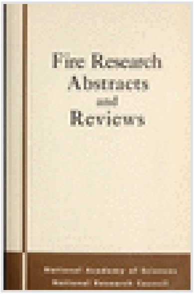


Fire Research Abstracts and Reviews, Volume 5 (1963)

Pages
260

Size
6 x 9

ISBN
0309309204

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

Volume 5 Number 1

Fire Research Abstracts and Reviews

Committee on Fire Research
and
Fire Research Conference

Division of Engineering and Industrial Research
NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
Washington, D. C.

FIRE RESEARCH ABSTRACTS AND REVIEWS is published three times a year by the Committee on Fire Research and the Fire Research Conference of the National Academy of Sciences—National Research Council, 2101 Constitution Avenue, Washington 25, D. C. It is supported by the Office of Civil Defense, Department of Defense, the U. S. Department of Agriculture through the Forest Service, the Department of Defense, the National Science Foundation, and the National Bureau of Standards under Contract OCD–OS–62–287. The opinions expressed by contributors are their own and are not necessarily those of the Committee on Fire Research and the Fire Research Conference.

Library of Congress Catalog Card Number 58-60075 rev

FOREWORD

With this issue, marking the beginning of the fifth year of Fire Research Abstracts and Reviews, one's thoughts return to the first issue of September 1958. Faithful and retentive readers will remember that it opened with a concise statement by the Committee on Fire Research on what the technical effort in the United States should be. A number of research areas in the physical sciences were outlined where a more thorough understanding of the Fire problem should prove profitable and which could be probed with the now available tools. Several Field Studies and Operations Research investigations were placed on an equal level of importance. What has become of this program? Has it met the expectations placed on it at that time?

It can be said fairly that the tempo of the research effort has quickened considerably. An inspection of the papers reviewed in Fire Research Abstracts and Reviews (which have already been culled considerably to restrict them to problems of concern to fire behavior and combat) shows a wide array of studies on a variety of subjects. The 37 references cited in the Survey of Current Fire Research Activities (FRAR *3*, 113, 1961) are impressive evidence of the thought-provoking problems in the Fire Research field. To these have been added more recently (among many others) further studies by Emmons, Spalding, Thomas, Morton on the fluid dynamics of fires, by Fristrom, Fenimore on the chemical kinetics and by Oppenheim, Plass on the radiative properties of flames. Since there are ample opportunities for discussing these findings (as at the Symposium on "The Use of Models in Fire Research," 1959; the American Chemical Society Symposium on "Fire Control Research," 1961; the IXth Symposium on Combustion, 1962) one can conclude that the research effort is in reasonably satisfactory shape even though most of work was supported by funds which were not allocated specifically for Fire Research.

The same, however, cannot be said of the Field Studies and Operations Research proposed in the original program. Very little of a novel and challenging nature has been undertaken (or, at least, reported) nor do the plans for the future give hope for improvement. A gulf remains, therefore, between the small-scale research effort which is making relatively good progress, and the practitioners of the art of fire fighting and prevention who depend on the results of well-conceived engineering studies to supply them with new techniques and methods. As was suggested by the 1961 Study of Fire Problems (FRAR *4*, 1, 1962) other equally pressing questions remain unresolved in the fields of training, education, and economics. Therefore, one must feel some concern that the organization and leadership for handling this phase of the Fire problem does not now exist and that moves toward the full implementation of the 1958 Program and of the 1961 Study are inching forward at a disappointingly slow pace.

W. G. BERL
Editor

CONTENTS

Volume 5 Number 1

VI. Radiation

VII. Suppression of Combustion

VIII. Model Studies and Scaling Laws

IX. Atomization of Liquids

X. Meteorological Interactions

XI. Operational Research Principles Applied to Fire Research

XII. Instrumentation

XIII. Fire-Fighting Techniques, Equipment Design, Materials of Construction

BOOK REVIEW

COMMENTS AND DISCUSSIONS

REVIEW

Fire Effects of Thermonuclear Detonations*

A. BROIDO
Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California

It is customary to begin an address with a statement about how happy one is to appear before such a distinguished gathering on such an auspicious occasion. Unfortunately, I find it most difficult to associate the word happy with a discussion of warfare, modern or old-fashioned. However, I don't have to tell an audience of members and future members of the medical profession that unpleasant matters rarely go away just because we close our eyes to them. And it certainly would be impertinent for me to tell the faculty and student body of this university that action based upon knowledge and thought is inevitably better than action or inaction from ignorance. Thus, I am gratified to see a colloquium such as this one take place and welcome the opportunity to describe to you some of the effects of a thermonuclear detonation.

Since the subject of this colloquium is "medical aspects of modern warfare," I shall try to confine my remarks to those items of medical consequence, particularly trying to correct some of the misimpressions and misconceptions of the extreme optimists as well as those of the extreme pessimists who have discoursed upon this highly emotional subject. Let me say at the outset that, whether we are optimists or pessimists and whether we consider nuclear weapons or conventional weapons, medical problems encountered in wartime assume a dimension unseen, and all too frequently inconceivable, in peacetime. On November 28, 1942, 489 people lost their lives in the Cocoanut Grove nightclub fire in Boston. The 181 victims who reached hospitals completely taxed the extensive medical capacity of the Boston area. Most of these victims went to the Massachusetts General Hospital, which was well prepared for burn treatment as a result of research projects underway there. Seventy-five of the casualties received at this hospital were dead on arrival. The 39 living patients were handled promptly and efficiently—but only because they arrived as the hospital was changing shifts and an entire shift of hospital personnel was available for the emergency.

In contrast to this peacetime disaster, the burn victims at Hiroshima and Nagasaki numbered in the tens of thousands—while more than 80% of the hospital beds were destroyed and most medical personnel were themselves victims of the detonation. Awesome as these figures are, they were more than matched several times during World War II by results of bombing attacks with conventional incendiary weapons in large numbers. For example, a fire raid on Tokyo on March 9, 1945, caused a mass fire which destroyed an area of 16 square miles (compared with less than 5 square miles at Hiro-

---

* (This paper is a slightly amended text of a talk given at a Colloquium on "Medical Aspects of Modern Warfare" at the Albert Einstein College of Medicine, May 15, 1962. In this and several other versions on the same topic the author has performed a signal service by presenting an authoritative report on the potential fire effects of nuclear explosions on cities.—*Editor*)

shima and less than 2 at Nagasaki) and caused more than 80,000 deaths and more than 100,000 injuries, perhaps more casualties than in Hiroshima and Nagasaki combined. Of course, since then we have greatly "improved" our weaponry and have done little, if anything, to decrease the fire-vulnerability of our surroundings, so we can expect the results of any future conflict to be even more catastrophic.

Now, what are the fire effects of a thermonuclear detonation and how important are they relative to the other effects? Here, perhaps I had better make the first of several confessions. The principal subject matter of this presentation really is not fire effects but thermal radiation effects—of which fire is one end product. I did not use the term "thermal radiation" in my title because the words are frequently not understood, or worse, misunderstood, conveying either no impression or a wrong impression.

Thermal radiation is simply that radiation emitted by an object by virtue of its temperature. Usually this "heat radiation" is found in the infrared portion of the spectrum, but if the temperature of the emitter is sufficiently high, for example the sun, a significant fraction of its thermal radiation is emitted in the visible. Although we popularly call this radiation "light" and distinguish it from heat, it is important to recognize that such distinctions are purely artificial and that the temperature-raising or heat effects of infrared radiation can also be produced by "light" radiation in sufficient quantities.

The thermal radiation effects of a nuclear detonation result because a large amount of energy is produced in a small mass of material in a very short period of time, raising the temperature of this mass to extremely high values. When an exposed object absorbs the emitted radiation its surface temperature is raised, often with disastrous consequences. The exact effects produced will be influenced not only by the location and dimensions of the fire ball, but by such spectrally dependent characteristics as the transmission of the interposed medium—air, clouds, fog, etc.—and the absorption of the exposed object. In fact, the effects are so dependent upon so many different parameters that the British Manual of Civil Defense, for example, goes into great detail on scaling laws for blast and fallout effects, but covers the thermal problem with this statement: "There is no simple scaling law for thermal effects of weapons of different powers."

Which brings me to my second confession: I can take a number of illustrative examples and tell you in simple situations what we can expect. I can take "worst case" examples and show you that they are less disastrous than some statements you may have heard. But, for an accurate description of what will happen in a complex, real-life situation, all I can do is put some rather broad limits on the range of possible results.

The first question one might ask is: How far from a nuclear detonation can one expect serious thermal effects? The most spectacular results so far reported (in an AEC-DOD statement in the June, 1959 Holifield Committee hearings) were for the Teak shot—one of two fired at high altitude near Johnston Island in the 1958 Hardtack series. The intensity of thermal radiation at ground level directly below this explosion, detonated just before midnight on July 31 at an altitude of 40 miles, was insufficient to produce even minor skin burns. Yet this same detonation produced small retinal burns in experimental rabbits at distances up to 300 nautical miles. Why? A cursory glance at the anatomy of the eye and some elementary optics provide the answer. The eye consists of a lens system which refocuses any impinging radiation into a retinal image of the emanating source. Assuming the same initial condition of the eye and neglecting any effects of atmospheric attenuation, as distance from the fireball increases the amount of energy per unit area of the retinal image does not change. Instead, the size of the image, and therefore the size of the burn lesions, decreases. During the Teak shot, for example, the lesions were approximately 2 millimeters in diameter at about 40 miles, decreasing to 0.5 millimeters at 300 miles.

Before the eye specialists among you are overwhelmed by the prospect of having to treat millions of cases of retinal burns, let me assure you that such prospects are extremely unlikely. The animals used in these experiments had been dark-adapted. They were oriented so as to be looking at the fireball. The altitude of the detonation maximized the fireball dimensions and minimized the duration of delivery of the thermal pulse to a time short compared to the blink reflex time of either rabbit or man. Thus, these experiments give an indication of what can be expected if one is sitting in the dark and looking up directly at the exact detonation point of a high altitude air burst. If he happened to be looking in some other direction and took a fraction of a second to face the explosion, he would be too late. If the detonation took place at more conventional altitudes, the radiation would be emitted over a longer period of time, and his blink reflex would then minimize the amount of energy delivered to the retina. Finally, he would have to be exposed on a clear night. The second Hardtack high altitude burst, called Orange, produced no thermal radiation effects and permitted no thermal radiation measurements because of cloud cover that existed at detonation time.

So much for the far-out thermal effects. How close to ground zero must we approach before we observe the more serious thermal effects? The distance is strongly influenced by weapon yield, both as it affects the amount of energy available and as it influences the time of delivery of this energy. Even in a vacuum the thermal radiation arriving at an exposed object decreases inversely as the square of the distance from the fireball. The radiation is further reduced as a result of attenuation by the atmosphere, by clouds, by smoke and dust kicked up by the detonation itself, and by any object interposed in the line of sight between the fireball and the receiver.

Some of these attenuating effects are obvious and straightforward; others are not. Thus, smoke and dust kicked up rapidly by a near-surface detonation will obviously attenuate much more of the thermal radiation from such a burst than will equivalent effects from a higher air burst, so that more severe thermal effects are to be expected from an air burst than from a surface burst. Also, as weapon yield goes up, pulse times lengthen and the thermal radiation produced becomes less and less effective in causing damage. This does not mean that the radius of effectiveness decreases with increasing weapon yield, but just that it does not increase as rapidly as one might first expect.

