquad (1)$$

Conservation of energy:

$$K\frac{\partial^2 T}{\partial x^2} - \left[\sum_{i=1}^{n} c_i \rho_i v_i\right]\frac{\partial T}{\partial x} - \left[(1-\varphi)\rho_r c_r + \varphi \sum_{i=1}^{n} c_i S_i\right]\frac{\partial T}{\partial t} = 0 \qquad (2)$$

Flow equation:

$$v_i = -\left[\frac{k_i(S)}{\mu_i(T)}\right]\frac{\partial p}{\partial x} \qquad (3)$$

State of fluids:

$$\rho_i = f_i(p, T) \qquad (4)$$

and from assumption (2):

$$\sum_{i=1}^{n} S_i = 1 \qquad (5)$$

where: φ = porosity
S = saturation
v = average velocity over the cross section
ρ = density
c = specific heat
K = average thermal conductivity
T = temperature
p = pressure
$k(S)$ = permeability
$\mu(T)$ = viscosity
i = (i)th phase
r = rock

No analytical solution has been found yet. However, at steady state, variables x and t can be combined as:

$$\xi = x - v_f t \qquad (6)$$

where v_f = velocity of combustion front.

Equation (1) becomes

$$\frac{d}{d\xi}[\rho_i v_i - \varphi v_f \rho_i S_i] = 0$$

and is solved giving

$$v_i=\varphi v_f S_i+\frac{\alpha_i}{\rho_i} \tag{7}$$

which shows the fluid flow in combustion is due to the pressure gradient in the system and the chemical changes. α_i is the mass rate per unit area at which the (i)th phase is generated or destroyed by chemical reactions.

By defining

$$\beta=\frac{1}{K}\left[(1-\varphi)\rho_r c_r v_f-\sum_{i=1}^{n}\alpha_i c_i\right] \tag{8}$$

equation (2) becomes

$$\frac{d^2T}{d\xi^2}+\beta\frac{dT}{d\xi}=0$$

the general solution of which is

$$T=Ae^{-\beta\xi}+B \tag{9}$$

In deriving criteria for successful steady-state combustion, further assumptions are made:

6) Crude oil is a single pure compound,
7) Only two zones, with chemical reaction taking place at their interface, are considered. The first zone contains only gas under pressure, and the second, water, oil, and gas.

The first criterion is essentially a hydrodynamic one and is based on the conception that the velocity of combustion front must be higher than that of the moving oil and lower than that of the water produced. The required inequality between the velocities of oil and water can be expressed by virtue of equation (3) as

$$\frac{k_o}{\mu_o S_o}<\frac{k_w}{\mu_w S_w}$$

where $\frac{k_o}{\mu_o}$ and $\frac{k_w}{\mu_w}$ are mobilities of oil and water respectively.

Hence,

$$S_o>\frac{\mu_w}{\mu_o}\frac{k_o}{k_w}S_w$$

the right hand side is the minimum oil saturation.

The second criterion is based on the idea that the peak temperature should occur at the combustion front itself, i.e., for $\xi<0$, $\frac{dT}{d\xi}>0$, and for $\xi>0$, $\frac{dT}{d\xi}<0$. Referring to equation (9) $\beta_2>0$, and $\beta_1<0$

and from equation (8)

$$\alpha_{o2}c_o+\alpha_{w2}c_w+\alpha_{g2}c_{g2}<(1-\varphi)\rho_r c_r v_f<\alpha_{g1}c_{g1}$$

(where subscripts 1 and 2 refer to zones; o, w, and g refer to oil, water, and gas).

This inequality is simplified by taking the following steps:

1) relating α's to each other by introducing

R_o = ratio by weight of oil to oxygen in the combustion process,
R_w = ratio by weight of water to oxygen in the combustion process,
y = the fraction by weight of oxygen used in combustion of the entering gas.

2) considering the combustion process of a single pure hydrocarbon as

$$2C_nH_{2m} + (2n+m)O_2 \rightarrow 2nCO_2 + 2mH_2O$$

The second criterion is obtained as

$$\frac{R_o}{R_w} > 2.14$$

or in the form of carbon-hydrogen mole ratio

$$\frac{n}{m} > 3.05$$

In considering the heat flux density (H) produced by combustion at the interface of two zones where the temperature (T_o) is the same for both phases, the minimum heat generation for the whole system to be adiabatic is

$$\alpha_{g1} = H/yT_o[R_o(c_o - c_g) - R_w(c_w - c_g)]$$

$$(\text{assuming } c_{g1} = c_{g2} = c_g)$$

In a real system, some heat loss will occur and by referring equation (7) to the first zone, the third criterion is expressed in the form of volume flow rate as

$$v_{g1} > \varphi v_f + \frac{H}{yT_o\rho_{g1}[R_o(c_o - c_g) - R_w(c_w - c_g)]}.$$

Subject Headings: *Combustion of* in situ *oil.*

A. S. C. Ma

Bartkowiak, A., Lambiris, S., and Zabetakis, M. G. (U.S. Bureau of Mines, Pittsburgh, Pennsylvania) "Flame Propagation Through Kerosene Foams," *Combustion and Flame* 3, 347–353 (1959)

This paper reports observations on the combustion of kerosene foams in various air-CO_2 mixtures. Foams one to three inches thick were prepared by mechanical agitation, pumping, or bubbling the appropriate atmosphere through the liquid. A variety of combustion bombs were used at 60°F and 1 atm. pressure. Spark ignition was used. Bubble size was not measured.

Kerosene foams in air could readily be ignited and burned in air at one atmosphere, contrary to the results reported by Thomas.[1] Propagation of flame through the foam appeared to involve combustion of the droplets produced by collapse of the foam at the flame front. The rate of flame propagation at atmospheric pressure decreased as CO_2 was added to the atmosphere, and propagation ceased with an atmosphere of 15 per cent (vol) CO_2 and 85 per cent air. For comparison, the propagation limit for kerosene vapor-air-CO_2 mixtures at 150°C was 38 per cent CO_2 and 62 per cent air.

The maximum pressure produced from ignition of kerosene foam-air mixtures in a closed bomb was proportional to the foam thickness and inversely proportional to the height of the air column above the foam. The maximum pressure and the rate of pressure rise for foam-air mixtures was much less than for vapor-air mixtures. For example, in a 1 $ft.^3$ cubical bomb, a typical kerosene foam-air mixture gave a maximum pressure of 20 p.s.i.g. in 1 second while a near-stoichiometric gasoline vapor-air mixture gave a maximum pressure of 120 p.s.i.g. in 0.1 second.

The heat of combustion of a unit volume of kerosene foam-air mixture was approximately the same as that of a unit volume of a stoichiometric kerosene vapor-air mixture.

Reference

1. Thomas, A. "Flame Propagation Through Air-Fuel Foams," *Sixth Symposium (International) on Combustion,* New York: Reinhold Publishing Corporation, 701–707 (1957)

Subject Headings: ***Foam, propagation of flames through kerosene; Flame propagation through foam.***

W. G. Courtney

King, I. R. (Experiment, Incorporated, Richmond, Virginia) "Comparison of Ionization and Electronic Excitation in Flames," *Journal of Chemical Physics* **31,** 855 (1959)

A comparison of ionization and abnormal excitation in premixed flames has been made using various fuel-oxidizer combinations. Ionization measurements were obtained using the Langmuir probe technique and were compared as to orders of magnitude with measurements of electronic excitation by Wolfhard and Parker[1] using the relative intensity of lines in the iron emission spectrum to distinguish between abnormal and thermal excitation in similar flames.

Fuels burning with air showed good correlation. The ammonia-oxygen flame showed high excitation together with moderately high ionization. With nitric oxide as oxidizer only thermal excitation was observed with high ionization. Even when thermal ionization was excluded by a lowered flame temperature, ionization remained high.

Hydrocarbon-nitrogen dioxide flames showed only thermal excitation with no ionization in that part of the reaction zone below 1200°K, above this ionization was high. A table showing the behaviour of several hydrocarbons and oxidizers is presented.

Reference

1. Wolfhard, H. G. and Parker, W. G. *Fifth Symposium (International) on Combustion,* New York: Reinhold Publishing Corporation 718–728 (1955)

Subject Headings: ***Flame, ionization and excitation in; Ionization in flames.***

G. L. Isles

VI. Radiation

Hinrichs, B. R. (Forschungsstelle für Feuerlöschtechnik an der Technischen Hochschule Karlsruhe, Germany) "Investigations on the Influence of Radiation on Protective Materials," *Luftschutz-Rundschau Heft 1–2* (January-February 1959)

A measuring technique is described which can be used to determine the reflection and transmission of materials for heat radiation. In addition, time-heating curves at the back of 10 (unspecified) materials are given for three distances (2, 14, 28 cm.) away from the heat source. The reflectivity for radiation of five substances is:

	Per Cent
Fine-weave, aluminized	96
Coarse-weave, aluminized	91
Glass fiber, metalized	55
Glass fiber, non-metalized	32
Black paper	11

The heat flux of the source was 1.12 kcal/hr/cm^2 at 2 cm. distance, .457 kcal/hr/cm^2 at 14 cm. distance, and .245 kcal/hr/cm^2 at 28 cm. distance. Radiation from benzene flames burning in a 25 cm. diameter tank produced approximately one-half the radiant flux at a distance of 2 cm.

Subject Headings: *Radiation, reflectivity and transmission of materials to.*

W. G. Berl

Oppenheim, U. P. (California Institute of Technology, Pasadena, California) "Experimental Verification of Theoretical Relations between Total Gas Absorptivities and Total Gas Emissivities for CO," *Journal of Applied Physics* **30,** 803–807 (1959)

This article describes a careful experimental study of the total absorptivity for radiation of gaseous carbon monoxide. Absorptivity was measured for gas temperatures ranging from 300 to 500°K and for radiation source temperatures of 300 to 1600°K. Gas pressure was also varied, particular interest being centered in pressures of approximately one atmosphere and in pressures greater than eighteen atmospheres. Further, the partial pressure of carbon monoxide was varied by mixing the carbon monoxide with argon or helium. The optical thickness of the carbon monoxide in a fixed absorption cell varied directly with partial pressure. Addition of argon and helium also served at high pressures to broaden the carbon monoxide lines to such an extent that the lines overlapped almost completely, even for moderate optical thicknesses.

The absorption experiments were undertaken primarily to test theoretical predictions of relations between absorptivities and emissivities of transparent gases. Comparisons of experiment with theory can easily be made in two limiting cases, the case of nonoverlapping dispersion lines and the case of completely overlapping rotation lines. In this article the checks were made in an interesting way. Theory gives an expression that relates the total absorptivity of gas at temperature T_g for radiation from a source at temperature T_s to the total emissivity of the gas at temperature T_s. Applying this theoretical formula, the absorption data may be plotted in the form of total gas emissivity *vs.* temperature. On the other hand, the total gas emissivity may be calculated independently from spectroscopic data and plotted on the same graph, emissivity *vs.* temperature. The two methods for obtaining the gas emissivity agree to within 20 per cent for nonoverlapping lines, thus confirming the theoretical predictions for this regime. Agreement is not quite as good for the completely overlapping line case, particularly at temperatures above 900°K. Nevertheless, the experiment does confirm the theoretical prediction that information of real practical value on high temperature gas emissivities may be obtained from measurements of low temperature gas absorptivities.

Subject Headings: ***Carbon monoxide, absorptivity and emissivity of; Radiation from carbon monoxide.***

F. H. Wright

Logan, J. G. (Space Technology Laboratories, Inc., Los Angeles, California) "Recent Advances in Determination of Radiative Properties of Gases at High Temperatures," *Jet Propulsion* **28**, 795–798 (1958)

This survey article describes recent progress in the determination of the radiative properties of gases, primarily air, in the temperature range of 3000 to 10,000°K.

Magee and Hirschfelder[1] presented the first calculations for the absorption coefficient of air in the range of 2000 to 18,000°K, considering photoelectric absorption by N, O, and O^- and absorption by NO_2. The possible significance of NO as an important contributor to radiation, as pointed out by Teller[2] and Meyerott,[3] has been discounted by the shock tube measurements of Keck, et al.[4] at Avco Research and the measurements by Weber and Penner[5] in cold NO. The shock tube technique used at Avco, wherein a confined gas is shock-heated to a particular state of interest by reflection of a strong shock from the closed end of the tube, appears most promising for the experimental determination of absorption coefficients. The Avco results have shown the relative importance of the contribution of the air components to radiation for a temperature of 8000°K and sea level density. One of the significant results of these studies was that at an altitude of 100,000 feet and a Mach number of 20, the radiative heat transfer from a 1 foot radius sphere would be only approximately 10 per cent of the aerodynamic stagnation point heat transfer.

Meyerott stresses the importance of additional work in other temperature and density ranges and with different gas mixtures to isolate particular contributors. Some examples of the relative importance of different species at 8000 to 12,000°K and sea level to 10^{-3} normal density are presented.

Gross absorption coefficients have been determined in the temperature range 4000 to 7000°K by use of a shock tube at Cornell Aeronautical Laboratory.[6] Typical features of the observed spectrum are presented.

Fraser, Nicholls, and Turner[7] have made theoretical studies of molecular band intensities and Breene[8] has undertaken the calculation of vibrational, electronic and atomic wave functions as well as wave functions for free electrons in the fields of various atoms.

Although at the present time, only transitions corresponding to infrared vibration-rotation bands make significant contributions to the total radiant heat transfer in rocket combustion chambers, the percentage of total heat transfer by radiation will become greater with increasing operating temperatures.

The use of the shock tube is recognized as one of the more promising experimental tools for the study of high temperature radiation phenomena. Shock tube drivers using plasma generators for inert gas heating will yield enthalpy and temperature conditions higher than currently available with combustion driver sections. Information from shock tube studies is extending the knowledge of internal molecular structure, collision phenomenon, reaction rates, and relaxation processes.

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Subject Headings: ***Gases, radiation from; Radiation from gases.***

L. A. Povinelli

Shorin, S. N. "Radiant Heat Exchange in an Absorbing Medium," *Akademiia Nauk SSSR. Otdelenie Tekhnicheskikh Nauk. Izvestiia* (*Academy of Sciences, USSR. Division of Technical Sciences. Bulletin No. 3,* 389 (1951)). Translated by B. W. Kuvshinoff, Applied Physics Laboratory, The Johns Hopkins University

In boilers and furnaces a mixture of gaseous combustion products and soot at high temperature transfers heat to the surroundings. This paper analytically treats transfer by radiation and compares the importance of this transfer mechanism with conduction and convection.

Initially the author outlines the aspects of radiation theory which are pertinent to the problem. This section is clearly written and serves to focus attention on the significance of the assumptions and formulation of the radiation transfer problem. A radiant flow vector is defined as

$$\vec{q}=\int_{4\pi} I\vec{\ell}d\omega \text{ kcal/m}^2\text{sec}$$

where I is the intensity of radiation and $\vec{\ell}$ is a unit vector in the direction of the rays contained in the solid angle $d\omega$. The radiant flow vector is important for the energy equation and is related to a radiation tensor by

$$q_j=-\frac{1}{k}\frac{\partial}{\partial x_i}P_{ij}=-\frac{1}{k}\frac{\partial}{\partial x_i}\int_{4\pi} I\ell_i\ell_j d\omega$$

where k is the absorption coefficient and ℓ_i is a directional cosine, namely $\ell_i=\cos(\ell, x_i)$. The components of the radiation tensor can be expressed as the sum of two quantities P'_{ij} and P''_{ij} and correspond to representing the intensity of radiation as an average plus a variable intensity. P'_{ij} arises from the average intensity and, as would be expected, can be related to local fluid properties; it is

$$P'_{ij}=\delta_{ij}\frac{1}{3}cU$$

where c is velocity of light and U is the radiant energy density. The variable intensity gives rise to P''_{ij} which is proportional to the tangential stresses due to "radiation pressure."

The ratio P''/P' is studied next. Near a boundary P''/P' is not negligible. However in an absorbing medium near equilibrium the ratio is sufficiently small so as to be negligible compared to unity. In regions where P''/P' is small, the radiant flow vector is given by

$$\vec{q}=-\frac{1}{3}\frac{1}{k}\text{grad } cU$$

At a boundary surface the distribution of radiation intensity is frequently identical on either side of the surface. For example a uniform distribution of intensity would be represented by two hemispheres. If the radiation is more intense on one side, then the radii of hemispheres would not be equal. For identical distributions of intensity the distribution function can be characterized by one ratio, m_n, which is the intensity averaged over 2π steradians divided by the flux. Using m_n the value of q normal to surface is

$$q_n=-\frac{1}{m_n^2}\frac{1}{k}\frac{d(cU)}{dn}.$$

The ratio of the two parts of the radiation tensor is

$$\frac{P''}{P'}=\frac{3}{m_n^2}-1$$

For uniform distribution m_n is 2.

The author next derives the energy equation for steady state. One special case occurs when div $\vec{q}$ is zero but $\vec{q}$ is not zero. For this case q is given by

$$\vec{q}=\lambda_{rad} \text{ grad } T$$

where the radiant heat conduction coefficient is given by

$$\lambda_{rad}=\frac{4}{3}\frac{1}{k}\frac{4\theta}{T}$$

Here θ is the flux of black body radiation at temperature T. Above 1000°K for furnace gases, λ_{rad} exceeds the usual conduction coefficient by orders of magnitude.

A one-dimensional problem is next formulated. Consider two parallel flat plates with the flow of gas at velocity w_0 normal to the plates. In a practical application one plate might be the end of a fire tube boiler. The differential equation describing this model is

$$\frac{4}{3}\frac{1}{k}\frac{d^2\theta}{dx^2}+\frac{1}{3}\frac{1}{k^2}w_0c_p\frac{d^3T}{dx^3}-w_0c_p\frac{dT}{dx}=0$$

The author neglects the third derivative and rearranges the equation to obtain

$$\frac{d^2\theta}{dx^2}-\left[\frac{3}{4}k\frac{w_0c_pT}{4\theta}\right]\frac{d\theta}{dx}=0$$

He treats the coefficient of the first derivative as a constant and obtains a solution

$$\theta=c_1+c_2\exp\left[\frac{3}{4}k\frac{w_0c_pT}{4\theta}x\right].$$

The remainder of the paper is a discussion based on the incorrect solution of the nonlinear differential equation. The main merit of this paper is the thorough discussion and formulation of the radiation transfer problem.

Subject Headings: *Heat transfer by radiation; Radiation, heat transfer by.*

A. E. Fuhs

Leah, A. S. and Watson, H. (The University, Leeds, England) "Radiation from Explosion Flames of Carbon Monoxide," *Combustion and Flame* 3, 169–186 (1959)

By comparing transient temperature, pressure, and bolometer records obtained during explosions of carbon monoxide and air in a spherical vessel, the authors present further evidence[1] that (1) in the early stages of the explosion chemiluminescent radiation is predominant, whereas after the maximum pressure it becomes a small percentage of the total fraction of the heat of combustion lost by radiation, and (2) the addition of small amounts of hydrogen or water vapor to the reactants causes large reductions in both the total amount of radiation loss as well as the chemiluminescent portion of this loss.[2]

These findings enable a reconciliation of apparently contradictory views which have existed in the literature[3, 4] concerning the relative importance of chemiluminescence (the nonequilibrium contribution of the radiation loss) in combustion processes.

In the case of the explosion of *dry* mixtures of 25 per cent carbon monoxide, 75 per cent air (initial pressure 1 atm, initial temperature 20°C) in a 4 inch diameter spherical vessel, the quantitative estimates of Leah and Watson indicate that, for times up to about one-fourth of the time t_m, to attain the peak pressure (t_m=316 msec), chemiluminescence accounts for more than 90 per cent of the radiation received by the bolometer. At the moment of peak pressure ($t=t_m$) about 12 per cent of the heat of combustion has been lost by radiation, 20 per cent of this loss ascribed to chemiluminescence. For times of the order of (3/2) t_m the corresponding values are 17.6 per cent for the total radiant loss of which chemiluminescence is responsible for 14 per cent. In contrast, for the mixture 0.52 per cent H_2, 24.94 per cent CO, 74.54 per cent air, only 2.1 per cent of the heat of combustion had been lost by radiation up to the time $t_m=57.4$ msec., and of this, 17.8 per cent is attributed to chemiluminescence.

The estimates reported are based on the difference between the amount of radiation received by a carefully calibrated calorimetric bolometer and the calculated *thermal* radiation corresponding to the observed temperature profiles. The experimental techniques and laborious calculations necessary to arrive at these quantitative estimates are outlined. For further detail the reader is referred to the dissertation of H. Watson.[5]

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Subject Headings: ***Carbon monoxide, radiation from flame of; Radiation from carbon monoxide flame.***

D. E. Rosner

Wraight, H. and McGuire, J. H. (Joint Fire Research Organization, Boreham Wood, England) "The Thermal Radiation from Some Cordite Fires," *Fire Research Note 389, Department of Scientific and Industrial Research and Fire Offices' Committee Joint Fire Research Organization* (1959)

Cubical stacks of cordite weighing 1000, 2500, 5000, 10,000, 20,000, and 40,000 pounds were burned in studies designed at establishing safe distances between such stacks. Thermal dosage meters consisting of metal sheets blackened on the front and coated with a temperature resistant paint on the rear were set up at distances from the flame selected to give dosages of 1 to 10 cal/cm^{-2}, the order of dose likely to cause ignition of cordite. Black body flame temperatures were measured with total radiation pyrometers and flame dimensions were found from photographs of the flames taken by two cameras at right angles to each other. The wind velocities were of the order of 10 to 32 ft/sec.

From the flame dimension measurements it was possible to correlate the maximum radius, Rm, of the approximately spherical fire ball and the time, Tr, for the flame radius to reach half its maximum value, with the weight, W, of cordite. Log-log plots of Tr *vs.* W and of Rm *vs.* W were linear. Since the black body flame temperatures were fairly constant for all the fires at 1390±50°C, indicating unit emissivity for the flames, it was possible to derive an expression relating dosage to distance for any given weight of cordite stack. The experimental data plotted in this way were quite highly scattered and the particular dosage measurements reported here cannot be said to support the validity of the correlation.

Subject Headings: *Radiation from cordite fires; Cordite, radiation from.*

J. B. Levy

VII. Suppression of Combustion

Friedrich, M. (Forschungsstelle für Feuerlöschtechnik an der Technischen Hochschule Karlsruhe, Germany) "Measurement of Conductivities of Wetting Agents and their Water Solutions," *VFDB-Zeitschrift* 8, 19–21 (1959)

The electrical conductivities of 7 (unspecified) foaming agents and 5 wetting agents were determined in a simple conductivity cell as a function of concentration and temperature. Compared to tap water (conductivity of .0004 ohm/cm^{-1}) the protein-based foams in 2 per cent solution showed a conductivity 6 to 14 times larger. The conductivities in dilute solution were approximately proportional to concentration of the foaming agent. A soap-based agent gave a 5.5-fold increase in conductivity. The conductivity of wetting agents varied widely.

The conclusion of this study is that dangers from electrical short-circuits are increased if the conductivity of the foaming agent is high. Stabilizing metal salts and freezing point depressants generally contribute an additional increment to the conductivity.

Subject Headings: *Foam, electrical conductivity of.*

W. G. Berl

Berlad, A. L., Rowe, R. D., and Yang, C. H. (Convair Scientific Research Laboratory, San Diego, California) "Flame Quenching in Converging Rectangular Channels," *Combustion and Flame* 3, 477–480 (1959)

A small, safe, nonflow system is described which enables the precise measurement of a quenching datum for converging rectangular flames. The apparatus consists basically of a steel quenching chamber into which three wedge-like converging channels have been built, an ignition section above the quenching chamber and a large plenum separated from the ignition section by a gate valve.

In testing, the quenching chamber is evacuated and filled with the fuel-oxidant mixture to the pressure of interest. The plenum is filled with inert (e.g., nitrogen) to the same pressure. The ignition in the chamber is timed to coincide with the full opening of the gate valve between the ignition section and the plenum. Upon ignition, the flame propagates downward into the mildly converging rectangular channels and becomes quenched when it reaches a sufficiently narrow portion of the channel. The activity of the flame is recorded by streak photographs, either schlieren or visible. From the photographs the wedge quenching distance can be determined.

It is claimed that the wedge quenching distance determined in the above manner closely approximates the results obtained for rectangular channels of constant separation. This claim leads to the conclusion that the quenching instability of the flame is determined by the wall separation in the immediate neighborhood of the reaction zone rather than by the depth of the channel.

The converging channel technique enables the study of the dynamics of the flame extinction process for any chosen set of imposed physical influences such as electrical, sound, or microwave fields.

By varying the pressure in the chamber, close-lying deflagrations and detonations may be more easily defined. This technique is especially valuable for highly reactive systems.

Subject Headings: *Flame quenching in channels.*

A. L. Goldstein

Anagnostou, E. and Potter, A. E., Jr. (Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio) "Quenching Diameters of Some Fast Flames at Low Pressures," *Combustion and Flame* **3**, 453–457 (1959)

The quenching diameters for the fast flames of stoichiometric mixtures of propane-oxygen, ethylene-oxygen, acetylene-oxygen, propane-50% oxygen-50% nitrogen, hydrogen-oxygen, and hydrogen-70% oxygen-30% nitrogen were measured in the pressure range of 0.06 to 0.35 atmospheres. The experimental method used was the determination of whether flames stabilized on a burner flashed back or quenched when the flow to the burner was interrupted.

Quenching diameters at one atmosphere were obtained by extrapolation. These values show good agreement with those of A. L. Berlad and of R. Friedman. There is not good agreement with the results of B. Lewis and G. von Elbe or with those of A. G. Gaydon and H. G. Wolfhard. In general, there is good agreement of the data presented in this paper only with data obtained by similar technique.

The order of increasing ease of quenching is acetylene, ethylene, hydrogen, and propane. The apparent anomalous position of hydrogen in this series is explained by the very high thermal conductivity of the mixture allowing heat to be transferred to the quenching surface at a high rate. The over-all reaction orders for all of the flames observed were very close to two.

Values for the product of measured quenching distances and flame temperatures were compared to the value of this product as calculated by A. E. Potter, Jr. and A. L. Berlad. The calculated values are consistantly 20 per cent higher than the experimental values. This indicates that either the estimated values of the constants used in the calculations are in error by 5 to 10 per cent or that the calculations are not representative of the experimental conditions.

Subject Headings: *Flame quenching diameters at low pressure.*

L. R. Griffith

Walker, E. J., Aidun, A. R., and Grove, C. S., Jr. (Syracuse University Research Institute) "Additives to Improve the Fire-Fighting Characteristics of Water," *Bureau of Yards and Docks, Department of the Navy Contract NBy 13027, Quarterly Progress Report No. 5* (January 1959)

In this report, the authors deal mainly with the screening of a variety of opacifiers, viscosity additives, and detergents received from various manufacturers, and also describe the new instrumentation which was required for the continuation of their research work.

In the screening of the opacifier samples, use was made of an opacifier measuring device which measures by means of a photocell the obscuration produced by the addition of opacifier to the water stream. It can be adapted to measure and control the concentration of opacifier in the actual fire-fighting equipment. Of the few samples tested, lampblack showed the best opacifier characteristics, but could not possibly be considered as an effective radiation protector since it is combustible and absorbs radiant energy. Aluminum powder proved to be the next best opacifier owing to its high reflectivity, but zinc oxide and clays were found inadequate.

Viscosity additives were selected for their ability to dissolve readily in water and to impart a constant viscosity value to the solution. Of the nine samples tested, only a proprietary product of the American Cyanamid Company showed the desired characteristics.

The detergents were selected for their ability to hold aluminum powder in suspension in water over extended periods of time. Although this work is still in its initial stage it was found that in the presence of some of the detergents aluminum powder darkens on standing, and appears to react with the detergent. In searching for a plausible explanation of this phenomenon, the pH of the detergent samples were determined and it was noted that Alkanol DW, the detergent which appeared to react the most with the aluminum, was slightly acidic.

Actual fire tests were conducted in which the extinguishment was carried out with aqueous solutions of aluminum powder, detergent, and viscosity agents in various proportions, utilizing a new pump system by which the addition of the opacifier-viscosity mix to the water stream can be mechanically controlled. The investigation is still incomplete, but results from the eight tests conducted indicate a definite improvement in the fire-fighting characteristics when the viscosity of the solution is increased. The data obtained on the influence of the other variables do not seem to be conclusive.

Initial studies in the transfer of radiant energy indicated a strong dependence of burning rate upon surface concentration of Al powder. In an attempt to corroborate these findings, two further series of tests were conducted. In the first series, alcohol was allowed to burn in a glass container and the burning rate, determined by weighing, was related to the quantity of fuel burned. Results indicated that following an initial increase the rate of burning slowly decreases as the alcohol is consumed and shows itself to be more or less independent of the presence or absence of Al powder at the surface of the liquid. It should however be noted that a large portion of the powder sank to the bottom of the container during the test. In a second series of tests, the same procedure was followed except that the alcohol was contained in a block of Celotex in order to simulate Class A fires. Again the presence of Al powder on the surface of the block showed no effect on the burning rate. It is realized that the mechanism of action of opacifiers in the extinguishment of fires is more complex than first expected and additional studies will be necessary to obtain a complete understanding of their deportment.

Subject Headings: *Water, fire-fighting characteristics of; Fires, use of water in.*

J. R. Jutras

Malcolm, J. E. (U.S. Army Engineer Research and Development Laboratories, Fort Belvoir, Virginia) "Application of Water in Fighting Fires, Evaluation of Methods," *U.S. Army Engineer Research and Development Laboratories Report 1603–TR, Project 8–76–01–400* (1959)

Results of investigations into the generation and use of water fogs in fire fighting are discussed. In normal practice, when water is applied in a solid stream or as a coarse spray to a fire, the water runoff is high and the extinction efficiency is correspondingly reduced. The cooling and wetting effects can be much enhanced if the water is applied as a fog with controlled drop size. The optimum size depends on the drop fall out rate and transport of the fog to the fire site. Drop sizes of about 100 microns diameter are necessary.

The main difficulty to be overcome is the production of a sufficiently dense fog with a required drop size at an economic and rational level. The theoretical power required for dispersion is low, but for most practical systems on the scale required for fire fighting, it is high due to the inefficiency of the devices used.

In this project, fog generation was investigated by using two types of equipment—devices using water only and devices using air and water. To test the fire extinction possibilities of water fog, tests were carried out using a mock-up giving a water fog of 1 kg. water/m.^{3}

Devices using water only: Tests were carried out initially using an aircraft hydraulic system gear pump, which gave a small volume flow of water at 100 p.s.i. This pressure is too low to produce a fine dispersion in a nozzle, but by passing the jet from a nozzle through a wire-mesh screen, about one gallon per minute was broken up into drops. Varying the spacing of the wire meshes seemed to make no difference in the drop size. Two layers of screening decreased the breaking up effect since the second layer led to flooding. The fact that the mesh spacing had no effect on the drop size seemed to indicate that the jet break up was caused primarily by impingement on the wire with no further break up due to impinging jets in the mesh spaces. The method was not investigated further since the drop size obtained was too coarse.

Another device investigated consisted of an aluminum cylinder 7 inches long tapering from 2½ to 3 inches in diameter. Sixty gallons per minute of water at 100 p.s.i. were fed tangentially into the inside of the cylinder 5 inches from the narrower end. This produced an uneven cone of water from the exit which broke up into a coarse spray. The evenness of the cone was improved by grooving the exit, but neither model gave sufficiently small drops.

Other tests were made using modifications of the Pohlman whistle which is usually used as an ultrasonic emulsifier. Its operation depends on locating a wedge mounted at its nodal points in a jet where the wedge will oscillate at its natural frequency. Attempts to obtain satisfactory oscillations using the standard wedge shape, and operating with a water jet in air, were unsuccessful. This was shown to be due to the difference in the jet behavior in air and under water. In the atmosphere the jet diverged from the leading edge of the wedge without actually passing over its surface, while tests made by introducing a small air stream into the vortices in front of the wedge operating under water, showed that the jet stream passed over the surface of the wedge. A number of other shapes for the wedge were tried, but, although oscillation operating in air was obtained, none of the shapes produced drops of the required size. All were too coarse.

Rotary and static systems were tried, but produced drops which were too large or ones which failed to provide the necessary capacity.

On the basis of published data, an evaluation of the possibility of using spinning discs to produce fog showed that this method requires much more power than other methods.

Devices using air and water: The most successful of all the devices tested was a binary fluid generator in which water was fed to the annular space between two cylinders, while air was passed through the inner cylinder, meeting the water stream at a nozzle. Ultrasonic vibration of the air stream, using a tunable resonant cavity in a closed system in the air supply, at frequencies from 1 to 15 kc. did not produce any change in the drop size produced. With air at 40 p.s.i., 100 micron average size drops were produced. The best results might be expected if the water stream could be spread out in a thin sheet before being broken up by the air jet. Two devices for spreading the water stream into a thin sheet before being broken up by the air jet were tested but physical dimensions required for large quantities of water become excessively large.

Therefore, attention was directed to improving the concentric jet generator. The air was introduced through a de Laval nozzle with four holes around the periphery at the nozzle constriction. Water was passed around this nozzle and the resulting air-water stream broke up the main water stream from the jacket at the nozzle exit. The resulting fog then passed out through a venturi. With air at 115 p.s.i. and water at 100 p.s.i. this arrangement broke up 89 per cent of the water into a fog with an average drop size of 140 microns. Increasing the air pressure to 200 p.s.i. improved the efficiency to 95 per cent.

An assessment of the Coanda duct was also made although no first hand tests were conducted. The duct operates by introducing pressurized air tangentially to the wall through a peripheral slit in a converging nozzle. This induces a large volume of air through the nozzle and for water fog generation, a second slit downstream of the air slit can be included for the water feed. Water up to 50 per cent of the weight of the total air efflux can be processed. For example, a duct 90 cm. in diameter can process 9 kg. of water and 9 kg. air/second. Therefore, to disperse 1500 g.p.m. of water as fog, 10 ducts would be required with 0.5 m^3/sec of air at 100 p.s.i., corresponding to ca. 300 horsepower.

Feasibility of fire extinction by airborne water fogs: Since it seemed possible that a device such as the Coanda duct could produce large quantities of water fog with reasonable power expenditure, tests on the fire extinction ability of such fogs were conducted on a mock-up. The Coanda duct operated as envisaged would give a fog density of 1 kg/m^3 and air currents of 25 to 30 m.p.h. A 1 x 1 meter grid of pressure jet nozzles was assembled with a Lycoming aircraft engine and propeller in line behind the grid to give an air current of about 25 m.p.h. Water at 175 p.s.i. was supplied to the nozzles in the grid so as to give a dispersion density of essentially 1 kg/m^3. Fires were started in 2-foot cubical wooden cribs primed with petrol and placed 13 feet from the grid. The drop size produced by the nozzles was too coarse to carry far, but in all the tests extinction was obtained in about 5 minutes.

Further investigation of fog generation and full-scale trials are recommended and the following conclusions are made:

1) Fog densities of 1 kg/m^3 will give a practical extinguishing effect.
2) The Coanda duct seems capable of providing an economic means of producing such a fog.

3) A drop size of 100 microns will be satisfactory from the point of view of transport and fall-out rate.

Subject Headings: *Water in fire fighting; Fires, use of water in; Extinguishment, of fires with water.*

M. G. Perry

French, R. J., Hinkley, P. L., and Nash, P. (Joint Fire Research Organization, Boreham Wood, England) "The Extinction of Fire in Petrol Storage Tanks," *Fire* **50,** 585, 591, 594 (March 1958)

Criteria are suggested for the extinguishment of gasoline tank fires using the "base injection" system of applying protein base air-foams. These criteria are based on small-scale fire tests, in which foam was applied through pipe lines communicating to the bottom portion of the test tanks. The largest of the test tanks was 9 feet in diameter and 30 feet in height. The criteria are:

Specific rate of foam injection: 0.09 U.S. gal/min/sq ft of burning fuel surface, based on the liquid solution input to the foam generator.

Expansion factor: 3.5 volumes of foam per unit volume of liquid solution input.

Time for 25 per cent liquid drainage from the foam: not less nor substantially greater than 3 minutes. A long drainage time is associated with a critical sheering stress (stiffness) higher than that indicated below.

Critical sheer stress: Not greater than 200 dynes per square centimeter.

The problems of extinguishing gasoline tank fires with most conventional methods are the vulnerability of prefire installed foam application equipment to damage by fire and the difficulty of approaching a tank fire with portable equipment once a fire is underway. Injection of foam into product lines is one means of overcoming these difficulties. The disadvantage of this technique lies in the fact that a rising column of foam injected at the base of a gasoline tank entraps globules of gasoline in the foam body. The turbulence created by the rising of the foam, and the height to which the foam rises, determine the extent of gasoline entrapment. Over 7 to 10 per cent gasoline by volume, based on the original volume of the unexpanded foam liquid solution in the foam arriving at the burning liquid surface, is sufficient to sustain combustion on the foam surface and preclude extinguishment. Foams of favorable fluidity and low expansion factor, i.e., 3.5, were observed to rise through gasoline columns with least turbulence and gasoline pickup. In practice, foams of expansion factors less than 3.5 drain liquid too rapidly, and hence change in character during the time required to reach the fuel surface. This property is shared also by foams of very high fluidity. Although not discussed in detail, the authors point out that the type of foaming agent and its concentration in solution with water are important factors in determining the characteristics of the expanded foam.

To generate foam of the desired characteristics for subsurface or base injection, use of an "in line" foam generator (venturi type air aspirator) feeding expanded foam into a centrifugal pump having about twice the rated water capacity as the in line foam generator is reported to be a satisfactory and relatively simple technique.

The following references, cited by the authors, discuss the problems associated with fire extinguishment by air-foams in greater detail.

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Subject Headings: ***Extinguishment of petroleum fires; Fires, extinguishment of petroleum; Petroleum, fires, extinguishment of.***

J. E. Malcolm

Shelberg, W. E. and Martin, S. B. (U.S. Naval Radiological Defense Laboratory, San Francisco, California) "An Exploratory Study of Protection Against Nuclear Thermal Radiation with Smoking and Intumescent Paints," *Research and Development Technical Report USNRDL–TR–241 NS 600–001* (June 1958)

Protection of surfaces exposed to intense thermal radiation for short-time periods, as occurs with a nuclear explosion, constitutes a problem of major significance. This problem was approached by the use of surface coatings which might have protective capability.

One type coating was a thermoshielding paint which interposed a rapidly produced, self-generated smoke screen between the radiation source and the protected surface. Paints having this property were not known to be available, requiring the invention of a suitable preparation. The many desirable properties of standard Navy gray paint were wanted in addition to the thermoshielding capability. The paint should commence smoking appreciably within the temperature range of 120 to 300° C, which is above the highest expected temperature caused by sunlight and yet low enough to protect highly flammable substances.

Another type of coating which might provide thermal radiation protection is intumescent paint, which is commercially available. It protects by expanding into an insulating sponge-like mat.

Both types of coating were evaluated experimentally. The initial step was to formulate thermoshielding paints. Random selection and empirical testing identified likely smoke-producing components for thermoshielding paints. A simple qualitative test, consisting of dropping ten milligrams of the chemical on a hot plate maintained at 300° C and comparing the resulting smoke with a "standard" formed from phthalic anhydride, was used to screen a large number of organic and inorganic chemicals. Not all the superior smoke-producing chemicals were incorporated successfully into Navy gray paint, although further investigation might disclose other test paints which may be compatible.

The paints were evaluated as coatings on ¾ inch diameter copper discs, called exposure blanks. One coat of primer and two coats of paint were used on each blank. The total mass of the coating on each blank was nearly uniform for all the paints. The color and reflectance of the surfaces did not vary.

A Mitchell thermal radiation source, providing acceptably constant radiation to an area of approximately 0.9 inch diameter, was used. Actual irradiance values were determined by radiation calorimetry. The exposure blank holder included a constantan needle which provided a thermocouple junction at the back surface of the exposure blank, and permitted measurement of surface temperature.

Square-wave exposures were used for most tests, with a limited number of simulated weapon pulse exposures for application data. Controlled factors in the tests were irradiance level (two levels) and exposure time, in terms of which temperature rises in the exposure blanks were continually recorded.

The tests showed that smoke protection against thermal radiation was provided by addition of nitrosoguanidine, tetracene, and sebacic acid to Navy gray paint. Thermoshielding sebacic acid paint and intumescent albi-99 paint protected against low irradiance—long duration exposure. Nitrosoguanidine and tetracene performed best at exposures combining high irradiance and very short duration. Intumescent albi-99 paint offered no protection whatever against such exposures, since its components decomposed rapidly instead of producing a relatively slow-forming foam blanket, as with lower irradiances and longer durations.

Thermoshielding sebacic acid paint was the only paint tested that protected against square-wave exposures ranging from low irradiance—long duration to very high irradiance—short duration.

The results obtained with the simulated weapon-pulse exposures substantiated those obtained with square-wave exposures. The thermoshielding sebacic acid paint was again the only test paint that protected consistently throughout the range of exposures used, which extended from that of a high peak irradiance from a moderately sized, 0.2-MT, weapon to those of lower peak irradiances from a 10-MT weapon. It reduced the surface temperature rise by from 7 to 18 per cent in these experiments.

The work described in the report involved careful empirical research. The experiments were well designed and the equipment simple but effective. A more detailed analysis of the heat transfer phenomena would have complemented the excellent experimental work and perhaps would suggest some means of extrapolation of the experimental data to other situations.

This work was exploratory in nature and could well be followed by a development program, leading to thermoshielding and intumescent paints affording even greater protection than achieved in the exploratory phase. The small discs used in the exploratory tests provided a conservative test of protection, since smoke quickly displaced from small surfaces no longer obscures the surface. Smoke displaced laterally from one area of a large surface may protect the adjacent area. Thus, any future development program for thermoshielding and intumescent paints could profitably include exposure of large surfaces at nuclear weapon tests.

Subject Headings: *Paint, protection against radiation by; Radiation, protection against, by paint.*

A. E. Noreen

Hough, R. L. (Wright Air Development Center, Wright-Patterson Air Force Base, Ohio) "Study of Liquid-Gas Interface During Discharge from the B-1A Fire-Extinguishing Agent Container," *Wright Air Development Center Technical Note 59–93* (April 1959)

This report describes an experimental investigation of the liquid-gas interface during the discharge of a container partially filled with liquid, the discharge resulting from high pressure propellant gas in the remaining part of the container. The investigation was motivated by the observation that during the discharge of a fire-extinguishing agent container of the type used in aircraft, a discontinuity in liquid flow occurs during the latter stages of the discharge. The purpose of the investigation was to determine the existence of liquid-gas interface distortion as the mechanism accounting for the liquid flow discontinuity.

The data consisted of fifteen high speed movie recordings of the liquid-gas interface during the discharge process. From the photographic records, the demarcation position between interface and container wall could be determined. Final data were presented as demarcation drop plotted against elapsed time of discharge for various initial container pressures. From the demarcation position-time data, the volume of liquid remaining in the container could be calculated, assuming an undistorted interface. This volume is designated as V_a. From a pressure-time history of the propellant gas, the gas volume and thus the actual volume of liquid remaining at any time could be calculated. If this liquid volume is designated as V_p, then $V_p < V_a$ determines a criterion for interface distortion. The data presented indicated that distortion of the interface did occur to such an extent that propellant bypass occurred. All tests were performed with triethylene glycol as the liquid and it was not possible to extrapolate the test results to conditions that would exist with other liquids.

Subject Headings: *Liquids, discharge behavior of.*

W. T. Snyder

VIII. Model Studies and Scaling Laws

Ashton, L. A. (Joint Fire Research Organization, Boreham Wood, England) "Fire Tests for Wood and Wood Products," *Journal of The Institute of Wood Science,* No. 2, 1–7 (November 1958)

The author describes the scope and purpose of tests used in the United Kingdom to classify building materials and structural elements under given fire conditions. Tests believed necessary to assess influence of materials on growth of a fire include tests for (1) combustibility, (2) surface spread of flame, and (3) fire-resistance. The first, a severe test, indicates whether a material is, or is not, combustible; it does not recognize grades of combustibility. The second test measures flame propagating properties and indicates ignitability, but it inadequately compares growth of fire in rooms lined with combustible and noncombustible materials. The third test rates the performance of a structural element such as a floor exposed to given fire conditions. This test is similar to that used in other countries. Although international standards for (1) and (3) have been requested from the

International Standards Organization, further study is required for (2) because of greater differences in concept in different countries.

In recent years attention to the influence of combustible materials on growth of fire in buildings increased. Time from ignition to flash-over (or the point when all combustible surfaces of the contents of a room first become inflamed) is considered a measure of available escape time for occupants. The British Standard test for (2) does not indicate the wide range in flash-over within materials in the least combustible class based on spread of flame. A tabulation shows ratings by spread of flame and by flashover time for 14 kinds of wall surface materials in furnished rooms built to one-fifth and one-tenth scale. A satisfactory laboratory measure of the contribution to flashover from wall surface materials has recently been developed.

A photograph and drawing show the combustion apparatus which is less than one foot in size.

Subject Headings: *Fires, tests for wood products; Wood, fire tests of products of.*

W. G. Morris

Crouch, C. W. (General Motors Corporation, Detroit, Michigan) "Laboratory Studies of Fire Action Result in Criteria for Emergency Roof Ventilation," *General Motors Engineering Journal* 6, 12–17 (1959)

The purpose of this investigation was to study the behavior of fires in large, undivided flat-roofed industrial buildings. In particular, methods of venting were investigated which would adequately protect against the spread of the hot combustion gases through the structure. Experimental measurements were carried out on ⅛ and 1/16 scale models.

To obtain the scaling law appropriate to this problem the steady-state balance between heat produced by combustion and heat discharged through vents was considered through the "chimney" equation. It was found that a reduction in model scale required that the heat output be scaled down by the five-halves power of the scale factor. Most measurements were carried out at a 1/16 scale; the model represented a building with a 20 foot ceiling including 36 bays, each 40 by 48 ft. for a total floor area of 69,120 sq. ft. Hot gases were produced by a gas burner appropriately scaled. All studies were conducted under steady-state conditions; adequate time was allowed for the structure to attain thermal equilibrium.

The experimental program was designed to study two types of venting devices: unit type vents and monitor type vents. The unit type vent is defined as a weather-tight structure installed on a building roof to provide a relatively small opening for natural convective exhaust of smoke and hot gases from a fire. The monitor type vent is defined to include all ventilators requiring relatively long and narrow roof openings. In size they range from building monitors one bay in width, extending the length of the building and having vented sash in the side walls, down to small monitors 4 ft. wide. Also included in the investigation was the effect of draft curtains on venting characteristics. Draft curtains are solid partitions which extend 6 to 12 feet downward from the ceiling. If adequate venting is present the draft curtains serve to contain the hot gases in a small region of the building.

Unit venting characteristics were obtained from the 36 bay model with a scaled 6 ft. draft curtain around the periphery of the model. The ratio of heat vented to heat produced was found for various vent-area to floor-area ratios. Approximately 20 per cent of the heat produced was conducted through the model structure. For venting to be effective much of the remaining 80 per cent should be vented through the roof to prevent the spread of combustion to the remainder of the building. In *Figure 1* a general venting curve for uniformly distributed open unit ventilators is given. This curve was found to be virtually independent of fire size. Monitor venting characteristics were studied by replacing two of the draft curtains with equivalent 4 ft. wide monitor vents (wider vents were found to be less effective) with additional monitor vents at appropriate intermediate positions. The corresponding curve for this type of venting is also shown in *Figure 1.* The effect of water sprinklers, the negative air pressure due to exhaust fans, transients, and external wind were also studied.

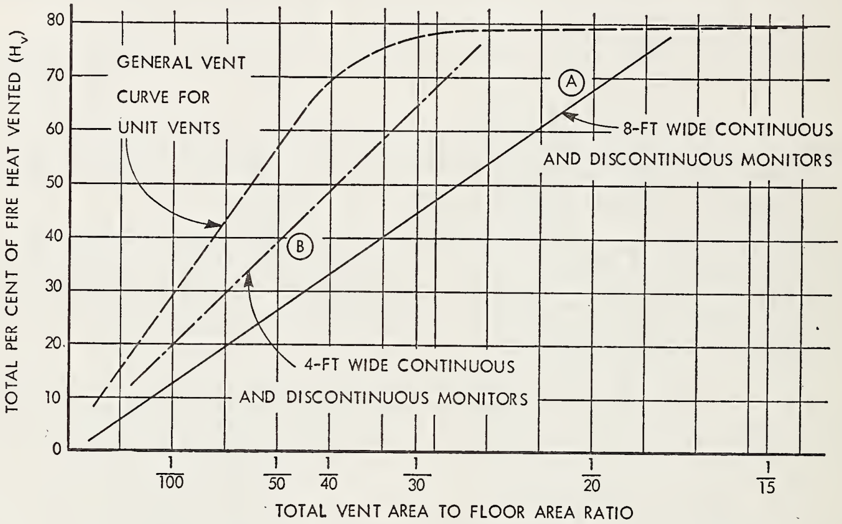

Figure 1. The monitor venting efficiencies, including all conditions of spacing and widths for both types of monitors, plotted in terms of total vent-to-floor area ratios

This paper gives a very interesting and important application of fire research to a problem of practical importance. Unfortunately the results are not given in the detail that might be desired. The paper also illustrates the considerable amount of work required before scaling of this type can be considered satisfactory for quantitative work.

Subject Headings: ***Ventilation, emergency roof.***

D. L. Turcotte

Yokoi, S. (Building Research Institute, Ministry of Construction, Japan) "The Rising Air Current from Fires," *Transactions of the Architectural Institute of Japan* No. 58 (1958)

From temperature measurements within the axially symmetrical column of gases rising above both concentrated and distributed alcohol burner heat sources, it was shown that the horizontal dimensionless temperature rise, $\frac{\Delta\theta}{\Delta\theta_m}$ at elevations $\frac{z}{r_o} > 2.5$ could be correlated with the scale $r/zc^{2/3}$, where r/z is the radial distance to height ratio and c is the scale of the turbulence. Two distinct regions were observed. Below a height of $z/r_o = 3$, the maximum temperature on the axis of the gas column remained essentially constant while at elevations above this the axial gas temperature continually decreased. It was further found possible to correlate temperature measurements in these two regions by plotting the dimensionless temperature rise along the axis

$$\textcircled{H} = \frac{\Delta\theta r_o^{5/3}}{\sqrt[3]{\frac{Q^2\theta_o}{c_p^2\rho^2 g}}}$$

as a function of the dimensionless height z/r_o. Here $\Delta\theta$ is the temperature rise above ambient (θ_o), r_o is the radius of the burner or assembly if source is distributed, Q is the rate of heat supplied to the air from the burner or burners, c_p is the specific heat of the gases in the column, ρ their density and g the acceleration of gravity. The data correlated were for concentrated heat sources varying in radius from 3.3 to 37.5 cm. and distributed heat sources of 16 and 20 cm. radius. For values of $z/r_o > 3$ the temperature rise was $\Delta\theta \approx z^{-5/3}$.

Similar studies were made with rectangular heat sources and it was found that three distinct regions exist. First, a region in which the axial gas temperature changes little with altitude; secondly, a region of increasing temperature change corresponding to that expected from a line heat source; and thirdly, a region of greater temperature drop corresponding to that to be expected from a point source. It was found possible to correlate the axial dimensionless temperature rise by the use of the same parameters as for circular heat sources. However, for the first and second regions axial gas temperatures were only correlated when sources of the same length to width ratios were compared. In the second region $\Delta\theta \approx 1/z$ as for a line source.

As an example of the way in which such data might be useful, computations were made of the height to which a television tower must be protected to prevent collapse resulting from loss of structural strength on exposure to a nearby building fire. For the assumed wooden building of 5 x 5 meters by 4 meters high, the computations and assumptions made resulted in an estimate that the tower should be protected for a height of 12.2 meters above the ground level or 8.2 meters above the building roof. It is not known to what extent the effect of winds, changes in turbulence (as scale of the fire increased), and the different heat loss characteristics of a solid fuel fire will affect the applicability of such data.

Subject Headings: ***Fires, rising air currents from.***

G. Robertson

Yokoi, S. (Building Research Institute, Ministry of Construction, Japan) "Temperature Distribution of the Hot Air Current Issuing from a Window of a Fire Resistant Model Building during a Fire," *Transactions of the Architectural Institute of Japan* No. 60 (October 1958)

Experiments have been performed with the use of metal models of buildings in which windows of various shapes were formed in the outer wall. Measurements were made of temperatures in the burning gas current issuing from the window. The experiments were conducted with models in which the building wall continuation above the window was simulated as well as for the situation in which there was no wall continuation. It was shown that, in general, although lower temperatures were observed, the shape of the temperature-distance profile along the axis of the gas flowing from the window was similar to that in the convection column above a rectangular heat source. However, the current from the window projects horizontally and then curves up vertically as a result of buoyancy. The observed differences in temperatures were attributed to losses of gases from the jet leaving the window during the horizontal portion of their travel.

It was found that windows of large width to height ratio resulted in currents which quickly turned vertical and remained near the wall above the window. It was observed that heat losses from the flaming gases were smaller for such windows resulting in higher gas temperatures. It was found that for windows of width to height ratios of one-half, the presence of the wall above the window had very little influence on the issuing current. However, for greater width to height ratios, a wall above the window had the effect of drawing the current up closer to the building and at the same time causing higher gas temperatures. It is shown that the temperature distribution as a function of distance along the axis of the issuing current from the various model windows can be correlated when plotted in dimensionless form using the following parameters

z/r_o	axial distance/window-size ratio
$\textcircled{H} = \dfrac{\Delta\theta r_o^{5/3}}{\sqrt[3]{\dfrac{Q^2\theta_o}{c_p^2\rho^2 g}}}$	dimensionless temperature ratio

the same dimensionless temperature ratio mentioned in reference 1 (see the following abstract).

An attempt to correlate the results reported for a full-scale fire in reference 1 with the model experiment results was not too satisfactory. The lower temperatures measured in the full-scale fire were attributed to the effect of winds in deflecting the issuing current in such a manner that the temperatures measured were not the maximum within the current.

Reference

1. Yokoi, S., Kawagoe, K., and Sekine, T. "Full-Scale Fire Experiment Involving a Building of Concrete Block Construction, Characteristics of Flames from a Window," *Bulletin of the Fire Prevention Society of Japan 6,* No. 2 (February 1957)

Subject Headings: ***Fires, temperature distribution in air currents from.***

G. Robertson

Yokoi, S., Kawagoe, K., and Sekine, T. (Building Research Institute, Ministry of Construction, Japan) "Full-Scale Fire Experiment Involving a Building of Concrete Block Construction, Characteristics of Flames from a Window," *Bulletin of the Fire Prevention Society of Japan* 6, No. 2 (February 1957)

Observations were made of the behavior of fire in a two-storied Matsui type concrete block building. This building was being used by the Tokyo Metropolitan Fire Board for studies of fire control with fog nozzles. Fires were started in 800 kg. (1760 lbs.) of waste timber [fire load of 53 kg/m^2 (10.8 lb/ft^2)] in the lower room of the building which was 4.30 m. long, 3.4 m. wide and had a floor to ceiling height of 2.47 m. There were two windows, one in each of two opposite walls of the room. Temperature measurements were made at positions 20, 26, 108, and 198 cm. below the ceiling at the center of the room. Maximum temperatures of about 850° C were observed.

Equipment was installed to measure temperature and velocity of the flames and gases leaving one of the lower windows. For this purpose twenty thermocouples were mounted in a vertical plane outside of and perpendicular to the center of the window. Selector switches and potentiometers were used to measure the output from these thermocouples. Five impact pressure tubes were located in a vertical line and in the plane of the upper portion of the same first floor window. Average pressure heads observed during the ten minute maximum of fire activity were plotted as a function of the positions of the pressure measuring tubes. These pressure heads were closely in agreement with values computed on the assumption of a uniform internal temperature and the assumed gas densities. It was found that the line of demarcation between inflowing and outflowing gases (neutral axis) was very nearly at the mid height of the window. Above this line the outflowing velocity head increased in a linear fashion. A plot was presented to show a general straight line trend between gas temperature and issuing velocity for the full period of the test. No explanation was presented as to the selection of gas densities necessary for velocity computations. It was reported that there was general similarity between curves of temperature and velocity as a function of distance below the top of the window opening.

A plot was developed from the temperature data to show the shape and temperature distribution within the flaming gases issuing from the window and rising outside the building. It was concluded that temperatures at the axis of these gases vary with respect to distance from the window in a manner quite similar to that observed with plane heat sources in previous studies.[1, 2]

References

1. Yokoi, S. *Bulletin of the Fire Prevention Society of Japan 5,* No. 1 (1955)
2. Yokoi, S. *Bulletin of the Fire Prevention Society of Japan 5,* No. 2 (1956)

Subject Headings: *Fires, full-scale, characteristics of flames from windows.*

G. Robertson

Fons, W. L., Pong, W. Y., Bruce, H. D., and Richard, S. S. (Pacific Southwest Forest and Range Experiment Station, Berkeley, California) "Project Fire Model," *Office of Civil and Defense Mobilization Contract No. DCM–SR–59–10 and U.S. Forest Service Contract No. 12–11–005–20170, Third Progress Report, Period April 30, 1957 to August 1, 1959* (August 7, 1959)

The third quarterly progress report on Project Fire Model summarizes continuing basic fire studies being carried on by research personnel at the Pacific Southwest Forest and Range Experiment Station under contract with the Office of Civil and Defense Mobilization.

The purpose of the project is to determine model laws for properties of wood fires through a systematic study of small, reproducible wood crib fires. A total of

14 test fires, burned under carefully controlled conditions, provide the basic data for analysis of fire characteristics. More test fires are planned for the future.

The test fires are the basis of uniformity for the entire experimental proceedings. Wood cribs of various sizes are constructed using ½ inch white fir sticks of uniform density bonded together at 1¼ inch spacing. Following assembly, the cribs are conditioned to moisture equilibrium in a humidity cabinet. Fuel moisture content of the wood cribs averaged 10.38 per cent. The cribs are ignited and burned on a concrete slab. As the fire advances, the position of the slab is advanced to consistently maintain the fire front at a fixed location with respect to observations and measurements.

Specifically, the purpose of the test fires thus far has been to (1) determine effect of fuel arrangement and volume on rate of spread, (2) measure heat absorption by the concrete base, (3) determine the amount and heat value of the charcoal remaining from test fires, (4) measure radiant energy, (5) measure convection column temperature structure, and (6) measure stack gas temperature and velocity.

The heat value of the wood fuel in the experimental fires was determined by an Emerson bomb calorimeter. Values obtained averaged 8647 Btu/lb on six samples. The white fir samples tested had a relatively wide density range but these variations in specific gravity failed to reveal any significant relation between density and measured heat values.

Rate of fire spread through the cribs of various sizes indicated that rate of spread increases with width and height up to a width of 16 inches and a height of 13 inches. Increasing the size of the cribs beyond the 13 inch and 16 inch values have only a minor effect on rate of spread. All cribs are constructed to a length of 35.5 inches for lateral uniformity.

The concrete base for each test fire is used to measure the heat transmitted to the base material. Following each test fire, the slabs are immersed in water in a calorimeter box and the intensity of heat penetration into the base material is calculated. Expressed in Btu/sec/ft of fire front, the data show the rate of heat penetration to be directly dependent on fire intensity. Width of the crib and density of the wood material in the crib is also of major importance.

There was an inverse relationship between the size of the fire and the portion of total heat content of the fuel that entered the concrete base. The largest fire produced only 2.3 per cent and the smallest fire yielded 7.1 per cent of the total heat content of the fuel.

Analysis of charcoal residues remaining from 14 experimental crib fires indicates heat values ranging from 5974 to 8898 Btu/lb. Heat values of carbon remaining in the charcoal were more nearly constant and averaged 11,640 Btu/lb. Results of the analysis are presented in table form giving weight of carbon and ash components of charcoal, per cent yield of charcoal from each fire, per cent of carbon and ash produced from the fuel, heat values (Btu/lb) of carbon and charcoal, and the portion of the heat of combustion of the fuel left in the charcoal.

Radiant heat measurements are presented for seven wood crib fires burned under carefully controlled conditions. A thermopile radiometer was positioned 14 feet from the center of the fire and 20° from the horizontal. Irradiance was then plotted against rate of combustion of the fuel. An increased rate of combustion was accompanied by a corresponding increase in radiant energy with the largest fire producing the highest relative values.

Temperature structure of the convection column was measured by a grid of 36 thermocouples suspended over the test fires. Maximum temperatures measured in the flame were between 1500 and 1600°F. The area of maximum temperature was 1½ to 3½ feet above the fire depending on fuel crib height and occurred where the flame was clean and combustion most complete.

One of the major goals of Project Fire Model is to achieve a complete heat balance on a free burning fire. The techniques for heat values of basal slabs and residual charcoal are well established. An improved method for measuring total radiation, and the total heat of combustion lost as convection heat or unburned gases will permit basic computations to be made on the complete heat balance.

The report is well illustrated with figures and tables covering all phases of the current research project.

Subject Headings: ***Wood, model fires in cribs of; Model fires in wood cribs.***

J. H. Dieterich

Fons, W. L., Pong, W. Y., Bruce, H. D., and Richard, S. S. (Pacific Southwest Forest and Range Experiment Station, Berkeley, California) "Project Fire Model," *Office of Civil and Defense Mobilization Contract No. DCM–SR–59–10 and U.S. Forest Service Contract No. 12–11–005–20170, Fourth Progress Report, Period August 1, 1959 to November 1, 1959* (November 15, 1959)

The fourth progress report on Project Fire Model is an extension of previous reports to cover continuing work and new developments in basic fire studies involving a steady-state model fire. Work is being carried on by research personnel of the Pacific Southwest Forest and Range Experiment Station under contract with the Office of Civil and Defense Mobilization.

The purpose of the project is to develop a steady-state, free-burning wood fire that may be reproduced consistently in the laboratory. Measurements are made on these fires having relatively uniform characteristics.

Eight test fires were burned during the three month period (August 1-November 1, 1959), making a total of 22 model fires burned under carefully controlled conditions since the start of the project in November 1958. Certain data have been recorded for all fires and some fires have been burned to yield specialized data. The eight fires described in this report were burned for the following specific purposes: (1) to learn the effect of the stack exhauster on rate of spread, (2) to obtain more complete radiation data, (3) to determine the effect of stick size on fire characteristics, (4) to sample convection column combustion gases, (5) to secure additional information on charcoal production and heat values and (6) to check results of two previous test fires.

Test fires continue to demonstrate a linear rate of spread after the initial build-up period. This in itself is an indicator of steady-state conditions during burning. The build-up period for each fire varied with crib width, crib height, and stick size. The smaller fires tend to reach a steady-state rapidly while larger cribs and larger material reach steady-state conditions more slowly.

Measurements were continued on determination of heat value of the white fir fuel used in the test fires. These additional measurements with a bomb calorimeter provided a more accurate average value. Consideration was given to the amount of water vapor condensing in the bomb calorimeter as compared with that amount of vapor liberated with test fire burning. The calculated average for white fir wood was established at 8135 Btu/lb.

Tests to substantiate the data concerning effect of crib height and width on rate of fire spread indicate an increased rate of spread with crib height up to about 13 inches and crib width up to about 16 inches. Increasing crib dimensions above these limits has only a minor effect on increased rate of spread. Average specific gravity and average moisture content of the six wood cribs used in this phase of the study is 0.375 and 10.63 per cent respectively.

Radiation measurements on test fires do not yet indicate the total radiation given off for any particular fire. Effort is being directed toward this end and adjustments are being made in instrumentation and physical setup of test fires to secure these missing data.

The rate of heat penetration into concrete base slabs appears to be a direct function of several factors; height and width of cribs and density of fuel material being most important. Heat penetration (Btu/ft/sec) into the base material increases with fire intensity (Btu/ft/sec) with variations resulting from the fuel size and density factors mentioned above.

All available data are summarized for effect of density on rate of spread and for residual charcoal analysis from test fires. Eight test fires, burning wood of various specific gravities, indicate a decreasing rate of spread with increasing density of fuel material. Charcoal analyses reveal that heat remaining in the charcoal as unburned compounds average 1.26 per cent of the total heat of the fuel for all 22 test fires.

One test fire was burned to determine the effect of the stack exhauster on rate of spread. The blower was turned on at the 18th minute and remained on until burning was completed. Rate of spread was linear and no changes were observed in rate of fire spread over the 35 minute period.