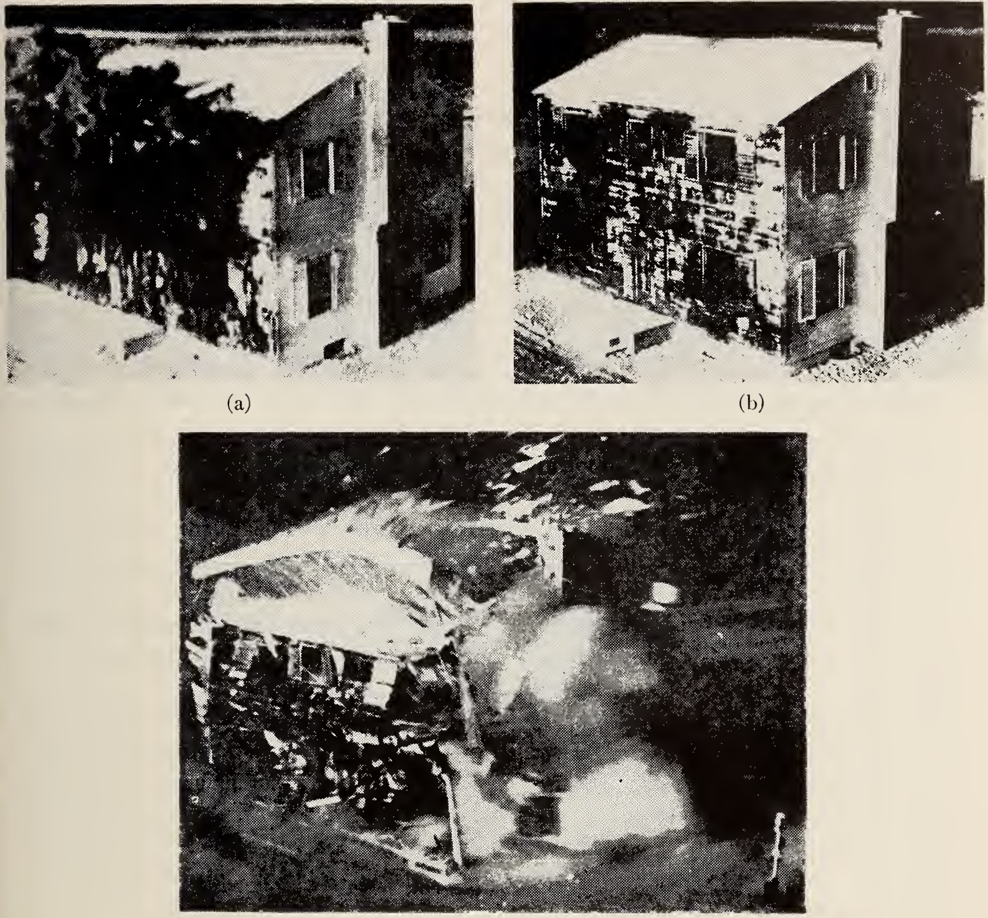
Perhaps the biggest uncertainty in predicting the distance to which thermal effects may be observed arises from our lack of knowledge about atmospheric attenuation. Clearness of the atmosphere is generally expressed in terms of visibility, but this is a measure of the direct line-of-sight transmission between a radiating object and the eye. Since atmospheric attenuation is largely a result of scatter rather than actual absorption of the radiation, multiple scattering will enable much of this radiation to reach a distant object. Thus, low visibility is not as advantageous as one might hope.

Now, suppose we have eliminated all of the complexities I have just mentioned and have obtained a curve of thermal radiation vs. distance from the detonation, what effects can we expect? One of the first effects that will be observed results from the direct exposure of bare human skin. Like any other receiving surface, the skin will be heated as it absorbs thermal radiation, and, if its temperature is raised above a critical value, a burn will result. If the skin is shielded by a layer of clothing, then it will be protected to some extent—unless the clothing ignites and in turn burns the skin. Thus, the extent to which a person exposed in the open will be burned depends upon how much clothing he happens to be wearing, upon such properties as the combustibility and the color and the opacity of his clothing, and upon how much of an air gap there is between the clothing and the skin.

At just about the same energy level necessary to produce burns on the skin, the most sensitive kindling fuels will begin to ignite. These kindling fuels include not only such thin materials as dried leaves and shredded newspaper, but also material like rotted wood, which appears to be a thick solid but which is really just an extended network of thin, porous, flammable material. Depending to some extent on factors such as relative humidity, moisture content, and duration of exposure, such kindling fuels may ignite and in turn ignite adjacent denser fuels. However, and this point has led to considerable confusion, it is impossible to produce sustained ignition by short pulses of thermal radiation in many fuels normally considered highly flammable. For example, a sound wood surface exposed to a short thermal pulse will char, perhaps quite badly, and flames may often be produced during the application of the radiant energy. But the temperature throughout the fuel will not be raised sufficiently to sustain an ignition and any flames which are started die out immediately after the exposure.

This last point is so universally overlooked—so frequently do we hear statements like: the thermal radiation pulse will "ignite virtually all flammable building materials"—that it would be profitable at this time, I think, to look at a few photographs. Figure 1(a) shows smoke pouring off the surface of a house exposed at 3500 ft from a 15-kiloton detonation at the Nevada Test Site. Figure 1(b) shows that as the thermal pulse faded all flames and smoke died out, leaving a charred but structurally sound surface. All too frequently, extinguishment of flames has been attributed to the effect of the subsequent shock wave. However, this frame-by-frame inspection clearly demonstrates that all flames were out before the effect seen in Fig. 1(c), which, of course, does show the arrival of the shock wave. Figure 2(a) shows three miniature houses exposed side by side at a distance too great to produce any severe blast effects. The house on the left is made of weathered, rotting wood. The house on the right is similarly constructed and in addition has trash, dry grass, and paper debris scattered around. The house in the middle is a well maintained structure made of fresh, sound wood. Figure 2(b) shows what remained following the detonation. The house on the right ignited almost immediately and burned rapidly to the ground. The one on the left was more slow to burn but disappeared almost entirely. The one in the middle survived.

You will notice that with Fig. 2(b) we have finally arrived at an illustration of the fire effects of a nuclear detonation. The fires illustrated here were started by thermal radiation from the detonation. Additional fires can be started by secondary blast effects: overturning of stoves, short circuiting of wires, etc. Since fire can spread rapidly, es-



(a) (b)

(c)

FIG. 1. Effects of thermal pulse on sound wood surfaces (FCDA photos). (a) During exposure; (b) Exposure ends; (c) Shock wave arrives.

(a) (b)

FIG. 2. (a) "The House in the Middle" before exposure (FCDA photo); (b) "The House in the Middle" after exposure (FCDA photo).

sentially the same degree of damage could very well result from fires produced by either effect alone. Thus, in considering the importance of thermal effects, one must compare the extent of ignition by thermal radiation with the extent of serious blast effects. Table 1 presents an official DOD summary to the Holifield Committee of the effects of 1 and 10 megaton nuclear weapons. The figures presented here are subject to considerable uncertainty. Many people will disagree with them. The basic conclusions one can draw from these figures, however, I believe are quite sound.

You will note that the area of thermal ignition is considerably larger than the area of blast effects and in fact is about as large as that given for the severe fallout effects—although the shapes of the two areas are not the same. The fallout pattern is assumed to be long and narrow; the fire pattern is assumed to be circular. Note also that the area given for fire effects represents only the area of initial involvement. Under extreme fuel and weather conditions, the final fire area may be many times larger.

Of course, once a mass fire has formed, its effects on people trapped in the open or in combustible structures within the fire area are obvious. Thus, thermal radiation effects, which for so long played second fiddle first to blast effects and then to fallout, are belatedly being recognized as capable of producing more damage for greater distances and with greater production of casualties than any other effect of a nuclear detonation.

If one accepts the relative order of magnitude of the numbers presented in this table, it is clear that a major concern of any effective civil defense program must be to find means of minimizing thermal radiation and fire effects. This is particularly true because mass fires may occur in peacetime, too, started by such events as earthquakes or a rambunctious cow knocking over a lantern. What can be done to reduce the likelihood of mass fire formation has been discussed elsewhere. Today I would like to focus on possibilities of survival should a mass fire occur.

TABLE 1. Summary of effects of nuclear weapons.*

Effect	1 MT	10 MT
Crater (dry soil)	R = 650 ft. D = 140 ft.	R = 1,250 ft. D = 240 ft.
Blast: Ignition–kindling fuels; debris injury to man	R = 3 mi. A = 28 sq. mi.	R = 7 mi. A = 150 sq. mi.
Thermal: Ignition–kindling fuels; 2nd degree burns	R = 9 mi. A = 250 sq. mi.	R = 25 mi. A = 2,000 sq. mi.
Initial nuclear radiation (700 r.e.m.)	R = 1.5 mi. A = 7 sq. mi.	R = 2 mi. A = 12.5 sq. mi.
Fallout (15 knot wind) (450 r.e.m. in 48 hr, no shielding)	40 mi. downwind 5 mi. crosswind A = 200 sq. mi.	150 mi. downwind 25 mi. crosswind A = 2,500 sq. mi.

* Testimony of Dr. Frank Shelton, Technical Director, Defense Atomic Support Agency, DOD, before Holifield Committee, 1959.

Statements about what might be needed to shelter people in a fire storm area are discouraging, to say the least. Often cited as illustrative of what we can expect in underground shelters in a fire storm area are the many victims found dead in shelters in bombed German cities such as Hamburg. Overlooked in these statements is the fact that these so-called shelters were located in basements of the typical, many-storied, well-built, German structures. When these structures were gutted by fire, as shown in Fig. 3, people in basement shelters below could certainly be "first asphyxiated and then cremated." However, a careful postwar review of the official German records by Kathleen F. Earp of the British Home Office reveals that more than 85% of the 280,000 people in the fire storm area did survive—including practically all of the more than 50,000 who sought refuge in bunkers and other non-basement shelters. Also overlooked in the pessimistic statements are such facts as the survival, near ground zero at Nagasaki, of the several hundred people who bothered to enter their hillside tunnel shelters.

In seeking information about the environment in large-scale fires we find, unfortunately, all too much practical experience to draw upon—in peace and in war, and in cities and in wildlands. The bombing attacks of World War II, however, added a new dimension to the fire problems. Large areas could now be ignited more or less simultaneously, enveloping whole cities in fire and burning them to the ground in a matter of hours. There is a tendency to forget that even before the introduction of atomic weapons at the end of World War II, such total devastation had been inflicted a number of times by conventional fire attacks on cities in Germany and Japan. For example, Fig. 4 shows a view of Hiroshima after atomic attacks and Fig. 5 shows the results of a conventional incendiary raid on Tokyo. As you can see, man has become more efficient in that he can accomplish the same result with fewer planes and weapons, but the effect is not particularly new.

Since World War II, we have, of course, made major improvements in our weapons of destruction and have done little, if anything, to decrease the fire vulnerability of our surroundings. Therefore, we can expect the results of any future conflict to be even more catastrophic. However, the fires we have already observed are sufficiently large that no new factors are expected which would significantly influence the environment within the fire zone.

For example, Professor Howard W. Emmons of Harvard has recently combined some of his earlier work with the work of others, including Sir G. I. Taylor and Professor Bruce R. Morton of England, into an analysis of the development of fire storms. His results show that the violent indrafts so characteristic of a fire storm can penetrate less than a half mile or so into a fire area and that inside these limits air to feed the fire must come as a result of mixing with the atmosphere above, rather than laterally. Thus, to people in the center of a mass fire a mile or so in diameter, the fire is already infinitely large and their environment would be no different if the fire were ten or a hundred or a thousand times larger.

In experimental investigations into methods of increasing chances of survival in a fire zone, we have so far been able to conduct experiments only on a scale small compared to the areas discussed here. However, we believe our results to be quite applicable not only to forest fires, which are the prime concern of the Forest Service, but also to urban residential areas—at least those consisting primarily of single family

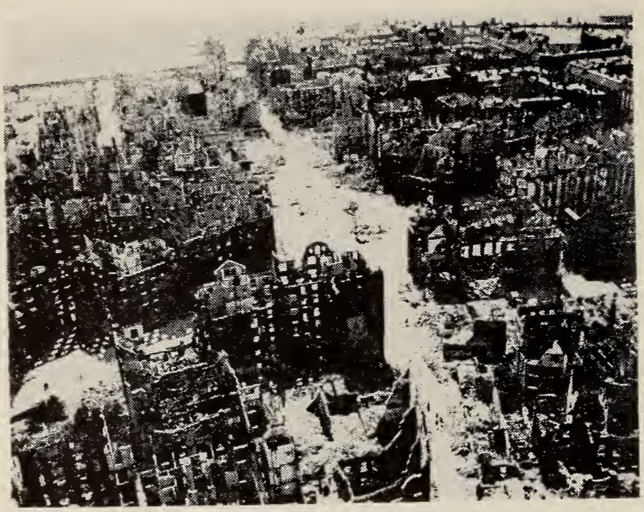


FIG. 3. Hamburg following the incendiary attack of 25 July 1943 (National Fire Protection Association).

FIG. 4. Atomic bomb damage in Hiroshima (U. S. Air Force photo).

FIG. 5. Tokyo after the March 1945 fire raid (Courtesy Dr. C. F. Sams).

dwellings. These results indicate that, with certain precautions, survival in simple underground shelters in the middle of a fire zone is highly probable.

Suppose, for example, that you find yourself in a simple backyard shelter with 3 feet of earth overhead and a mass fire raging around you. What can happen to you inside this shelter?

The first claim I have heard is that all the air will be sucked out of the shelter, implying the creation of an extreme vacuum overhead. I know of no evidence to indicate that anything but a very slight drop in pressure can possibly occur. The next argument, which probably formed the rational basis for the first one, is that the fire will consume all of the oxygen in the vicinity. If one computes the amount of oxygen needed to completely burn a typical single family residence, it may be shown that the necessary oxygen is contained in a column with base equal to the area of the house and height of just a few hundred feet. If one includes the air available over the street, backyard, and other open spaces this brings the necessary height down considerably lower. Looking at the turbulent air patterns that exist over a smooth sand beach or pavement heated by the sun, it seems obvious that the nonuniform fuel complex represented by any urban area will guarantee considerable turbulence. Short range downdrafts between burning buildings and violent lateral movement of air will be superimposed on the general strong updrafts. Thus, considerable internal mixing of air is bound to occur in all regions within the fire area and any general depletion of oxygen will be momentary at worst. One interesting point to bear in mind is that there is a close relationship between the amount of oxygen necessary for human survival and the amount of oxygen necessary for combustion. Thus, the continuation of active burning may be considered sufficient evidence that oxygen concentration in the vicinity has not dropped below that necessary for survival.