Two new studies concerned the effect of stick size on rate of spread (5 fires) and composition of stack gases from a single experimental fire. Four stick sizes were used with uniform spacing between sticks in each crib. Rate of spread increased with decreasing fuel stick-size below one inch material, but a slight increase was suggested in one test fire using sticks 1¼ inch in size. Additional tests are needed to clarify this apparent change. Stack gases were sampled for chemical analysis using both Orsat and infrared spectral analysis. Of the 46.34 Btu/sec liberated as heat of combustion by this test fire, 5.5 per cent was lost in the form of incompletely oxidized gases.

Future plans include (1) use of large stack to remove all convective gases from crib fires, (2) use of gas-chromatograph for quantitative analysis of stack gases, and (3) use of various wood species in density—rate of spread investigations. Achieving the heat balance on a free burning fire remains a primary objective of Project Fire Model investigations.

Ten figures and five tables adequately illustrate current research findings.

Subject Headings: *Wood, model fires in cribs of; Model fires in wood cribs.*

J. H. Dieterich

Gross, D. (National Bureau of Standards, Washington, D.C.) "Flame-Spread Measurements by the Radiant Panel Flame-Spread Method," *Forest Products Journal* **10**, 33–36 (1960)

The National Bureau of Standards has developed a surface flammability test based on a radiant energy source.[1] Using this method, the present paper assesses the importance of maintaining close control over material and test conditions and illustrates the effectiveness of various flame retardant treatments.

A brief description of the apparatus indicates that the principle of operation involves the irradiation in a standard manner of a 6 by 18 inch test specimen by a 12 by 18 inch refractory panel radiating an amount equivalent to a black body of the same dimensions at a standardized temperature (670°C). After the specimen is placed in position, an igniter initiates flaming at the upper edge of the specimen. Observations are made of the progress of the flame front for 15 minutes or until the flame traverses the entire length of the specimen, whichever is less. A flame spread index I_s is computed as the product of the flame spread factor F_s and the heat evolution Q

$$F_s = 1 + \frac{1}{t_3} + \frac{1}{t_6 - t_3} + \frac{1}{t_9 - t_6} + \frac{1}{t_{12} - t_9} + \frac{1}{t_{15} - t_{12}}$$

where the t's are the times in minutes from specimen exposure to the arrival of the flame front at the position in inches corresponding to the subscript. The heat evolution (Q) is the ratio of maximum stack temperature rise with the specimen minus the maximum rise with asbestos to the slope of the curve of maximum temperature rise as a function of heat input rate.

This flame spread index is a rather complex function and, as the author mentions, it would be desirable to correlate the results of these surface flammability test methods with actual building conditions. Lacking this, it would probably be useful to attempt a correlation between these results and those obtained with the Forest Products Laboratory 8-foot tunnel test.

The author emphasizes the importance of close control over the density and moisture content of any lumber to be considered as standard. He correlates flame spread index with mean density of red oak. In spite of the large scatter of the results, from his plot there is a suggestion that flame spread index decreases as density increases. He suggests that the scatter in the results is due to the surface grain orientation and distribution which were not controlled.

Since moisture content was shown to have a large effect on flame spread index, the author re-emphasizes the necessity for carefully controlled moisture conditioning of the specimens.

Flame-spread tests are reported on eight types of fire-protective coating systems as well as on one conventional paint coating applied to Douglas fir plywood. Also reported are test results on some Australian building boards with various coatings, both conventional and fire-retardant. In all instances, fire-retardant paints were more or less effective. Water-soluble paints that intumesce strongly to produce a thick surface barrier foam seemed to be particularly effective fire retardants.

However, attempts to correlate the radiant panel test results with the Australian "spread of flame index" were only moderately successful, perhaps due to variations in conditioning. The radiant panel flame spread method described and illustrated in this paper has the advantage of being relatively rapid and simple. It would seem that one reason for the relatively large scatter of results is the use of small specimens where variations from one specimen to the next are not as easily controlled as would be the case where the specimens are large and any inhomogeneity over a small part of the specimen would be relatively unimportant. In view of this, it would probably be more satisfactory to use a manufactured hardboard as a standard material. This would be more controllable in its physical characteristics and might possibly reduce the scatter of the results.

The author does not mention the means used to observe progress of the flame front. Since a flame front such as this is not a regular phenomenon, it would be of value to know how this observation was made. Furthermore, as can be seen from the definition of F_s, if but one of the time intervals, t_n+3-t_n, is abnormally short for some reason, it will have a decisive effect in increasing F_s, thus introducing more scatter into the results.

Reference

1. Robertson, A. F., Gross, D., and Loftus, J. "A Method for Measuring Surface Flammability of Materials Using a Radiant Energy Source," *Proceedings of The American Society for Testing Materials 56,* 1437–1453 (1956)

Subject Headings: ***Flame spread by radiant panel method.***

A. Strasser

Bruce, H. D. and Miniutti, V. P. (U.S. Forest Products Laboratory, Madison, Wisconsin) "Measuring Surface Flammability," *ASTM Bulletin* **230**, 61–68 (1958)

A method of classifying building materials as to fire hazard was developed by the Underwriters' Laboratories with a large (25 foot long) furnace. The present paper describes the results of a project undertaken to scale down the size of the Underwriters' Laboratories furnace and still produce an apparatus capable of yielding significant results. A detailed description of the construction and operation of an 8-foot tunnel furnace is presented, with further mention of the availability of blueprints for anyone wishing to duplicate this apparatus. In this furnace, a firebox with a standard gas combustion rate of 3400 Btu. per minute heats a test specimen while a standardized igniting burner plays its flame over the first four inches of the 8 foot long specimen. Combustion gases from the burning specimen are sent up a stack where temperature and smoke density are observed, while the experimenter measures the rate the flame travels along the tilted specimen. In this way, progress of the side pattern where the flame is steady is measured, rather than that of the flickering flame tips.

Results of the experiments are expressed in terms of three indexes, a "flame-spread index," a "fuel-contributed index," and a "smoke-density index." The flame spread is expressed as an index relative to the rate on red oak which is assigned an index of 100. For flame speeds faster than that on red oak, the index is the ratio of the time to reach the end of a red oak specimen to the time to reach the end of the test specimen. For flame spreads slower than that of red oak, the ratio of the distances on the test specimen to the distance on red oak in a given time is used.

To obtain the "fuel-contributed index," a temperature-time curve at the chimney is obtained with the specimen, with red oak and with asbestos board, each in turn. It is assumed that the asbestos board contributes no heat and thus the integrated temperature produced over the total time with asbestos in place is subtracted from that produced by the specimen and the standard red oak. The fuel-contributed index is then the ratio of the corrected specimen results to the corrected red oak results. Similarly, the smoke density index is a ratio of the corrected integrated smoke density from the specimen to that for red oak.

It is thus seen that the reported results depend on the ability to maintain a satisfactory standard. It was found that the rate at which flame spreads on red oak is dependent on its density and therefore in tests of miscellaneous materials the standard used was allowed to vary in density only between 37.0 to 41.0 lb/cu ft compared with a normal density spread of about 32 to 46 lb/cu ft.

In order to determine the reproducibility of the results, two or three specimens of 15 materials were tested "with a degree of control over the variables moderate enough to be easily obtained in most laboratories." Under these conditions, 12 of the 15 specimens produced deviations from the mean in flame spread index by less than 5 per cent while with the other three, deviations from the mean varied from 10 to 22 per cent. The fuel-contributed index was even more reproducible on this basis while the smoke density index was less so.

During the development of the furnace, various operating conditions were varied to determine their effect. During these tests it was found that a stock hardboard had a flame spread index averaging 97 and was more uniform than red oak. Because of the relative cheapness of the hardboard, it was thereafter used as a test material and comparison standard.

Operating variables which were tested included gas combustion rates in the firebox, specimen distance, burner positions, slope of tunnel as well as moisture content and density of specimens. The effect of small variations on operating conditions on the flame spread index for two materials (fiberboard and hardboard) showed that it would probably be feasible to duplicate results with different small tunnel-furnaces provided a reasonable amount of attention is paid to duplicating of facilities. Since one of the main purposes of the work was to encourage other laboratories to enter this field of surface flammability testing, development of this small tunnel-furnace in such a manner as to enable duplication of results is a significant achievement.

The practical significance of the small tunnel-furnace test was brought out by a series of tests in which flame spread indexes as measured by the tunnel-furnace were compared with flame spread in a room. Eleven of the materials tested in the small tunnel were applied to portions of the walls and ceiling of an experimental room and tested for flame spread. Standard crib fires were set in the paneled corner of the room and a flame spread index in the room was defined. The flame spread index values calculated for wall-corner fires were plotted against such values obtained in the small tunnel-furnace with the plot indicating that the correlation was satisfactory.

Although the authors measured and reported both smoke density indexes and fuel-contributed indexes, they make no mention of the use which they might make of these values. Although they point out that fire hazard, interpreted as hazard to life, comprises more than flame spread and includes intensity and duration of radiation, concentration of smoke, air temperature at breathing level, and oxygen deficiency, they make no attempt at correlating these factors with their smoke density index or with fuel-contributed index. The small tunnel-furnace has thus been shown to be valuable in the determination of surface flammability as measured by the flame spread index, especially in view of its good reproducibility and correlation with room tests. Whether this development is of equal value in determination of other aspects of fire hazard remains an open question.

Subject Headings: *Flammability, measurement of.*

A. Strasser

Lawson, D. I. (Joint Fire Research Organization, Boreham Wood, England) "Fire Accidents—The Contribution of Some Textiles," *Research* **11,** 126–133 (1958)

This article summarizes the information relating to burning accidents which has formed the basis for a British Standards Institution Report PD 2777 (1959).

Surveys of burns accidents in Birmingham, England and in South Wales show that the majority occur in the home. Half of them are due to clothes catching fire and burns involving clothing have the highest mortality. Children under four years of age and elderly people are most vulnerable. The greater risk is to females and the garments most frequently involved are nightdresses and dresses. The greatest danger in the British home is the unguarded fire.

The safety of fabrics is considered by the criteria (1) ease of ignition, (2) liberation of heat, and (3) vertical speed of propagation of flame. Threshold values for the ignition of fabrics are quoted (both in the presence and absence of a flame) together with the effect of flame-retardant treatment on these.

Measurements of the heat transmitted by burning fabrics to a nearby surface are reviewed; this is proportional to the weight per unit area of the fabric. However, the heat transferred to the skin from burning fabrics is always greater than that necessary to cause burns.

The vertical speed of flame propagation gives a measure of the time available either to extinguish or discard a burning garment and methods of measurement are summarized.

Fabrics may be classified by the flame-resistance rating, i.e., the time for flame to be propagated 100 inches in the vertical direction. This is a measure of the reciprocal flame velocity and is directly proportional to the weight per unit area of the burning fabric.

Investigations of cotton and wool/cotton mixture fabrics in most common use show that the bulk of burning accidents are associated with materials having flame-resistance ratings in the range 25–60. Low flame-resistance fabrics do not cause many accidents simply because such lightweight materials (less than 2½ oz/yd^2) are not frequently worn. Thus the prohibition of the sale of such fabrics is likely to have little effect on the number of accidents as the bulk of these are caused by materials to which there is no alternative. It is more realistic to educate the public to clothe children and old people in fabrics with a safe flame-resistance rating.

The British Standards Committee recommended that fabrics having a durable flame-resistance rating in excess of 150 should be warranted as flame-resistant and be so identified. Many useful fabrics, e.g. woollen fabric above 5 oz/yd², 45/55 wool/terylene mixtures over 4 oz/yd², acetate above 7½ oz/yd², and nylon and terylene should meet the standard (as well as fabrics subjected to durable flame-retardant treatments).

An Appendix deals with the derivation of an expression for the speed of propagation of flame on fabrics.

Subject Headings: *Textiles, contribution to fire accidents; Fire accidents, contribution of textiles to.*

R. Long

X. Meteorological Interactions

Croft, J. F. (Royal Military College of Science, Wiltshire, England) "The Convective Regime and Temperature Distribution above a Horizontal Heated Surface," *Quarterly Journal of Royal Meteorological Society* 84, 418–427 (1958)

Measurements of the temperature distribution above a horizontal heated surface, as well as observations of the structure of the associated convective flow, are in fairly good agreement with theories of Malkus [1] and Priestley.[2] The agreement is somewhat better for the similarity theory of Priestley. Observations were made for both the open heated plate (semi-infinite case) and for enclosed air layers between the heated plate and a cooled surface above.

Based on a small-scale turbulence mixing process, the similarity theory of Priestley leads to the equation

$$\log\frac{T}{T_a}=\beta z^{(1-\delta)}, \tag{1}$$

in which T is the air temperature at height z, T_a the temperature at $z=\infty$, and β and δ are constants.

Temperature measurements over the heated surface (an 8×10 cm. aluminum plate heated electrically from below) were made with a Michelson interferometer. This method gives a spatial mean temperature over a horizontal section at any level above the plate. The plotted data showed that log z is linear in terms of log $\log\frac{T}{T_a}$ and are thus in agreement with Eq. (1). The constant β increases linearly with plate temperature. At heights between 0.25 and 0.4 cm. (depending on the temperature of the plate) there is an abrupt change in the slope of the straight line curves. Below this point $\delta=1.2$ and in the layer above δ had a mean value of 1.5. Also, in the upper layer the data conformed to the non-dimensional equation

$$\theta_0^{-1}\log\frac{T}{T_a}=3.1\left(\frac{z}{z_0}\right)^{-1/2}. \tag{2}$$

The parameters θ_0 and z_0 are

$$\theta_0=\left(\frac{Q^3}{Kg}\right)^{1/4} \text{ and } z_0=\left(\frac{K^3}{Qg}\right)^{1/4}$$

where K is the thermal conductivity of air and g is the acceleration due to gravity. The quantity Q is related to the heat flux H by the equation

$$Q = \frac{H}{\rho c_p T}$$

in which ρ is the air density and c_p its specific heat at constant pressure.

The theories of Priestley and Malkus suggest powers of z of $-1/3$ and -1 respectively in Eq. (2), or values of δ of $4/3$ and 2 in Eq. (1). Priestley's value of $4/3$ conforms more closely, especially at the higher temperatures where δ appears to be about 1.4.

The second part of the experiment dealt with the observations of the flow patterns above the plate. The optical system for accomplishing this was a form of schlieren system which could be used with or without the knife-edge at the image of the intense point source of light. The mirage-type image on the screen was very sensitive to density variation over the heated plate.

The shallow layer adjacent to the heated plate gave rise to patterns of paired filaments of light, nearly straight and parallel, on the screen which suggested a Bénard cell type of motion. Whether or not this type of motion occurs depends on the value of the Rayleigh number (Ra) which is defined as

$$Ra = -\frac{\beta g d^4 \alpha}{K\nu}$$

where β is the temperature gradient in the pre-convective state, d the depth of the fluid layer, α the coefficient of expansion of the fluid, and ν its kinematic viscosity. In each case in which cellular motion existed throughout the whole enclosed layer, the Rayleigh number came within the range of values in which cellular convection is known to occur. Above the paired filaments could be seen the turbulent zone to which Eqs. (1) and (2) applied. The two convective zones which could thus be viewed on the screen corresponded to the two regimes which were evident in the plotted data.

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1. Malkus, W. V. R. "Discrete Transitions in Turbulent Convection," *Proceedings of The Royal Society A225,* 185–212 (1954)
2. Priestley, C. H. B. "Convection from a Large Horizontal Surface," *Australian Journal of Physics 7,* 176–201 (1954)

Subject Headings: *Convection above heated surface.*

G. M. Byram

Gifford, F. (Weather Bureau Office, Oak Ridge, Tennessee) "Smoke Plumes as Quantitative Air Pollution Indices," *International Journal of Air Pollution* **2,** 42–50 (1959)

The purpose of this work is to provide simple relationships between diffusion coefficients in the atmosphere and the geometry of smoke plumes. The Gaussian distribution for atmospheric dispersion is assumed and two models for diffusion are considered.

For a continuously emitting source at the origin of an (x, y, z) coordinate system the steady state concentration of a contaminant is assumed to be given by

$$K=\frac{Q}{2\pi(\overline{Y^2}\,\overline{Z^2})^{1/2}U}\exp\left[-\frac{y^2}{2\overline{Y^2}}\right]\exp\left[-\frac{z^2}{2\overline{Z^2}}\right]$$

where K is the concentration of the contaminant emitted by a source of strength Q, U is the mean wind speed (x=Ut), and $\overline{Y^2}$ and $\overline{Z^2}$ the horizontal and vertical variances of the concentration. An opacity method is utilized to determine the edge of the plume. The horizontal variance at the widest point of the plume ($\overline{Y_T{}^2}$) is related to the maximum half width y_m by

$$\overline{Y_T{}^2}=ey_m{}^2$$

where e is the base of the natural logarithm.

To complete the solution a particular relationship is assumed between the dispersion of the x coordinate. If the relation given by Sutton [1] is accepted,

$$\overline{Y^2}=\frac{1}{2}C_y{}^2x^{2-n},\ 0<n<1$$

where C_y is the "virtual diffusion coefficient" in the y direction and n is the stability parameter. An alternative formulation due to Frenkiel [2] may be employed

$$\overline{Y^2}=\overline{\nu_y{}^2}\left(\frac{x}{U}\right)^2$$

where ν_y is the Lagrangian turbulence intensity in the y direction.

The two types of diffusion coefficients introduced above may be related to the gross dimensions of smoke plumes. If the distance from the source to the maximum width is x_m the appropriate relations are

$$C_y{}^2=2x_m{}^n\left(\frac{y_m}{x_m}\right)^2$$

$$\overline{\nu_y{}^2}=U^2\left(\frac{y_m}{x_m}\right)^2$$

with similar equations for the z direction. Expressions were also derived based on plume length. The author points out that some method of averaging plume dimensions is desirable because of the random deformation of the center line.

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1. Sutton, O. G. "A Theory of Eddy Diffusion in the Atmosphere," *Proceedings of The Royal Society A135,* 143–165 (1932)
2. Frenkiel, F. N. and Katz, I. "Studies of Small-scale Turbulent Diffusion in the Atmosphere," *Journal of Meteorology 13,* 388–394 (1956)

Subject Headings: ***Smoke as air pollution index.***

D. L. Turcotte

Scorer, R. S. and Klieforth, H. (Imperial College, London, England) "Theory of Mountain Waves of Large Amplitude," *Quarterly Journal of the Royal Meteorological Society* 85, 131–143 (1958)

The authors present a theory in terms of equations showing how air streams with given sets of characteristics when steadily flowing across a ridge can develop lee waves of large amplitude. When the amplitude reaches a certain value, a rotor or closed rotation in the vertical plane develops either in the trough or under the crest of a wave. By substituting selected values of the undisturbed wind speed profile, stability, and one convenient wave length in the equations, streamlines were constructed to illustrate lee waves and rotors in several model air streams. These can be scaled to represent other wave lengths. Form of the mountain ridge that will produce such waves in these model air streams was constructed by plotting additional streamlines from other equations. One computed ridge form with its lee waves and a rotor produced by one family of model air streams is illustrated.

Observations are cited that support the theory. At Cross Fell, England, stable easterly winds produce cap clouds over the crest of a ridge, roll clouds farther downwind, strong downslope wind at the ground, and a reverse flow beneath the roll clouds. Winds across the Sierra Nevada in California often produce lee waves with rotors that may reach the ground and carry dust vertically upward and then over. An example is given, illustrated by a streamline diagram based on measurements from a sailplane.

The possible variation in wind directions on lee slopes suggested by this theory is important in forest fire behavior and control. Strong downslope winds, vertical drafts, and flow opposite to the main stream could occur within the scope of a single fire. The model air stream illustrated did not have the unstable air in which turbulence and changeable winds are ordinarily expected. Instead, an inversion was assumed at some 8000 feet elevation.

In developing the theory an equation published in 1955 by the senior author is adopted as the starting point. If displacement of a particle from its original level is limited, then the vertical displacement in two-dimensional motion satisfies that equation in terms of displacement, stability, wind speed, gravity, and speed of sound.

A general formal solution for all conditions would not be useful because the number of conditions is very great. In application, special cases are chosen to illustrate dynamical properties of disturbed stable air streams with periodic horizontal lee waves. The latter condition requires the equation to be linear in the displacement term. A model air stream composed of three layers is chosen and each layer has a constant wind speed profile and constant parameter of stability and wind speed. The wave length used in the study is 6 km. The maximum amplitude and that at the interface of the upper two layers is limited.

The senior author has published several articles in the Quarterly Journal concerning theory of lee waves, and these articles since 1949 are often cited by other workers in this field. The paper reviewed here refers to one in the October 1955 issue of the same periodical for an explanation of the symbols.

Subject Headings: *Wind flow over mountains.*

W. G. Morris

Robin, A. G. and Wilson, G. U. (Bureau of Meteorology, Canberra, A.C.T., Australia) "The Effect of Meteorological Conditions on Major Fires in the Riverina (New South Wales) District," *Australian Meteorological Magazine* **21**, 49–75 (1958)

This study attempts to determine the weather conditions that exist when large wildfires occur in an interior, flat region of southeastern Australia. It does not, however, discuss the effect of weather on these fires as the title would imply. Five weather variables are combined in a series of four scatter diagrams to produce three categories of separation between a sample of 25 major fire days and another sample of 130 no-fire days. Unfortunately, it is not possible to relate these categories to actual probability of occurrence of large fires because of the manner in which the sample was selected. Consequently, application of results is obscure. The authors find, however, that major fires prefer hot, dry days.

The paper presents no new techniques. Considerable procedural detail is included which could have been omitted, whereas pertinent information such as fire-occurrence data and weather characteristics of days when fires occurred but did not become large should have been included but were not. That some degree of separation was possible between the no-fire days and the major-fire days in the sample has about the same significance as separating heavy rain days from clear days without even considering the in-between situations.

The study was stimulated by the authors' assumption that when fire danger tables indicate very high or extreme danger, large fires should occur. Since often they did not, the tables were assumed to be inadequate. Instead of determining the rate of occurrence of fires of various size classes under different degrees of fire danger, the authors single out the rare, extremely large fire to be investigated as if it were the result of certain weather conditions that they attempt to define. True, more fires may be expected on hot, dry days, and more of these fires may grow to large size on the worst days, but the authors overlook the fact that weather conditions favorable for easy ignition and rapid spread do not necessarily produce any fire, let alone a large fire.

The district to which this study applies, the Riverina, is a mostly flat, triangular area some 200 miles on each side in southeastern Australia. Its southern boundary lies roughly 200 miles from the ocean. Low mountain ranges lie to the east and south while the Riverina itself averages 500 feet in elevation.

The area is said to contain a "good network of stations," though most of them report only maximum temperature and rainfall. The bulk of the weather used in the study was observed at Wagga, at the east end of the district. A large proportion of the fires considered occurred in the vicinity of this station. No upper air data was available. Because of the flatness of the land, the 3 p.m. temperature and dew point readings were found to be "generally conservative over the region." The surface wind, however, was "not always representative of the general wind circulation" and was sometimes observed as much as 30 miles distant from the fire. "Rainfall observations generally show continuity except in the case of instability showers," probably the prevailing type of precipitation in the study area during the summer.

Data for the study consist of weather observations for 155 selected days. Of these, 25 are "major fire days" selected from the 29-year period, 1926–54. All but one major fire day occurred in December, January, or February. A "major fire day" is defined as "a day on which a single fire burns in excess of 20,000 acres in grassland, 5,000 acres in dedicated forest areas, or 500 acres in exotic pine plantations."

The major fire days are compared with 130 days on which "no fire was known to be burning" (the authors call these "non-major fire days"). These no-fire days were selected from the five December-February fire seasons of 1949–54. This sample was reduced by removal of all days on which any fire less than "major" was known to occur. Also eliminated were whole months when fuels were not uniformly reported as "cured" throughout the Riverina.

The weather parameters—(1) maximum temperature, (2) 3 p.m. dew point temperature, (3) rainfall in inches, (4) number of days since rain, and (5) 3 p.m. surface wind speed—were combined in scatter diagrams with each of the 155 days plotted as either a major fire day or a no fire day. These parameters were selected as the most likely to separate the two types of days. Maximum temperature and 3 p.m. dew point were combined in the first scatter diagram.

Position of the major fire days indicated their preference for low dew point, high temperature combinations. Five zones were drawn on this chart representing different proportions of major fire days.

A second scatter diagram combined amount of rain and days since that rain. This chart was divided into three zones representing different proportions of major fire days, the pattern of points indicating some preference of major fire days for long intervals since the occurrence of light rain. This chart was much less effective in separating major fire and no-fire days than the first.

Next, each case was replotted by its zone classifications from each of the first two diagrams. This third diagram was divided into three sections, which were dominated by the dew point temperature zones of the first chart. On a fourth diagram the section classifications are plotted against 3 p.m. wind speed. Though wind speed is used, the authors point out that winds below 25 knots produced no apparent effect on proportion of major fires. They conjecture that this may be because stability is an important factor in producing major fires.

Validity of the final diagram is checked against 11 major fire days observed in other parts of Australia. These fall in the same two categories as do the major fire days of the original data and in about the same proportion. No non-fire days were used in the check. By selecting check data from other areas, the authors have dismissed the possibility of serious differences in fuels, topography, fire occurrence frequency (risk), and differences in fire control efforts, all of which would affect fire occurrence and fire size distribution. It is unlikely these factors would be identical in several areas. Ability of the system to distinguish between no-fire and major fire days was not checked, no non-fire days being included.

The authors suggest that the four diagrams may be useful in fire-weather forecasting in flat country where fuels are fully cured and abundant. They overlook the above-mentioned possible difference in fire occurrence characteristics between areas. They suggest interpretations of the three final categories varying from almost certainty of a major fire "if prompt and adequate suppression measures are not taken," to "fires may occur, but it is unlikely that they will develop into major fires." Unfortunately these statements are not supported by this study.

Whereas the study is able to show differences in weather conditions between 25 major fire days and 130 no-fire days, it does not show the differences between the major fire days and the rest of the 2,617 days from which they were selected. There is therefore no indication of how major fire days would compare with or could be separated from the general run of days. The study establishes, however, that severe fire weather conditions do occur in the Riverina, and that some fires may become large under severe fire weather, particularly as indicated by maximum temperature and 3 p.m. dew point.

Subject Headings: *Meteorology conditions on fires; Fires, effect of meteorological conditions on.*

O. P. Cramer

McIntosh, C. B. (Eastern Illinois State College, Charleston, Illinois) "Atmospheric Conditions and Explosions in Coal Mines," *The Geographical Review* **47,** 155–174 (1957)

In the mining industry it has long been believed that coal mine explosions and stormy weather are in some manner related. The author of this article has attempted to correlate changes in climatic conditions with coal mine explosions.

Methane, the gaseous combustible in coal mines, accumulates in abandoned cavities in the mine. Any drop in atmospheric pressure will draw this gas from the cavities, thereby enriching the mine's atmosphere with combustible. During the passage of low pressure areas, the atmosphere of a southern Illinois coal mine was sampled for methane analysis at the main return entry one-half mile from the exit and 410 feet below the surface. As a result of close examination of atmospheric pressure and associated methane content of mine air, it was possible to make the following generalizations:

1) Any marked decrease (increase) in atmospheric pressure results in an increase (decrease) in the methane content of the mine air.
2) The faster the decrease in atmospheric pressure, the faster methane content increases. The converse is also true.
3) A moderate to close relationship exists between methane content and absolute pressure.
4) Of two pressure falls of similar pattern and magnitude, the fall taking place below the average pressure for the mine will tend to bring about a greater increase of the methane content than a fall above average pressure.
5) Any single depression of air pressure depletes the supply of methane in the methane storage cavities.

It has been convincingly demonstrated by the U.S. Bureau of Mines that coal dust dispersed in air will burn with explosive violence. It has subsequently been shown that water absorbed on the dust can prevent dust explosions. The main function of the absorbed water is to agglomerate the dust particles, thereby reducing their dispersion into the surrounding atmosphere. In view of these facts the author attempts a correlation of the coal dust moisture content with surface air temperature. Cold surface air drawn into the mine becomes warmed by the mine's environment, consequently reducing its relative humidity. This "dry" air in turn removes any absorbed water from the coal dust, thereby increasing its potential dispersion into the mine air. The opposite effect is obtained with hot surface air. A positive correlation between surface air temperature and coal dust moisture content is obtained.

Conditions favorable to coal dust explosions—increased methane content and dry coal dust—are therefore closely associated with frontal passages. It should be noticed that the periods of highest methane content do not coincide with those of dry coal dust. This suggests that there should be two peak periods of explosion frequency—one for methane, the other for dust.

Of the 428 major coal-mine explosion disasters between 1839 and 1935 compiled by the U.S. Bureau of Mines, weather statistics for 64 of these explosions were not available. For the remaining 364, climatic conditions were obtained for a seven-day period centered around the explosion day (E-day). These explosions were divided into twelve groups. The first group contained all the disasters prior to 1901, the period between 1901 and 1950 was divided into ten equal groups and the last group covered the years 1951 to 1953. The atmospheric pressure and water vapor pressure averaged for each of these groups and plotted against this seven-day period revealed that in all but two of the twelve groups a pressure drop equal to, or greater than any other pressure drop in the week, took place during a 36-hour period ending either on E-minus 1 day or on E-day. For the seven groups from 1921 to 1953, the patterns showed a 48-hour period before E-day during which relatively dry air was flushing the mine and fostering a loss of moisture from the coal dust. Prior to 1921, little regularity was observed between climatic conditions and coal mine explosions. Even though the yearly density of mine explosions has been greatly reduced during the last 25 years, this latter period shows a closer correlation with weather conditions. The author attributes this closer correlation to the introduction of safety technology into mining operations.

A careful analysis of the data revealed the occasional occurrence of two disastrous explosions on the same day or on each of two successive days. By collecting together into groups those explosions separated by not more than two days, 48 of the 364 major explosions could be catalogued into 25 groups. Eighteen were characterized by the fact that the first explosion was located either west or north of the second. This time sequence is in accordance with the general motion across the United States of a cyclonic depression or frontal system. Correlation with a cyclonic depression or frontal passage was accepted when the explosions occurred in association with the same depression as it passed over one mine and then the other in which explosions occurred. A plot of number density of explosions versus the frontal passage time shows two peaks. The first peak occurs at the time of passage of the minimum atmospheric pressure over the mines, the second about 24 hours after frontal passage. Since the atmospheric temperature usually drops with the passage of a frontal zone, the second peak may be attributable to dust explosions. Since coal dust explosions are, in general, spatially more extensive than methane explosions, dust explosions should result in higher death numbers than methane explosions. A plot of the average number of deaths per explosion versus the frontal passage time revealed a definite increase in the average number of deaths per explosion for the second peak over the first. This tends to substantiate the author's supposition that the second peak is attributable to dust explosions.

Subject Headings: *Mines, effect of atmospheric conditions on explosions in; Explosions in mines.*

H. E. Perlee

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FOREWORD

The readers of *Fire Research Abstracts and Reviews* may not have had an opportunity to become fully informed about the functions of the Committee on Fire Research of the National Academy of Sciences—National Research Council. In brief, the main objective of the Committee is to encourage and maintain a vigorous research program in the fire field. This is done in several ways:

> by presenting to the scientific community and by encouraging individuals to undertake research problems whose solution would be of major significance in the understanding of fires.
>
> by improving communications among research workers in this field through the publication of a Journal, the sponsorship of Symposia, the organization of informal meetings on specialized topics, and the publication of an annual Directory of Fire Research.
>
> by encouraging financial support from sponsors who have a stake in a well-balanced and vigorous fire research program and by advising appropriate persons and organizations on the state of the art.

It is clear that these tasks represent an ambitious and difficult undertaking. The members of the Committee on Fire Research have unstintingly given much of their time. Together with their capable staff they deserve grateful recognition of their service.