The next argument is that large quantities of carbon monoxide will be produced and will be drawn into the shelter. Unfortunately, our experiments have shown that this is indeed possible—in fact under many circumstances, highly probable. However, the amount of fuel available in any single location is consumed in a relatively short period of time—an hour or two of active burning at the most. Also, almost any shelter big enough for you to get into has enough oxygen in it to permit you to survive for an hour or two. Thus, if you can just close down the ventilation system for an hour or so, you should have little difficulty surviving the flaming portion of the fire burning overhead, and, provided the vent is located so that it will not be buried by rubble, any air you draw in subsequently should be relatively free of carbon monoxide. Conversely, if the vent is located in or near the house and winds up under a rubble pile, the high carbon monoxide concentration could be present for days thereafter.

The final problem of concern to anyone underground in a fire area would be the heat problem. Here again, it is easy to show that heat transfer through 3 feet of earth, or its equivalent, during a period of an hour or two is negligible and, again, the only problem that can conceivably occur would result from smoldering rubble piled high over the shelter.

Thus, if I were trapped in a forest fire area I would not hesitate to seek safety in an available underground shelter. And if I were building a fallout shelter, I would spend a few extra dollars to build it in my backyard rather than in my basement—locating the intake vent as far as possible from any combustible material. In such a shelter, I would expect to survive anything except the close-in blast effects.

One last point I would like to make concerns the interrelation of fire effects and the fallout pattern that one may expect. Mass fires produce convection columns with updrafts strong enough to move rather sizeable objects. Fallout patterns have been observed in experiments in the Nevada desert and over the Pacific Ocean where, since neither sand nor water can burn too well, few fires have been formed. I strongly suspect, and our wind tunnel experiments tend to confirm this suspicion, that in a region where mass fires are produced, the fallout distribution will be totally unlike that predicted from observations in Nevada or in the Pacific.

Figure 6 illustrates our wind tunnel results on the influence of a fire-induced convection column on fallout patterns. Figure 6(a) is the sort of pattern that is observed without fire, and Fig. 6(b) is a similar pattern with fire introduced into the tunnel. As may be seen, these results indicate the patterns will be moved further downwind; fallout will spread over a much larger area, and, consequently, the highest contamination levels will be well below those found if the fallout area were smaller. Figure 6(c) shows the effect of a smaller-scale fire in clearing an area downwind of it. Again, the fire zone and a large area downwind are remarkably free of fallout.

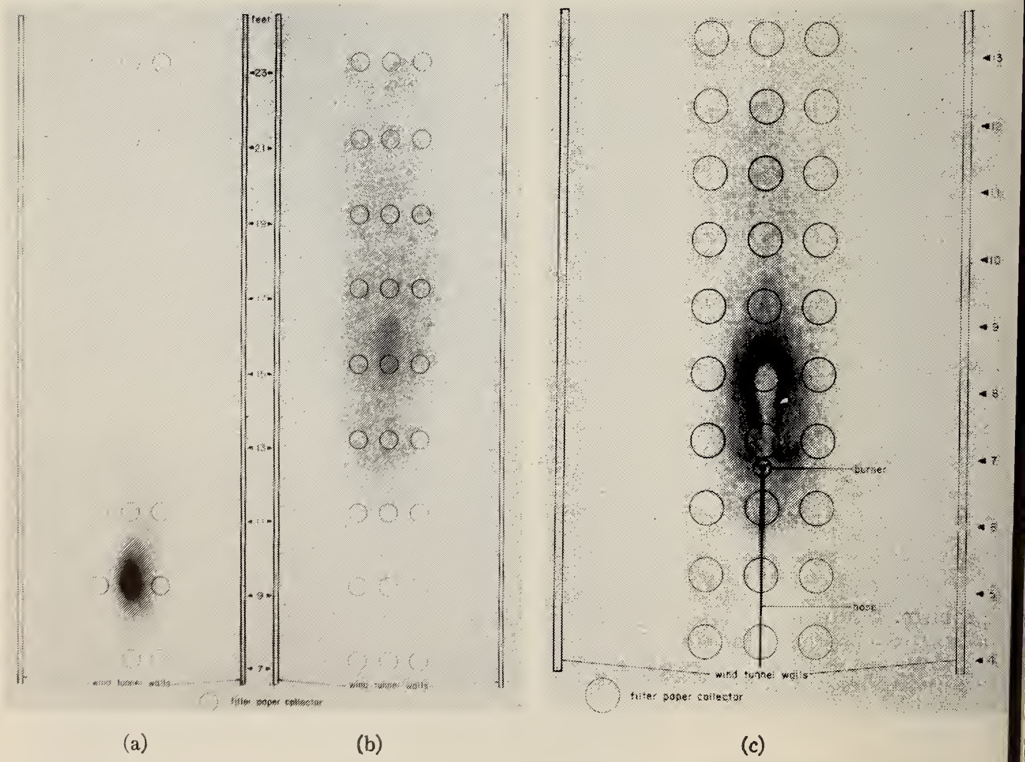


Fig. 6. Fallout patterns in wind tunnel: (a) Without fire; (b) Same conditions but with fire upwind; (c) Heat source is a small burner.

To summarize, then, the thermal and fire effects of thermonuclear detonations may, under the right circumstances, produce more casualties than any other effect of such detonations. The fires that are produced may be larger than any previously observed. Nevertheless, a careful look at our fire experiences of the past permits a reasonable prediction of effects to be expected in such large fires. Although the casualty figures which may be predicted are horrifying, statements to the effect that within such fire areas "all life ceases" represent a considerable exaggeration. Appropriate precautions may greatly reduce the number of casualties—not only in wartime but in peacetime also, especially in regions like southern California where large scale fires occur with distressing regularity under conditions in which a major loss of life can be expected at almost any time.

ABSTRACTS

I. Ignition Phenomena

Salooja, K. C. (Shell Research Ltd., Chester, England) "Effect of Temperature on the Ignition Characteristics of Hydrocarbons," *Combustion and Flame* **5,** 243–247 (1961)

Studies of the chemical reaction rates in flames are of both practical and theoretical interest. It is generally assumed that chemical reactions are the rate-controlling factors in continuous flow engines. Many investigators[1–4] have carried out fundamental studies on ignition lags of fuel; the ignition lag is regarded as a convenient index of the overall reaction rate responsible for ignition.

The object of the present studies is to investigate the ignition characteristics of fuels from temperatures near their minimum ignition points and upward and to observe the effect of fuel-air composition on this relationship. The method used was similar to that of Brokaw *et al.*[3] The hydrocarbons examined were selected from different structural categories and included *n*-heptane, methylcyclohexane, iso-octane, diisobutylene, benzene, and ethylbenzene. The results are presented on their ignition characteristics up to 800°C at 50°C intervals.

The results show that: (i) ignition lag decreases as the temperature is increased, (ii) all fuels investigated have between 0.1 and 0.3 sec lag at 800°C, (iii) at low temperature the lags are quite different for each fuel. The curves of the various fuels cross over each other so that at low temperatures one fuel may have the lowest ignition lag while at a higher temperature another would be favored. Benzene has the highest lag for temperatures below 700°C. Diisobutylene has the most unusual combustion behavior. It has the shortest lag up to 650°C and the longest lag above 730°C. Furthermore, its ignition lag remains virtually constant between 600 and 700°C.

Activation energies for the overall process were calculated and presented in a table.

The effect of fuel concentration from about 0.5 to 2.0 times stoichiometric was observed. There is practically no effect of fuel concentration on ignition lag at 800°C. In all cases at 550°C the lag increased at lean mixtures. Here again diisobutylene appeared to have an anomaly in that there is a cross over of the curves.

References

1. Mullins, B. P.: Fuel **32,** 218, 234, 327, 343, 363, 451, 467, 481 (1953).
2. Miller, R. E.: *Seventh Symposium (International) on Combustion*, p. 417. Butterworths, 1959.
3. Brokaw, R. S., Jackson, J. L., Weast, R. C. and Gerstein, M.: Ind. Eng. Chem. **46,** 2547 (1960).
4. Salooja, K. C.: Combustion and Flame **4,** 117 (1960).

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

W. C. Johnston

Schön, G. (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany) "Electrostatic Charging Processes and the Ignition Hazards Associated with Them," *Chemie Ingenieur Technik* **34,** 432–436 (1962)

A brief review is given (with 19 references to German reports, largely of work from the Physikalisch-Technische Bundesanstalt, Braunschweig) of the physical principles of electric charge build-up on solids, liquids, and sprays and of the resultant ignition hazards. Many commonplace operations, such as the flow of liquids or dusts through pipes or the fragmentation of solids and liquids can lead to the build up of appreciable electrical potentials. Arc discharge in a combustible atmosphere may supply sufficient energy to cause ignition and explosion.

It is argued that the charging-up processes depend on the difference between the charging and leak current. Experimental results are given for the charging current of a liquid (gasoline), pumped from a grounded reservoir through conducting tubes into an insulated receiver as a function of velocity and tube diameter. An approximate relation

$$J_\infty = \beta(\bar{v}R)^n$$

was found, where J_∞ = charging current, $\bar{v}$ = flow velocity (cm/sec), R = tube radius (cm), $\beta = 1.5\times10^{-12}$, and ($n \simeq 2$). A brief theoretical analysis of the charge build up for this experiment is given. The importance of adequate "grounding" of containers and of piping systems is emphasized.

During the discharge of carbon dioxide as "snow" from high-pressure containers charge accumulations have been observed in the resulting gas–solid mixture. The magnitude is a complex function of the fraction of CO_2 converted to solid and the presence of dust, rust, or water. Explosions from this cause have been reported during the "inerting" of potentially combustible areas.

Subject Headings: *Ignition, by electrostatic charge; Electrostatic charge, ignition hazard of.*

W. G. Berl

Litchfield, E. L. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Chronology and Topography of Sparks at Minimum Energy for Ignition," *Combustion and Flame* **5**, 235–241 (1961)

A study was made of the spark ignition of 8.5 per cent methane–air mixtures at 0.1 atmosphere pressure. By schlieren observations, the size of the shock-heated column, and of the inner kernel from which the flame originates, at which a self-sustaining flame front was established, was measured and the corresponding time delay was determined.

Single exposure schlieren photographs of the spark region were made with short duration (about 0.1 μsec) flash illumination. The time between the spark breakdown and the schlieren exposures was varied from 0.25 μsec to 20 msec, thereby giving a time history of the ignition process. The electrodes were 1 inch diameter with the electrode gap set at both slightly more than the quenching distance (0.63 in.) and slightly less (0.60 in.). The stored initial energy was 40 mJ and discharged through a hydrogen thyratron tube. No information on the wave shape or the duration of the pulse was given.

The results show that an essentially cylindrical shock wave is generated which expands at decreasing velocity. Within this column is another cylindrical kernel which expands at a lower velocity and from which the flame front emerges when the kernel wave velocity becomes less than the normal flame speed. The velocity of this inner front is the same even if the spark is discharged in a pure air mixture or if the electrode gap is less than the quenching distance so that no ignition occurs. The emergence of the flame front occurs after about 1 millisecond and the inner kernel has expanded to about 1 cm diameter.

The author discusses some of the observed structure of the wave fronts and compares his quantitative data with that of other investigators at atmospheric pressure. In general, ignition time is found to be inversely proportional to pressure.

The author presents some conclusions in regard to the mechanisms of energy dissipation from the spark column and the rate of energy release; however, they seem quite speculative. Measurements of spark voltage and current would have immediately clarified some of these points.

Subject Headings: *Ignition, by sparks; Methane, spark ignition of.*

R. W. Ziemer

Rae, D. (Safety in Mines Research Establishment, Buxton, England) "A Measurement of the Temperature of Some Frictional Sparks," *Combustion and Flame* **5**, 341–347 (1961)

A frictional spark is a solid fragment made visibly hot by impact and friction and possibly subsequent chemical reaction. The ability of such sparks to ignite gas mixtures is the subject of another paper.

The temperatures of certain frictional sparks were measured by a dual photocell device, utilizing the two-color method. The particles were heated by combustion to temperatures from 2500° to 4000°K, and had lifetimes of a few milliseconds. The wavelengths used were such that Wien's approximation to Planck's radiation law could be used. The photocell circuit could be adjusted so that the ratio of photocurrents coming from tubes sensitive in different wavelength regions could be calibrated against a standard lamp. In this manner, temperature measurements could be made to within ±100° at 2500°K. Since only ratios are used, the results are independent of the size of the sparks, even when they burst into fragments. A transient calibration was accomplished by discharging a capacitor through the circuit, and comparing this with the signal resulting from viewing the light from a standard lamp through a chopper.

It was found that a number of measurements could be made of particles placed on and ignited by a hot wire. In this manner determinations were made on fragments of burning pyrophor, magnesium, and titanium; also of sparks from the impact of titanium against rusted steel.