WALTER G. BERL
Editor

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REVIEW

Fire-Fighting and Prevention

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(The following article is reprinted from the May 1960 issue of DISCOVERY, through the courtesy of the author, Mr. E. A. Hibbitt, and of the then editor, Dr. A. R. Michaelis. The full text is included and it is hoped that it will be of general interest to the readers of FIRE RESEARCH ABSTRACTS AND REVIEWS. With the author's permission his charming and illuminating illustrations of historical interest were eliminated. Their absence does not detract from the arguments presented in the review. However, they form an interesting link with the history of the technology of Fire Fighting and their inspection is recommended.—EDITOR)

Scientific research to improve methods of fire-fighting and fire-prevention is of comparatively recent origin, but it is now being carried out by a large number of organisations throughout the world. Some of this work is sponsored by public bodies, but a good deal is being done privately by manufacturers of fire-fighting and fire-prevention equipment, and by fire insurance companies.

Water has always been the principal medium used for fighting fires, and it is unlikely that it will be superseded in the foreseeable future. Water is cheap, usually plentiful, and has the highest specific heat of any known substance, which gives it remarkable cooling properties. The difficulty has always been to find the best method of using it.

Theoretically, the ideal way to extinguish a fire with water is to use exactly the right quantity which, in vaporising, will absorb sufficient B.T.U. to cool the burning substance to below its ignition temperature. If this could be achieved the danger of damage by water to valuable commodities untouched by the fire would be eliminated. (It is not infrequent in fire-fighting for the water to cause more damage than the fire itself. This is one reason why the automatic sprinkler installation is not universally popular.)

Early Equipment

The syringe or squirt ("sipho," as the Romans called it), described in the writings of Hero of Alexandria, is attributed to the inventive genius of an Alexandrian engineer named Ctesibius. Apart from the simple bucket, it was the principal fire-fighting weapon, until the devastation of a number of towns by fire compelled the authorities to give some attention to improving their fire-fighting arrangements.

Many fire-engines were invented, but few had any practical value, until two brothers, Jan and Nicolaas van der Heijden, of Amsterdam, invented a manual pump, and for the first time used leather hose between pump and nozzle, thus enabling the fire-fighting jet to be taken close to, or even into, the burning building.

The Great Fire of London provided a stimulus to inventors in this country. It was immediately after the Great Fire that the first fire insurance offices were formed, and they soon sought to extend their custom by offering their clients the inducement of protection by the insurance office's own fire-brigade. The development by Newsham of an improved type of fire-engine enabled the newly formed brigades to be equipped with a pump which would give them a reasonable chance of extinguishing a fire if they could get to it in time.

Early fire-pumps were usually on sleds, and had to be loaded on to a cart to be taken to the fire. Later pumps were fitted with wheels and were manhandled to the fire. It was not until late in the 18th century that pumps were horse-drawn. By this time the pumps were so large as to require thirty men or more to work them. It was the custom to employ spectators for this work and to reward them for their exertions with a plentiful supply of beer.

The invention of the steam engine resulted in the gradual replacement of the manual engines by horse-drawn steamers, which were much more efficient, and enabled fire-brigades to dispense with the services of spectators whose motives in offering their assistance were often suspect. Many of these steam fire-pumps are still in existence, and their performance compares favourably with the best that the modern fire-engine can do.

The invention of the internal combustion engine caused a second revolution in fire-engine design, and the reciprocating pump was at last abandoned in favour of the centrifugal pump. The latter has, of course, the great advantage that the fire-fighting jets can be shut off without stopping the pump and without the danger of bursting hose.

The centrifugal pump, driven by a petrol or diesel engine, is today universally used for fire-fighting, and usually has an output of 500–900 galls./min. at a pressure of 100 lb./sq. in. Since the war there has been a good deal of research on the use of high-pressure pumps to produce a fire-fighting mist instead of the conventional solid stream. The advantages are obvious. The object of fire-fighting with water is to absorb the heat liberated by combustion by making it convert water into steam. This can be done much more efficiently by using the water in the form of a spray or mist, which gives it a greatly increased specific surface.

The principal disadvantage, so far as the fireman is concerned, is the obvious one that the more the water stream is broken up, the shorter is its effective throw. Fire-fighting is a warm business, and it is sometimes impossible for firemen to get close enough to the fire to use high-pressure spray successfully. Nevertheless, the enormous theoretical advantages to be gained from the use of this type of equipment, not only in increased efficiency in fire-fighting but also in the tremendous reduction in the quantities of water used, have influenced many brigades to equip themselves with this type of pump.

Recent research indicates, however, that there is little appreciable advantage in using very high pressures, and it would appear from experiments carried out that a pressure of about 100 lb./sq. in. is probably sufficient. The difficulty in using very high pressures is to find suitable flexible hose capable of withstanding it. Most fire-brigades' hose is either woven flax (called "canvas") or rubber-lined cotton or nylon, and is manufactured to withstand a working pressure of about 150 lb./sq. in. A hose which had to withstand a working pressure of 500 lb./sq. in. and at the same time retain the essential qualities of lightness and flexibility would have to be much stronger and would inevitably be much more expensive.

For comparatively small fires, which can be fought from close range, the water spray undoubtedly has a very real practical value, but it is quite unsuitable for fighting large fires with the equipment at present in use. Whether it will ever be possible to combine the advantages of water spray with equipment which will enable it to be used on large fires, without the fireman having to be roasted in the process, is extremely doubtful.

Flammable Liquids

Fires involving flammable liquids are among the most difficult to fight. They occur frequently and may vary from a pan of fat to an oil storage-tank containing several thousands of gallons. They are usually extinguished by smothering in one way or another, although once again high-pressure water spray may be used to emulsify the surface and extinguish the fire by a combination of dilution and cooling. The simplest way to extinguish a fire involving a flammable liquid is to put a lid on it or throw some kind of blanket over it.

Where the fire is large, a smothering agent such as foam must be used. There is, in fact, a wide variety of smothering agents, but foam is the most commonly used and is used almost exclusively on the large fire. Experiments have been conducted for fighting fires involving crashed aircraft, in which up to 10,000 gallons of petrol or kerosene may be released into the fire by the impact. Carbon dioxide, if used in sufficient quantity (and one must think in terms of several tons of liquid CO_2), has some initial effect, but is too quickly dispersed, and even where extinction is achieved in the first attack, there is always a serious danger of a flashback as long as flammable vapours are present.

Bicarbonate of soda, to which free-flowing agents such as aluminum or zinc stearate have been added, has also been tried recently. This so-called "dry powder" is the latest development in extinguishing media, and the use of this powder in small hand-extinguishers is achieving spectacular results.

Its use in fighting large flammable-liquid fires, however, appears to be very limited, and it is unlikely that it will replace foam as the principal medium.

Foam is made by aerating a solution of a protein-base compound (largely derived from slaughterhouse waste) and water. The bubbles formed contain air, and are fairly stable, so that the foam will remain on the surface of the liquid, sometimes for several hours, before eventually breaking down. This is a useful quality in fighting fires involving a flammable liquid, because it enables the firemen to build up the foam blanket over the surface of the burning liquid until it is entirely covered. He can then allow it to cool without fear of a flashback occurring, as might be the case if an inert gas were used.

Research has shown that the fluidity of a foam is its most important property in controlling a fire, the greater the fluidity, the greater the effectiveness of the foam. At the same time, there is a critical rate of application which must be achieved if the fire is to be extinguished. Where this cannot be achieved because of a shortage of equipment or foam compound, very little will be accomplished by getting to work at all, and it would probably be better to allow the fire to burn until sufficient quantities of compound and the right equipment are available.

The technique in fighting crashed aircraft fires (provided they crash within striking distance of the airport's fire-tenders) is to smother the entire aircraft in foam within about three minutes, the whole output of specially designed foamtenders being used for this purpose. Only in this way can they hope to extinguish the fire. To apply the foam at a lower rate would merely result in the foam's being broken down too rapidly for complete coverage to be achieved.

A technique has been adopted in the United States in recent years of "foaming" a runway whenever an aircraft is compelled to carry out a crash landing. The object is to damp out any friction sparks by carpeting the runway with foam to a depth of about four inches, thus reducing the danger of the ignition of spilled fuel from damaged tanks. No one has yet established that this is in fact what happens, and although there have been instances where the foaming of a runway has been successful, there have also been instances where it has not. The Ministry of Civil Aviation in this country remains unconvinced, and has instructed airport controls to inform any pilot requesting this facility that it cannot be done.

One factor in fire extinguishment which is still not properly understood is the inhibition of combustion by the vapours of certain liquids. The best known, although the least efficient, is carbon tetrachloride, used in the familiar hand-pump carried on many motor-cars. The inhibitory effect of these compounds has been closely studied. Methyl bromide is another halogen compound commonly used, and has a much higher efficiency than carbon tetrachloride. Unfortunately, the vapours produced by the decomposition of these compounds when they are used on a fire are toxic and, in the case of methyl bromide, lethally so. They must, therefore, be limited in their use to places where the vapours are unlikely to be inhaled, and for this reason methyl bromide is principally used in fixed automatic installations such as are found in those parts of an aircraft inaccessible for fire-fighting when in flight; for example, the engine nacelles and fuel-tanks. For this purpose an extinguishing agent such as methyl bromide is particularly valuable because of the small quantities needed and the consequent saving in space and weight. Difluorochlorobromomethane is being used in some of the latest aircraft.

Chlorobromomethane, used in hand-extinguishers, has been commercialised with some success, and is to some extent replacing carbon tetrachloride. It is more efficient and less toxic, but more expensive. Experiments with other halogen compounds continue, but some of these are much too expensive to produce to be used extensively.

Large Fires

The major problem in fire-fighting is still, however, the prevention of the large fire. It is significant that about three-quarters of the financial loss by fire in the United Kingdom is attributable to a comparatively small number of large fires. If some method could be found of preventing such fires from developing, the loss would be very considerably reduced.

So far, the methods of fighting such fires have been strictly traditional and largely abortive, the principal object being to prevent the fire from spreading to neighbouring buildings and to allow the affected building to burn itself out. This does not always happen, of course, and there have been many cases where a large fire has been controlled without the total loss of the building.

Nevertheless, the fire that caused the greatest single financial loss of all time, the destruction of the General Motors plant at Livonia in the United States, proved impossible for fire-brigades to control. The eventual bill of $53 million was met in large measure by British insurance companies.

In 1957 the Fire Research Station at Boreham Wood, Herts., began to consider the possibility of using the humidified exhaust gases from a jet engine to control a large fire at least long enough for firemen to get to the seat of the fire with their jets. The greatest difficulty in fighting large fires, particularly in basements, is that the accumulations of smoke and heat prevent the firemen from fighting the fire at close quarters.

Arrangements have now been made to carry out practical tests with a jet engine loaned to the Research Station for this purpose. The problem now arises of carrying out experiments on a scale large enough to reproduce as nearly as possible the conditions likely to be met in practice. Work is at present being done on a model to produce a scale equation which could be used to relate the results to a fire in a large building. The results of these experiments are awaited with interest.

The Arithmetic of Fire-Fighting

The most profitable field of research must, of course, be in prevention, but it must be realised that the elimination of all possibility of fires starting is impossible as long as combustible materials of any kind are used in buildings.

Despite the developments that might take place in fire-fighting technique, it is unlikely that any serious reduction in fire loss will be achieved without a much wider use of automatic fire-protection equipment. The link between the fire and the fire-brigade is too dependent on chance, and in many cases the size of the fire on the arrival of the brigade has precluded any possibility of saving the building or its contents.

In this respect the present investigation being carried out at the Fire Research Station into the growth and spread of fire may prove of the greatest importance. There is a stage in the development of a fire when the heat output from the burning materials is such that the best efforts of the fire-brigade in pouring water on to the blaze are quite useless except in checking the spread of the fire to neighbouring buildings.

An attempt has been made to evaluate the combustibility of a building and its contents by assessing these in terms of B.T.U. per square foot of floor area. This is referred to as the "fire load." For example, if a single floor of a warehouse building contains 100,000 lb. of combustible material of an average calorific value of 8000 B.T.U./lb. distributed over a floor area of 4000 sq. ft., the fire load can be calculated as follows:

$$\frac{100{,}000 \times 8000}{4000} = 200{,}000 \text{ B.T.U./sq. ft.}$$

The total potential heat output of this floor, however, would be 800,000,000 B.T.U., and the whole of this would be released very rapidly once the contents of the floor had been heated to their ignition temperature. This might occur within some twenty minutes of the fire starting, depending on a number of factors including the presence of an adequate supply of oxygen. Where, because of closed doors and windows, sufficient oxygen is not present to allow complete combustion to take place, the gradual build-up of heat from a slow smouldering fire will increase the air temperature in the room, thus increasing pressure until a stage is reached when one or more windows will be pushed out, allowing a fresh supply of air to reach the fire. This usually results in a sudden flash-over when the entire combustible contents of the room, already at their ignition temperature but which have failed to burn because of oxygen starvation, will burst into flame. If this is the sort of situation which meets the fire-brigade on arrival, they are faced with an almost impossible task in controlling the fire.

Every fire-brigade, despite the highest standards of training and efficiency, and with the best equipment in the world, must take some minutes to build up its attack on the fire. A start is made with one fire-fighting jet, then two, three, and so on, until perhaps twenty or thirty jets are at work. Each jet will be pouring water into the building at the rate of about 100 galls./min., and every pound of water is capable of absorbing 1000 B.T.U. in being converted to steam. With ten jets working, a total of 1000 galls./min. will be pouring into the building. Much of this will, unfortunately, run to waste, but assuming that the whole of it is converted to steam, the maximum absorption of B.T.U. cannot possibly exceed 10,000,000 B.T.U./min. On the other hand, the release of energy by the burning of combustibles is going on at the rate of some 40,000,000 B.T.U./min.

In practice, the fire-brigade is much worse off in its efforts to fight the fire than these simple calculations show, largely because of the inefficiency of its equipment, which concentrates the attack in a number of isolated places instead of uniformly over the whole floor area, and because of the comparatively large quantity of water that never reaches the fire, failing to enter windows, for example, and running to waste down the outside of the building.

This is why so many fires in large buildings result in the total loss of the building and its contents. The heat output of the burning materials far exceeds the potential heat absorption of the total quantity of water that the fire-brigade can possibly pour into the building. The experienced fire officer knows this and prefers to use his resources to prevent the fire from spreading, allowing the main fire to burn itself out.

The present building by-laws have gone some way towards limiting the possible spread of fire by requiring that the elements of a structure shall possess a certain degree of fire resistance. The building by-laws do not, however, limit the size of the building, nor do they impose any limitation on the cubic capacity of any single compartment.

The construction of buildings used for trade or manufacture of several million cubic feet without any internal fire partitions is not uncommon. As a consequence, several local authorities are incorporating in private Acts similar powers to those contained in the London Building Acts whereby special fire precautions may be required in buildings above a capacity of 250,000 cu. ft. This figure has been chosen as representing the largest size of compartment in which it would be possible for the fire-brigade to fight a fire with any real hope of success. Above this size it is usual to require that an automatic sprinkler installation should be provided.

Automatic Equipment

Automatic fire-protection equipment is designed either to detect the fire and call the fire-brigade, or to detect and attack the fire simultaneously, as in the case of the automatic sprinkler. There is little purpose in installing equipment which will merely detect a fire without calling the fire-brigade.

Automatic detectors may be of several types, heat-sensitive or light-sensitive, the commonest depending for its operation on the thermal expansion of metal. The sensitivity of all these detectors is capable of adjustment, but the degree of sensitivity must not be such that false alarms will be caused.

One type of detector employs a small radioactive source which renders the air in an open chamber in the detector electrically conductive by the emission of alpha particles. Combustion products from a fire enter the chamber and radically change its electrical characteristics. This change triggers a cold cathode electrometer tube which then passes current to operate a relay.

Experiments have been conducted with infra-red detectors, but these have been limited to explosion suppression and to the location of the seat of a fire through smoke. The difficulties in the way of a wider use of this type of detector lie in the fact that infra-red rays travel in straight lines and can be interrupted. This obviates their use in premises where fires might start in places which would be shielded from the detector.

Conclusion

Fundamentally, fire-fighting has changed little despite improvements in pumps and hoses, and the success of the fire-fighters is directly related to their experience and courage rather than to the technical efficiency of their equipment. There is little hope that matters will improve to an extent that will make any material difference to the speed and efficiency with which fires can be fought. The use of the humidified gases from a jet engine may prove successful in controlling the large basement fire, but the prospect of achieving useful results in large buildings which are well alight on the arrival of the brigade is extremely remote.

There are two ways to prevent the large fire. Either it must be detected and attacked at its source before it can grow and spread, or the size of any single compartment must be limited by law. The second is a negative approach, and in modern industrial continuous-process plants is quite impracticable. There is no reason, however, why the law should not permit these large uncompartmented buildings provided that automatic fire-protection equipment is installed. If this were done the number of large, expensive fires would certainly be gradually reduced.

ABSTRACTS

I. Ignition Phenomena

Lawson, D. I. (Joint Fire Research Organization, Boreham Wood, England) "Wood and Fire Research," *Journal of The Institute of Wood Science* 4, 3–13 (1959)

This paper is a review of work carried out in the last 10 years by the Joint Fire Research Organization (England) on the ignition of wood and the subsequent development of flaming combustion. Most of the work described has been published previously in outline but the present summary should provide a useful qualitative survey for the general reader and for newcomers to this field of research.

In the experimental study of ignition the chief results quoted are those on ignition by radiation; this is relevant to the study of fire spread in built-up areas, and to the inter-building distance required to prevent this. Ignition was observed to start above the solid surface in the gaseous products of thermal decomposition expelled from the heated wood; the flame then struck back to the solid surface. Ignition of the gases usually occurred spontaneously when the surface temperature reached about 500°C, but it could be induced by an auxiliary igniting source when surface temperatures were only 280°C. As the gases were lost from the surface areas of the sample, combustion died down unless the ambient temperature was raised; this is needed either to generate more gases from a lower level in the solid or to start reaction on the less reactive charcoal formed on the surface of the sample. This behavior is also relevant to spread of flame through a building since the improved thermal economy between two adjacent surfaces such as crevices in floors, joints, doors and doorframes make these into flame centers. Improved constructional fit of these components by good workmanship therefore reduces the fire risk. Flame retardant paints may also reduce the fire hazard by reducing the initial spread of flame but they become ineffective when once the fire has gained sufficient hold to distill off combustible gases. This distillation can generate such volumes of flammable gases that, if they ignite, flame will suddenly sweep through a room or a building; this effect is known as "flashover."

This behavior of the solid is compared and contrasted with the behavior of sawdust and shavings. In these materials spontaneous ignition can be induced, particularly if they reside on a warm surface; the requisite conditions for this are that air must be able to diffuse through the pile at a sufficient rate to maintain oxidation but not so fast that it cools the interior. Spontaneous ignition, or heating with charring, has also been observed in stacks of fiber insulating board and similar materials. The fire hazard from smouldering dusts and shavings is greatly aggravated by the insidious nature of the phenomenon. Smouldering is easily started by a cigarette, for example; it can then continue unnoticed in large deposits for weeks; and it can be transmitted through a layer as thin as ⅛ inch. It can then ignite other materials which may rapidly blow up into flaming combustion.

Subject Headings: ***Wood, combustion of.***

R. H. Essenhigh

Vanpée, M. and Wolfhard, H. G. (U.S. Bureau of Mines, Pittsburgh, Pennsylvania) "Comparison Between Hot Gas Ignition and Limit Flame Temperatures," *ARS Journal* **29**, 517–522 (1959)

In a system containing a combustible gas mixture, ignition may occur through contact with a hot burned gas. If the temperature of a jet of inert gas issuing into a combustible gas mixture is raised until ignition of the gas mixture occurs, then the temperature of the jet is taken as the hot gas ignition temperature. In a previous paper[1] it was found that the hot ignition temperatures of a variety of fuels arranged themselves into an order which was very different from that known to exist for spontaneous ignition or spark ignition. However, there was a close relationship to hot wire ignition temperature. Hot gas ignition temperatures are much lower than adiabatic flame temperature of stoichiometric mixtures; in fact, they are close to the flame temperatures for limit mixtures. Thus, there is a possibility that the reactions governing limit flames are the same as those leading to hot gas ignition. If this is true, different fuels should show the same order of temperature in both cases.

Hot gas ignition temperatures were measured with the same equipment described earlier.[1] Two conditions for hot gas ignition temperatures were used: (1) a hot air jet mixing with a pure fuel and (2) a hot nitrogen jet mixing with a fuel-air mixture. A luminous column formed in the center of the jet for temperatures below ignition temperatures. The column grew in length and width as the temperature of the jet was increased. At the ignition temperature the column branched out, and a propagating flame moved throughout the explosive mixture.

Limiting flame temperatures were determined by producing a diffusion flame around a sintered stainless steel hemisphere.[2] The fuel entered the flame from the hemisphere, and air flowed slowly past the hemisphere. The air was diluted progressively with nitrogen until extinction occurred. This extinction resembled the bursting of a soap bubble. The oxygen index of the air at the extinction point was noted (oxygen index=oxygen in air, divided by total amount of oxygen and nitrogen), and the limiting flame temperature was calculated, assuming stoichiometric combustion.

The effect of additives on the hot gas ignition temperature was investigated. Lead tetraethyl and iron carbonyl when mixed with the outer explosive mixture and with carbon dioxide used as hot igniting jet had no influence on the ignition temperature. Chlorine in the outer mixture raised the ignition temperature only slightly, while the effect of adding chlorine in the hot jet was quite large. Methyl bromide had a strong inhibiting effect, since two per cent of this compound in the outer mixture raised the ignition temperature by nearly 150°C. Nitric oxide when added to the outer mixture in small concentrations lowered the ignition temperature slightly; in larger concentrations a small inhibiting effect became noticeable.

Comparison of the results shows that a relationship exists between hot gas ignition temperatures and limit temperatures of stoichiometric flames. The implication of this relationship is that the same reactions are responsible for both flame propagation under limiting conditions and hot gas ignition. Several exceptions should be pointed out. Methane clearly has an exceptionally high hot gas ignition temperature, as does methyl alcohol. Benzene appears to deviate below the proposed curve, having a lower hot gas ignition temperature. The effects of the additives seem to corroborate this conclusion.

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2. Simmons, R. F. and Wolfhard, H. G. "Some Limiting Oxygen Concentrations for Diffusion Flames in Air Diluted with Nitrogen," *Combustion and Flame 1,* 155–161 (1957)

Subject Headings: *Ignition, by hot gases.*

W. C. Johnston

Woods, F. J., Williams, K. G., and Carhart, H. W. (U.S. Naval Research Laboratory, Washington, D.C.) "Ignition of Hydrocarbon Vapors by Continuous DC Arcs," *NRL Report 5423* (December 1959)

This project was initiated to study further the ignition of hydrocarbon/air flammable vapors by DC arcs. The present report is an interim one.

The main apparatus consists of an air metering and saturating circuit which feeds the flammable atmosphere to a Plexiglass ignition chamber, the base of which is formed by the fixed metal plate electrode. The retractable electrode (steel ball) is mounted so as to move vertically from the fixed plate.

The fuel used was a blend of n-octane and n-heptane, selected to give saturated air mixtures at ambient temperatures with spark ignition energies $\leqq 0.3$ millijoules.

The electric circuit enabled arc currents from 0.4 to 4.6 amperes with a line voltage of 240 volts DC. Inductive or capacitative current components were eliminated as far as possible.

Studies were made initially of the arc formation. The results are shown graphically and correlated algebraically for a steel fixed electrode (negative polarity) and a steel ball as the retractable electrode. When plates of several different metals were used as the fixed electrode, differences in behavior were noted, but the arc in most cases behaved very erratically.

Systematic investigations on the ignition of the flammable vapor with electrode separation speeds of 0.034 and 0.009 in/sec, showed that no ignition in flammable mixtures occurred until the electrode separation had reached a critical value. These separations were comparable to the minimum quenching distance needed for spark ignition. The separation required decreased as the ball diameter decreased. Calculated minimum ignition currents for varying ball diameters were in reasonable agreement with the experimental values.

With higher separation rates the ball diameter has less effect and minimum ignition currents are reduced. Some initial experiments using a bouncing contact are reported. The report concludes with a discussion of the factors considered to be important in this problem and an interpretation of the experimental results.

Subject Headings: *Ignition, of hydrocarbons by DC arcs; Hydrocarbons, ignition by DC arcs.*

M. G. Perry

Lintin, D. R. and Wooding, E. R. (Safety in Mines Research Establishment, Sheffield, England) "Investigation of the Ignition of a Gas by an Electric Spark," *British Journal of Applied Physics* **10,** 159–166 (1959)

This experimental study of spark ignition is concerned primarily with measuring the development of a steady flame in a combustible gas after reaction has been initiated by an electric spark. The progress of the flame front was followed by means of shadow photographs taken at intervals after passage of the igniting spark. Measurements were restricted to various methane-air mixtures at ambient temperature and pressure.

The experimental apparatus is described in detail. This includes description of the electric circuitry of the ignition system, of the electrode design, and of the optical system for obtaining shadow photographs of a developing flame "kernel." The experiments were carried out in the following manner. Reaction was initiated by the passage of an electric spark. The amount of electric energy released was close to but either slightly greater or less than the minimum energy required to ignite the gas. In either case the flame kernel which resulted from the passage of a spark was photographed by a flash shadowgraphic technique at intervals in the time range from 23 μsec after sparking to about 5 msec after sparking. By then, the flame kernel had either become a steadily propagating flame or had disappeared.

During the first 200 μsec of kernel growth in a given mixture, flame kernels which finally failed to propagate did not differ noticeably from flame kernels which did propagate. At about this time unstable kernels were expanding at a rate noticeably less than were stable kernels, became diffuse after 1 msec, and disappeared completely after 5 msec. During this same time interval the rate of growth of a stable kernel fell to a minimum value at 1 msec and rose slowly during the next few milliseconds to a steady-state rate of propagation characteristic of the gas mixture.

Various observations of stable and unstable kernels revealed that a characteristic feature of a stable kernel is the minimum rate of growth occurring about 1 msec after sparking. Associated with this minimum rate of growth is a critical radius, the kernel radius at the time of minimum growth, and the time required for the kernel to grow to the critical radius. The variation of each of these quantities with mixture composition was determined. The minimum velocity or rate of growth and the time required to reach the critical condition were each nearly independent of mixture composition. On the other hand, the critical radius varied with mixture composition in the same manner as quenching distance. For a given mixture the critical radius is in fact comparable to, but somewhat smaller than, the corresponding quenching radius (that is, the radius of the smallest tube through which a flame will propagate). The authors believe that the critical radius coincides with the first release of energy from the gas by the combustion process.

Subject Headings: *Gases, ignition, by electric sparks; Sparks, electric, ignition of gases by.*

W. A. Rosser, Jr.

McGuire, J. H. (Joint Fire Research Organization, Boreham Wood, England) "Fire Danger from Static Electricity," *British Chemical Engineering* **3**, 136–140 (1958)

This is a qualitative survey of static electricity as a fire hazard. Generation and discharge of static electricity are covered, as well as fire hazard and preventive measures. Static electricity is generated when two surfaces are separated, usually in a shearing motion. In the case of solids, various "electrostatic series" have been proposed. In such a series, a material rubbed against another listed below it will be the positively charged body. Contradictory lists have appeared. The mechanism of charge generation by rubbing solids together is unknown. It can hardly be a contact potential effect, as suggested in this article, since contact potentials are at most a few volts, not the thousands of volts observed in static charges. Static electricity produced in fluid flow results from shear of the adsorbed electric double layer. Examples are cited.

The most dangerous discharges are those involving the discharge of an insulated conductor, in which essentially all the stored energy is discharged. Discharges from insulators tend to be diffuse. Spark energies range from 1–200 μj, produced by pulling a blanket from a nonconducting rubber-covered mattress, to 0.01–2.5 j, produced by a belt drive.

Several examples of the fire hazards are given, such as explosions during liquid fuel transfers, and the ignition of firedamp by discharges from an insulated metal hose in contact with a dust-laden compressed air stream.

The most obvious preventive measure is that of grounding all conductors. The charging rate is low ($\sim 10^{-8}$ amp.), hence the resistance to ground may be as high as 10^8 ohms and still effectively ground the conductor. Conducting surface coatings are sometimes effective in grounding solid insulators. Another possibility in this case is dissipation of the charge on the insulator by ionizing the air in its vicinity. A high-voltage, low-energy discharge, or a radioactive source can be used for this purpose. Care must be taken that the radioactive material not be spread in case of a fire, if the latter method is used.

Nonconducting liquids and bulk powders present a somewhat different problem. They are not readily grounded. Flow rate reduction and air ionization reduce the rate of charging of flowing bulk powders. Liquids must be made relatively conducting by the addition of suitable additives. Bulk resistivities of the order of 10^{11} ohm/cm are required.

The author calls for further work in four areas: additives for increasing the conductivity of nonpolar liquids; mechanism of charge generation for solids; nature of the diffuse discharge from insulators; and the use of corona discharges for air ionization. Some information is now available in the first area.[1]

Reference

1. Klinkenberg, A. and Van der Minne, J. L. "Electrostatics in the Petroleum Industry," *Elsevier Publishing Company,* New York (1958)

Subject Headings: ***Ignition, by static electricity; Static electricity, ignition by.***

P. R. Ryason

Burgess, D., Grumer, J., and Zabetakis, M. (U.S. Bureau of Mines, Pittsburgh, Pennsylvania) "Research on the Fire and Explosion Hazards Associated with New Liquid Propellants," *Office of Naval Research, Bureau of Ships, N Aonr-11–60 Progress Report No. 3* (November 1, 1959—January 31, 1960)

This is the third of a series of reports on the subject. The work is divided into three phases: I. Ignition; II. Flame Propagation; III. Flame Spreading and Extinguishment. Unsymmetrical dimethyl hydrazine (UDMH) and mixed amine fuels (MAF), defined only as MAF-1 and MAF-3, were the fuels tested during this period.

The effect of pressure on the spontaneous ignition temperature (S.I.T.) of UDMH in NO_2-air atmospheres is graphically represented at 15 and 45 p.s.i.a. as a function of the volume per cent of NO_2. S.I.T. values are always lower at the higher pressure. Small additions of oxygen to He-NO_2 mixtures markedly lower the S.I.T. of UDMH.

Flame propagation of UDMH was determined. Using a 1-liter spherical, stainless steel bomb with central spark ignition, the mean velocities of flames propagating through UDMH-air mixtures, and the peak pressures were found comparable to conventional hydrocarbon-air mixtures. For UDMH concentrations ranging from 3.3 to 15.4 per cent, the peak pressures ranged from 70 to 100 p.s.i.g. at the above limits to a maximum of 130 p.s.i.g. at 8.8 per cent; the mean burning velocities ranged from 32 to 46 cm/sec near the limits to a maximum of 210 cm/sec at 6.8 per cent.

Burning rates of open fires of pools of UDMH, MAF-1 and MAF-3 were measured in terms of liquid regression rates in trays of various sizes. For UDMH, in a 50 cm. square tray in a 76 cm. diameter tray, the values were 0.32 and 0.34 cm/min, respectively. In a 20 cm. square tray, burning rates of 0.20, 0.15, and 0.08 cm/min were measured for UDMH, MAF-1 and MAF-3, respectively. From the data, an ultimate burning rate of very large pools of UDMH was estimated to be about 0.38 cm/min.

Consideration was given to boil-over in large pools of the above fuels, caused by heat transfer into the liquid resulting in boiling below the liquid surface. Because of strong absorption of infrared radiation, boil-over with these amines is shown to be less than with conventional hydrocarbons.

Tests were made of the potentialities of water for fighting fires involving UDMH, MAF-1 and MAF-3 by determining the mixtures of fuel with water which do not ignite. The differences between the three fuels are minor with respect to the dilution with water to render the fuel nonflammable.

Subject Headings: *Flame, propagation, in propellants; Propellants, ignition of; Ignition, of propellants.*

W. G. Labes

Amiot, Louis-Philippe (Laval University Forest Research Foundation, Quebec, Canada) "Flammability and Heat Content of the Organic Material of Certain Types of Forests," *Report of Forest Research of Laval University, Part 3* (1959).