The pyrophor particles burned at a maximum temperature of about 2950°±100°K; whereas the magnesium particles had a burning temperature of about 4000°K. The latter measurement required considerable extrapolation of the calibration.

Titanium particles ignited on a hot wire burned at about 2800°K. Single sparks from titanium against rusted steel can attain temperatures up to 3000°K, and end up with an explosion, apparently as a result of their large size. The titanium and rusted steel appear to undergo a "thermite" reaction.

Subject Headings: *Frictional sparks, temperature measurement of; Temperature measurement, of sparks.*

J. K. Richmond

II. Thermal Decomposition

Heinrich, H. J. and Kaesche-Krischer, B. (Bundesanstalt für Materialprüfung (BAM), (Berlin-Dahlem, Germany) "Contribution to the Explanation of Self-Ignition of Wood," *Brennstoff-Chemie* **43,** 142–148 (1962)

To study the mechanism of self-ignition (called spontaneous combustion by some) of wood, experiments were made in three ways: (1) thermal decomposition was followed gravimetrically, (2) resulting thermal effects were observed by differential thermal analysis (DTA), and (3) the constant environmental temperature at which wood cubes eventually ignited was determined.

1. For thermal decomposition a Gast electronic microbalance, an aluminum block oven, chromel-alumel thermocouple, a recording temperature programmer, and a continuous weight recorder were used. Wood specimens were chips of beech of such weight that the maximum weight loss did not exceed 20 mg. They were dried by evacuating the apparatus for several hours before the oven was moved into position and heating started to raise the temperature 1°C/min. From the curves of weight loss against time and temperature against time the weight loss was plotted as a function of temperature. Decomposition became appreciable at 200°C, became rapid between 250° and 350°C, and was complete near 400°C with about 83 per cent weight loss. Differentiation of the integral decomposition curve gave the velocity of decomposition as a function of temperature, which revealed distinct maxima at 260°, 280°, and 330°C. By 380°C the reaction velocity fell nearly to zero. The three maxima reveal that the overall reaction is made up of at least three superimposed partial reactions, perhaps more if some have overlapping maxima.

Supplementary tests showed that specimen and oven kept the same temperature when the rate of heating was 1°C/min but for higher rates the specimen temperature lagged behind the oven temperature and the integral decomposition curves shifted to higher temperatures although the ultimate weight loss remained the same, about 83 per cent.

2. For DTA, wood cylinders 37 mm high by 25 mm in diameter, of beech, spruce, or pine, were heated either in nitrogen or in air with temperature rising 1°C/min. A continuous record was made of the difference in temperature between the center of the wood cylinder and the space between cylinder and glass wall of the container, with the tem-

perature difference expressed as a function of the oven temperature. An apparent initial endothermal effect was shown by tests with an asbestos cylinder in place of wood to be due to the difference in heat conductivity between wood or asbestos and gas. With wood heated in air there was a distinct peak of temperature at 190° for spruce, 205° for pine, or 210°C for beech that was absent when the heating was in nitrogen. Therefore an exothermic oxidation reaction is indicated. Above 220°C the DTA curves in air and in nitrogen were essentially the same and showed peak temperatures near 260° and 330°C for beech, 280° and 330°C for spruce, and 270° and 340°C for pine. Of the three maxima in reaction velocity observed in the tests of thermal decomposition in vacuum the first and third thus are found to be exothermic whereas the middle one occurs without heat effect.

3. For tests at constant environmental temperature, a wood cube 6 cm on a side, wrapped in a cage of fine wire mesh, was placed in the center of an 18 cm cubic cage of perforated sheet steel with the space between cages packed with rock wool for good thermal insulation and the whole was then set in a drying oven held constantly at a desired temperature. A thermojunction inserted at the center of the wood cube served to record its temperature. Suitable inlets and vents permitted the cubes to be flushed with a slow stream of air or of nitrogen during test. With the oven at 180°C and air present spruce, beech, or pine cubes reached the oven temperature in $7\frac{1}{2}$ hours, a heating rate of 0.4°C/min, and passed beyond the oven temperature without any fluctuation in the rate of rise in temperature because exothermic oxidation had already set in. After 9 hr for spruce, 11 hr for beech, and 15 hr for pine, when a temperature of 230°C and the onset of exothermic decomposition were attained, the temperature of the wood cube began to rise at a sharply accelerated rate until the cube began to glow. In nitrogen, on the other hand, the temperature leveled off at the oven temperature. In nitrogen with the oven at any temperature above that at which exothermic decomposition sets in (about 220°C) the temperature no longer leveled off at the oven temperature but surged past it to a peak and finally fell back toward the oven temperature as the decomposition reaction became exhausted.

Access of air to effect the highly exothermic oxidation reaction is necessary for self-ignition of wood. The exothermic decomposition reactions that occur in an inert atmosphere as well as in air do not yield enough heat to carry self-heating to the point of self-ignition. The test in constant environmental temperature with good thermal insulation yields the lowest temperatures at which self-ignition can occur in practice. For beech and pine the ignition temperature so defined is 180°, for spruce 160°C. But for very resinous pine, ignition can occur at lower temperature, even as low as 100°C. Blue stained wood and wood attacked by beetles also may ignite at lower temperature than normal wood. Experiments with resin obtained from pine, spruce, and larch revealed marked susceptibility to oxidative self-heating at relatively low temperatures.

Subject Headings: *Wood, spontaneous ignition of; Spontaneous ignition, of wood.*

F. L. Browne

III. Heat and Material Transfer

Huckaba, C.E. and Dickert, B.F. (University of Florida, Gainesville, Florida) "Transient Heat Conduction in a Multilayer Multicomponent System," *Chemical Engineering Progress Symposium Series 58*, American Institute of Chemical Engineers, 91–106 (1962)

This paper presents a numerical solution and a set of experiments on a particular two-dimensional, unsteady heat conduction problem. Reasonably good agreement between the numerical theory and experiment is obtained. The configuration studied is a series of stainless steel discs with discs of explosive between them surrounded by a containing heat insulating material. It is assumed that the discs of explosive provide an instantaneous source of heat. Using thermocouples, the temperature in the stainless steel and insulation is measured as a function of time.

The heat conduction problem with a given set of heat sources is solved using finite difference methods. A relatively loose network of grid points is used. The thermal conductivities of the heat source and insulating materials are taken to be temperature-dependent while other properties are constants. In order to obtain a solution with a reasonable amount of computer time, approximations are made on the relative magnitude of the radial and longitudinal temperature gradients. Although there is considerable scatter in the experimental data the numerical results seem to agree with experiment reasonably well.

Unfortunately results of the type presented in this paper are restricted to a particular problem. Extension to any other configuration would require verification. However, the success of the technique should encourage others who must solve multidimensional composite heat transfer problems.

Subject Heading: *Heat, conduction of, in multicomponent systems.*

D. L. Turcotte

Webster, C. T., Wraight, H.G.H., and Thomas, P.H. (Joint Fire Research Organization, Boreham Wood, England) "Heat Transfer from Burning Fabrics," *Journal of Textile Institute Transactions* **53**, T-29-T-37 (1962)

A possibility exists that some fabrics might have so little weight that heat transferred to the skin from combustion of the fabric would be unlikely to cause a burn. Measurements were therefore made of the heat transfer from burning fabrics. The measurements are also of interest in the study of flame-spread because the heat transferred from a flame to material ahead of it is a factor in determining the rate of flame-spread.

Two different experimental methods were used. For most materials a continuous record of the rate of heat transfer was obtained. With certain materials of low flammability another experimental arrangement was used which gave only the total heat transferred per unit area. In the first method the fabric was fitted over a wire cage surrounding a vertical iron pipe, which received heat from the burning fabric. The fabric was 2 cm from the pipe. In each experiment the lower edge of the fabric was ignited and the flames passed upwards. The pipe was filled with water, which was continuously stirred and its temperature measured. The heat transfer rate was measured by thermocouples at the inner and outer surface of the pipe. With some slow-burning fabrics uneven burning around the circumference gave results too variable to be useful. Therefore, a second method was devised in which a strip of fabric was held 1¼ cm away from a vertical asbestos board and then ignited at its lower edge. A copper block was mounted in a hole in the board opposite the center of the fabric, about 60 cm above its lower edge with its face flush with the surface of the board. The temperature rise of the block was measured by a thermocouple to give the total heat transferred to the block.

For most of the fabrics tested, cellulosic materials and wool-cotton mixtures, the amount of heat transferred from untreated fabrics is generally proportional to the weight per unit area of the fabric. From 1 g of fabric approximately 1200 cal of heat are transferred to the nearby surface. Some materials resulted in substantially less heat transfer. A cellulosic material with flame retardant resulted in heat transfer of only 230 cal/g.

Comparison of heat transferred to a surface as a function of time with heat dosage–time curves for second-degree burns and for unbearable pain suggested that most fabrics will transfer sufficient heat to cause severe burns provided the weight per unit area is in excess of 1.1 mg/cm^2. Fabrics of such low weight per unit area would be regarded as of little commercial importance; for example, a light muslin is about 3.5 mg/cm^2.

The maximum heat flux from the flame to the surface is about 0.7 cal cm^{-2} sec^{-1}.

Subject Headings: *Heat transfer, from burning fabrics; Fabrics, burning of, heat transfer from.*

A. E. Noreen

IV. Diffusion Flames

Kimura, I. and Ukawa, H. (University of Tokyo, Tokyo, Japan) "A Study of the Combustion of Laminar Fuel Jets," *Transactions Japanese Society of Mechanical Engineers* **27**, 736–746 (1961)

The flame length in the case of the combustion of a laminar jet of a gaseous fuel, which issues into the open air from a circular nozzle, is analyzed under the assumptions that the length of the nozzle diameter is much shorter than the flame length; combustion takes place without change in the number of moles; the densities, kinematic viscosities and diffusivities of the gases are everywhere constant and equal; and furthermore, the Schmidt number equals 1.

The fundamental differential equations for flow field and concentration field are as follows:

$$u(\partial u/\partial x)+v(\partial u/\partial y)=\nu y^{-1}(\partial/\partial y)[y(\partial u/\partial y)], \tag{1}$$

$$(\partial u/\partial x)+(\partial v/\partial y)+(v/y)=0, \tag{2}$$

$$u(\partial C/\partial x)+v(\partial C/\partial y)=Dy^{-1}(\partial/\partial y)[y(\partial C/\partial y)], \tag{3}$$

where x = distance from nozzle exit along jet axis; y = radial distance; u = axial velocity component; v = radial velocity component; ν = kinematic viscosity; C = concentration of a hypothetical gas composed of fuel gas and negative oxygen; and D = diffusion coefficient.

Since the boundary conditions for the u-field and the C-field are similar in this problem, the C-field can be expressed in a closed form which is similar to the u-field. From the obtained C-field, flame length H_0 is expressed as follows:

$$H_0 = (3/8\pi)(V/DC_{st}), \tag{4}$$

where V = fuel flow rate, and C_{st} = mole fraction of fuel gas in stoichiometric mixture.

Hottel and Hawthorne[1] have analyzed the flame length of laminar fuel jets, disregarding the flow field, and in this case flame length H_1 can be expressed as follows:

$$H_1 = -(1/4\pi)[V/D \ln(1 - C_{st})]. \tag{5}$$

It may be considered that H_1 expressed by Eq. (5) is the flame length when the fuel gas issues into a forced air flow of equal velocity, and H_0 expressed by Eq. (4) is the flame length when the fuel gas issues into the open air. When $C_{st} \ll 1$, from Eqs. (4) and (5), we get

$$H_0/H_1 = 1.5. \tag{6}$$

In relation to the above theoretical result, experiments on city gas flames in the open air and air streams are conducted, using the normal and the inverted arrangements. The experimental results show that the flame in open air is influenced by buoyancy and disturbance which is caused by combustion. However, it seems that if these are absent, the experimental results on the length of flames agree with the theoretical result, i.e., Eq. (6).

Furthermore, in this report some discussions for the effects of buoyancy and disturbances on the flame length are presented.

Reference

1. Hottel, H. C. and Hawthorne, W. R.: *Third Symposium on Combustion and Flame and Explosion Phenomena*, p. 254. Williams and Wilkins, 1949.

Subject Heading: *Combustion, laminar fuel jets.*

T. Kinbara

Agoston, G. A. (Stanford Research Institute, Menlo Park, California) "Controlling Mechanism in the Burning of Pools of Liquid Fuels," *Combustion and Flame* **6**, Letters to the Editor, 212–214 (1962)

The experimental observations of Blinov and Khudyakov[1] on the burning of liquid petroleum products in cylindrical containers or pans are explained by treating the burning of liquid pools in a manner analogous to that used in the convective evaporation and combustion of fuel drops.