The litter layer of the soil under 12 types of forest in Lotbinière County and in Laurentides National Park, Quebec, was sampled, dried, crushed, sieved to 2 mm. diameter, and briquetted. The heat of combustion was measured in a Parr oxygen calorimetric bomb. Hygroscopicity was determined by conditioning briquettes in 35 per cent and in 79 per cent relative humidity for 1½ months and then drying them at 105°C for 24 hours. Kindling temperature was measured by inserting briquettes in an electric furnace through which air flowed at a rate equivalent to a ½ mile per hour wind, recording the rate of rise in temperature of the furnace and of the briquettes by thermocouples and observing the time and temperature at which the temperature rise of the briquettes began to accelerate sharply, which was also the time at which smoke poured from the furnace. Three thermocouples were set on the surface and a fourth 5 mm. above the surface of the briquette. In series 1, the furnace was preheated to 200°C, the briquette inserted, and the furnace temperature raised 12°C a minute. In series 2, the furnace was held constant at one of five temperatures between 184° and 230°C. In series 3, the furnace temperature was held constant at 190°–192° or at 200°–203°C.

The heat of combustion varied from 7903 Btu/lb for litter under a sugar maple population to 9416 Btu/lb for litter under a mixed balsam fir and spruce population. Litter under coniferous trees had higher heat of combustion than litter under deciduous trees.

The hygroscopicity varied from 7.5 to 9.1 per cent moisture content in 30 per cent relative humidity and from 13.4 to 16.1 per cent in 79 per cent relative humidity. The differences were independent of forest type. In the forest, however, the moisture content of the litter may depend on the level of the ground water table so that the forest type may still indicate the ease with which fire can be set.

The kindling temperature was practically the same for all samples, between 230° and 235°C measured on the surface of the briquette. The kindling temperature was reached in 16 to 23 minutes in the furnace held at 190°–192° or at 200°–203°C (series 3). There was no ignition in the furnace when held at 184°C; at constant furnace temperatures at 206°C or more the kindling temperature was higher the higher the furnace temperature (series 2). Still higher kindling temperatures were observed in series 1 in which the furnace temperature rose 12°C a minute. Briquettes at 15 per cent moisture content took longer to reach kindling temperature but ignited at the same temperature as dry briquettes.

Subject Headings: ***Flammability, of forest materials; Forests, flammability of organic materials in.***

F. L. Browne

II. Thermal Decomposition

Kaesche-Krischer, B. and Heinrich, H. J. (Bundesanstalt für Materialprüfung, Berlin-Dahlem, Germany) "Pyrolysis and Ignition of Polyvinylalcohol (PVA)," *Zeitschrift für Physikalische Chemie* **23**, 292–296 (1960)

As a continuation of a study on flame propagation in dust dispersion of polyvinylalcohol (PVA) in air[1] the thermal decomposition of PVA at low pressure and in the presence of oxygen was studied.

Experiments were carried out by measuring weight changes of powdered material on a continuously recording balance, mounted within a furnace. For thermal decomposition studies the temperature of the furnace was increased at a rate of 1°C/min. Two distinct regions of reaction were noted: between 100°–260°C water only was split off from the polymer, presumably due to reaction between H- and OH-groups on the same chain; above 260°C, a new reaction set in, leading to formation of aldehydes and acrolein; at even higher temperatures (350°C) the carbon skeleton of the polymer was destroyed with the formation of high-molecular weight liquid hydrocarbons.

Oxygen added readily to the material which was dehydrated below 260°C. Measurements were reported in which the dehydrated material was exposed to oxygen at various temperatures (25°–105°C). At sufficiently high temperature and pressure (75°C and 550 mm. Hg., for example) ignition of the powder occurred. Where self-heating was small, unimolecular reactions were observed with the oxygen adsorption taking place at constant temperature.

The conclusions were that oxygen adsorption takes place rapidly on dehydrated PVA. If the heat generated in this reaction exceeded the heat loss, the subsequent aldehyde and hydrocarbon stage of decomposition was reached, whereupon the reaction products would burn in a gas-phase flame.

Reference

1. Kaesche-Krischer, B. *Staub 19,* 200 (1959)

Subject Headings: ***Thermal decomposition, of polyvinylalcohol; Polyvinylalcohol, thermal decomposition of.***

W. G. Berl

Coleman, E. H. and Thomas, C. H. (Joint Fire Research Organization, Boreham Wood, England) "The Products of Combustion of Chlorinated Plastics," *Journal of Applied Chemistry* 4, 379–383 (1954)

An experimental study was made to determine the products from some chlorinated plastics after heating them to various temperatures in air. This was done to evaluate the toxic nature of the gaseous products which might result from fires in which these materials would be involved. The major products found were hydrogen chloride, carbon monoxide, and carbon dioxide. Carbonyl chloride was detected, however, in amounts which were unimportant compared to the concentrations of the other toxic gases.

The materials studied were chlorinated polymethyl methacrylate, polyvinyl chloride with and without stabilizers and plasticizers, and vinyl and vinylidene chloride copolymer. Samples of these materials of about 0.25 gm. up to a maximum of 2 gm. were placed in a boat heated by a concentric coil of nichrome resistance wire and contained in a 5.5 liter flask. This size flask filled with air at 1 atm. provided enough oxygen for complete combustion of 1.05 gm. samples of chlorinated polymethyl methacrylate. An arbitrary heating period of 15 minutes at temperatures of 300°to 1000°C was used. The product gases were analyzed for hydrogen chloride, chlorine, carbonyl chloride, carbon monoxide, and carbon dioxide.

One-half gram samples of chlorinated methacrylate resin (45 per cent carbon, 27 per cent chlorine) released about one-third of its chlorine content as hydrogen chloride at 300°C and progressively larger amounts at higher temperatures. Carbon dioxide was formed at all temperatures tested but mostly above 750°C. The solid residue remaining at 900° to 1000°C was negligible.

At 550° and 950°C various size samples were employed to determine the effect of sample to air ratio on the decomposition products. The product sample to air ratio at 550°C had relatively little effect on the products other than an increase in the amount of hydrogen chloride, carbon monoxide, carbon dioxide, and hydrocarbons. The same behavior was found at 950°C except the carbon monoxide to carbon dioxide ratio increased as the sample to air ratio increased. Luminous flames were sometimes observed for sample to air ratios near stoichiometric and in these cases the ratio of carbon monoxide to carbon dioxide was less.

One-fourth gram samples of the vinyl chloride containing materials (31 to 57 per cent chlorine) were tested at 300°, 600°, and 900°C. These materials showed the same general behavior as the chlorinated polymethyl methacrylate. The amount of hydrogen chloride evolved was approximately proportional to the chlorine content of the original sample.

Subject Headings: ***Plastics, combustion products of, from chlorinated.***

C. P. Talley

Madorsky, S. L. and Straus, S. (National Bureau of Standards, Washington, D.C.) "Thermal Degradation of Polymers at High Temperatures," *Journal of Research of the National Bureau of Standards* **63A**, 261–268 (1959)

Previous studies of thermal degradation of polymers made at temperatures up to 500°C were extended to 850°C. The molecular structure of the polymer determines its stability, the mechanism of degradation, and the amount and chemical nature of the products. Tertiary or quaternary carbon atoms in the chain weaken adjacent C-C bonds in the chain. Abundant hydrogen on the chain, through random scission, leads to volatile products that vary from a single carbon atom to the largest fragments volatile at the pyrolysis temperature. Scarcity of hydrogen leads to monomers formed by unzipping at chain ends and ends produced by random scission. Polymers of class 1, in which scissions occur primarily in the backbone of the chain, vaporize completely at high temperature. Polymers of class 2, in which scissions occur primarily between carbons of the backbone and side groups to form double bonds in the chain and perhaps crosslinks between chains, on prolonged heating lose 60 to 70 per cent by volatilization and then leave a partially carbonized residue. Highly crosslinked polymers of class 3 promptly yield a honeycombed structure of carbonized residue amounting to 40 per cent or less of the original sample.

Polymers of class 1 were represented by polystyrene (molecular weight 230,000), class 2 by poly(vinylidene fluoride) polymerized to high molecular weight by γ-radiation, and by polyacrylonitrile (number-average molecular weight 40,000), and class 3 by polytrivinylbenzene.

Ten- to 50-mg. samples were pyrolyzed in a closed system evacuated to 10^{-4} mm. of mercury by rapid encompassment with an electric furnace preheated to the desired temperature. Furnace temperature was attained within 1 minute at the higher temperatures or 5 minutes at lower temperatures (in older equipment). Polystyrene was pyrolyzed also in helium at atmospheric pressure. Charred residues were weighed. Three volatile fractions were collected. Fraction V_{pyr} condensed in the cool portion of the sample tube projecting beyond the furnace. Fraction V_{-190} passed a liquid nitrogen cold trap and was collected in a sample tube. Fraction V_{25} condensed in the cold trap but volatilized at room temperature. Fractions V_{25} and V_{-190} were analyzed by mass spectrometer.

Polystyrene volatilized completely at 850°C in vacuum; in helium 98 per cent volatilized. Fraction V_{-190}, mostly carbon monoxide, was about 0.1 per cent. Fraction V_{25} increased and V_{pyr} decreased at higher temperature, higher pressure, or both. At 362°C in vacuum fraction V_{25} consisted of 94.4 per cent styrene, 5.6 per cent toluene; at 850°C in vacuum or 362°C in helium much benzene appeared and styrene decreased; at 850°C in helium ethylene was the chief component (49.2 per cent) with some ethane and propadiene. Fraction V_{pyr}, of average molecular weight 264 to 321, consisted largely of dimers, trimers, and tetramers.

Poly(vinylidene fluoride) did not volatilize beyond 87 per cent (heated rapidly) or 68 per cent (heated slowly) at 800°C. Fraction V_{-190}, chiefly hydrogen and carbon monoxide, was about 0.1 per cent. Fraction V_{25}, almost entirely hydrogen fluoride, usually exceeded fraction V_{pyr}, especially when heated slowly.

Polyacrylonitrile did not volatilize beyond 94 per cent. Fraction V_{-190} consisted of hydrogen and was very small. Fraction V_{25}, chiefly hydrogen cyanide, acrylonitrile, and vinylacetonitrile, amounted to 12 to 14 per cent of the volatile products; it repolymerized on standing. The average molecular weight of fraction V_{pyr} was 330.

Polytrivinylbenzene stabilized at 68 per cent volatilization for rapid heating and 63 per cent for slow heating. At 500°C the volatile products were 82 per cent V_{pyr}, 13 per cent V_{25}, 5 per cent V_{-190}; at 800°C they were 84 per cent V_{pyr}, 5 per cent V_{25}, 11 per cent V_{-190}. Fraction V_{-190} contained chiefly hydrogen and methane with small proportions of higher hydrocarbons and with the proportion of hydrogen increasing markedly the higher the temperature. Fraction V_{25} contained hydrocarbons from methane to $C_{11}H_{16}$ with significantly more methane and ethylene the higher the temperature. The average molecular weight of fraction V_{pyr} was 372, 325, and 316, respectively, at 470°, 500°, and 800°C.

Rates of thermal degradation in vacuum were measured by the loss-of-weight method with a tungsten spring balance for higher temperatures or a continuously recording electronic balance at lower temperatures. From the rates and the Arrhenius equation the activation energies in the temperature range 218° to 440°C were 48, 31, and 73 kcal/mole, respectively, for poly(vinylidene fluoride), polyacrylonitrile, and polytrivinylbenzene.

It is uncertain whether fragmentation increases at higher temperature and pressure through primary scission of the polymer or by subsequent splitting of the initial fragments while still in the hot zone, especially if escape is retarded by collisions with other molecules.

Polystyrene vaporizes completely. Polytrivinylbenzene is already highly crosslinked owing to the trifunctionality of the monomer; it therefore quickly forms a carbonaceous residue. Poly(vinylidene fluoride) and polyacrylonitrile probably become crosslinked during pyrolysis when H and F or H and CN split off and provide new functionality.

Subject Headings: ***Polymers, thermal degradation of; Thermal decomposition, of polymers.***

F. L. Browne

Straus, S. and Wall, L. A. (National Bureau of Standards, Washington, D.C.) "Influence of Impurities on the Pyrolysis of Polyamides," *Journal of Research of the National Bureau of Standards* **63A**, 269–273 (1959)

Low and variable activation energies and pre-exponential factors and presence of carbon dioxide and water in the products when nylon was pyrolyzed suggested that impurities, especially water and acid catalysts, superimpose a hydrolytic mechanism on the free-radical degradation normally to be expected of polyamides. Therefore nylon-6, made from caprolactam, was purified by various methods, the rate of volatilization at 335°C in vacuum determined by the loss-of-weight method, and the lighter products were analyzed by mass spectrometer.

For unpurified nylon the rate of volatilization reached a maximum of 0.9 per cent a minute when 25 to 30 per cent had been volatilized and of the total volatile products 7.5 per cent was carbon dioxide and 2.2 per cent was water. Leaching in water for 5 to 10 days to remove catalyst and redrying at 110°C in vacuum reduced the maximum rate to 0.6 per cent a minute and the carbon dioxide and water to 4.8 and 1.6 per cent, respectively. Further purification by immersion in absolute ethyl alcohol for 2 days to remove water and redrying reduced the rate of volatilization to 0.5 per cent a minute and the carbon dioxide and water to 2.2 and 0.5 per cent, respectively. (More prolonged leaching in water increased the rate again, possibly because of oxidative degradation.)

The leached, alcohol-immersed, redried nylon was further purified: (1) by heating in *p*-dioxane at 110°C for 4 days; (2) by placing above sodium hydride in a closed tube evacuated to 10^{-4} mm. of mercury and heated to 105°C for 8 hours a day for 20 days; (3) by treating as in method 2 except for use of sodium in toluene for dehydrating agent; (4) by immersion for 20 days in toluene kept freshly supplied by distillation from toluene in contact with sodium, all in a closed system that excluded air and provided for escape of hydrogen.

With purified samples the maximum rate of volatilization, yield of carbon dioxide, yield of water, respectively, were: method (1) 0.88, 2.5, 0.3; method (2) 0.53, 2.5, 1.3; method (3) 0.64, 2.3, 0.2; method (4) 0.44, 1.3, 0.5. Some toluene or *p*-dioxane retained in samples by methods (1), (3), or (4) appeared in the volatile pyrolysis products. (Prolonging method (4) to 76 days speeded volatilization, probably from degradation by long contact with warm toluene.)

Treatment of nylon-6 with ammonium hydroxide to neutralize acids facilitated hydrolytic degradation, indicated by increased yields of carbon dioxide and water.

Nylon 66/6, a copolymer of nylon-6 and nylon-66 (hexamethylene-diamine-adipic acid salt), was pyrolyzed before and after treatment with phosphoric acid. Treatment doubled the yield of carbon dioxide and reduced that of cyclopentanone by a factor of 10. Evidently the cyclopentanone came directly from the poylamide rather than from adipic acid or adipic acid end groups.

Pyrolyses at 345° and 365°C showed that purification by method (4) raised the activation energy from 34 to 43 kcal/mole and the pre-exponential factor from 4.1×10^7 to 3.2×10^{10}.

The rate curves for nylon purified by method (4) corresponded almost precisely to expectation for random breakdown when not overshadowed by hydrolytic degradation caused by acids or water. It is estimated that perfectly purified polyamide would pyrolyze by a purely thermal free-radical mechanism with a pre-exponential factor of 10^{13} and an activation energy of 50 kcal/mole, or perhaps a pre-exponential factor of 10^{16} and an activation energy of 60 kcal/mole.

Subject Headings: *Thermal decomposition, of polyamides; Polyamides, thermal decomposition of.*

F. L. Browne

Coleman, E. H. (Joint Fire Research Organization, Boreham Wood, England) "Gaseous Combustion Products from Plastics," *Plastics* **24**, 416–418 (1959)

The toxic hazards resulting from combustion of synthetic resins and plastic materials are reviewed. Results of previous investigations are summarized in tables; information is given for method of testing, analyses of decomposition products, and physiological effects of some gases occurring in fires. The degree of hazard was assessed by exposing small animals to combustion or pyrolysis products, and by chemical analysis. The experimental results showed that in the majority of fires, the principal toxic product is carbon monoxide. If large amounts of plastics are involved, the use of a self-contained breathing apparatus may be required due to irritant products, copious smoke emission, and deficiency of oxygen.

Detailed results and conclusions are as follows:

1) At temperatures above 600°C, chlorine in chlorinated plastics is converted principally to hydrogen chloride with only a trace of phosgene. Chlorine in plywood plastic veneers (a polyvinyl chloride plastic) also converts mainly to hydrogen chloride. When plywood backing is involved in the combustion, the oxygen concentration may fall to a low level and lead to a hazardous carbon monoxide concentration.

2) The main toxic combustion product of phenolic and melamine resins combined with fillers is carbon monoxide. Only small and tolerable concentrations of hydrogen cyanide and ammonia are found.

3) The effect of expanding agents used in plastic foams is small. The major decomposition product of toxicological significance is hydrogen chloride. Small concentrations of very toxic methyl succinonitrile are also present.

4) Combustion in air of wood and rubber produces mainly carbon monoxide and carbon dioxide. Pyrolysis of rubber in nitrogen yields 3.5 per cent hydrogen sulfide and up to 3.4 per cent sulfur dioxide. Silk and wool heated in air produce quantities of hydrogen cyanide and ammonia in addition to carbon monoxide and carbon dioxide.

5) Combustion gases in burning structures that are composed of timber and fiber insulating board vary, depending upon prevailing conditions. The major hazards are carbon monoxide and deficiency of oxygen.

6) Combustion products from halogen compounds used as vaporizing liquid fire-extinguishing agents depend mainly upon the rate of application to the fire, the size of the fire, and size of the compartment in which they are used. The principal products are hydrogen halides, occasionally small amounts of free halogens, and only rarely, traces of carbonyl chloride. The principal toxic constituent in the fuel plus fire-extinguishing agent is carbon monoxide from the combustion of fuel itself.

Subject Headings: *Plastics, combustion products of.*

J. M. Singer

III. Heat and Material Transfer

Bevans, J. T. (Shell Development Company, Emeryville, California) **and Dunkle, R. V.** (University of California, Berkeley, California) "Radiant Interchange within an Enclosure," *Journal of Heat Transfer* (*ASME Transactions Series C*) 82, 1–19 (1960)

The authors have accomplished a rather monumental task by discussing in unusual detail the problem of heat exchange in an enclosure which may or may not be filled with a gas. The paper is divided into three parts—"Absorption and Emission Behavior of Gases," "General Interchange Equations," and "A Method for Solving Multinode Networks and a Comparison of the Band Energy and Gray Radiation Approximations." The entire work is analytical in nature.

In the first part attention is directed to the radiation characteristics of typical gases. The fact that the spectra of gases consists essentially of individual lines and bands is stressed, and use is made of this property in formulating expressions for the absorptivity of individual bands or lines. The formulations are made in a way which makes them most suitable for later computational processes. The expressions are then discussed in the light of limited amount of experimental data. From this discussion it is concluded that the absorption of a band does not follow the normal exponential law (Beer's law). The band absorption seems to be represented more closely by a function which depends on either the square root or the logarithm of the optical "thickness," depending on the value of the absorption. Many references are made to previous work, in particular to that of Elsaesser, Goody, Goodman, Howard, Penner, and Hottel.

In the second part of the paper the authors develop the analytical expressions which are required to solve problems involving radiative interchange within an enclosure. The general approach is based on the net work analogy method which has been developed by Oppenheim. At first a very general set of equations is developed which leaves all radiation coefficients and fluxes as arbitrary functions of the frequencies. Next the equations are modified and certain allowable assumptions are made for the case in which the absorbing medium inside the enclosure is a gas which radiates and absorbs within definite frequency bands. The method of solution corresponding to these equations is termed the "band energy" method. In this modification the previously defined absorptivity coefficients are introduced. As a further simplification the equations are rewritten for the case of "gray" surfaces and substances, i.e. the case in which radiation coefficients are independent of the frequency. The authors stress the fact that the applicability of the band energy method is still very restricted since the experimental information on radiation characteristics of gases and surfaces is generally insufficient for usual engineering applications.

The final part of the paper is concerned with actual computations. At first a reiterative method of solution suitable for the type of equations which have been developed in the previous part is outlined. The method of solution is illustrated by means of an example in which the radiative heat transfer between two opposing sides of a cubical enclosure is computed. All surfaces are assumed to be "gray" and no absorbing medium is considered. The remaining sides of the cube are assumed to be "refractory" walls, i.e. they are assumed to have no net heat transfer. Each side is subdivided into four strips, thereby approximating the temperature variation in the refractory walls. Having illustrated the mathematical method of computation, the authors proceed to an example which is designed to point out the differences between the "band energy" approximation and the "gray" radiation assumption. In this example the exchange between two infinite plates was considered neglecting again the presence of any absorbing medium between the plates. The "band energy" concept was, therefore, applied by simply splitting the radiation into reasonable frequency intervals. Two separate cases were computed. In both, the high temperature plate was made of titanium but the low temperature plate was considered to be alternately of titanium and aluminum. The results were compared with those previously obtained by Goodman, who took the exact radiation characteristics of the surface into account. A comparison shows that the "band energy" approximation leads to values of the heat transfer rate which differ only by about 1 to 2 per cent from the exact solution. The "gray" surface assumption on the other hand leads to differences of about 30 per cent and it is above the exact value in the one case and below in the other. As a final example, the heat transfer between two titanium plates is considered with carbon dioxide as the absorbing medium between the plates. Here the heat exchange rate between the surface and the gas, computed on the basis of "gray" substances, exceeds that obtained on the basis of the "band energy" method by about 63 per cent.

With this paper the authors have provided a very thorough review of the basic problems involved in computing the radiative heat transfer in an enclosure containing a gas. Use is made of previous experimental and analytical work and a new computational approach is suggested and illustrated. The use of proper energy "bands" does, of course, improve the accuracy over that obtained from the "gray" radiation assumption. The computational difficulties are, however, correspondingly much higher and, as the authors point out, the data required for such a more exact evaluation are generally not available. Even with the methods proposed, therefore, the accurate computation of radiant heat transfer for typical engineering remains a formidable and tedious problem. It might also be mentioned that the authors emphasize that the proposed procedures are restricted to diffuse radiation. Most of the analytical work in the field is based on this assumption. Nevertheless, many engineering problems do involve surfaces which definitely do not reflect diffusely. The study of problems of this kind should be of great interest in future investigations.

At the 4th National Heat Transfer Conference held in August 1960, the authors received an honorary award for their paper.

Subject Headings: *Radiation, interchange within an enclosure; Gases, absorption and emissive behavior of.*

R. H. Sabersky

IV. Diffusion Flames

Kingman, F. E. T., Coleman, E. H., and Rasbash, D. J. (Joint Fire Research Organization, Boreham Wood, England) "The Products of Combustion in Burning Buildings," *Journal of Applied Chemistry* 3, 463–468 (1953)

The chance of escape of the occupants of those rooms in a burning building which are not immediately affected by the fire, depends on the rate of deterioration of the atmosphere in these rooms and the effect of smoke on visibility.

During trials of the effect of various wall linings on the rate of destruction, two full-scale houses were burnt out. Gas samples were taken by suction through a pipe from two first floor bedrooms, one with a door open, one with a door closed, all other internal doors in the house being open. The fire was started in the ground floor living room by the ignition of 8 lbs. of wood shavings simulating the upholstery of an easy chair. The position of other furniture and fittings is shown. The two houses were identical in shape and contents except that House No. 1 was lined with fiber insulating board only and House No. 2 was lined with fiber insulating board covered with a ⅜ in. layer of plaster board.

Measurements of smoke density were made by recording the decrease in response of an illuminated photoelectric cell due to the presence of smoke in the light path from the source of illumination. Methods are described for construction and calibration and the relationship between smoke density and mass concentration and between smoke density and visibility is discussed. Gas analysis of the atmosphere in the rooms was made on samples taken through the tubes by the Bone and Wheeler method. Oxygen, carbon dioxide, carbon monoxide, hydrogen, saturated and unsaturated hydrocarbon concentrations were determined at three minute intervals after the start of the fire. Complete tables of results are presented.

In House No. 1, flashover took place after 4 minutes and in House No. 2, after 23 minutes. In House No. 1, in the bedroom with the door closed, the oxygen content decreased after 6 to 9 minutes to 15 per cent and then fell rapidly to less than 2 per cent. In the same room, with the door open, the change was more rapid. The decrease in oxygen was accompanied by a corresponding increase in carbon dioxide but towards the end of the fire the carbon dioxide content decreased and increasing amounts of carbon monoxide, hydrogen, and hydrocarbons appeared. This corresponds to the composition of gases changing from primary products of combustion to the products of destructive distillation and incomplete combustion due to lack of oxygen. The results in House No. 2. were similar but on a longer time scale, the products of combustion in the atmosphere were correspondingly smaller and the oxygen content did not fall below 15 per cent until after 30 minutes had elapsed. Structural collapse gave a sudden change in composition. It would appear that the danger point in all cases was reached when the oxygen content had fallen to such a low value that the occupants would have been asphyxiated. Before this stage was reached the carbon monoxide content, though sufficiently high to have unpleasant effects, did not reach the lethal limit of exposure.

The development of smoke was recorded and a table is presented showing the amount of smoke against time under the various conditions. House No. 1 became smoke-logged after about 5 minutes, the closed door holding back the smoke a further 5 minutes. In House No. 2, the room with the door open was smoke-logged in 10 minutes and the room with closed door after 23 minutes. Thus, a noncombustible lining would give the occupants an extra 15 to 20 minutes for escape, especially if the door was closed.

It is suggested that laboratory experiments on thermal decomposition and combustion of cellulosic materials under controlled conditions do not provide information as to the changes in atmosphere which can be expected in the early stages of a fire in those parts of the house remote from the fire, whereas the safety and possibility of escape of the occupants may depend on these changes.

Subject Headings: ***Fires, products of combustion in.***

G. L. Isles

Klein, H. A. (Wright Air Development Center, Wright-Patterson Air Force Base, Ohio) "The Effects of Cabin Atmospheres on Combustion of Some Flammable Aircraft Materials," *Wright Air Development Center Technical Report 59–456* (April 1960)

The effects of varying atmospheric conditions on the combustion of some flammable materials that create fire hazards in aircraft were studied. In a test chamber, Klein used oxygen, oxygen-nitrogen, and oxygen-helium mixtures in various proportions.

Cabin pressures were varied from sea level to 25,000 feet altitude. Cotton cloth, aircraft electrical wire and jet fuel, hydraulic fluid, and lubricating oils were tested.

Results with the cotton cloth in an atmosphere of oxygen and nitrogen indicate that the burning time decreases as the proportion of oxygen in the atmosphere increases regardless of the partial pressure of nitrogen. Similar results were obtained with oxygen-helium mixtures. Thus, from the fire standpoint, no beneficial effect is obtained by using helium instead of nitrogen.

Minimum burning currents were obtained for three basic types of wire insulation. This current level reached a fairly constant value for polyvinyl-chloride insulation when nitrogen was added, thereby indicating that fires can be prevented with suitable atmospheres. Klein found that no practical atmospheric composition will prevent wires that are insulated with silicone rubber, glass, and Dacron braid from burning.

When sufficient oxygen existed in the atmosphere for a current-carrying wire to burn, the flame spread to adjacent wiring lying either perpendicular or parallel to the burning wire.

Drops of test fluids were dripped on a heated plate to determine ignition temperatures. They varied widely for hydraulic fluids. The ignition temperatures of all fluids increased as the cabin pressure decreased whether the atmosphere is pure oxygen or a normal air mixture.

Spontaneous ignition temperatures determined by the Bureau of Mines[1] are much lower than Klein's values, probably because of the great difference in test conditions. Ignition temperatures in pure oxygen are generally higher than in an oxygen-nitrogen mixture having an equivalent partial pressure of oxygen.

Klein concluded that using the minimum oxygen content with the maximum inert gas content provides an optimum atmosphere for a space vehicle insofar as reducing fire hazards.

Reference

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Subject Headings: ***Flammability, of aircraft materials.***

L. E. Bollinger

V. Combustion Principles

Calcote, H. F. (AeroChem Research Laboratories, Inc., Princeton, New Jersey) "Ion Production and Removal in Flames," *AeroChem Research Laboratories Technical Publication No. 15* (March 1960)

This is the latest in a series of papers by Calcote dealing with ionization processes in flames. Previous papers have dealt with electrical properties of flames,[1] relaxation processes in plasmas,[2] and a critical review of the possible mechanisms for the formation of ions in flames.[3] The present paper is an attempt to formulate several possible mechanisms capable of accounting for ion formation and removal in flames which are consistent with the known facts. In the mechanisms proposed, chemi-ionization, charge exchange, dissociative recombination, and ambipolar diffusion are involved.

Using a Langmuir probe technique, the author has obtained ion profiles through a number of flames at various pressures. Results indicate the mol fraction of ions in a flame is independent of pressure and that the maximum ion concentration occurs near the rear (downstream) edge of the luminous zone. At this point the fuel has been consumed, the H_2O and O_2 concentrations have leveled off, and intermediates such as OCH_2, H_2, and CH_4 have essentially decayed to their final value. The recombination coefficient, obtained from the decay of ion concentration behind the flame front was of the order of 10^{-7} cc/sec and was also found to be independent of pressure, indicating that recombination is occurring by a dissociative process. At pressures below 66 mm. Hg., it was found necessary to make corrections for ambipolar diffusion. From the rate of recombination and the measured ion concentrations, the rate of ion formation was determined and found to be very nearly proportional to the pressure squared.

The above information is interpreted in terms of a chemi-ionization process, that is, one in which the energy of an elementary exothermic chemical reaction leaves one of the products in an ionized state. Calcote has previously shown such processes are quite possible in flames. Therefore the problem of explaining the mechanism of ion formation in flames is essentially one of finding a series of elementary reaction steps which lead to ionization and which are consistent with known experimental facts. In writing such equations the author has assumed that the ion producing reaction should be exothermic and that the reactants should be simple species which are known to be present in hydrocarbon-air flames. Recently the H_3O^+ ion has been identified [4,5] by means of a mass spectrometer as the most prominent ion in hydrocarbon-air flames. The appearance of H_3O^+ as the dominant ion at first appeared mysterious because no elementary reactions could be written down which might be expected to produce it from neutral species. However, because water is present in large concentrations, it turns out not to be difficult to write down reasonable reactions for its formation once another ion has been produced. With this in mind, Calcote has written down a number of possible mechanisms capable of producing such an ion. For example, the CHO^+ ion has been positively identified in hydrocarbon-air flames. Once this ion has been formed, it is a simple matter to form H_3O^+ by the ion-molecule charge exchange reaction:

$$CHO^+ + H_2O \rightarrow CO + H_3O^+$$

Other ions such as CH^+, CHO_2^+, $C_2O_2H^+$, OH^+, and CO^+ are also shown to be capable of producing the H_3O^+ ion in sufficient quantity by charge exchange. Calculations show, in the case of CHO^+, an initial ion concentration of only 10^7 ions/cc may account for the observed ionization in flames if we assume charge exchange takes place. The half-life of such an ion is very short, approximately 10^{-7} sec., and so identification may be difficult. The H_3O^+ ion, once formed, would then disappear by dissociative recombination.

$$\begin{aligned} H_3O^+ + e &\rightarrow H_2O + H \\ &\rightarrow OH + 2H \qquad \text{etc.} \end{aligned}$$

The author has presented an excellent and logical picture, consistent with known facts, for the mechanism of ion formation and removal in flames. Further verification will have to await additional mass spectrometric data.

References

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3. Calcote, H. F. "Mechanisms for Formation of Ions in Flames," *Combustion and Flame 1,* 385–403 (1957)
4. Deckers, J. and van Tiggelen, A. "Ion Identification in Flames," *Seventh Symposium* (*International*) *on Combustion,* London: Butterworths Scientific Publications 254–255 (1959)
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Subject Headings: ***Ions, formation and removal in flame; Flame, ions in.***

I. R. King

Fire Research 1958. *Report of the Fire Research Board with the Report of the Director of Fire Research. Section IV. Detection, Extinction, and Inhibition of Fire and Study of Explosions, pp. 18–30* (Department of Scientific and Industrial Research and Fire Offices' Committee, London, England)

Detection

A draft of a new British Standard has been prepared in which methods are described for test of heat-sensitive detectors. Current work involves studies of detector spacing under ribbed or otherwise nonplane ceilings. Some work has shown that ceilings of clerestory roofs tend to collect hot gases near the peak and greater spacing may be used with maintenance of prompt response.

Extinction

Studies have been conducted with high and low pressure water sprays for extinction of fires in rooms. With water flow rates between 5 and 25 gal/min at pressures of 80–500 psi, it was found that between 4 and 9½ gal water/1000 ft³ room volume were required for both control and extinction of fires. The results showed little effect of nozzle pressure or flow rate on the amount of water required for control and extinction. It was concluded that the most effective means of attack was achieved by initial control with a spray and then extinguishment of the residue with a stream.