It is assumed that a liquid pool burning at a specific ambient pressure under nonturbulent natural convection conditions, with negligible radiation, can be treated as a spherical fuel drop. A function is introduced to represent the regression (i.e., burning) rate in nonconvective (purely diffusive) burning, in the absence of flame radiant heat transfer and of heat conduction through the pan walls. An expression for burning rate as a function of pan diameter is derived:

$$v = (a_3/d^n) + (a_2a_3/d^{(n-3p)}) + a_4 + a_2a_4d^{3p}$$

where v is the burning rate, d is the pool diameter, and all the rest are constants. Assuming some reasonable and some arbitrary values for the constants ($3p=1$; $n=1$; $a_3=20$), a curve is calculated which matches the data of Blinov and Khudyakov.

The initial decrease of burning rate with increasing pan diameter is explained by an increasing contribution of radiative heat transfer and decreasing influence of rim effects. A minimum burning rate is reached at $d=90$ mm, and the rate now rises due to the effect of nonturbulent natural convection. An eventual leveling off of the rate curve with very large pan diameters, above 500 mm, is thought to result from a possible change in the character of the convection, such as a transfer from laminar to turbulent convection.

Reference

1. Blinov, V. I. and Khudyakov, G. N.: *Proceedings of the Academy of Sciences of the U.S.S.R., Physical Chemistry Section* **113**, 241 (1957).

Subject Headings: *Combustion, of liquid pools; Liquids, burning of, in pools.*

B. Greifer

V. Combustion Principles

Kende, I. and Gal, D. (Agreochemical Research Institute, Budapest, Hungary) "Investigation of the Inhibiting Effect of Styrene of the Gas-Phase Oxidation of Hexane with Labeled Molecules," *Combustion and Flame* **6**, 109–115 (1962)

The reaction of oxygen and hexane in a bulb was investigated at 226° and 238°C. Reaction rates were followed by pressure changes and by product analyses. The products were obtained by the freeze-out method. Carbon dioxide and aldehydes were determined. Styrene was found to inhibit the reaction, and some details of its action were determined by the use of styrene labelled at the α position with C^{14}.

The rate-of-pressure-change curves were analyzed in terms of a simple version of the theory of branching chain reactions. The pressure change was exponential with time, $p=N\exp(\phi t)$. The inhibitor appeared to have no effect on the reaction mechanism, as judged by a formal kinetic analysis. However, the results of the experiments with the isotopically labeled inhibitor did not support this result. On the assumption styrene does not affect the initiation rate (only the branching and termination rates) an equation was derived relating the time to attain the maximum rate in the presence of the inhibitor t_{max}, to the time to attain the maximum rate in the uninhibited reaction t_0.

This did not fit the experimental data well at the higher styrene concentrations. The theoretical analysis does not consider wall effects explicitly. Wall effects were present, as shown by the use of a KCl coating on the walls to obtain reproducible results.

When labeled styrene was used as the inhibitor, C^{14} activity was observed in both the CO_2 and the aldehydes. Rate curves for the formation of CO_2 and aldehydes are given. The CO_2 rate curves show that with lower inhibitor concentrations, less CO_2 is formed from the inhibitor, and the overall rate of CO_2 formation is decreased. There seems to be a correlation between the inhibiting action of styrene and its oxidation.

It is suggested this technique will be suitable for clarifying mechanisms of oxidation inhibition by other organic inhibitors. No explicit reactions are written for the styrene inhibition of hexane oxidation.

Subject Headings: *Hexane, oxidation of; Oxidation, of hexane; Inhibition, by styrene, of hexane oxidation.*

P. R. Ryason

Laffitte, P., Cusin, F., and James, H. (Laboratoire de Chemie General, Sorbonne, Paris, France) "Kinetic Study of the Carbon Monoxide–Oxygen Reaction through the Inhibition Mechanism of this Reaction," *Combustion and Flame* **6**, 163–172 (1962)

Dry carbon monoxide was oxidized by dry CO_2–free air in the presence of small amounts of ethane ($\sim$0.3% to $\sim$0.16%). A static system was used; the reaction vessel was fused quartz, and the temperature range was 500° to 600°C. Ignition delays were observed, and in the low temperature region pressure changes were followed.

The results are interpreted in terms of the theory of branching chain reactions. The variations of the slopes of the $d\Delta P/dt$ curves in the slow reaction above the second limit yield a total order of 1.5 and an activation energy of 59±2 kcal/mole for the initiation reactions

$$CO + \text{surface} \rightarrow CO\ (\text{adsorbed})$$

$$CO\ (\text{adsorbed}) + O_2 \rightarrow CO_2 + O.$$

The order is interpreted as a consequence of a competitive chemisorption of ethane. The exact reaction for this chemisorption is not given. The activation energy for the initiation step was also evaluated at the maxima in the delay curves and a value of 55±1 kcal/mole obtained. This activation energy is identified with the activation energy for chemisorption. The actual initiation reaction is considered to be

$$CO\ (\text{adsorbed}) + O_2 \rightarrow CO_2\ (\text{adsorbed}) + O.$$

Kinetics of chain branching and chain breaking in the gas phase are discussed. The difference between the activation energies of the chain branching and chain termination steps is given as 20±1 kcal/mole. Since the termination steps probably have very small activation energies, 20 kcal/mole is likely the overall activation energy for the branching reactions.

The inhibition of CO oxidation by ethane is asserted to involve both a surface inhibition of the initiating step and a gas phase inhibition reaction

$$C_2H_6 + O\cdot \rightarrow C_2H_5\cdot + OH\cdot$$

which "captures" oxygen atoms.

Subject Headings: *Carbon monoxide, oxidation of; Oxidation, of carbon monoxide; Inhibition, of carbon monoxide oxidation.*

P. R. Ryason

Singer, J. M. and Grumer, J. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Carbon Formation in Very Rich Hydrocarbon–Air Flames," *Bureau of Mines Report of Investigations 6007* (1962)

Except in special instances, smoking flames are undesirable in gas burning equipment. Accordingly, knowledge of smoke limits and the chemistry of very rich flames should be useful in designing gas appliances or other combustors of hydrocarbons. Although smoking tendencies of various hydrocarbon fuels have often been investigated, these studies have revealed little about flames at the smoke limit. Fuel–air compositions and the flow rate for smoking on a given burner diameter had not been investigated and it was not known whether the mechanism of smoke formation varied with fuels or with the fuel–air ratio.

A variety of propane and ethylene diffusion and premixed flames near the smoke limit were studied by various techniques. These primarily involved the determination of chemical composition profiles and temperature profiles within the flame zone. Complimentary techniques made use of spectroscopic analysis, measurement of ionization levels and examination of the form of particulate matter by means of electron microscopy.

The smoke limits, expressed in terms of fractions of stoichiometric and average flow velocities were measured in a Bunsen burner type flame, of varying diameter. Various types of flame are described, the change in shape and colour being attributed to aerodynamic rather than chemical reaction phenomena. The flame height was also measured and this is combined with the yellow tip limits, tube diameter and average gas velocity to provide a correlation between smoke limits and yellow tip limits in ethylene–air flames.

In determining the chemical constituent profile and temperature profile in weakly smoking flames, two types of flames were investigated, (a) open burning conical flames on cylindrical burners as in the experiments described above and (b) enclosed flat flames on a flat flame burner. A fully dimensioned diagram of this latter burner is presented. A very detailed analysis of the chemical constituents in various parts of the flame was made by probing the flame and analysing the sample using a mass spectrometer. Temperature measurements were made with a fine thermocouple. The results of these measurements are presented and lead the authors to the following conclusions pertaining to the mechanism of carbon formation in weakly smoking flames.

1) The similarity of gaseous combustion products in smoking flames and the similarity of temperature levels show that the mechanism for initial carbon formation is approxi-

mately the same for smoking flames of different configurations, premixed flames, and diffusion flames.

2) The absence of oxygenated products and the existence of high temperatures show that cool flame reactions do not occur in smoking hydrocarbon flames.

3) The absence of high-molecular-weight hydrocarbons and the temporal history of small concentrations of low-molecular-weight hydrocarbons in these flames show that carbon is not formed mainly by polymerisation but rather by direct splitting of carbon–carbon and carbon–hydrogen bonds.

4) Acetylene is the only stable combustion product that is present in carbon-forming zones whose loss from the gas phase parallels the amount of solid carbon formed.

5) The role of carbon monoxide in carbon formation is difficult to assess because of its involvement in many gas and gas–solid reactions. However, the experimental concentrations of carbon monoxide (and hydrogen) are less than theoretically expected from equilibria considerations. The concentration of carbon monoxide decreases with distance from the port in regions of the flame where the temperature is roughly from 500° to 700°C. This is the temperature region where the chemical equilibrium favors the formation of carbon from carbon monoxide. In such regions, the flame already carries carbon formed in earlier zones. Therefore, it is concluded that carbon monoxide may be involved in carbon growth, especially as the flame cools and in the presence of freshly formed carbonaceous particulates.

6) The carbon yield is increased when a solid surface such as a glass filter sheet is inserted into the yellow zone of a hydrocarbon flame. A water-cooled filter is more effective than a noncooled filter.

7) Judging from the results of this study, it is unrealistic to assume that (a) laminar diffusion flames burn by an infinitesimally thin zone where fuel and air meet in stoichiometric proportions with no fuel outside the flame, no free oxygen within the flame, and no extensive preflame reaction; (b) only diffusional mass and heat transport are significant; and (c) flame gases are in thermochemical equilibrium. Actually, considerable quantities of flame products and nitrogen from surrounding air are present in diffusion flames (inside of the luminous surface of the flame). Even free oxygen exists in small quantities well within the luminous flame front, and temperatures in excess of several hundred degrees Centigrade exist throughout the gases flowing towards the flame. Concentrations within the flame do not correspond very well to those expected from thermochemical equilibria considerations.

8) It was frequently observed that gases in the flame region where carbon first appears are richer in carbon-bearing compounds than the initial fuel–air mixture. It is concluded that this enrichment is by selective diffusion along concentration and temperature gradients and that it is fairly common in slow-burning very rich flames. The effect should increase the carbon yield above its normal value.

Electron microscope photographs of carbonaceous matter collected from rich flat flames of propane–air and ethylene–air show carbon growth to be either hollow filaments or granular spheres depending on the position in the flame.

Other experimental studies undertaken consist of the location of smoke zones in flames; chemical analysis of the carbonaceous matter collected from flames; pyrolysis of acetylene in concentrations appearing in smoking flames; identification of the spectral species present in smoking flames; flame ionization and the effect of radically altering the flame and burner geometry.

A very comprehensive bibliography of eighty references and a discussion of the literature pertaining to smoke formation add to the usefulness of this report.

Subject Headings: *Flames, hydrocarbon, carbon formation in; Carbon formation, in rich flames.*

G. L. Isles

Blackshear, P. L. (University of Minnesota, Minneapolis, Minnesota) "The Measurement of Physico-Chemically Controlled Ablation Rates," *National Bureau of Standards Contract CST-667, Technical Report No. 1* (July 1962)

This is the first progress report on a program in which the burning rate of cellulose is being measured under controlled conditions. Most of the paper is devoted to a review of a few of the more pertinent references that develop the concepts and formulae that the author intends to apply in interpreting the results of his measurements. Results of the author's preliminary experiments are presented and discussed, and a new apparatus, designed to provide more accurate data (and now under construction), is described.

From a study of literature on the reaction mechanism and the reaction rate for the combustion of wood, the author decides to adopt an Arrhenius-type pyrolysis law for the mass flux of material leaving the solid. The temperature appearing in the law is taken to be the "surface" temperature. The author acknowledges that the empirical rate constants in this law might depend strongly on both the initial experimental conditions and time.

Spalding's formulation of mass transfer theory is discussed and is adopted in order to relate the instantaneous mass burning rate to external and surface conditions (through Spalding's potential parameter B) and to the mass transfer coefficient. Theoretical results for the mass transfer coefficient are reviewed, and very rough correction procedures to account for variable fluid properties in the gas and for non-zero normal velocities at the surface are indicated. A prescription is given for deducing the surface temperature and the reaction rate constants from measured burning rates by employing Spalding's formulae.

The preliminary experiments consisted in setting cellulose cylinders on a Roller–Smith milligram balance, igniting the cylinders, and recording their weight at convenient intervals of time. Cylinders of various diameters and heights, constructed by bolting together α-cellulose filter discs, were employed. Mass transfer coefficients were calculated from theoretical results for free convection and were used in conjunction with the measured mass burning rates to compute B. Tables of the burning rate and of B for the various experiments are given, and a graph of B as a function of the initial moisture content of the cellulose is presented. The burning rate was found to increase as the initial moisture content of the sample was decreased. A preliminary indication that the burning rates (and hence, presumably, the empirical pyrolysis rate constants) are not very strongly dependent upon time was also obtained.

In the new experiment cellulose discs are to be rotated by a DC motor while they are burning in a hot air stream. The hot air is to be supplied by a blower and is to be heated in a heat exchanger by hot combustion products from a propane–air burner. The test section is to be enclosed so that final composition measurements can be made. The mass burning rate is to be measured by a novel device. Two selsyn rotors are connected by a torsion bar forming the shaft on which the cellulose disc rotates. The natural (torsional) vibrational frequency of the system depends upon the moment of inertia (and hence the mass) of the disc. This natural frequency will be measured by an electronic counter in order to determine the mass of the disc as a function of time.

Subject Headings: *Wood, combustion and pyrolysis of; Ablation rate, measurement of.*

F. A. Williams

Masdin, E. G. ("Shell" Research, Ltd. Chester, England) **and Thring, M. W.** (The University of Sheffield, Sheffield, England) "Combustion of Single Droplets of Liquid Fuel," *Journal of the Institute of Fuel* **35,** 251–260 (1962)

This paper concerns the application of well-developed experimental droplet-burning procedures to the study of fuels of practical importance. Some data are reported for kerosene, gas oil, heavy fuel oil, pitch creosote, and benzene. Results of practically all of the conventional measurements are presented, and discussions of the influence of these results upon combustor performance are given.

The apparatus consisted of a furnace with controllable temperature, gas composition, and flow velocity, into which a fuel droplet, suspended on a silica fiber, was inserted. Most of the data was obtained from photographic observations of the droplet.

Ignition delay times (in air) are reported as a function of furnace temperature for 1500 μ diameter droplets of each of the five fuels named above. These results are correlated by the formula

$$\text{delay time} = A \exp(b/T),$$

where T is the absolute temperature and A and b are constants. Although this correlation may constitute useful empiricism, it affords practically no insight into the physical and chemical processes controlling the delay time. Both A and b depend upon the size of the droplet, and the values of b differ considerably from those obtained by Mullins[1] on small ($\sim 100\ \mu$) droplets and believed to be representative of the overall activation energy of the chemical process. Comparison could profitably have been made with existing theory.[2]

The burning or evaporation constants for kerosene in air, in vitiated air, and in an inert atmosphere are given as functions of temperature. The decrease in the burning constant with increasing vitiation and the increase in the burning rate with an increasing forced convective velocity are discussed.

Fractional distillation is mentioned in connection with the observation that the square of the droplet diameter does not decrease linearly with time for gas oils.

The phenomena of droplet swelling and of residual solid fuel formation are discussed for heavy fuel oil and for pitch creosote. Irregular diameter-time graphs are exhibited and interpreted. A two-stage burning mechanism is discussed, involving gaseous combustion of the volatile components followed by surface combustion of the solid residue. Empirical burning times for each stage are given. Observations of the size and structure (principally, graphite crystallites) of the residual solid fuel are reported.

The concluding discussion of the effects of these phenomena upon combustor performance is interesting but, as the authors indicate, may be misleading since it is not couched in the framework of a spray combustion theory.

References

1. Mullins, B. P.: Fuel **28,** 205 (1949); *ibid.* **32,** 327 (1953).
2. Williams, F. A.: *J. Chem. Phys.* **33,** 133 (1960).

Subject Headings: ***Droplets, combustion of; Liquids, burning of droplets.***

F. A. Williams

Van Dolah, R. W., Zabetakis, M. C., Burgess, D. S., and Scott, G. S. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Review of Fire and Explosion Hazards of Flight Vehicle Combustibles," *Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, ASD Technical Report 61–278* (October 1961)

This report represents a critical review and compilation of various properties of combustible materials which are important in considering the prevention of fires and explosions in flight vehicles. Fuels, oxidizers, monopropellants, hydraulic fluids, and lubricants are included.

The report is divided into three sections. In the first section, brief discussions of the definitions of some terms and aspects of theories pertinent to the general problem are presented. Ignition of gaseous and liquid mixtures by means of various sources is discussed; flame propagation in homogeneous and heterogeneous systems including the effects of various parameters such as temperature, pressure, velocity of flow, gravitational fields, nature of oxidant, and effect of irradiation are briefly considered; flame extinguishment is also discussed. Finally, a brief discussion of the basic features of detonations is included.

In the second section the phenomena described above are considered in their application to problems of fire and explosion hazards on flight vehicles. Emphasis is placed on prevention of fires rather than on extinguishment, as a consequence of the hazards associated with even a small fire under flight conditions and the difficulties of applying conventional methods of extinguishment on flight vehicles. The cases of possible fires of monoisopropylbicyclohexyl, asym-dimethylhydrazine, and liquid hydrogen are considered to illustrate hazards and preventive measures.

In the final section, data on oxidizers and fuels of interest are presented, mainly in the form of vapor pressure–temperature curves in which flammability regions are indicated. Vapor pressure data are presented for fluorine, oxygen, chlorine trifluoride, nitrogen tetroxide, nitric acid, 90 weight per cent hydrogen peroxide, and for ethylene oxide. Vapor pressure data are also given for a number of fuels including hydrogen, ammonia, pentaborane, *asym*-dimethylhydrazine, methyl cyclpentodiene (monomer and dimer), methylhydrazine, *cis*-dimethyldecalin, *cis*- and *trans*-decalin, and tetralin. Figures illustrating the flammability characteristics and spontaneous ignition behavior in air of the above fuels are included. For hydrazine, monomethylhydrazine, and *unsym*-dimethylhydrazine, data on the effect of added nitrogen tetroxide on the flammability limits and the spontaneous ignition temperature are illustrated.

Subject Headings: ***Combustibles, fire and explosion of; Hazards in flight vehicles, of combustibles.***

J. B. Levy

Essenhigh, R. H. (The Pennsylvania State University, University Park, Pennsylvania) "Combustion Phenomena in Coal Dusts," *Colliery Engineering* **39,** 23–28, 65–70, 103–104 (1962)

The dust explosion wave in an experimental test gallery is diagrammatically illustrated. The mixture of coal dust and stone dust laid on the floor is dispersed and ignited by firing a cannon into an impetus tube. This "pioneer flame" extends 75 feet from the impetus tube or about 100 feet from the closed end. The intensity of the "pioneer" blast decays whereas that of the downward traveling flame increases. The combined effects result in a minimum blast intensity 100 to 150 feet from the closed end. For limit concentrations of dispersed coal dust this minimum becomes the extinction point. Rejecting the idea that this is due to the thermal load of the inert admixture, the author advances the assumption that inhibition of flame propagation results from dilution of dispersed coal dust by stone dust so that the lower limit of flammability is attained. During exposure to cannon and impetus tube, volatiles are liberated (the author does not speak of later-occurring volatile release) which, burning preferentially, augment the flame. The percentage of available volatiles is $V-V_0$, and the amount actually liberated $(V-V_0)(F-F_0)$ where $F-F_0$ is the "surface of escape." Alkali halides are more efficient than stone dust in quenching volatile reactions. "Firedamp has negligible effect on the initial blast intensity but it can be influential at the extinction point."

The dispersed dust quantity is independent of coal rank and fineness or type of stone dust (lubrication effect). The dust cloud concentration D_a of a mixture of coal and stone increases with depth of deposit, h_0, according to the equation:

$$D_a=D_m[1-\exp(-h_0/H_0)],$$

where D_m is the maximum concentration of mixed dust "at infinite depth," and H_0 an empirical constant.

The percentage of stone dust required for extinction by dilution of coal dust to the lower flammability limit D_L, is S_p, given by the "gallery extinction equation"

$$\ln[(100-S_p)/(S_m-S_p)]=D/D_0,$$

where D is the "nominal" coal dust concentration, corresponding to complete and uniform dispersion of the dust laid; D_0 is a constant corresponding to H_0; and S_m is the maximum of S_p for a given blast intensity. (Obviously this equation breaks down for $S_p=S_m$.)

An "Index of Inflammability" is defined as $Z=100/(100-S_m)=D_m/D_L$.

Consideration is given to the extra thermal load provided by unstable stone dusts that decompose or vaporize, and to the effect of firedamp, replacing coal dust on a weight–thermal basis.

Subject Headings: *Dust flames, propagation and extinction limit of; Coal dust, combustion of.*

H. M. Cassel

Nagy, J. and Portman, W. M. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Explosibility of Coal Dust in an Atmosphere Containing a Low Percentage of Methane," *U.S. Bureau of Mines Report of Investigations 5815* (1961)

Under certain conditions low percentages of methane may be present during coal mining operations. The present work describes the effect of low percentages of methane (0–5%) on the explosibility of coal dust in air atmospheres, in order to provide a broader understanding of the hazards of ignition and explosion, and thus to facilitate development of control and preventative measures.

Initial pressures and pressure-time curves were obtained for dust clouds produced and contained in cylindrical chambers and ignited by a continuous electrical spark. The initial pressure due to the dispersing cloud was subtracted from the peak pressure to obtain the maximum explosion pressure. The rate of pressure rise was taken as the steepest slope of the pressure-time curve.

The results of the investigations may be summarized as follows:

1. With low dust concentrations (0.1 to 0.4 oz/cu ft) small amounts of methane increase the explosion pressure; with larger dust concentrations (0.5 to 2.0) small amounts of methane decrease the explosion pressure.
2. The rate of pressure rise of the explosion increases as the methane concentration is increased until a maximum is reached, subsequent increases in methane concentration causing a reduction in the rate of rise.
3. The minimum explosive concentration of the coal dust decreases approximately linearly as the concentration of methane increases from 0 to 5 per cent.
4. The explosion pressure increases linearly as the initial pressure within the chamber increases.
5. Convection currents created by the air or gas blast used to disperse dust produce an increase in explosion pressure and rate of pressure rise.

Subject Headings: *Coat dust, explosion of, in methane; Methane concentration, effect on explosion, of coat dust.*

R. G. Siddall

Brown, K. C. and James, G. J. (Safety in Mines Research Establishment, Sheffield, England) "Dust Explosions in Factories: A Review of the Literature," *Safety in Mines Research Establishment Research Report No. 201* (1962)

The review covers: (1) combustion of single particles; (2) formation of dust clouds; (3) ignition of dust layers and clouds; (4) flame propagation; and (5) prevention of hazards in coal mines and industry.

(1) Photographic investigation of the burning of individual coal particles shows an initial broad trace, due to the burning of volatiles, followed by a longer trace, due to burning of residues. Orning (1942) studied the temperature history, finding a minimum after consumption of volatiles. He also noticed that at reduced temperature ignition may start only between neighboring particles, thus demonstrating a cooperative effect. He confirmed Nusselt's law (1924) for the lifetime of particles at atmospheric pressure but observed (1950) that increased pressure more than counterbalanced the effect of increase in oxygen partial pressure, inhibiting complete combustion. The phenomenon was explained by Spalding (1950).

(2) Reproducible dispersion of dust layers, depending on particle distribution and shape, hygroscopicity, cohesive forces, and static electrical effects, is difficult to achieve. Methods of dispersion by impinging gas jet, mechanical stirring or vibration, and by use of small detonators are discussed.

(3) Experiences on ignition by open flames, hot surfaces, adiabatic compression, and shock waves, friction, and sparks are reviewed.

(4) After Taffanel and Durr (1911) had produced stationary coal dust jet flames, Cassel and coworkers (1949) succeeded in the study of self-sustaining Bunsen-type dust flames exhibiting well-defined inner cone, blowoff and flashback. Applying flat flames burning on Mache nozzles, they showed an increase in burning velocity with increased flame area and estimated the contribution of radiation in the heat transfer through the flame (1957)

Flame propagation through open and closed tubes is discussed. In the authors' opinion the mechanism of ignition and flame propagation has not been explained satisfactorily although, regarding the necessity of considering radiative transfer, there is general agreement since Nusselt (1924) advanced the idea of radiation as the single source of ignition.

(5) Preliminary to estimating possibility of hazards, laboratory tests are required as well as large-scale experimental work. On a small scale, testing equipment for flame propagation; minimum ignition temperature; minimum explosible concentration; critical oxygen percentage; minimum spark energy; proportion of incombustible dust required for preventing ignition; and explosion pressure are indispensable. On a large scale, the characteristic of feeding once ignited dust flames by the whirling up of dust deposited on floors constitutes the most dangerous source of hazards. Measures to inhibit the spreading of such flames and the resulting destruction are discussed in detail: venting (Hartman 1957), dispersion of noncombustible dust, or water, wire screens as flame arrestors.

233 references are given.

Subject Headings: *Dust particles, combustion of; Explosions, in factories and mines, prevention of.*

H. M. Cassel

VI. Radiation

Long, V. D. (Imperial College, London, England) "Estimation of the Mean Radiating Temperature of a Cylinder of Combustion Gas," *Journal of the Institute of Fuel* **35,** 431–437 (1962)

The author begins by quoting the simplest relation expressing radiant heat flow (q_r'') between a gas-filled enclosure and unit area of a plane heat sink, viz.

$$q_r''=\sigma\mathfrak{F}(T_g^4-T_s^4)$$

where σ is the Stefan-Boltzmann constant; $\mathfrak{F}$ is an overall exchange factor which depends on gas and surface emissivities and geometry and has the maximum value of unity; T_g is the effective mean gas temperature; and T_s is the mean sink temperature. $\mathfrak{F}$ may be estimated by a formula of Hottel but the estimation of T_g presents difficulty.