Studies of the percolation rate (seepage through walls) of unlined hoses have shown that the increase in this rate during subsequent pressurizations may be considered as a function of the initial percolation rate.

Investigations have been continued on the effect of foam fluidity and its effectiveness in controlling a petrol fire. In these studies the shear stress of the branchpipe foam applied at the rate of 0.1 gal/min was varied from 95 to 400 dyn/cm^2 (1 to 10 per cent foam liquid). It was found under these test conditions that foams with shear stress in the range of 130 to 170 dyn/cm^2 (2 to 3 per cent) were most rapid and economical in their extinction capabilities.

Tests of foam on simulated aircraft crash fuel fires of 100 ft.^{2} area were completed. The foams used exhibited shear stress values of 300 and 1000 dyn/cm^2 and were applied under two different application rates. The results of these tests are still under study.

Further investigations have been made on the base injection of foam for control of fuel storage tank fires. A tank of 50 ft. diameter and 30 ft. high was used. A variety of application rates, as well as a different number of injection points were used. The foam developed by an in-line generator was produced by the method developed at the station.[1] A centrifugal pump was used for injection purposes. The results are in process of analysis.

Studies of dry powder extinguishing agents have involved investigation of the effectiveness of free flow and hydrophobic additives. Tests were made by forming pellets of the dry powders exposing them to high humidity atmospheres and determining their crushing strengths. Powders coated with metallic stearates exhibited lower crushing strengths than uncoated powders or powders containing unsatisfactory fluidizing additives.

Further studies of dry powders have been concerned with the problem of their compatibility with foams. A test method was described in which the drainage rate of a foam was measured after being forced to flow through petrol containing the powder under study. Five powders have been tested in this way with two types of protein foams, each produced at two shear stress values.

Studies of a mixture of difluorochlorobromomethane (CF_2ClBr) and 25 per cent difluorobromomethane (CF_2Br_2) as an extinguishing agent were made. It was applied to an 18 in. diameter petrol fire. The results show that the mixture was somewhat superior to chlorobromomethane and thus is likely to be useful as an extinguishing agent.

Progress is reported in assembly of special jet engine with after burner and water spray injection equipment. This is planned to provide inert gas (about 8 per cent oxygen content) at the rate of 50,000 ft^3/min for the purpose of inerting the atmosphere within burning enclosures. Small-scale tests of this method for control of building fires are reported.

Inhibition

Brief mention is made of fundamental research underway at Oxford on the combustion process and its inhibition. The rate-pressure relationship for a variety of gases has been explored. A critical pressure of reactants has been observed above which the reaction may be greatly accelerated to explosion by change of reactant concentration while below this pressure no such violent reaction may occur.

Studies were conducted on the effect of various halogenated hydrocarbons on the induction period of gaseous reactions. Most of the materials of this type tested showed no effect.

Changes in surface to volume ratios of reaction vessels were made to explore the effect on induction period and reaction rate. It was found that the former was increased and the latter decreased.

Studies are also underway on the effects of alkali halides in the form of surface coatings on reaction vessel walls on the form of reaction. No definite conclusions were reported.

Explosions

Work is also under way at Oxford to shed light on the transition of a gaseous detonation reaction into deflagration. Hydrogen-oxygen mixtures are being burned in horizontal tubes in which a light membrane is used to separate two different gaseous mixtures.

Further studies of work to clarify the action of wire gauzes in quenching flame reactions are reported. Perforated metal plates have been used in these studies. It was found that, provided the perforation diameter was less than the quenching size, the velocity of flame that could be quenched increased in proportion to the thickness of the arrester. A similar effect was not observed with wire gauze.

Work at Buxton (Safety in Mines Research Establishment) has continued on testing of industrial dusts. Research is also under way on studies of flame propagation in dusts. A review of technical literature on dust explosions is in process of preparation.

Investigations of methods for venting gas explosions in long galleries or ducts was reported. It is shown that limitation of reaction pressures is most effectively achieved when vents can be located near the source of ignition. It is emphasized that venting of the burning or burned gas is preferable to attempts to vent unburned gas ahead of the flame front. The effects of bends or T connections in creating turbulence and increasing burning velocities is reported.

Reference

1. FIRE RESEARCH 1954. *Report of the Fire Research Board with the Report of the Director of Fire Research, pp. 17–18* (Department of Scientific and Industrial Research and Fire Offices' Committee, London, England)

A. F. Robertson

Dalmai, G. (Laboratoire de Chimie generale. Faculté des Sciences de l'Université de Paris, France) "A Contribution to the Study of Flame Propagation in Closed Tubes," *Revue de l'Institut Français du Pétrole* XIII 1683–1724 (1958)

This paper reports a study of flame propagation in closed tubes at minimum flame propagating pressures. The study is concerned primarily with the phenomena observed in vertical combustion tubes, closed at both ends, and provided with an ignition system giving a series of spark discharges (as opposed to an ignition system wherein a single spark discharge is used to initiate the combustion reaction). In such a system, at reduced pressures and under certain other specific conditions, two flammable concentration ranges were observed. The range comprising the leaner of the fuel mixtures is termed the first domain of combustion, and in this first range, ignition may be effected by a single spark discharge or by a series of spark discharges. The range comprising the richer fuel mixtures is termed the second domain, and was observed only when the series spark discharges were used to initiate the combustion reaction. In horizontal combustion tubes, the second domain of flame propagation was not observed. In the vertical tube system studied, for a given fuel concentration within the over-all limits for flame propagation, a minimum system pressure may be determined, permitting propagation of a flame throughout the entire tube length. At lower pressures, a flame front progressed only a fraction of the tube length. Using data obtained under certain spectific conditions of fuel type, tube diameter, and tube length, a plot of system pressure (i.e. minimum value permitting propagation of flame the entire tube length) as a function of the fuel concentration indicated a peak value at an intermediate fuel concentration, between rich and lean values. This peak value for the system minimum flame propagating pressures marks the transition from the first to the second domain of combustion. It follows that determination of the system's flammable limits at a pressure less than this peak value will yield two isolated ranges of flammability, one corresponding to the first domain, and the other to the second domain of combustion.

The experimental approach embodied the basic elements of classical flammability limit determinations. As fuel components of the combustion systems, butane, propane, and methane were used. As the oxidizing atmosphere, either air or nitrogen monoxide was used.

It was shown that the phenomenon of the minimum flame propagating pressure peak was dependent on tube diameter, tube length, and type of fuel. The investigation of these variables was carried out to great length, and included a statistical analysis to evaluate the significance of each of the variables. The most dominant variable was shown to be the diameter of the tube for a given fuel system. Tube length and the distance between the igniting electrodes were shown to influence significantly the minimum flame propagating pressures.

The author compares the results of his study with those of other investigators. Over 70 references are cited.

Concerning the characteristics of the systems studied, the following observation was presented: "In our experiments, taking place in tubes closed at the two extremities, the propagation of flame was not uniform, and was related to the flow of hot gases behind the flame front, which could vary depending on the tube length. The propagation was characterized in general by a strong initial acceleration, followed by acoustical or nonacoustical vibrations, and then by uniform movement." The author presented the opinion that the vibrations cited above, whether caused by flame front ocillations or tube harmonics, were responsible for flame extinctions at the critical concentration ranges, at pressures below the system peak minimum flame propagating pressure.

In one series of experiments it was shown that by placing a 20 liter dampening chamber filled with nitrogen, at the igniting electrode end of the flame tube, and diaphragming the portal between the tube and the dampening chamber, the flame ocillations were reduced, and the pressure "peak" was suppressed. It was demonstrated that the energy required for ignition, and the ignition temperature varied inversely with the system pressure. The influence of the tube wall surface was investigated. Surfaces investigated included: new pyrex glass surface; HF washed pyrex surface; calcium carbonate coated surface; PbO coated pyrex surface; colloidal Pt coated pyrex surface.

Only a weak correlation of flammable limits with tube wall surface was observed. The author proposed that active species diffusing to the tube wall and undergoing some change, would not return to the reaction zone, but rather to the reacted gas zone, since in the diffusion time the flame front would have propagated ahead of the diffusing particles. Also the loss of active species at the tube wall was considered to be of minor effect (at least in tubes of diameter appreciably greater than the system quenching distance).

A discussion of the experimental results obtained, and probable reactions, involving gas compositions of the preflame, reaction, flame-wall, and reacted gas zones of the combustion wave, was presented. Analyses were reported of the reacted gas composition as a function of the initial fuel concentrations. Product gas concentrations reported were those of residual, unburned fuel, products of fuel pyrolysis, carbon dioxide, carbon monoxide, and hydrogen peroxide.

In essence, the author attributed the appearance of a peak minimum flame propagating pressure in systems with repeated spark discharges and the second domain of combustion to a diffusion effect where, in the richer mixtures, active centers preferentially diffused from the spark discharge in waves corresponding to the series frequency, until the concentration of propagating centers or species was sufficient to establish a sustained reaction chain, leading to anisotropic flame propagation. It was noted that in the fuel concentration range corresponding to the second domain of combustion, the velocity of propagation following ignition was constant, whereas, in the first domain, ignition was followed by rapid acceleration of the flame front. It was rationalized that the first of a series of spark discharges, or a single discharge, generated a sufficient number of active centers to establish the reaction chain in the first domain of combustion.

No precise remarks were made concerning the stability of the active centers with respect to diffusion times in the electrode space. Other observed effects in the study were cited to support the author's analysis.

Subject Headings: *Flame, propagation in closed tubes.*

J. E. Malcolm

Wicke, E. and Vortmeyer, D. (Institute for Physical Chemistry, University of Hamburg, Germany) "Combustion Zones for Heterogeneous Reactions in Granular Beds through Which a Gas is Flowing," *Zeitschrift für Elektrochemie* 63, 145–152 (1959)

A theoretical analysis is presented in which the conditions are analyzed for the existence of steep temperature gradients within a porous solid as a result of exothermic heterogeneous reactions under steady-state conditions. Analogous to the thermal theory of flame propagation of a combustible, premixed gas an ignition temperature is introduced at which point the rate of heat generation exceeds the rate of heat loss by conduction and convection. However, in the present case the rate of heat generation is governed by heterogeneous reaction of the gas with the solid. Consequently, the combustion zone is a function of the heat of reaction, the energy of activation for chemical reaction, the temperature of the solid, the gas velocity and concentration of the gaseous reactant. For the one-dimensional case as a result of the interplay between heat flow along the temperature gradient and the gas flow, the ignition zone may move in either direction relative to that of the gas. The theoretical analysis is based on several assumptions, such as (1) the simple kinetics of an unimolecular reaction without a volume change (concentration terms are used throughout rather than weight or mole fractions), (2) the absence of temperature gradients within the particles comprising the granular bed, (3) the absence of mass diffusion and energy transfer in the region preceding the ignition zone, (4) uniform distribution of particles in the granular bed, and (5) the existence of an ignition temperature. As is to be expected, the application of a model involving an ignition temperature is not completely satisfactory, since the value of this ignition temperature cannot be deduced from a priori consideration.

Experimentally, the formation and location of the ignition zones were examined in granular beds of activated charcoal (average particle diameter of 0.4 cm.) through which mixtures containing 5 to 11 per cent O_2 (in N_2) were passed at various gas velocities and temperatures. The carbon particles were packed inside a quartz tube surrounded by a special furnace so arranged as to minimize heat loss to the outside and to approach "adiabatic conditions." In order to reduce the complication resulting from partial depletion of solid reactant, the extent of reaction during an experiment never exceeded 20 per cent. Also, in conformity with the theoretical model the gaseous reactant (O_2) was completely consumed by suitable design of the apparatus. In general the experimental results confirm the behavior of the system as predicted by the theoretical model. Specifically, the rate of change in the location of the ignition zone as a function of gas velocity, gas temperature, and gaseous reactant concentration leads to quantitative relationships which permit an estimate of the thickness of the reaction zone. This thickness is found to be a function of the Reynolds number and the particle diameter of the granule. The paper is not concerned with the problem of the establishment of the ignition zone (i.e. ignition), but with the steady-state properties of such a zone present in a granular bed undergoing exothermic, heterogeneous reaction.

Subject Headings: ***Combustion, through granular beds.***

H. Wise

VI. Radiation

Stull, V. R. and Plass, G. N. (Aeronutronic, a Division of Ford Motor Company, Newport Beach, California) "Emissivity of Dispersed Carbon Particles," *Journal of the Optical Society of America* **50**, 121–129 (1960)

Using the Mie theory of scattering, the absorption and scattering cross sections can be calculated for spherical particles in an infinite, homogeneous, nonconducting medium if the wave length, particle radius, and propagation constants for the particle and medium are specified. Temperatures to be expected in flames establish the wave length of the peak of the black body curve and, hence, the wave lengths of interest. Radii of carbon particles in flames have been reported in the range 50 to 1000 Å. The propagation constant for the medium is well known. Only the optical properties (electrical conductivity and dielectric constant) of the particle are needed to permit calculation of the cross sections. Using the model of a classical damped harmonic oscillator for the bound electrons and the same differential equation with restoring force equal to zero for the free electrons, the conductivity and dielectric constant are determined in terms of the number of oscillators per atom, the natural frequency, and the damping constant. Values for these three parameters can be extracted from the literature.

The intensity of radiation, watts/(steradian)(area)(sec^{-1}), from the flame due to carbon particles can be expressed in terms of the cross sections previously calculated, the particle size distribution, and particle number density. Radiation from the particles in an element of volume within the flame is attenuated by absorption and scattering. Formulas for first and higher order scattering assuming isotropic scattering are given.

Graphs of the total and scattering cross section, σ_t and σ_s, are presented as a function of wave length in the range 0.4 to 20 microns for carbon spheres with radii 159, 446, 700, and 987 Å. For the longer wave lengths σ_s/σ_t is much less than unity; for this case scattering is negligible. Emissivity as a function of wave length with the number of particles in the emitting column as a parameter is plotted for particles of uniform radii equal to 50, 200, 500, or 800 Å. Similar graphs are given for typical particle size distributions.

If the known information is the intensity of radiation, the curves can be used to estimate the number and size of carbon particles. The procedure can be inverted to estimate the intensity of radiation given the particle information. As a rule of thumb, if the particle radii are approximately 200 Å, the intensity will be essentially black body if there are more than about 10^{14} particles in a column of emitters with a cross section of one square centimeter. If there are fewer than 10^{11} particles, the emissivity is less than about 0.1 over most of the spectrum.

Experimentally, it has been observed that the peak of the intensity-wavelength curve occurs at a shorter wave length than the peak of the black body curve for a temperature equal to the flame temperature. The results of the analysis presented in the paper agree with this experimental fact. A curve of emissivity as a function of wave length has a negative slope. Taking the product of the emissivity and the black body curve shifts the peak to shorter wave lengths.

Subject Headings: *Carbon, emissivity of particles; Emissivity, of carbon particles; Radiation, from carbon particles.*

A. E. Fuhs

VII. Suppression of Combustion

Penner, S. S. (California Institute of Technology, Pasadena, California) **and Mullins, B. P.** (National Gas Turbine Establishment, Farnborough, Hants, England) *Explosions, Detonations, Flammability and Ignition,* Chapters XVI and XVII. New York: Pergamon Press (1959)

Chapter XVI—Explosion Prevention by Addition of Water and/or Air

This chapter is devoted to a consideration of the prevention of explosions in aero-engine test installations by the addition of water and/or air. Kerosene-air was taken as a model of the hydrocarbons likely to be involved and the empirical lean limit of 55 per cent of stoichiometric, leading to a limit flame temperature of 1590°K, was chosen as a general lean limit.

The authors then proceed to derive mathematical expressions for flow rates of water and air necessary to reduce the flame temperatures of rich, lean, and stoichiometric mixtures below the limit temperature and also the flow rates necessary to reduce the burned gas temperatures to any given value. Examples are given which illustrate the application of these expressions.

A system wherein part of the fuel is first burned, water is sprayed in and vaporized, and a heat exchanger is then incorporated into the gas stream is also considered and curves are constructed which allow the solution of problems involved with this type of system. Cases at and below atmospheric pressure are considered.

The extinction of flames by water alone is also discussed and the experiments of Billet on the effect of droplet size in monodisperse water mists on the extinction of butane-air flames are summarized.

Heterodisperse sprays are considered in some detail and the relation between weight mean diameter, Sauter mean diameter and weight median diameter is demonstrated mathematically. The results of Nukiyama and Tanasawa on drop size measurements with a twin-fluid, air-blast atomizer are summarized, including the expression for Sauter mean diameter in terms of the weight flow rates of air and water and the air velocity relative to the liquid. Recent English work on the effect of drop size in sprays on the extinction of liquid fires in open vessels is reviewed and the important factors are pointed out. The chapter closes with a brief discussion of limiting safe fuel-air weight ratios at different initial temperatures and pressures. This is quite simple since the weak limit for hydrocarbon-air mixtures is effectively independent of pressure over the range 0.25 to 12 atm. while, since the limit temperature of 1590°K is too low for dissociation to occur to any appreciable extent, the temperature rise is likewise independent of pressure.

The chapter represents an interesting and clear summary of the factors involved in methods of calculation of the amounts of water and air necessary to prevent explosion in hydrocarbon-air mixtures. The material is of interest mainly to engineers rather than chemists.

Chapter XVII—Explosion Prevention by Other Means

In this chapter there are sections devoted to inert gases, aqueous foams, organic halides, inert dusts, flame arresters, and explosive vents. The chapter is rather brief and the topics are not discussed as comprehensively as those in the preceding chapter. The section on aqueous foams describes the basic action of foams clearly and presents some of the recent British work. The section on organic halides presents a brief account of some of the work in this area; mention of the work of Wolfhard, Wise and Rosser, and others on the chemical aspects of these extinguishing agents would have been desirable here. The section on inert dusts represents a good summary of the present status of this area, although the work of Dolan and Dempster on the effect of particle size of dust on efficiency of extinguishment has unaccountably not been mentioned. The sections on flame arresters and explosive vents contain useful summaries of the recent literature in these areas.

Subject Headings: *Explosions, prevention of; Foam, use of, in explosion prevention; Flame arresters, use of, in explosion prevention; Dusts, use of, in explosion prevention.*

J. B. Levy

Friedrich, M. (Research Division for Technique of Extinguishing Fires, Karlsruhe Polytechnical Institute, Germany) "Extinguishment Action of Powders." *VFDB Zeitschrift, Special Issue No. 2* (January 1960)

The article is a reprint of a Ph.D. Thesis on the subject of combustion inhibition by dry powders (71 references).

After a brief general review of chain-reactions in flames, three mechanisms of powder action were suggested: (1) dilution of the flame zone by gases liberated during thermal decomposition of the powder; (2) cooling of the reaction zone due to the heat capacity of the powder; (3) chemical inhibition due to specific surface effects or liberation of gaseous inhibiting decomposition products.

The objective of this investigation was to determine quantitatively the contributory effect of the three mechanisms under conditions resembling the practical case of inhibition. The extinguishing power of a variety of substances was determined on a test-rig in the following manner: In one series (I) a mound of 44 μ particles was thrown quickly onto a "standard" diffusion flame (5 cm. high, 1.7 cm. wide) of hydrogen, illuminating gas, or carbon monoxide. In a second series (II) a screen was added which dispersed the powdered material, creating an improved dust cloud. Preliminary experiments showed that the extinguishing power increased as particle size decreased. However, below 44μ satisfactory dust clouds could not be achieved with the dispersing device under investigation. The minimum weight of powder to just quench the flame was determined.

As shown in Table 1, the hottest (H_2) flame could be extinguished by only a few substances, while more substances and a smaller weight were effective with illuminating gas and CO. The formation of a good dust cloud increased the effectiveness of the materials considerably. Extinguishment increased from ammonium to cesium compounds. The most effective anion was oxalate, containing water of crystallization.

By weighing the powder after traversing the flame, the amount of thermal decomposition to gaseous products was determined. As shown in Table 2, the decomposition was negligible in nearly all cases. Thus, the mechanism of quenching by dilution with inert gases is unlikely. The decrease in oxygen content, due to the presence of solid particles, can be considered to be of secondary importance since it does not explain the observed differences in extinguishing power among the various solids. It was also shown in a separate experiment that *none* of the powders were able to extinguish a carbon bisulfide diffusion flame.

No relationship could be deduced between heat capacity and extinguishing power of the test substances. For example, the specific heats of sodium chloride and potassium chloride are .27 cal/g°C and .163 cal/g°C, respectively, while the latter is a severalfold more effective extinguishment agent. Also, in simple calorimeter experiments, no significant heat was removed from the flame by the powder.

TABLE 1

MINIMUM QUANTITIES (IN MILLIMOLS) OF VARIOUS SUBSTANCES TO EXTINGUISH HYDROGEN, ILLUMINATING GAS, AND CARBON MONOXIDE DIFFUSION FLAMES

I Clumps
II Powder Cloud

x = no extinguishment with 6 grams or less
xx = marked effect on flame, but no extinguishment
xxx = insufficient amount for establishing a satisfactory cloud

Median Particle Diameter 44μ

Material	Hydrogen		Illuminating Gas		Carbon Monoxide	
	I	II	I	II	I	II
NH_4HCO_3	x	—	—	31.1	30.2	17.2
Li_2CO_3	—	—	—	40.4	35.0	21.5
$NaHCO_3$	—	—	—	38.4	37.2	22.1
Na_2CO_3	—	—	—	26.6	26.2	14.6
$Na_2CO_3+10\ H_2O$	—	—	—	7.8	7.5	4.4
$KHCO_3$	xx	xx	33.0	13.5	17.4	10.0
K_2CO_3	xx	xx	16.6	8.3	8.6	6.8
Rb_2CO_3	xx	xx	9.3	4.8	4.1	2.7
Cs_2CO_3	xx	xx	13.3	7.5	6.6	4.9
$CaCO_3$	—	—	—	—	42.3	33.6
$BaCO_3$	—	—	—	—	40.3	31.8
$SrCO_3$	—	—	—	—	41.8	32.6
NH_4F	—	—	—	—	89.2	70.4
NH_4Cl	—	—	—	—	60.0	46.2
NH_4Br	—	—	—	—	16.8	11.2
NH_4I	—	—	—	23.1	9.8	6.7
LiF	—	—	—	—	139.5	112.5
LiCl	—	—	—	—	89.3	35.0
LiBr	—	—	—	—	44.1	24.7
LiI	—	—	—	—	29.4	71.4
NaF	—	—	—	—	80.2	63.7
NaCl	—	—	—	—	59.4	49.1
NaBr	—	—	—	—	33.9	28.6
NaI	—	—	—	—	23.8	20.2
KF	xx	xx	73.2	34.5	27.4	18.1
KCl	xx	xx	60.0	28.6	24.8	15.3
KBr	—	—	42.8	19.6	15.8	10.7
KI	—	—	33.2	15.3	12.4	9.2
RbCl	xx	xx	27.8	9.4	9.5	7.0
RbBr	—	—	21.4	8.0	7.7	5.4
RbI	—	—	18.0	7.3	6.4	4.6
$NaNO_3$	xx	xx	xx	27.6	22.9	13.3
KNO_3	xx	xx	xx	21.4	11.3	7.9
Na_2SO_4	—	—	—	—	41.9	36.1
$Na_2SO_4+10\ H_2O$	—	—	—	—	14.4	10.3
K_2SO_4	—	—	—	—	40.7	33.5
$KClO_3$	xx	xx	xx	21.2	8.9	6.1
NH_4-Oxalate+H_2O	—	—	—	19.0	21.1	13.0
Li-Oxalate	—	—	—	41.6	36.7	22.8
Na-Oxalate	—	—	—	31.3	26.4	16.0
K-Oxalate+H_2O	1.6	xxx	0.65	xxx	0.48	xxx
K-Oxalate	7.2	4.5	4.9	xxx	2.7	xxx
Rb-Oxalate+H_2O	0.69	xxx	0.28	xxx	0.21	xxx
Rb-Oxalate	2.6	xxx	2.1	xxx	1.3	xxx
Cs-Oxalate+H_2O	3.6	2.1	1.8	xxx	1.5	xxx
Ca-Oxalate	—	—	—	—	39.4	32.5
Ba-Oxalate	—	—	—	—	25.6	22.1
Sr-Oxalate	—	—	—	—	29.3	24.5
K-Oxamate+H_2O	4.1	xxx	1.9	xxx	1.4	xxx
Sand	—	—	—	67.5	70.8	50.0
Fe-II-Oxalate+2 H_2O	—	—	—	—	11.3	6.8
Pb-II-Oxalate	—	—	—	—	6.5	4.0
Tl-II-Oxalate	—	—	—	—	6.6	4.1
K-Tartrate+½ H_2O	—	—	xx	xx	5.3	3.9
Na-Tartrate+2 H_2O	—	—	—	—	16.7	10.0
K-Acetate	—	—	xx	xx	11.0	7.1
Na-Acetate	—	—	—	—	44.7	27.5
$K_4[Fe(CN)_6]+3\ H_2O$	—	—	xx	xx	1.3	xxx
K_2O_4	xx	xx	xx	xx	1.7	xxx
KCN	—	—	—	—	25.3	14.6
NaCN	—	—	—	—	54.0	35.9

TABLE 2

PERCENTAGE DECOMPOSITION OF POWDERS AFTER TRAVERSING HYDROGEN, ILLUMINATING GAS, AND CARBON MONOXIDE FLAMES

I Clumps
II Powder Cloud
Median Particle Diameter 44μ

Material	Hydrogen		Illuminating Gas		Carbon Monoxide	
	I	II	I	II	I	II
NH_4HCO_3	—	—	—	3.1	2.7	2.9
Li_2CO_3	—	—	—	0.015	0	0
$NaHCO_3$	—	—	—	0.49	0.25	0.31
Na_2CO_3	—	—	—	0.035	0	0
$Na_2CO_3+10\ H_2O$	—	—	—	0.95	0.12	0.13
$KHCO_3$	—	—	0.018	0.33	0.014	0.017
K_2CO_3	—	—	0	0.02	0	0
Rb_2CO_3	—	—	0	0.015	0	0
Cs_2CO_3	—	—	0	0.027	0	0
$CaCO_3$	—	—	—	—	0	0
$BaCO_3$	—	—	—	—	0	0
$SrCO_3$	—	—	—	—	0	0
NH_4F	—	—	—	—	0.012	0.018
NH_4Cl	—	—	—	—	0.02	0.024
NH_4Br	—	—	—	—	0.037	0.04
NH_4I	—	—	—	4.20	0.24	0.58
LiF	—	—	—	—	0	0
LiCl	—	—	—	—	0	0
LiBr	—	—	—	—	0	0.02
LiI	—	—	—	—	0	0.13
NaF	—	—	—	—	0	0
NaCl	—	—	—	—	0	0
NaBr	—	—	—	—	0	0.11
NaI	—	—	—	—	0	0.17
KF	—	—	0	0.46	0	0
KCl	—	—	0	0.58	0	0
KBr	—	—	0	0.62	0	0.12
KI	—	—	0	0.68	0	0.21
RbCl	—	—	0	0.73	0	0
RbBr	—	—	0	0.76	0	0.16
RbI	—	—	0	0.82	0	0.24
$NaNO_3$	—	—	—	0.30	0	0.13
KNO_3	—	—	—	0.26	0	0.10
Na_2SO_4	—	—	—	—	0	0
$Na_2SO_4+10\ H_2O$	—	—	—	—	0.05	0.12
K_2SO_4	—	—	—	—	0	0
$KClO_3$	—	—	—	0.31	0	0.12
NH_4-Oxalate+H_2O	—	—	—	5.5	2.5	2.8
Li-Oxalate	—	—	—	0.9	0.3	0.8
Na-Oxalate	—	—	—	2.15	0.9	1.05
K-Oxalate+H_2O	3	—	2.4	—	2.1	—
K-Oxalate	2.2	2.6	2.3	—	1.9	—
Rb-Oxalate+H_2O	3.4	—	2.6	—	2.4	—
Rb-Oxalate	3.0	—	2.5	—	2.2	—
Cs-Oxalate+H_2O	2.4	2.8	1.8	—	1.4	—
Ca-Oxalate	—	—	—	—	0	0.13
Ba-Oxalate	—	—	—	—	0	0.14
Sr-Oxalate	—	—	—	—	0	0.25
K-Oxamate+H_2O	2.7	—	2.1	—	1.8	—
Sand	—	—	—	0	0	0
Fe-II-Oxalate+2 H_2O	—	—	—	—	1.3	1.7
Pb-II-Oxalate	—	—	—	—	1.8	2.1
Tl-II-Oxalate	—	—	—	—	1.9	2.4
K-Tartrate+½ H_2O	—	—	—	—	0.34	0.62
Na-Tartrate+2 H_2O	—	—	—	—	0.21	0.46
K-Acetate	—	—	—	—	0.25	0.52
Na-Acetate	—	—	—	—	0.43	0.74
$K_4[Fe(CN)_6]+3\ H_2O$	—	—	—	—	0.15	—
K_2O_4	—	—	—	—	0	0
KCN	—	—	—	—	0	0
NaCN	—	—	—	—	0	0

To investigate the effectiveness of oxalates, thermal decomposition experiments were carried out in a tube heated at a rate of 3°/min. As shown in Table 3, the residue is carbonate and carbon, while the gas is primarily CO(94–95%) and CO_2 (5–6%).

TABLE 3

THERMAL DECOMPOSITION OF OXALATES

Material	Start of Decomposition °C	Maximum Decomposition °C	Residue
Lithium oxalate	210	555–683	Li_2CO_3 + Soot
Sodium oxalate	248	570–652	Na_2CO_3 + Soot
Potassium oxalate	200	525–617	K_2CO_3 + Soot
Rubidium oxalate	220	610–695	Rb_2CO_3 + Soot
Cesium oxalate	260	635–728	Cs_2CO_3 + Soot

The mode of action of the powders was investigated by determining the peroxide formation in flames in their presence and absence. Qualitative evidence was adduced that peroxide formation was reduced when powders were present, although no quantitative conclusions were reached on this point.

In summary, the results are as follows:

1) The best extinguishing effect is shown by alkali metal compounds, optimizing with cesium compounds containing water of crystallization. Among halogen-containing compounds, iodides are most effective.

2) Cooling by the powder and diluting action from liberated gases are not the important mechanisms for extinguishment.

3) Well-formed crystals are more effective than poorly crystallized material, probably by forming a more uniformly dispersed dust cloud.

4) The electrical conductivity of flames in contact with extinguishing solids is greatly increased. However, no clear-cut relationship between conductivity and extinguishment has been detected.

In an Appendix a number of methods were discussed to specify the physical characteristics of powders, viz., electrostatic charge on powders escaping from a nozzle, particle size, density specific surface, packing density.

Subject Headings: ***Extinguishment, by powders; Powders, flame extinguishment; Flame, extinguishment, by powders.***

W. G. Berl

Thomas, P. H. (Joint Fire Research Organization, Boreham Wood, England) "Use of Water in the Extinction of Large Fires," *Institution of Fire Engineers Quarterly* **19,** 130–132 (1959)

The author presents correlations of experience data for forty-eight unplanned, extinguished fires. The data include the number of hose nozzle streams used, the fire area in square feet, and the time of control in minutes, for fire areas of 2,000 to 600,000 square feet.

Plots of data are included. The approximate functions derived from these correlations are

$$J = 0.1\sqrt{A}$$
$$T_c = \sqrt{A}$$

where J is the number of hose nozzle streams in use at the time of fire control, A is the fire area in square feet, and T_c is the time in minutes from the start of water application to the time of fire control.

It is pointed out that the number of nozzles used in these fires might reflect the operating technique, that is, regular nozzle spacing at the fire perimeter. The data are interpreted to indicate an average spacing of 30 feet. An alternate interpretation concerns the nozzle operator's ability to cover and extinguish a specific area of fire. An average of 17 square feet of fire area per nozzle-minute is estimated. No estimates of nozzle delivery rates are given, but it is stated that estimates of the delivery rates indicated that a considerable excess of water was used. These estimates are based on laboratory scale fire studies. The author observes that this apparent use of water in excess suggests need for study for improving operational techniques in fire fighting.

This work concerns a source of data not frequently exploited. In the absence of experimental determinations of extinguishing requirements for large-scale fires, actual fire-fighting experience, properly documented, can provide significant information.