The author goes on to review the various methods available for estimating the mean radiating temperature T_g including those of Lobo and Evans; Hottel; Fishenden and Saunders; and Dwyer. He then compares graphically values of T_g derived from Hottel's correlation, from the logarithmic mean and from the geometric mean of extreme temperatures for a range of values of outflowing gas temperature and a flame temperature of 3500°F. In this graph the flame temperature is assumed adiabatic and the logarithmetic mean values are based on two sink temperatures of 2000° and 1000°F. In the range of practical interest, the maximum difference between extreme values of T_g is about 180°F, which is equivalent to about 20 per cent divergence in radiative transfer.

The author's own treatment involves estimating the range of possible values of T_g in a cylindrical chamber with a "one-dimensional" temperature profile, in which the temperature remains constant radially but falls axially from a maximum at the inlet to a minimum at the outlet. The method sets two limits between which the temperature lies. The range of possible values depends on the ratio of sink to outgoing gas temperatures. The mean temperature so obtained may be used to predict the highest possible rate of radiant heat transfer in a furnace by considering an idealized model in which the fuel burns instantaneously at the adiabatic flame temperature and the temperature thereafter falls one-dimensionally to the exit value. Actual furnace behavior may be compared with the maximum rate and the minimum rate (which would occur in a well-stirred isothermal chamber with instantaneous combustion) by a coefficient of performance.

According to the author, the work of Lobo and Evans for large furnaces corresponds to the oversimplified model of a well-stirred chamber with instantaneous combustion. Rather surprisingly the method proved equally good for oil- and gas-fired furnaces, and gave estimates of overall heat transfer which are unlikely to be improved by any more rigorous method.

To permit a comparison of limiting and actual heat transfer in small cylindrical furnaces, heat balance data relating to two furnaces have been obtained. The heat transferred to the sink by radiation has then been compared with the calculated values for well stirred and "one-dimensional" profile chambers respectively.

The author briefly discusses the following results.

	Furnace	
	A	B
Radiation from heat balance (therms/hr)	7.6	13.0
Calculated heat transfer (therms/hr):		
Well-stirred (Lobo and Evans)	3.9	9.1
One-dimensional (Hottel)	9.7	21.5
One-dimensional (Author)	11.2	25.0

Subject Headings: *Temperature, mean radiation, of combustion gas; Combustion gas, radiation temperature of.*

R. Long

Beér, J. M. and Claus, J. (Research Station of the International Flame Research Foundation, IJmuiden, Holland) "The 'Traversing' Method of Radiation Measurement in Luminous Flames," *Journal of the Institute of Fuel* **35,** 437–443 (1962)

The thermal decomposition of hydrocarbons with the formation of incandescent soot particles mainly accounts for the radiation from luminous flames. The authors point out that there is considerable interest in correlating soot concentrations and temperature with radiations from flames because the results would be useful in predicting the heat transfer.

Radiation measurements on large industrial flames are discussed in this paper, the work forming part of the program of the International Flame Research Foundation at IJmuiden. By means of a narrow angle total radiation pyrometer enclosed in a water-cooled cylindrical jacket, the modified Schmidt method has been used to determine the effective flame emissivity and an effective radiation temperature, on the assumption that the spectrum of the wall radiation is continuous, the flame is grey, scattering is negligible, and the flame temperature is uniform along the beam and equal to the wall temperature. This method, although not rigorous, has been found to yield satisfactory results in hot furnaces like the IJmuiden tunnel furnace.

Thring, Foster, McGrath, and Ashton have used Mie's theory to predict the extinction coefficient for luminous hydrocarbon flames. The present authors have correlated experimental soot concentrations and temperatures measured in pressure-jet oil flames in the IJmuiden tunnel furnace with Schmidt emissivities using the formula

$$E_f = 1 - \exp\left[-K\int_0^L C\ dl\right](1-E_g)$$

where E_f is the total effective flame emissivity; E_g is the emissivity of the nonluminous gases; $\int_0^L C\cdot dl$ is the soot concentration integrated across the flame (mg l^{-1} cm); and $K = A'\lambda_{0.5}^{-a}$, where A' is a constant, a has values close to unity in general, and $\lambda_{0.5}$ is the emission mean wavelength (μ).

On plotting the experimental results, K was found to be 0.014 and 0.03 at 1675°K background temperature for flames with and without a stabilizer disk, respectively. Two possible explanations put forward were:

(a) Inapplicability of the Schmidt method because of considerable temperature and soot concentration gradients across the flames.
(b) Agglomeration of soot particles in the narrower stabilised flames decreasing the projected area of the soot.

The "traversing" method of radiation measurement was thus carried out to test the reliability of the Schmidt method under the conditions described. The authors have used a probe to obtain radiation traverses across the flames, and have correlated the radiation with soot concentrations and temperatures measured across the same paths. In the calculations, use was made of the relationship between luminous emissivity (E_l), soot concentration (C), and path length (l).

$E_l = 1 - \exp(KCl)$ with the extinction coefficient K expressed as a linear function of soot temperature ($K = BT$) so that $E_l = 1 - \exp(-BTCl)$.

The total radiation coming from all layers of the flame, in front of the radiation probe was predicted, and the radiation temperature of the flame in which changes in soot concentration and temperature were taken into account was calculated.

Computed traverses agreed well with those measured by the radiometer probe, when the values of B were those determined from the Schmidt method for the whole flame thickness. This substantiated the existence of the two values of the extinction coefficient K as determined for the two different types of oil flame in the IJmuiden furnace.

Subject Headings: ***Luminous flames, radiation measurement in; Radiation, measurement of, in luminous flames.***

R. Long

VII. Suppression of Combustion

Atlantic Research Corporation (Alexandria, Virginia) "A Study of Extinguishment and Control of Fires Involving Hydrazine-Type Fuels with Air and Nitrogen Tetroxide," *Technical Report No. ASD-TR 61-716, Wright Air Development Command Contract AF 33(616)-6918* (May 1962)

The use of hydrazine-type fuels with nitrogen tetroxide in missile systems has emphasized the need for information on materials and techniques for the extinguishment and control of fires arising from accidental spills of these propellants. Because of the unusual properties of these fuels, conventional fire-fighting techniques and standards could be inadequate for fires arising from leaks or accidental spills.

In this investigation, screening tests using small fires (6.5 sq in.) were conducted in the laboratory to evaluate extinguishing agents, which a theoretical analysis had indicated might be effective against hydrazine fires. The most promising agents were further evaluated in larger fires (up to 2304 sq in.) in an outdoor facility to confirm and extend the small-scale results and to provide data for scaling factors.

The fuels studies were: hydrazine, unsymmetrical dimethylhydrazine (UDMH), a 50:50 mixture by weight of hydrazine and UDMH, and JP–X (40 per cent UDMH and 60 per cent JP–4 hydrocarbon fuel). Both air-oxidized and nitrogen tetroxide-oxidized fires were investigated.

Water sprays effectively extinguished hydrazine fires by diluting the hydrazine to a concentration which would not support combustion. About one gallon of water was required per gallon of fuel. Fog was much less effective than water spray because the water droplets evaporated in the flame and reduced the amount of water available for dilution.

The alkaline hydrazine causes an alcohol-type foam to break down rapidly. The use of foam is, in effect, a gentle application of water. About 0.1 gallon of water in the foam is required per square foot of fire.

Dry chemical powders containing primarily sodium or potassium bicarbonate were also very effective against hydrazine fires, although the hydrazine could be reignited after extinguishment. As little as 0.04 pound of powder per square foot of fire applied rapidly extinguished fires.

Chlorobromomethane reacted with hydrazine and failed to extinguish the fire.

UDMH fires were extinguished by water sprays when the fuel concentration was reduced to approximately 30 weight per cent. The major scaling factor is the amount of UDMH present.

An alcohol-type foam was a more efficient method of applying water to UDMH fires. At least 0.25 gallon of contained water per square foot of fire is required.

Dry chemical powders composed of sodium bicarbonate were effective against UDMH fires. Rapid application of 0.1 pound of powder per square foot of fire was necessary for extinguishment. The UDMH could be reignited by a hot wire after extinguishment.

Trichlorotrifluoroethane (Freon 113) was effective against UDMH fires when applied at a rate of 0.5 gallons per minute per square foot to a total quantity of 1 gallon per gallon of UDMH.

The vapors above a 50:50 mixture of hydrazine and UDMH are primarily UDMH. The requirements for extinguishment are therefore similar to UDMH.

Water sprays were ineffective against JP–X fires because when water was added two immiscible layers formed, a hydrocarbon layer above a UDMH–water layer. The fires burned until the hydrocarbon was consumed.

A 6 per cent, alcohol-type foam was effective against JP–X fires. Approximately 0.16 gallon of contained liquid per square foot was required.

Sodium bicarbonate dry chemical was very effective against JP–X fires, requiring 0.1 pound per square foot for extinguishment.

When nitrogen tetroxide vapor is the oxidant 1.7, 3.8, and 2.7 gallons of water per gallon of fuel are required for extinguishment of hydrazine, UDMH, and the 50:50 mixture, respectively.

Contact of liquid nitrogen tetroxide with either hydrazine, UDMH, or a 50:50 mixture of hydrazine and UDMH resulted in explosions which precluded any attempt at fire extinguishment.

Subject Headings: *Fires, hydrazine type, extinguishment of; Extinguishment, of hydrazine fires.*

A. E. Noreen

Aidun, A. R. and Grove, C. S., Jr. (Syracuse University Research Institute, Syracuse, New York) "Additives to Improve the Fire-Fighting Characteristics of Water," *Bureau of Yards and Docks, Department of the Navy Contract NBy 13027, Final Report* (December 1961)

An investigation directed toward development of methods to improve the fire extinguishing effectiveness of water was conducted at Syracuse University Research Institute during the past four years.

The early part of this program was devoted primarily to determining the feasibility of the concept of improving the fire-fighting properties of water by the use of chemical additives. This study was divided into two phases: one phase was concerned with methods for increasing the viscosity of water, and the other phase with methods for reducing the transmission of radiant energy. Laboratory tests were devised for examining viscosity additives and opacifier additives.

The promising results obtained from the use of chemical additives led to the development of small- and large-scale fire tests. The investigation was directed toward the development of specific formulations which would improve water's extinguishing characteristics. Field fire tests were performed at Syracuse, N. Y., and at the Navy Fire School, Norfolk, Virginia in an effort to confirm the laboratory results.

Runoff Simulator Study

An apparatus was designed and constructed in order to screen out promising viscosity additives by studying the film cooling and runoff characteristics of plain and viscosity-modified water. A given amount of solution was allowed to flow down an inclined heated plate. When the last of the flowing solution left the plate, a liquid film remained. If the amount of water held on the plate can be increased by the use of viscosity additives, the rate at which the plate reheats should be lower and more cooling would be available to prevent reignition of material involved in fire.

Almost all of the viscosity additives tested were found to improve the runoff properties of water. Some viscosity additives, however, were found to be more effective than others. The results of the Runoff Simulator test indicate that optimum viscosity is in the range of 5 to 20 cp.

Opacifier Study

Methods were developed for the study of radiant heat transmission properties of various opacifiers. Lamp black and aluminum powder were found to be the most effective additives in absorbing or shielding radiant energy. Lamp black is a good radiant energy absorber but its use may be undesirable in efforts to prevent fire spread to adjacent structures. Aluminum powder appears to be a promising opacifier additive as it will reflect radiant energy away from the fuel.

Small-Scale Fire Tests

Eight pieces of California clear pine, each 1″×3″×10″, presoaked in kerosene, were used. The pieces of wood were arranged in two tiers placed at right angles to each other. This wood crib was placed in a steel chamber 4′×4′×8′ high. A 12″ square hole was cut at the bottom of two of the sides, opposite each other, in order to provide a draft.

A single nozzle (Full Jet 1/8 GG, manufactured by Spraying System Company), located directly above the crib, was used to spray the solution on the fire. The fire was ignited and allowed to burn until it reached a level of constant burning, as evidenced by visual observation and temperature records. The solution was then sprayed on the fire, and the time required to extinguish the test fire was determined.

All the viscosity additives tested tended to improve the fire extinguishing properties of water. Some viscosity additives were found to be more effective than others. The results also indicate that opacifiers such as aluminum powder in combination with viscosity additives further improve the extinguishing properties of water. The major portion of the improvement was, however, attributed to viscosity additives alone. Tests with opacifiers were therefore discontinued in order to concentrate efforts on the viscosity additives. It was also found that a detergent has very little effect, if any, on the extinguishing properties of water according to this test.

The overall results indicate that optimum viscosity is reached at or about 10 cp.

Large-Scale Fire Tests

A fire box, approximately 13′×12′×12′ high, was constructed of galvanized sheet metal. Four natural exhaust stacks and one variable exhaust fan were provided for adequate removal of smoke.

California clear pine, 2″×4″, was arranged in three tiers. The bottom tier consisted of 13 pieces each 36″ long, the second tier consisted of 12 pieces each 35″ long and the top tier consisted of 12 pieces each 34″ long, spaced one inch apart. Only the pieces of wood in the bottom tier were presoaked in kerosene. Water was sprayed from four (Full Jet 1/4 GG) nozzles equally spaced at a distance of 1.4′ from the center line of the crib and approximately 12′ above the wood crib. The solution was sprayed at a rate of 3.6 gpm.