Subject Headings: ***Water, use in extinction of large fires; Fires, use of water on; Extinguishment, use of water in.***

J. E. Malcolm

Rasbash, D. J. and Stark, G. W. V. (Joint Fire Research Organization, Boreham Wood, England) "Extinction of Running Oil Fires," *The Engineer* **208**, 862–864 (1959)

This reports an experimental study of a specialized type of fire, characteristic of fires in oil coolers, such as are used in cooling electric power transformers, or in turbine driven electric generator cooling and lubricating systems.

The test model consisted of a bank of 21 steel tubes, 7 feet long by 2 inches in diameter, arranged in three rows of seven each at nine inch centers, and suitably reinforced for fire exposure. A thermocouple was located in the center of the bundle (the center tube) in order to determine the configuration temperature. The described tube bundle was mounted in the vertical position for most of the tests, but a few tests were conducted with the bundle mounted horizontally. In either position oil, in most cases transformer oil, at 5.4 to 7.8 gal/min, was distributed evenly over the tubes by a manifold. Some more volatile oils were also used.

Up to 24 nozzles five feet from the test bundle were used to apply water. Seven different nozzle designs were used. The test procedure comprised preheating the bundle by means of a small gasoline fuel fire at the base of the bundle, followed by application of the oil fuel to the tubes. A selected preburn time was allowed prior to the application of water spray to permit attainment of the desired tube temperature. Water spray was applied for 45 seconds while the fuel was kept flowing. Several hundred tests were conducted in the configuration which was located out-of-doors prior to establishing quantitative relationships.

The following observations were made:

1) Nozzles directing water spray into the burning surfaces were more effective than those providing a spray shroud.
2) A large decrease in effectiveness with decrease in nozzle pressure was noted at nozzle pressures less than 50 psig.

3) A basic design value for the water spray rate of application (about 1.45 gal/min/ft²) for extinguishing fires of this type was suggested.

It was pointed out that the type of fire test used was much more severe than that used by the Factory Mutual Laboratories in obtaining the rate value of 0.3 gal/min/ft² previously recommended by the Factory Mutual Laboratories.[1]

4) The water spray rate required for extinguishment increases with increasing tube bundle temperature.
5) At a specific rate of water spray application, the bulk of the effect on the test fire was noted within a few seconds after application of the spray was initiated.
6) Containment, or "control," of the test fires could be obtained at water spray application rates considerably lower than the suggested basic design extinguishing rate.

A reference to a prior publication reporting the experimental details of this investigation is given.[2]

References

1. "Water Spray Protection for Oil-Cooled Transformers," Associated Factory Mutual Fire Insurance Companies. Factory Mutual Laboratories, Norwood, Massachusetts (1954)
2. Rasbash, D. J. and Stark, G. W. V. "Design of Sprays for Protective Installations. Part III. The Extinction of Oil Fires on Banks of Tubes," *Department of Scientific and Industrial Research and Fire Offices' Committee, Joint Fire Research Organization F.R. Note No. 303* (1958)

Subject Headings: ***Fires, oil, extinguishment of; Extinguishment, of oil fires; Fires, extinguishment of oil.***

J. E. Malcolm

Rasbash, D. J. and Stark, G. W. V. (Joint Fire Research Organization, Boreham Wood, England) "Extinction of Fire in Burning Liquids with Water Spray from Hand Lines," *Institution of Fire Engineers Quarterly*

In this paper the authors discuss tests on the extinguishment of transformer oil fires by means of hand line water spray nozzles, and make recommendations on water spray extinguishing techniques derived from test data reported elsewhere.

Test results are given on nozzles having flow rates from 1.7 to 23 gpm (US) at 100 psig nozzle pressure, and yielding spray drop sizes of 0.4 to 1.0 mm. (mass median drop size). The nozzles applied spray to transformer oil fires in tubs 8 feet in diameter. For more than 60 tests, the times of extinguishment in the individual tests were plotted against the number corresponding to the consecutive order of the test. This plot depicted the operator's improvement in technique with the least effective nozzles in the period of the first few tests, after which the time required for extinguishment was noted to be constant within the limits of test reproducibility. On the other hand, the first trial with the most effective nozzle (16.8 gpm flow rate, and 0.4 mm. drop size) yielded essentially the consistently obtained extinction time with that nozzle.

A formula correlating results from this type fire (using an experienced nozzle operator) relates extinction time, fuel fire point, and spray characteristics

$$t = 600{,}000\frac{D^{0.85}}{R^{0.68}T^{1.67}}$$

where

t = extinguishing time (secs.)
D = drop size (mm.)
R = nozzle flow rate (gal/min)
T = fire point of fuel minus the ambient temperature (°C)
(fire point of a fuel is usually 10 to 20°F higher than the flash point)

A critical flow rate below which extinction was not obtained is expressed by

$$R_c = 250\ (D/T)$$

A table gives recommendations on the use of hand line water spray nozzles having 12 gpm delivery rate at 75 psig nozzle pressure for five classes of fuels

high fire point—over 250°F
moderate range fire point—120 to 250°F
low fire point—under 120°F—water immiscible
low fire point—under 120°F—water miscible
low fire point—under 120°F—partially water miscible

In general, water sprays are not recommended for the last three of these except that for water immiscible fuels fine water spray can be used if the hazard of fire reflashing is accepted and fire size limitations are recognized. Extinguishment should not be attempted where the fire diameter exceeds 10 feet and the fuel fire point exceeds 100°F or when the fire point is less than 100°F and the fire diameter exceeds 5 feet.

The possibility and limitations of extinguishing water miscible fuel by water dilution are pointed out. For some such fuels very high dilution ratios are required to accomplish extinction.

Effects of nozzle pressure and practical limitations in nozzle design are considered. Experimental data other than those concerned with transformer oil fires are not given but eight references are cited.

Subject Headings: *Fires, extinguishment by water sprays; Water, sprays, for flame extinguishment; Extinguishment, by water sprays.*

J. E. Malcolm

Young, H. H. (Midwest Research Institute, Kansas City, Missouri) **and Eggleston, L. A.** (U.S. Fire Protection Engineering Service, Inc., Kansas City, Missouri) "Study of Fire Extinguishing Agents and Preventive Techniques for High Energy Fuels," *Wright Air Development Center Technical Report 59–334* (May 1959)

This study constitutes a review of available published information, laboratory screening of extinguishing agents, and an experimental study of the extinguishment problem of open pool fires burning high-energy boron-containing fuels. These fuels possess unusual fire extinguishment difficulties because of their toxic nature, chemical reactivity, wide flammability limits, high heat release, and low ignition temperature.

In the course of performing laboratory screening of extinguishing agents, the authors, to conserve fuel and establish constant intensity fires, developed a pool burning technique employing continuous fuel replenishment. The apparatus consisted of a water bath in which a plate of known open area is supported producing a fire pot within which fuel is admitted and the fuel level maintained during burning. With alkyl pentaborane (HEF-2), they found that neither dry chemicals, water, inert gases, nor conventional mechanical foams were effective in fire extinguishment. Recommended was the use of inert gas foam using nitrogen, carbon dioxide, or automobile exhaust gas at the rate of ¼ gpm/sq ft of burning surface.

With alkyldecaborane (HEF-3) water spray or amine-loaded streams were ineffective, but conventional air foam proved feasible for practical fire extinguishment provided a foam blanket was maintained long enough to prevent spontaneous surface reignition.

Although the hydrolysis effect is one which prevents the water bath fuel replenishment method from being generally acceptable for high-energy fuel fire extinguishment evaluation, the results of these experiments have direct application for aircraft and shipboard operational problems.

Subject Headings: ***High energy fuel, extinguishment of; Extinguishment, of high energy fuels.***

D. Dembrow

Gleim, V. G. and Shelomov, I. K. (Department of Chemistry, Rostov Institute of Railroad Transport Engineers, U.S.S.R.) "The Physical Chemistry of Foams," *Journal of Applied Chemistry, U.S.S.R.* (*in English translation, Consultants Bureau, Inc.*) **32,** 799–805 (1959)

This paper contains the results of a theoretical study of the effects of temperature, pressure, and the physicochemical properties of the system on the strength and average life of foam, and is an extension of previous work by several other Russian authors.

The first part of the paper deals with the rupture of films of pure liquids, the film in question being the wall of a bubble. As such a film is ruptured the foam is destroyed, and the aim of this part of the paper is to derive expressions which give measures of film strength and average foam life for any pure liquid. The rupture of the film is assumed to take place by the formation and growth of a fluctuation bubble in the film. The energy of formation of such a bubble (of radius R) is expressed in the form

$$W=4\pi\int_0^R (\Sigma Pi)R^2dr, \qquad (1)$$

where ΣPi is the resultant pressure in the film. By assuming that the liquid and gas phases are in equilibrium it is shown that

$$\Sigma Pi=\frac{2\sigma}{r}-\lambda, \qquad (2)$$

where σ is the surface tension, and λ the stress in the film due to surface tension. This stress is put equal to $2\sigma/\delta$ where δ is the film thickness, and the integration of equation (1) is carried out, leading to the result

$$W=4\pi\sigma R^2\left(1-\frac{2}{3}\,\frac{R}{\delta}\right). \qquad (3)$$

In performing the integration λ is assumed to be constant $\left(=\frac{2\sigma}{\delta}\right)$ irrespective of the presence of a bubble, or bubbles. Nevertheless, in deriving the condition for spontaneous growth of a fluctuation bubble (which will lead to rupture of the film) the stress in the film is modified to $2\sigma/(\delta-2R)$, the reduced denominator being strictly necessary to allow for the reduction of film thickness due to the formation of a bubble of diameter 2R in it. The condition for spontaneous growth of a bubble is

$$\Sigma Pi<0 \tag{4}$$

or,

$$\frac{2\sigma}{R}<\frac{2\sigma}{\delta-2R}$$

i.e.

$$R>\frac{1}{3}\delta$$

The critical bubble radius is thus $R_{cr}=\frac{1}{3}\delta$.

The minimum energy required to rupture the film is then found by substituting the critical value R_{cr} into equation (3), leading to the result

$$W_{cr}^{L}=0.346\pi\delta^2\sigma. \tag{5}$$

It would appear to the reviewer that in performing the integration of equation (1) one should put $\lambda=2\sigma/(\delta-2R)$ which leads to a modified form of equation (3). The value of R_{cr} remains unchanged, and the corrected value of W_{cr}^{L} will be

$$W_{cr}^{L}=0.234\pi\delta^2\sigma. \tag{6}$$

The authors then assume a relationship between W_{cr}^{L} and the rate of spontaneous bubble formation μ of the form

$$\mu=AVe^{-\frac{W_{cr}^{L}}{kT}}, \tag{7}$$

where V is the film volume, and A is a constant of proportionality. Since the formation of only one bubble of radius in excess of the critical value is enough to rupture the film, μ can be replaced by $1/\tau_{av}$ (where τ_{av} is the average film life), and thus

$$\tau_{av}=\frac{1}{AS\delta}\,e^{\frac{W_{cr}^{L}}{kT}}, \tag{8}$$

where S is the film area.

The second part of the paper consists of an entirely similar analysis for solutions of surface active substances. Due to adsorption processes at the fluctuation bubble surface a modified surface tension is needed in the Laplace pressure term $\left(\frac{2\sigma}{R}\right)$. After considerable analysis it is shown that the requisite surface tension is

$$\sigma_n=\sigma+\phi, \tag{9}$$

where

$$\phi=CG\ln\left(\frac{G\times1000}{RT\beta}\right), \tag{10}$$

C being surface concentration, G surface activity, and β the thickness of the surface layer. Equation (1) is then integrated as before, the form of ΣPi for this case being taken by the authors as

$$\Sigma Pi = \frac{2\sigma_n}{R} - \frac{2\sigma}{\delta}. \tag{11}$$

The integration leads to the result

$$W_{cr}^{S} = \frac{4}{3}\pi\delta^2\psi^3(7\sigma+6\phi), \tag{12}$$

where

$$\psi = \frac{\sigma+\phi}{3\sigma+2\phi}. \tag{13}$$

In arriving at this result the value of R_{cr} is derived from an equation analogous to that used for pure liquids, and is found to be $\delta.\psi$. If the corrected values of surface stress is used [i.e. $2\sigma/(\delta-2R)$] the resultant form of equation (12) is

$$W_{cr}^{S} = \pi\delta^2\left[2\psi(2\sigma+\phi) - \sigma \ln\left(3+2\frac{2\phi}{\sigma}\right)\right]. \tag{14}$$

On the assumption that film thickness is independent of concentration the authors divide expression (12) by expression (5), arriving at the result

$$\frac{W_{cr}^{S}}{W_{cr}^{H_2O}} = 11.57\psi^2\left(1-\frac{2}{3}\psi+\frac{\phi}{\sigma}\right)\frac{\sigma}{\sigma_{H_2O}}. \tag{15}$$

The corrected form of this expression, which is obtained by dividing expression (14) by expression (6), is

$$\frac{W_{cr}^{S}}{W_{cr}^{H_2O}} = 4.27\left[4\left(1+\frac{1}{2}\frac{\phi}{\sigma}\right) - \ln\left(3+2\frac{\phi}{\sigma}\right)\right]\frac{\sigma}{\sigma_{H_2O}}. \tag{16}$$

The value of τ_{av} for the solution case will be found by substituting the correct form of W_{cr}^{S} into equation (8).

The third and final part of the paper consists of a comparison of theoretical results obtained by the authors with experimental results due to other workers. Theoretical values of film strength $\left(W_{cr}^{S}/W_{cr}^{H_2O}\right)$ calculated from equation (15) and experimental values of the logarithm of foam stability ($\log \tau$) are compared graphically for aqueous solutions of n-propyl alcohol, n-butyl alcohol and isoamyl alcohol by plotting each of the variables against the concentration of alcohol in the solution. The reason for plotting $\log \tau$, although not stated by the authors, is that this variable should be proportional to W_{cr}^{S}—see equation (8). In every case the two curves exhibit a similar shape and a similar maximum and the authors state that this agreement indicates the validity of the theoretical analysis. To give an estimate of the discrepancy between equations (15) and (16) the reviewer calculated numerical values for a number of cases under consideration by the authors and found numerical agreement within 5 per cent in all cases. Hence the use of two different forms of the surface stress λ can lead to results which are almost identical. This makes it difficult to see how a comparison of general curve shapes can be used to indicate the validity of the theoretical approach.

The authors also consider the influence of the length of hydrocarbon radical in the foaming agent on the foaming power of its solutions, by plotting the previous two variables against (a) the number of carbon atoms in the alcohol molecule for solutions of homologous alcohols and (b) the number of carbon atoms in the acid molecule for solutions of homologous fatty acids. Once again the curves indicate a similar shape with a fairly sharp peak indicating that film strengths and foam stabilities pass through maximum values with increase in length of the hydrocarbon chain, and then decrease rapidly. The surface activity in the same series of homologs increases continuously. It follows that higher fatty acids and monohydric alcohols which are preferentially adsorbed at interfaces because of their high surface activities lower film strength and thus exert a foam breaking effect. Therefore, substances which have high adsorption potentials and at the same time do not confer any significant strength on the surface films may act as foam breakers.

Subject Headings: *Foam, physical chemistry of.*

R. G. Siddall

VIII. Model Studies and Scaling Laws

Thomas, P. H. (Joint Fire Research Organization, Boreham Wood, England) "Studies of Fires in Buildings Using Models. Part I. Experiments in Ignition and Fires in Rooms," *Research* **13**, 69–77 (1960)

Factors affecting the severity and duration of fires are being studied experimentally in many laboratories; a strong motivation for these studies is the desire to establish a more rational basis for municipal building codes relating to fire prevention.

Experimental study of fires is chiefly carried out on small-scale models and the validity of the modeling must always be demonstrated. The present paper brings together a number of published experimental results on various topics that are important in fires in buildings and discusses the modeling problem in each case.

The first problem considered is that of ignition. Since fires start by ignition of material and since flame spreading may be regarded as a process of continuous ignition of fresh material, the study of ignition has always held a pre-eminent place in fire research. Ignition is a complex process, yet experiments have shown that over a wide range of conditions ignition can be regarded as occurring when the material involved is raised to a certain temperature, the "ignition temperature." Model experiments are valid whenever a constant ignition temperature can be found.

There are regimes for cellulosic materials for which the ignition temperature cannot be regarded as a constant for the material and method of ignition. In fact, very rapid surface heating and very slow heating of the material do not lead to ignition at a constant temperature. A theoretical treatment based on the well established thermal theory is applicable to the latter case and provides a basis for modeling. However, even with this theory as a guide, application of model results to large-scale phenomena must be made with caution since reaction kinetics, radiation, and air flow conditions, etc., may change with scale.

Of great practical interest is research carried out on fires in vented enclosures. The modeling problem is particularly important for these fires since full-scale experimentation on large fires is extremely expensive.

Three phases are usually distinguished in the time history of a fire in an enclosure. At first, when the fire is small, it behaves as though it were in the open. If the fire continues to grow it eventually involves the whole compartment, the final stage of growth frequently being so rapid that it is called "flashover." Subsequently the fire burns for a relatively long time at an approximately steady rate until the supply of fuel is exhausted. During this phase of the fire the temperature in the compartment rises gradually to a maximum and then, in the last stage of development, decays.

Burning in a compartment differs from that in an open fire since the enclosure conserves heat and restricts air supply. The burning rate in an enclosure with small openings is governed by the rate of air flow into the enclosure; air flow rate has been reported to be approximately proportional to $A\sqrt{H}$ where A is the area of the opening and H its height. This air flow parameter proves useful in correlation of model results which show that for very small openings the rate of burning is proportional to air flow rate and increases rapidly with air flow. With further increase in opening size the burning rate increases more slowly and finally approaches a constant value, the value observed for a fire in the open. Under these circumstances, i.e. for well ventilated fires, the burning rate no longer depends upon air supply but does depend upon the surface area of the fuel.

Modeling of fires in enclosures is possible. For small openings the experiments show no marked scale effect; the mean burning rate in all cases corresponds to an air-fuel ratio of about five to one. However, temperature in the enclosure is not modeled exactly but increases slightly with scale.

The rate of burning appears to increase very slightly with increase in fuel surface area; effectively the burning rate is independent of fire load. These results show that for fixed low ventilation conditions the duration of the fire is proportional to the total fire load, not the fire load per unit area. On the other hand, for well ventilated fires the rate of burning (the mass of fuel consumed per unit time) increases with the surface area of the fuel material but does not depend on the air supply. In this case also, modeling at moderate scale will prove successful.

Subject Headings: ***Fires, in buildings, use of models in; Building fires, use of models in study of; Models, study of building fires by means of.***

F. H. Wright

Thomas, P. H. (Joint Fire Research Organization, Boreham Wood, England) "Studies of Fires in Buildings Using Models. Part II. Some Theoretical and Practical Considerations," *Research* **13**, 87–93 (1960)

It has been shown in Part I that for fires with low ventilation, the rate of burning is independent of fire load and for a given degree of ventilation the duration is proportional to the total fire load and not the fire load per unit area. However, if one fire lasts longer than another because of a smaller window, the temperature attained will be lower. This tends to make the severity of the exposure less than the increase in duration would lead one to expect at first sight. If the window openings are large the rate of burning for a given thickness of fuel is proportional to the amount of fuel and the duration tends to become independent of the amount of fuel. The radiation within the enclosure, however, is dependent on the burning rate of the fuel. Thus in both regimes the fire resistance required of a structure must be assessed in a way rather different from that assumed in present regulations.

Part II of the paper discusses several special problems of fires in enclosures and touches lightly upon modeling. For example, in the study of roof venting of fires in large rooms it is generally found to be possible to make a model of the air flow provided the flow is turbulent. The induced velocity of the air u is proportional to $[\theta L/(T_A+\theta)]^{1/2}$ where θ is the temperature above ambient in the enclosure, T_A the absolute ambient temperature and L the linear scale of the model.

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

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

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

In an effort to gain further insight into problems of fires in enclosures, a qualitative theory of the dependence of burning rate on air flow rate is developed. The heat balance equation for the enclosure is combined with an expression for the dependence of burning rate on temperature. The burning rate, R, is defined as the mass rate of fuel consumption. For a vented enclosure R depends primarily upon the mass flow rate of air into the enclosure, which in turn depends upon the size and geometry of openings into the enclosure. Flames and hot gases also flow out through these openings.

To calculate the dependence of burning rate on air flow rate, a heat balance equation is first written; the heat produced by combustion is equated to the heat lost from within the enclosure. Heat produced may be assumed to be proportional to the air flow rate whenever the fire is not sufficiently ventilated, and this is the usual case when the openings are relatively small. Heat lost includes heat transferred to the interior of the walls of the enclosure and of the fuel, heat lost by escape of hot gases through openings, and heat lost by radiation through openings, etc. The expression for heat lost is extremely complex and is simplified by making several assumptions. Then, if a mean specific heat $\bar{c}$ of the hot gases, a mean temperature $\bar{T}_f$ and a mean heat transfer coefficient $\bar{h}$ for the enclosure are defined, the heat transfer equation shows that the ratio R/M (burning rate to air mass flow rate) depends on the parameters $Q_o(\bar{T}_f-T_o)\ \bar{c}$ and $\bar{h}A_w/M\bar{c}$ where Q_o is the heat produced per unit mass of oxygen, T_o is the ambient temperature and A_w is the effective surface area of the walls, ceiling, and fuel.

On the other hand, the burning rate R is proportional to A_f, the effective surface area of the fuel, and to m'', the mass rate of fuel decomposition per unit area. It is assumed that the formation of volatiles from the solid material is thermally determined, the reactions occurring in the gaseous phase being determined by the gaseous composition within the enclosure; m'' is therefore assumed to be a function of the heat transfer rate at a particular time and, for a given mean heat transfer coefficient, it will depend on the temperature $\bar{T}_f$. From this burning rate expression, curves of R/M vs. $\bar{T}$ may be plotted with A_f/M as parameter and these curves may be combined with curves obtained from the heat balance to yield a curve of burning rate vs. air flow.

In this paper the procedure for obtaining this curve is indicated and a representative curve is sketched, but no quantitative work is shown. However, the curve is plausible and agrees with some experimental findings. At high air flow rates it shows that the burning rate depends on the fuel surface area and does not depend on air flow rate. This is the result observed for large ventilation where heat transfer to the fuel is presumably the controlling factor.

As the air flow rate decreases, the value of $\bar{h}A_w/M\bar{c}$ increases, i.e. wall loss becomes relatively more important in relation to the rate of heat production and the temperature in the enclosure drops. The value of R/M tends to approach a constant value. In this range, where the windows are relatively small, the burning rate is found experimentally to be in almost direct proportion to the air entering the enclosure.

At extremely low airflows the combustion is no longer flaming but is rather a process of destructive distillation and under these conditions the ratio R/M is practically independent of air flow rate.

Thus, the theory agrees with many experimental findings. Its predictions do not, however, agree in detail with some experimental results on the effect of increasing the fuel surface area. Reasons for the lack of agreement are suggested in the paper and new systematic experiments are proposed.

The theory outlined above could be used as a basis for discussing the observed feature of fires in compartments and provides a basis for a quantitative theory or a correlation in terms of dimensionless variables.

Radiation from the opening in a burning building, and radiation from the flames that escape through the opening provide hazards to nearby buildings. The intensity of this radiation and the size of the flames escaping from the openings in a burning enclosure are discussed briefly and the possibilities of modeling are explored.

The treatment of this topic is, however, somewhat superficial—a trait that marks both Parts I and II of this paper. Several interesting subjects are dealt with, relevant experimental findings are explored and some of the physical causes of the events are disentangled. As a result, even though the choice and arrangement of subject matter seem a little haphazard, the paper yields insight into a number of extremely important practical fire problems.

Subject Headings: *Fires, in buildings, use of models in; Building fires, use of models in study of; Models, study of building fires by means of.*

F. H. Wright

Diakov, N. M. (Central Scientific Institute for Research on Prevention of Fire, U.S.S.R.) "Influence of Area and Space Layout of Building Construction in Relation to Direction of Fire Spread," *Data on Fire Resistance of Materials in Building Construction—Publications Department of the Soviet Ministry of Economic Development for the Central Scientific Institute for Research on Fire Protection,* 43–55 (1958) Translation by Colts Ltd., Surbiton, Surrey, England

A simple theoretical analysis is made of the effects on fire spreading of the location and relative areas of openings in buildings. The author introduces the concept of a neutral zone, a region inside the building which has the same pressure as the air outside; the pressure below this zone is subatmospheric, and that above is superatmospheric. Given the location of the zone, the direction of gas motion through any opening in the building is determined, and consequently, the influence of convection currents on flame spreading may be deduced.

The location of the neutral zone is calculated on the basis of the hydrostatic forces which are produced by differences in gas density between the inside and outside of the building. Important assumptions include the following: (1) the gas inside the building is always at a uniform temperature; (2) the mass of material entering the building is equal to that leaving; (3) gas velocities at the neutral zone are negligible compared with velocities at openings in the building; and (4) for the purpose of calculations, the openings in the building may be represented as two openings, one above and one below the neutral zone. Each opening is treated as an orifice, and the use of Bernoulli's equation for incompressible flow leads directly to a simple relationship for the heights separating the neutral zone from the two openings.

Calculations show that the location of the neutral zone depends on the ratio of gas temperatures inside and outside the building and on the ratio of the open areas above and below the neutral zone. Values of neutral zone height, represented as the fraction to total height between the upper and lower building openings, are presented by the author in a nomogram for various values of the area ratio and combustion products temperature. Six examples of the use of the nomogram are presented. The effects of changing the area ratio and building shape are illustrated in some detail.

Although the results of these simple calculations cannot be used to make detailed calculations for a complex structure, the concepts presented in this paper do illustrate important features of the effects of openings in buildings on the process of flame propagation.

Subject Headings: ***Fire spread.***

E. E. Zukoski

Mourachev, V. I. (Academy of Building and Architecture, Moscow, U.S.S.R.) "Methods Adopted in the U.S.S.R. for the Study of Fire Resistance of Building Elements and Some of the Results Obtained," *Presented in French Conseil International du Bâtiment* (*EPA-OEEC*), Paris, France (1959)

The general principles concerning the evaluation of the resistance of a material to fire are dealt with. It is proposed that the real limit of fire resistance, R, expressed in hours, must be greater or equal to the product of the theoretical duration of the fire, D, expressed in hours, and the index of fire resistance, K_0. The factor K_0 can be greater or less than unity depending upon whether structural integrity outlasts the fire. Fire duration, D, is actually a complex function determined by type of combustible involved, material specific heat, material combustibility, heat release per unit time and area, building geometry and ventilation, and extinguishing methods employed. The complexity of this function has necessitated the use of a standard fire concept.

Temperature developed during a fire can be used to characterize fire intensity. All fires exhibit an ignition period with undefined temperature rise, a period of intense combustion with a rapid temperature rise approaching a maximum, and an extinction period with temperature declining first rapidly and then more slowly. A standard fire, i.e. temperature-time relation, has been adopted by the Soviet which closely resembles that adopted by other countries. The duration of an actual fire is converted to a standard fire equivalent by equating the areas under the respective temperature-time curves. The experimental fire duration is determined by the decrease of the rate of material heating below that of the standard fire. Experiments have shown that this occurs when the real fire temperature has fallen to between 600° and 400°C. Considering experimental evidence it is possible to express the duration of a theoretical fire as $D=0.02\ q$, where q is the average kilograms of combustibles per square meter of floor space. In obtaining this simple expression it is assumed that no attempt at extinguishment is made.

The limiting resistance of a material is exceeded when it ceases to be fire retardant or loses its mechanical strength. The retardant quality is exceeded when breaks appear in a material allowing fire spread or the cold side temperature exceeds a stated value. While the retardant qualities are obvious and of importance during a fire the question of mechanical strength is important during and after the fire and requires considerable study.

In considering a criterion of limiting fire resistance several are possible. If the fire resistance of an element has been computed with an index less than one, then the complete collapse of the element is the valid limit. However, for elements with an index greater than one, this criterion is not acceptable as it gives no indication as to the functioning of the element prior to collapse. In consequence, the criterion of limiting fire resistance adopted is that the irreversible changes in the element are such as to render the element incapable of performing its function.

Experiments were carried out on concrete, reinforced with mild steel, and concrete prestressed with cold drawn steel wire. For both of these materials complete destruction of the elements was caused by plastic failure. The prestressed section was a simply supported ribbed section. Two reinforced beams were tested, one being simply supported, the other being restrained by supports. The prestressed sample failed first and the simply supported reinforced piece second. The restrained sample failed last and retained its functional ability three times longer than the simply supported pieces. All samples tested showed that the observed increase in deflection was composed of a reversible and an irreversible part. The reversible part was caused by a thermally induced reduction in metal strength which was recovered upon cooling, and an irreversible part which was caused by physical alteration of the materials.

To separate and evaluate the various components of the increased deflection, tests were performed in which heating of the elements was stopped prior to the plastic failure and the specimen allowed to cool. It was found that in the reinforced beams the irreversible changes constituted only a small fraction of the total deflections. From this it was concluded that the time of plastic failure was not a suitable criterion of limiting resistance. In the case of the prestressed elements, the irreversible changes were responsible for approximately 60 per cent of the total change. For this case it was theorized that the irreversible changes occur as soon as the metal is heated to the point where hot flow takes place.

To confirm this latter reasoning, tests were performed wherein a prestressed wire was heated to 300°C and then cooled. At 200°C hot flow was observed. Subsequent to cooling a residual deformation of the steel per unit length of 0.0038 was observed. This would result in a beam deflection of 1 per cent of the span in the panels used in this work. Further experiments showed that a total loss of pretension, which occurred when heated to 300°C, resulted in a reduction in rigidity to one-third its initial value. After heating, prestressed beams behaved in the same manner as non-prestressed beams.

Since the reinforced samples displayed a residual deformation proportional to the heating time until the elastic limit became equal to the working stress and at that time the residual deflection was only 1/180 of the span, a resistance index of 1.1 or 1.2 was satisfactory. The residual deformations were between 1/230 and 1/280 and the reinforcing rods regained all their strength upon cooling. Minor repairs to the lower beam surface restored the element.

In the case of the prestressed beams a return to initial supporting power occurs only if the wire is not exposed to a temperature sufficient to cause the irreversible loss of strength induced by cold working. At 200°C a loss of strength was noted in the specimen tested. In addition to the loss in supporting strength the loss in rigidity must be considered in setting a standard.

Analysis of experimental data indicated that for similar geometries a reinforced element displays a limiting resistance at least twice that of a prestressed element. This has been compensated for in the Soviet standards by an increase in required concrete cover to protect the prestressed wire better from heat.

Tests of other steels, e.g. welded reinforcements, deformed and special hot rolled steel, showed little variation in resistance except for the latter which was somewhat superior.

With restraint at the supports, an increase in limiting resistance was obtained if the ratio of steel at the support to steel in the span was greater than two.

Subject Headings: ***Fire resistance, of building elements.***

H. N. McManus, Jr.

IX. Atomization of Liquids

Fraser, R. P. and Eisenklam, P. (Imperial College, London, England) "Liquid Atomization and the Drop Size of Sprays," *Transactions, Institution of Chemical Engineers* **34**, 294–319 (1956)

This paper may be divided into three parts: (1) a review of the designs of atomizers in practical use in many fields; (2) a presentation of previously unpublished measurements of the drop-size distributions of sprays produced by selected atomizers under varying conditions; and (3) a critical discussion of many methods for representing the drop-size distributions of sprays. The prolonged discussion following the paper may be considered to constitute an additional part (4).

1) The authors refuse to call a simple pressurized orifice nozzle an atomizer because of its poor performance in dispersing the spray, a function which they feel is a necessary attribute of an atomizer. Detailed discussions and drawings are presented for common swirl spray nozzles (in which the liquid is injected tangentially into a swirl chamber from which it leaves through a central orifice), fan spray nozzles (simple pressure nozzles internally contoured in such a way that a fan-shaped liquid sheet is formed, which breaks up into a spray), impact nozzles (in which the liquid leaving a simple orifice nozzle is atomized by impact on a solid surface), rotary atomizers (rotating disks or cups, centrally fed with liquid,

which shed droplets centrifugally at their periphery), and twin-fluid atomizers (in which a high-velocity gas stream impinges on a liquid jet). Also described are a number of other specific designs, some of which the senior author has patented. The turn-down ratios and other control aspects of these atomizers are given.

The main fields in which various atomizers have been employed are summarized in the following list, in which the atomizer types are given roughly in the order of decreasing degree of utilization.

Combustion of liquid fuels

In boilers for raising steam—swirl spray, twin-fluid, drooling steam.
In furnaces, air heaters, etc.—swirl spray, twin-fluid.
In internal combustion piston engines—pressurized orifice.
In jet engines—swirl spray.
In rocket engines—impinging jet, twin-fluid pressurized orifice.

Process industries

In spray evaporators and driers—rotary, twin-fluid.
In humidifiers, gas washers and condensers—swirl spray, impact.
In application of surface finishes, paints, lacquers, plastics, slips, and metals —twin-fluid.

Agriculture

Swirl spray, fan spray.

Fire-fighting

Impinging jet.

Of course, specific instances may be cited in which almost any given type of atomizer has been found to be most suitable for particular applications in each of the above categories. As pointed out by E. R. Hoare in the discussion following this paper, the reasons why certain atomizer types are predominant in certain fields are not always made clear, although in many cases these will be obvious. Only one brief paragraph is devoted to atomizers for fire-fighting applications, in which the observations of J. F. Fry *et al.*[1] are discussed.

2) In the new drop-size distribution measurements, water sprays from fan spray, swirl spray, and twin-fluid atomizers were directed vertically downward, and sampling was carried out in a horizontal direction between 1 and 3 feet from the exit of the nozzle. The sampling was performed by passing a microscope slide coated with an oil mixture through the spray at constant velocity. The properties of the oil mixture were adjusted in such a way that the impinging droplets would penetrate the surface and then remain suspended from the surface in the oil. An analysis of the required physical properties of the oil mixture is cited.[2] The final mixture used was:

Aniline	3.5% by weight
Benzene	2.0% by weight
Vaseline	8.0% by weight
Shell Carnea Oil 69	86.5% by weight

which gave considerably greater submersion than most previously employed mixtures. It was observed that the diameters of the submerged droplets decreased sufficiently slowly that photographs taken within 1 or 2 minutes after collection exhibited droplet diameters negligibly different from those in the initial sample. Studies of these photographs yielded the drop-size distributions.

Although a few sample size distributions are shown, the majority of the data is given in terms of the conventional Sauter mean diameter, d_s (proportional to the ratio of the mean volume to the mean surface area) and a peculiarly defined dispersion coefficient measuring the width of the size distribution. The authors found empirically that, for water discharging into atmospheric air, the data could be correlated by the equations

$$\log d_s = 1.823 + (4.42/P) + 0.203(FN) \quad (25 \leqq P \leqq 100,\ 0.35 \leqq FN \leqq 2.2) \tag{1}$$

for their fan spray nozzle and

$$\log d_s = 1.808 + (6.94/P) + 0.138(FN) \quad (25 \leqq P \leqq 200,\ 0.05 \leqq FN \leqq 2.0) \tag{2}$$

for their swirl spray nozzle when sampling 1½ feet below the nozzle exit. Here P is the pressure (psig) at which the liquid is fed into the nozzle and FN is the "flow number," defined as the ratio of the flow rate (gal/hr) to $\sqrt{P}$. Their dispersion coefficient decreased with increasing P for the swirl spray nozzle and remained nearly constant (at a value slightly above that for the swirl spray nozzle) as P varied for the fan spray nozzle. An insufficient number of measurements were made on the twin-fluid atomizer to obtain a correlation similar to equations (1) and (2) for d_s, but it was observed that d_s decreased markedly as the air-water ratio in the atomizer increased and that the dispersion coefficient was always considerably larger than that of either of the other two nozzles.

Some additional experiments on rotary disk atomizers spraying a water and oil emulsion are also reported. The rotary atomizers exhibited smaller values of d_s and considerably smaller values of the dispersion coefficients. The dependence of droplet size upon disk diameter and rotation speed is shown.

A number of general observations concerning the appearance and characteristics of the sprays are recorded. In addition, theoretical and experimental results of other authors relating to the dependence of the performance of the various atomizers upon the density, viscosity, and surface tension of the liquid are reviewed. Also discussed are (a) the effect of the pressure of the ambient atmosphere upon the mode of disintegration of the liquid sheets (e.g. the appearance of holes in the sheets at low pressures) and (b) the effect of the shattering of large, high-velocity droplets upon the size distribution of the spray.

3) A typical fan spray nozzle experimental droplet-size distribution was compared with the Rosin-Rammler distribution, the Nukiyama-Tanasawa distribution, a distribution extensively used by the National Gas Turbine Establishment which is somewhat similar to that of Nukiyama and Tanasawa, the log-normal distribution, and the root-normal distribution. While the Rosin-Rammler distribution provided better agreement with experiment than any of the other equations, none of these distributions fit the data very well. The authors therefore conclude that, if accuracy is required, the best procedure is to record the experimental distribution

itself without fitting it to any distribution equation. The authors did not attempt to compare their data with the generalized Rosin-Rammler distribution first proposed by Tanasawa, viz.,

$$dn/dx = ax^t \exp(-bx^s), \tag{3}$$

where dn/dx is the number of droplets per unit size range, x is the droplet diameter, and a, b, s, and t are constants. The distribution in equation (3) should be more flexible than the others because it has one additional adjustable parameter; Tanasawa[3] attained some success in correlating experimental size distributions from a number of different types of atomizers with this equation.

4) In the discussion following the paper the great difficulty in obtaining samples which are truly representative of the actual size distribution in the spray was emphasized. J. R. Joyce and A. E. W. Austen favored atomizing molten wax, heated to a temperature such that its viscosity and surface tension is the same as that of the liquid of interest, and collecting the solidified droplets which may then be sorted into various size groups. While it appears that the sampling method used by the authors would tend to give too few of the smaller droplets, objections can also be made to all other procedures that have been suggested.

Among the other topics mentioned in the discussion was a brief reference to fire-fighting applications by D. J. Rasbash.

References

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Subject Headings: ***Sprays, drop-size distribution; Atomization, of liquids; Liquids, atomization of; Droplets, size distribution, in sprays.***

F. Williams

X. Meteorological Interactions

Scorer, R. S. (Imperial College, London, England) *Natural Aerodynamics,* Chapters 7, 8, 9. New York: Pergamon Press (1958)

This book applies the fundamentals of fluid mechanics to those problems peculiar to our atmosphere. Using a minimum of theory and a maximum of lucid description, the author covers the subject in a manner which should appeal to a technical reader who is not an expert in meteorology. The first six chapters review the fundamentals of fluid mechanics with emphasis on atmospheric applications. These chapters are titled inertia forces, motion on a rotating earth, vorticity, viscosity, boundary layers, and wakes and turbulence.

Beginning with chapter 7 titled buoyant convection, subjects peculiar to the atmospheric problem are considered. Buoyant convection occurs when the lower levels of the atmosphere are heated and therefore become unstable, i.e. the heating causes the density to decrease and the affected air will rise. Under ordinary atmospheric conditions such unstable conditions would be found over towns and sun-facing ridges which are particularly efficient in heating the air above them. Obviously a surface fire of appreciable magnitude would be particularly apt to cause such an instability.

Buoyant convection may be divided into two types. The first is slow convection which occurs when the gravitational potential energy of an unstable air mass is converted directly into heat energy. Included in this type are Benard cells. The usual atmospheric buoyant convection is of the second or penetrative type. In penetrative convection the gravitational potential energy is converted into upward motion. This type of atmospheric phenomenon is usually referred to as a thermal.

When convection effects are discussed in the atmosphere it is necessary to introduce the adiabatic lapse rate given by

$$\frac{dT}{dz}=\frac{(\gamma-1)g}{\gamma R}$$

where g is the gravitational acceleration, γ the ratio of specific heats, and R the gas constant for air. This relation gives the change in temperature with altitude for an unmixed parcel of air; i.e. the adiabatic change in temperature with height. If the temperature gradient is greater than the adiabatic lapse rate, then the lapse rate is termed superadiabatic and the air is unstable because buoyancy forces are in the same direction as the displacement. The potential temperature is defined as the temperature a parcel of air would have if brought adiabatically to a standard pressure. If the lapse rate is superadiabatic the potential temperature decreases upward.

In the eighth chapter the author turns his attention to plumes and jets. If a buoyant fluid attains a velocity greatly in excess of that corresponding to its buoyancy it will behave like a pure jet; its motion is governed completely by inertia forces. As the fluid rises and becomes diluted, the momentum added by buoyant forces steadily increases. The total momentum increases until the fluid behaves like a buoyant plume; a pure buoyant plume is governed by the ratio of inertia to buoyant forces.

By a dimensional approach the author treats pure jets and buoyant plumes as well as jets and buoyant plumes in smooth cross-winds. Sutton's theory of turbulent atmospheric diffusion is discussed in qualitative terms. Observed properties of plumes are considered including coning, thermality, looping, fanning, and fumigation. The latter phenomenon is particularly interesting because it allows the concentration of a pollutant to reach high levels many kilometers from the source. By means of fumigation the sulphur dioxide from a smelter in Canada was able to destroy vegetation up to as much as 80 km. from the source.

Properties of plumes near their source are also discussed. Included are bifurcation, down wash, cumulation, and puffing. An example of puffing would be smoke appearing in puffs from a chimney. Because of the buoyancy of the effluent, the surrounding air tends to sink into the upwind side of the chimney causing surges of the effluent. Similar explanations are given of the other phenomena.

The ninth chapter is titled air waves. The earth's atmosphere is peculiar in that it behaves like a shallow liquid on the gross scale and like a compressible gas locally. The compressibility results in sound and shock waves. Sound waves are commonly experienced; examples of shock waves are sonic booms and the pressure wave from an atom bomb. These phenomena are called "little bangs." The atmosphere as a shallow liquid can transmit gravity waves similar to the surface waves on a saucer of milk. These waves cause pressure fluctuations at distances of more than 1000 km. from the source and are called "big bangs." An example of a big bang would be the pressure oscillations caused by the Great Meteorite which fell on Siberia in June 1908. Pressure oscillations of the order of 100 microbars were measured in England 6000 km. from the source. Hydrogen bombs also cause big bangs. Explosions which rock the entire atmosphere are given the name "aeroclysm." The eruption of Krakatoa in 1883 is the only aeroclysm in recorded history.

The atmosphere also has tidal waves similar to the tides of the seas. However, the period of the atmospheric tides is exactly twelve hours where oceanic tides have a period of half a lunar day. The tide in the earth's atmosphere is almost certainly produced by the diurnal variations in the heating by the sun. Interesting conclusions about the evolution of our planet can be drawn from the period of these tides. The wavelike phenomenon associated with mountains and ridges is also discussed. Included are lee waves, shear layers, separation, rotors, and forest blowdowns. These atmospheric flows would seem important in any complete understanding of the propagation of forest fires. The book concludes with chapters titled clouds, and fallout, and philosophy of method.

Subject Headings: *Convection, in the atmosphere; Air waves; Plumes.*

D. L. Turcotte

Long, R. R. (Johns Hopkins University, Baltimore, Maryland) "The Atmosphere in Motion," *Science* **131**, 1287–1292 (1960)

Although the needs of weather forecasting have dominated research in meteorology in the past, the contribution of the large amount of empirical and statistical research of the past 40 years (including recent work in numerical forecasting) to forecasting has been small.

Future progress demands fundamental research such as that which is now going on in a field which might be designated as geophysical fluid mechanics. This term characterizes those investigations in fluid mechanics which meet the needs of meteorology, oceanography, and astrophysics.

Problems in geophysical fluid mechanics are subject to two important influences. First is the influence of a rotating platform, such as the earth's surface, on the motion of a fluid as seen by an observer moving with the platform. The second influence is that of density, or buoyancy, variation in geophysical fluid systems.

Although the laws governing the motion of fluids can be expressed in precise mathematical form, only a few solutions of the equations have ever been found. Also, the geophysical motions of fluids in their natural state are so disordered and chaotic that it is unreasonable to ask for knowledge of the motion in detail. Average values of temperature, speed, and so on, would be better but as far as they have been developed today, equations based on averages do not determine the problem in a mathematical sense.

Another approach is to resort to simplification and experiments on a small scale. Such methods have not been used much in geophysical fluid mechanics because it has been thought that the vast systems involved were beyond the reach of modeling techniques. However, this estimate may have been overly pessimistic as the two following examples from recent work indicate.

Stratified flow and mountain waves

The observed flow of water over a small rounded object in the bottom of a glass walled channel (20 feet long, 2 feet deep, and 6 inches wide) was in excellent agreement with theory. When the water is stably stratified and the current is moderately slow, the streamlines in the interior of the liquid acquire a wavelike form "downstream" from the object. Such waves occurred when a model of the Sierra Nevada mountain range and the adjacent Owens Valley of California was placed in the tank, although theoretical solutions were not possible in this case. However, it was possible to meet certain similarity requirements between the model and full scale for a specific day (January 30, 1952) when the structure of the actual flow was known. This experiment indicates the possibility of a new approach to certain types of forecasting.

The tornado vortex

A second example of the interplay between theory and experiment comes from a recent study of vortices and bears directly on the tornado. Consider a vessel of water mounted on a rotating turntable. If water is drawn from a hole in the bottom of the vessel at a rate above a certain minimum and if friction can be neglected, the resulting flow can be predicted mathematically.

Although the flow cannot be predicted mathematically at very low withdrawal rates, the experiment reveals an exceedingly strong vortex development in a narrow central core. Friction appears to be essential to the formation of this type of vortex, the study of which has led to a new theory of vortices. This work may have some very significant implications about the form, velocity field, basic causes, and eventual forecasting of the tornado.

The investigations may be very significant for the possible use of similarity methods in studying various fire phenomena. An example is the intense fire whirlwind which on occasion can approach the tornado in destructive intensity.

Subject Headings: ***Air waves, mountain; Atmosphere, flow of air in.***

G. M. Byram

Besson, P. (Nainville-les-Roches) "The Fire Storm," *Protection Civile, Vol. 55, January 1959 Reprinted in German in VFDB Zeitschrift* 9, 5–12 (1960)

This article discusses in qualitative fashion the establishment and structure of fire storms. The material is based on analyses of wartime experiences in Hamburg, Kassel, Darmstadt, Dresden, Tokyo, and Hiroshima, the only recorded examples of the phenomenon. Comparison with large peacetime fires shows a much larger loss in life and property in fully-developed fire storms.

A number of prerequisites are essential to the establishment of fire storms: building density above 30 per cent; high loading with combustible materials, as is frequently the case in inhabited areas; an area, meeting these conditions, of at least 2–3 km.^{2}; a large number of simultaneous initiation centers; absence of strong winds; dry and cool weather.

In contrast to the more conventional frontal fires in which the direction of propagation is determined by the prevailing wind, the fire storm is characterized by a strong influx of air into the hot convection column of the fire. Although the outward, radial propagation rate is relatively slow, the intensity of the fire is great. Temperatures in buildings reach 1000°C. Wind velocities are in excess of 100 km/hr and cyclonic winds in excess of this have been measured. The convection column may reach 7000 m. in height, accompanied by occasional rain from interaction of the column with cold air layers.

The development of the fire storm is rapidly brought about by consolidation of many individual fire centers and reaches its maximum intensity in a few hours. Loss of life is heavy, mainly from oxygen starvation. A number of civil defense recommendations are given, such as to reduce building density and fire loading, supply a self-contained supply of air to shelters, evacuation of people to large open areas.

In summary, the author reaches the following conclusions:

1) Hermetically sealed shelters offer no protection in view of the danger of asphyxiation. By coincidence, in areas where fire storms are most likely to develop, i.e. the center of cities, shelters are most difficult to construct.

2) The many ignition sources which nuclear explosions generate increase the need to extinguish small sources of fire at an early stage to prevent build-up to a fire storm.

3) The hazard from carbon monoxide must be kept in mind in any discussion of nuclear damage effects.

Subject Headings: ***Fire storms.***

W. G. Berl

Davies, R. W. (California Institute of Technology, Pasadena, California) "Large-Scale Diffusion from an Oil Fire," *Advances in Geophysics* 6, 413–415 (1960)

This brief paper presents information pertaining to the diffusion of oil smoke from a fire which broke out on May 22, 1958 at the Hancock Oil Company refinery near Long Beach, California.

Since the visibility was very good on the second day of the fire, many photographs of the smoke plume were taken. From the photographs, weather reports, and interviews it was possible to trace the shape of the smoke plume for 120 miles.

The plume rose vertically to an altitude of approximately 3500 feet. It was then dispersed by the wind which increased from a negligible speed at 4000 feet to a speed of 50 knots at an elevation of 11,500 feet. The average Richardson number for this altitude range was 1.2. The Reynolds number was about 10^{12}. The temperature gradient was approximately two-thirds of the adiabatic lapse rate.

For this particular fire the smoke plume tended to diffuse laterally rather than vertically. About one mile downstream from the fire the plume was a mile wide and 3500 feet thick at an elevation of 6000 feet. Thirty miles downstream it was approximately 8 miles wide and 6000 feet thick, and the top of the plume was at 11,000 feet.

The author noted that the shear was in the vertical direction and the large scale vertical fluctuations were well repressed. The settling pattern of the oil smoke and droplets indicated that the energy in small-scale vertical velocity fluctuations was appreciable.

Table 1 lists several lateral diffusion coefficients obtained from the plots of the smoke plume. Although the plume widths were determined to within 5 per cent over the first 20 miles, the meteorological data and altitude measurements were less accurate. The coefficients are therefore only accurate to within 20 per cent.

TABLE 1

DIFFUSION COEFFICIENTS D COMPUTED FROM THE OUTLINE OF THE SMOKE PLUME

Distance downstream (km.)	Envelope width W (6.6σ) (km.)	$D = \frac{1}{2}\frac{\Delta\sigma^2}{\Delta T}$ $\left(\frac{\text{cm}}{\text{sec}} \times 10^6\right)$
5.2	5.2	4.2
10.8	7.2	5.4
13.2	8.1	7.3
23.2	10.4	10.3
38.2	14.0	15.0
65.0	22.2	83.0

A general discussion of the smoke plume behavior is presented at the end of the paper.

Subject Headings: *Diffusion, oil-smoke; Smoke, diffusion, of oil-fire.*

A. W. McMasters

Turner, J. S. (University of Manchester, Manchester, England) "A Comparison Between Buoyant Vortex Rings and Vortex Pairs," *Journal of Fluid Mechanics* 7, 419–433 (1960)

The author discusses the motion of buoyant vortex rings and vortex pairs, a subject which is related to rise of smoke plumes and explosion clouds in the atmosphere.

A solution for a vortex ring rising in uniform surroundings—a problem previously treated by the author—is reviewed first. One of the important steps in this solution consists of equating the rate of change of momentum to the buoyancy force. Following the same method of attack the motion of a vortex pair in uniform surroundings is analyzed. The problem of the rising vortex pair, having previously been considered of academic interest only, is now believed to describe the behavior of smoke plumes bent over by a cross-wind. In this concept the plume should be imagined as having become almost horizontal. Such plumes are sometimes observed to split into two separate and distinguishable bands, and the flow in a plane normal to these two bands is believed to be well represented by that due to a vortex pair. The motion of a vortex pair, therefore, may be expected to describe the motion of each portion of the pair of plumes. The concept is illustrated by a photograph of a plume produced by a buoyant fluid in a water tank.

The author then turns his attention to the motion of vortex rings and vortex pairs in an atmosphere having a uniform density gradient. Three cases are examined: the case when the momentum and the circulation vanish together, and the cases when the circulation vanishes before and after the momentum respectively. When the two quantities vanish simultaneously, the radius of a vortex ring is shown to increase linearly with altitude, and the ring reaches a certain maximum radius and elevation. The mathematical expressions which are obtained are identical to those describing the height of a vertical plume rising in an atmosphere with a constant density gradient, and the author proposes that this rising plume be regarded as a special case of the rising vortex ring. In this comparison the plume has to be imagined as consisting of a series of concentric ring vortexes with the centerline of the plume as their axis.

When the circulation remains finite at the instant that the momentum vanishes, the author predicts that a ring vortex will break up after reaching a certain maximum elevation. This maximum elevation increases with increasing circulation. It is suggested that releasing smoke in intermittent bursts—so as to increase circulation—would increase the effective height of a smokestack. The solutions which correspond to finite momentum at zero circulation are also computed, but the author doubts that they correspond to a physically important phenomenon.

The rise of a vortex pair in an atmosphere with constant density gradient is treated in a completely analogous way. The principal results are quite similar, e.g. a definite altitude is again reached if the magnitude of the vorticity is such that it vanishes at the same time as the momentum. In contrast to the conclusions sions reached for the vortex ring, the author believes that physical significance may be attached to the solution corresponding to a vortex pair in which the momentum outlasts the circulation.

Subject Headings: *Vortex rings and pairs.*

R. H. Sabersky

Countryman, C. M. (California Forest and Range Experiment Station, Berkeley, California) **and Colson, D.** (U. S. Weather Bureau, Washington, D.C.) "Local Wind Patterns in Wildcat Canyon," *California Forest and Range Experiment Station Technical Paper No. 28* (*December 1958*)

Air movement in response to topography is vitally important to the understanding and predicting of forest fire behavior. Area forecasts, based on momentary observations of weather factors at a few points, are not adequate for forecasting local weather patterns. Intensive local surveys are needed.

In 1954, a 20-station survey was made of winds in Wildcat Canyon, a 4 mile long, westward-draining tributary of the San Mateo drainage in San Diego County, California. Elevations range from 400 feet above sea level at the canyon mouth to 3040 feet at the extreme head. Vegetation was mainly brush of various species, and heights up to 10 feet, depending on elevation and aspect.

Stations were located so as to sample a wide variety of type situations. Wind speed and direction were recorded continuously at all stations, usually at 20 feet above the ground but higher in a few instances.

The most common wind direction was westerly during the survey period, July through September. Direction varied increasingly with increasing height of ridges and anemometer location above the ground. In the bottom of the canyon, winds were mostly from two directions only, up and down the direction of drainage.

Highest wind speeds occurred at the highest station. Strong winds, resulting from air drainage, were measured near the mouth of the canyon.

A definite diurnal rhythm of air movement occurred, up-canyon during the day, down-canyon at night. No definite relationships between transition times and the general weather pattern could be deduced from this limited study, partly, no doubt, because the general pattern itself changed little during the period.

Winds aloft had rather slight effect on daytime surface winds, especially in the canyon proper. Gradient winds tended to overcome the lighter drainage winds at night.

The survey indicated that local wind patterns induced by rugged topography can persist in the face of any but strong gradient winds. This emphasizes the need for localized data. The apparent need is to study type situations from which conditions in other areas can be deduced or worked out through the use of models. Possibly the greatest benefit from the Wildcat Canyon wind survey was the knowledge obtained on how to proceed with similar work in the future.

Subject Headings: ***Wind, pattern of, in Wildcat Canyon.***

G. R. Fahnestock

Monin, A. S. (Institute of Physics of the Atmosphere, Academy of Science, Moscow, U.S.S.R.) "Smoke Propagation in the Surface Layer of the Atmosphere," *Advances in Geophysics* **6**, 331–343 (1960)

The turbulent diffusion of nonbouyant pollution (smoke) in stratified surface layers of the atmosphere is described in terms of a similarity theory developed earlier by Monin and Obukhov.[1, 2] According to the theory, the shear stress τ and heat flux $\dot{q}$ (stratification) characterize the turbulent diffusion process through two kinematic parameters: the friction velocity $u_\tau \equiv (\tau/\rho)^{\frac{1}{2}}$ and a stratification "length" L built up from u_τ and the heat flux $\dot{q}$. This postulate, combined with the principle that turbulent diffusion velocities are *finite,* leads to both a simple expression for the shape of smoke plumes and a hyperbolic system of equations governing the concentration profiles within smoke plumes.[3] In contrast to studies of diffusion based on parabolic equations, the concentration of pollution (smoke) is considered to be identically zero beyond the visible plume. In this sense the theory is similar to random walk models of diffusion,[4] or diffusion theories in which relaxation rates are included.[5] Subject to these assumptions, an approximate similarity in concentration profiles is demonstrated for different distances downstream of a stationary, transverse, linear source of pollution under conditions of arbitrary distribution of horizontal wind velocity and stratification. The maximum concentration in the smoke plume is found to be approximately inversely proportional to the distance from the source.

Experimental agreement with the principal conclusions of the similarity theory is stated to be satisfactory, although the correlations shown graphically do exhibit considerable scatter. Whether this reflects an inadequacy of the theoretical framework itself or limitations of the experimental techniques is perhaps too early to say.

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Subject Headings: ***Atmosphere, smoke propagation in; Smoke, propagation of, in atmosphere.***

D. E. Rosner

Scorer, R. S. (Imperial College, London, England) "The Rise of Bent-Over Hot Plumes," *Advances in Geophysics* **6,** 399–411 (1960)

The plume emitted by a chimney will bend over if a wind is present. This problem is treated by the author utilizing dimensional analysis and intuitive arguments. The change in shape of a normal section from circular to bifurcated during the bending over process is not considered. The general problem is divided into three separate cases: (1) the bent-over jet in which buoyancy may be neglected, (2) the bent-over plume in which buoyancy dominates, and (3) the plume in which buoyancy has a negligible effect until after the plume is bent over. Only an atmosphere of uniform potential temperature is considered.

Since none of the fluid mechanical details of the problem are considered, numerous assumptions and approximations are required. It is assumed that the plume becomes passive when the vertical velocity w is less than λU and that the plume will bend over when $w = \mu U$ where U is the wind velocity and λ and μ are proportionality constants to be determined by experiment. For the plume in which buoyancy has negligible effect until after it is bent over, the total vertical rise from the orifice is given by

$$h = 0.58 \frac{F}{\lambda^2 U^3} + 2.5a \left[\frac{W_0}{U} \left(-\mu^{-\frac{1}{2}} + 2\mu^{-1} \right) - 2 \right]$$

where the flux of buoyancy is $F = \pi a^2 w_0 g B_0$ with a the radius of the orifice, w_0 the velocity of efflux, g the gravitational acceleration, and B_0 the buoyancy at efflux $(\Delta\rho/\rho)$. The above relation is appropriate if buoyancy becomes important after the plume is bent over but before it becomes passive. The author concludes that an increase in efflux velocity produced by narrowing a chimney mouth may decrease the equivalent chimney height under some circumstances.

Subject Headings: ***Smoke, use of bent-over plume.***

D. L. Turcotte

XII. Instrumentation

Benson, G. M. (University of California, Livermore, California), **El-Wakil, M. M., Myers, P. S., and Uyehara, O. A.** (University of Wisconsin, Madison, Wisconsin) "Fluorescent Technique for Determining the Cross-Sectional Drop Size Distributions of Liquid Sprays," *ARS Journal* **30,** 447–454 (1960)

By taking careful regard of minute technical details, the authors have succeeded in developing a unique laboratory instrument for determining the cross-sectional drop size distribution in a dynamic liquid spray. The conical spray of the liquid, in which a fluorescent dye is mixed, is exposed to the high intensity radiation from a high pressure capillary mercury-arc lamp flashed by capacitor discharge. This radiation is focused into a thin sheet by two plano-parabolic quartz lenses so that the sheet intersects the spray nearly perpendicular to the spray nozzle axis, irradiating a narrow cross section of the spray. The drops act as primary radiators due to the fluorescent dye addition. Inasmuch as the optical system was fixed, the variation of cross-sectional distribution with axial distance from the injector was investigated by moving the spray nozzle.

The requirements of similar absorption and fluorescent spectra, minimum fluorescent induction and decay times, and high solubility of the dye additive in the primary fluid were admirably satisfied by an aqueous uranin solution for investigations with glycerine, water, alcohol, and alcohol-ether mixtures. An alternative fluorescent dye, soluble in many fuels is rubrene (tetraphenylnaphthacene).

In order to accurately record the images produced by the fluorescent drops, an extensive lens testing program was conducted to optimize the camera optical system. Conflicting requirements of a low f-number, maximum amount of radiation, and high resolving power were met by optimizing the system. Since the edge effects, due to random variation in radiation from the drops, are magnified by reproduction of the film negative the original negatives were used for drop counting purposes, under the same conditions for which the system was calibrated.

Resultant data, which indicated the expected decrease in average drop size with injection pressure, were carefully analyzed to determine the minimum number of drops to be counted in order to assure maximum accuracy of representation. By considering the envelope of least upper bounds of the percentage change with respect to total number of drops counted in each size range, the authors conclude that a minimum of 1200 drops must be counted in order to assure less than 10 per cent deviation.

The inclusion of detailed data on operating conditions for the various spray analyses presented in this outstanding report on a unique system for drop size analysis makes this paper an outstanding contribution to the state of the art. The accuracy, simplicity, and versatility of the apparatus described provide an excellent recommendation for its acceptance as a basic research tool in the field of spray analysis.

Subject Headings: ***Sprays, drop-size distribution, measurements in; Droplets, measurement of distribution in sprays.***

C. C. Miesse

Schriesheim, A. (National Bureau of Standards, Washington, D.C.) "Method for the Controlled Burning of Combustible Materials and Analyses of the Combustion Gases," *Journal of Research of the National Bureau of Standards* **57**, 245–249 (1956)

A laboratory method was used to burn a given quantity of a combustible material in a fixed amount of air at a series of initial temperatures. In order to duplicate large-scale controlled burning experiments it was necessary to maintain the combustion chamber at atmospheric pressure until the initial temperature had been reached. Since varying amounts of air remained in the fixed volume chamber at different initial temperatures, it was necessary to make the ratio of weight of sample to weight of air at any temperature constant.

Materials tested consisted of marine-grade plywood covered with either a plastic coat or fire retardent paint. In some cases the plywood was covered with both paint and plastic. The paints and plastics were also tested individually.

Gas analysis was performed using a mass spectrometer. Hydrogen chloride was determined by titration and carbon monoxide when in low (<1000 p.p.m.) concentration by a color chart indicator technique.

The experiment was conducted at three initial temperatures; 250°, 400°, and 550°C. At the highest temperature the principal combustion product was CO_2. No water analysis was made. The effect noted by coats of polyvinyl plastics and asphalt aluminum paints is to lower the ratio of CO_2 to CO in the combustion gases. The chlorine containing plastics yielded both hydrogen chloride and trace quantities of chlorinated hydrocarbons. Sulphur dioxide was found when the asphalt aluminum paint was incorporated into the sample burned. The sulphur is present in the asphalt resin base. Trace quantities of hydrocarbons (C_1-C_3) and olefins were found when burning the samples at 550°C. At this temperature both cracking and decomposition of lower hydrocarbon fragments are responsible for the appearance of these species. Trace quantities of aromatics such as benzene and toluene were also found.

The experiments conducted here show the utility of scaled-down conflagration experiments. The conditions do not quite duplicate field conditions; this factor is offset by the facility of a reasonably complete gas analysis that would not be possible in field-scale model burning experiments.

The principal purpose of this investigation was to evaluate the various coatings tested for special purpose dwellings and the possible usefulness of organic coatings with special thermal breakdown properties.

Subject Headings: *Combustion products, analysis of; Plastics, combustion products of.*

P. Breisacher

Thomas, P. H. and Smith, P. G. (Joint Fire Research Organization, Boreham Wood, England) "Simple Dosage Meter for High-Intensity Thermal Radiation," *Journal of Scientific Instruments* 37, 73–76 (1960)

This paper describes completely the construction details and procedures for the calibration of a simple radiation dosage meter for measuring the total amount of radiant heat falling upon a given area in a short time. The meter is self-contained, needs no power supply, and can retain indefinitely an indication of any thermal radiation which has fallen upon it.

The meter uses a temperature sensitive paint which either melts or undergoes a definite color change at a specified temperature. By accurately measuring the area of melting or color change an indication of the thermal dosage is determined. Calibration curves are given for two versions, one suitable for 5–18 cal/cm^2, the other for 16–60 cal/cm^2.

Included in the paper is an approximate theoretical analysis which may be considered sufficiently accurate to provide a basis for designing dosage meters for various ranges of thermal dose.

The apparatus can also be used to measure the value of heat flux, if this is constant for some time.

Subject Headings: *Dosage meter, for thermal radiation measurement; Radiation, dosage meter for measurement of.*

W. C. Woodward, Jr.

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