Almost all the viscosity additives that were tested improved the fire extinguishing properties of water. Dow ET–460–4, Dow ET–570 and CMC were found to be the most effective viscosity additives. The improvement obtained with these additives at 5.5 cp viscosity was found to range from 50 to 75 per cent. The optimum viscosity for these additives could not be determined due to lack of proper spray patterns at viscosities higher than 5.5 cp. It was also found that the fires that were extinguished with these additives seldom reignited while almost all the fires extinguished with water reignited.

Viscosity appears to be a major factor involved in improving the fire-fighting properties of water. Other factors which must also contribute to the effectiveness of these additives are not very well understood.

Field Fire Tests

The results of the initial field fire tests were difficult to interpret because of a number of variables that affected the test results. The experience gained as a result of these tests was used to conduct the last series of tests on a more consistent basis. In this series of tests, efforts were made to minimize some of the variables such as fuel, the spray patterns of the solutions and method of fire fighting. New wood cribs 8′×8′×4′ high were constructed with 2″×4″×8′ long pieces of lumber. The spray pattern of viscous water was checked and adjusted to approach as closely as possible that of plain water. The firemen were instructed to fight all the fires in the same manner. They were to attack the bottom tier first and then move up to the other tiers. This procedure was to be repeated on all four sides of the crib.

During the initial field fire tests it was found that Dow ET–460–4 loses its viscosity under the shear force of the centrifugal pump of the fire truck and was replaced by Dow ET–570, which is considerably less shear-sensitive. It was also found that the spray pattern of viscous water and plain water could vary depending on the type of viscosity additive used and the viscosity of the solution, changing from a full cone spray pattern to a hollow cone spray pattern as the viscosity is increased. Viscous water does not break into fine droplets as does plain water. The hollow cone spray pattern was not as effective as full cone spray pattern in extinguishing crib fires. Nozzles that are at present commercially available are not designed to spray viscous water.

The results of the last series of field fire tests indicate that viscous water is more effective in initial "knockdown" and flame extinguishment than plain water. The viscous water was also found to be effective in hindering rekindling of fire after the initial suppression. In most cases the fire did not reignite. In those cases where reignition occurred, the rekindling was slower in starting, and cribs that rekindled burned at a lower rate than those that were sprayed with water. Viscous water (Dow ET–570) at 50 cp was found to improve the "knockdown" time over water by 40 per cent, the flame extinguishment time by 52 per cent and the complete extinguishment time by 28 per cent. Increasing the viscosity of water was found to improve the fire fighting characteristics of water up to a viscosity of 50 cp. The effect of increasing the viscosity beyond 50 cp could not be ascertained because of difficulty in adjusting the spray pattern of viscous water to approach the spray pattern of plain water.

Optimum viscosity depends on the type of fire being fought. A low viscosity solution would be more effective against a fire that is protected against direct spray such as a deep-seated hay fire. A low viscosity solution will penetrate more readily into such a fire than a high viscosity solution. A high viscosity solution would be more effective against a fire which is easily accessible by direct spray. A high viscosity solution will stay on the burning structure longer, and will therefore quench such a fire more effectively. The authors recommend a study to determine the optimum formulation and viscosity for different types of fires.

The results of laboratory fire tests indicate that viscous water (5.5 cp) was 50 to 75 per cent more effective than plain water in extinguishing the wood crib fires. The results of field fire tests indicate that viscous water (50 cp) was 28 per cent more effective. An attempt was made to explain this discrepancy. The variables of the experiments were more closely controlled in the laboratory tests than in the field tests. The large-scale fire tests were conducted indoors where the draft and exhaust system were uniform for all the tests. Outdoor tests such as field fire tests, on the other hand, are affected by weather. The spray nozzles were located in fixed positions above the fire in the laboratory tests while they were operated manually in the field tests. Extinguishment tended to be more efficient in the more effectively controlled laboratory fire tests than in the field tests.

The results also suggest that the use of viscous water might be of greater advantage in a sprinkler system of fire protection than for use from manually operated nozzles. The laboratory tests which simulate the sprinkler system yielded better results for viscous water as compared to plain water in extinguishing fire than the field tests.

The formulations that were found to be effective in the field fire tests were solutions of Dow ET–570 and of carboxymethyl cellulose, at viscosities between 10 and 50 cp.

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

K. Sumi

Davis, J. B., Dibble, D. L., and Phillips, C. B. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Firefighting Chemicals—New Weapons for the Fire Suppression Crew," *Pacific Southwest Forest and Range Experiment Station Miscellaneous Paper No. 57* (April 1961)

This paper is a study of the effect of thickening agents which increase the viscosity of water on the control and suppression of forest fires. Four chemical mixtures were used: (1) bentonite foam; (2) viscous water made up of sodium carboxymethylcellulose or sodium alginate to produce a controlled viscosity; (3) calcium alginate gel made up of sodium alginate and calcium chloride in water; and (4) diammonium phosphate in water. Two types of test procedures were tried: (1) field experiments under controlled conditions on grass, brush, and wood fires where extinguishment times and rates of rekindling were noted; and (2) field experiments with uncontrolled operational conditions on actual fires in the Nevada–California area were performed.

In the controlled experiments, fire suppressant effectiveness was found to be related to the viscosity. Recommended viscosity was between 100 and 400 cp requiring 4 to 6 pounds of thickening agent per 100 gallons of water. Bentonite foam was superior to plain water in heavy fuel fires but permitted low spreading of fires of grass and leaves. Viscous water was superior to plain water in preventing rekindling. Calcium alginate was even more effective and diammonium phosphate produced a fireproof barrier.

In the uncontrolled experiments, various operational problems were brought out: pumping pressure, corrosion, slipperiness, failure of some mixtures to penetrate matted material, cleanup problems after extinguishment, and other difficulties. However, in 24 out of 40 actual fires under a variety of fire-fighting conditions, crews commented on the superiority of viscous to plain water.

Subject Headings: ***Chemicals, fire-fighting; Water, improvement by chemicals, for fire fighting.***

D. Dembrow

Davis, J. B., Dibble, D. L., Phillips, C. B., and McBride, R. S. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) "Viscous Water and Algin as Fire Control Materials," *Pacific Southwest Forest and Range Experiment Station Technical Paper 71* (1962)

The characteristics and uses of viscous water and algin gel as fire control materials, based on laboratory and field tests and trials on forest and wildland fires, are described in this report.

Viscous water as defined in this report is plain water that has been thickened to a consistency of light motor oil (100–200 cp) with the addition of a viscosity agent. The agent is a polymer which has an affinity for water and produces fibers or threads of water which tend to unite. The two viscosity agents most used in fire retardents are sodium alginate and sodium carboxymethylcellulose (CMC).

Algin gel is the viscous water of sodium alginate to which a small amount of calcium chloride solution has been added. The addition of calcium chloride binds the water fibers together and the resulting structure is similar to that of gelatin. Because of its rigidity algin gel can form thick layers on fuel surfaces.

In laboratory tests with algin gel, the authors found that for temperatures ranging from 1000° to 1700°F and for drying times up to five hours, algin gel was superior to either bentonite or borate in preventing ignition of test fuels. The authors cite test results of other workers using viscous water. These results demonstrated the effectiveness of viscous water over plain water in extinguishing laboratory fires. Suppression time was reduced by one-fourth and the rate of rekindling was lowered materially.

Numerous field tests by other workers using viscous water and algin gel were acknowledged in this report. In most of these tests the extinguishment time or the reduction in rate of spread through treated portions of the fuel was measured to determine the fire suppressing and retarding effectiveness of the material. In one study viscous water retarded the spread of fire for a short time only, while algin gel was effective in retarding the spread of fire in both light and heavy fuels for several hours. In another study algin gel was the only retardent of several tested that completely prevented fire penetration into the treated fuel.

The effectiveness of viscous water and algin gel in operational tests was evaluated on 218 forest and wildland fires over a two-year period. On 85 per cent of the fires where viscous water was used, viscous water was rated positively or probably superior to plain water. On 13 per cent of the fires it was considered no better than plain water, while on the remaining two per cent, plain water was given a higher rating. Based on the limited number of fires where algin gel was used (six fires) this chemical appeared to be superior to plain water on two-thirds of the fires.

Little difference was found in the effectiveness of viscous water when used in different fuel types. It was least effective in timber fires when used in mop up, being more effective in direct attack. On more intense fires viscous water appeared to be more effective than on low intensity fires.

The report concludes with a section devoted to the characteristics of use of viscous water and algin gel. Methods of mixing, pumping and handling, and the problems in their use are briefly described. Some guidelines on usage are also presented.

Subject Headings: *Forest fires, control materials; Viscous water and algin gel, fire control by.*

W. Y. Pong

Palmer, K. N. (Joint Fire Research Organization, Boreham Wood, England) "The Quenching of Flame by Perforated Sheeting and Block Flame Arresters," *Symposium on Chemical Process Hazards*, **1960**: *Institute Chemical Engineers*

An effective flame trap consists of a solid matrix containing a group of passages of small cross-sectional areas through which gas or vapour can flow but which are too small to permit a flame to pass. The passages may be formed by the use of crimped metal ribbon, wire gauge, perforated sheeting, sintered metal or packed towers. They may be required to arrest flames arising from an ignition source either upstream or downstream of the trap.

The paper under review represents a contribution to the information available on the relation between the structure of the flame trap and its flame quenching properties. The work is a continuation of experiments reported previously by the same author.[1] In this paper are presented the results of experiments in which arresters consisting of sheets and blocks perforated with circular section holes were subjected to propane–air explosions. The sheeting consisted of brass or of polyvinylchoride of various thicknesses in the range 0.124–0.046 cm, the blocks used were of brass plate 1 cm thick, a number up to five of which could be placed in the apparatus in series. The size and spacing of the perforations were varied. The flame traps were tested in apparatus consisting essentially of a tube 6.4 cm in diameter, closed at one end, which could be filled with explosive mixture and in which the flame trap was mounted. Ignition could be caused at the open or closed end, and the velocity of the resulting flame was observed close to the flame trap by means of a camera. This velocity could be varied by changing the position of the flame trap relative to the ignition source.

The author found, as in reference 1, that the spatial velocity of the flame as it approached the flame trap was important in determining whether or not the flame passed through. For each arrester there was a critical velocity of approach above which the flame passed through and below which it was quenched. Two series of experiments were performed to determine the effect of the geometry of the flame trap on the critical velocity approach. In the first, the aperture diameter was varied systematically in the range 0.055 to 0.559 cm for brass and in the range 0.065 to 0.339 cm for polyvinylchloride, while in the second the thickness of the (brass) arrester was varied in the range 0.072 to 5 cm. Results for two mixture strengths are reported: 4% and 2.75% propane/air.

It was found from the first series of tests that the critical velocity was increased as the aperture size diminished, and that no systematic effect of the material of the arrester could be observed. The second series, as might be expected, showed that increasing the thickness of the arrester increased the critical velocity. The results are valuable in that they draw attention to the importance of the flame approach velocity in determining the performance of the arrester, but are difficult to use in practice in that it is not easy to assess the flame approach velocity in practical cases.

Reference

1. Palmer, K. N.: *Seventh Symposium (International) on Combustion*, p. 497. Butterworths, 1958.

Subject Heading: ***Flames, quenching of, by flame arresters.***

D. C. Martin

Rasbash, D. J. and Rogowski, Z. W. (Joint Fire Research Organization, Boreham Wood, England) "Relief of Explosions in Duct Systems," *Symposium on Chemical Process Hazards*, **1960**: *Institute Chemical Engineers*

Ducts are frequently used in industry to carry flammable gases from one part of a plant to another. To restrict damage due to explosions arising from the accidental ignition of the gases in such a duct system, relief vents are sometimes provided, which serve to control the progress of the explosion and restrict the maximum pressure to an acceptable value. The paper under review describes some results obtained as part of a program of research in progress to find the influence of the size and setting of relief vents on their ability to reduce the maximum pressure and flame speed of explosions occurring in ducts.

The duct systems considered were restricted to straight lengths of circular or rectangular section with and without a single obstacle to the gas flow in the form of either a central orifice, a central strip across the duct, a T piece or a bend. Two ducts of circular section were used, one 3 in. and the other 6 in. in diameter. One duct of rectangular section 1 ft. square was employed.

Three series of experiments were performed:

1) To determine the effect of end vents in straight ducts. In this series of experiments the influence of the area of vent on the maximum pressure and flame speed was determined for various duct lengths, for all the duct sections mentioned above, and for various initially stagnant mixtures of propane–air and pentane–air. The influence of the position of the point of ignition was also studied.

2) To determine the effect of obstacles placed inside a duct on the maximum pressure and flame speed. The results reported for this series of tests refer only to the duct of circular section 6 in. in diameter, and were for the most part obtained in a duct 12 ft. long, closed at one end. The obstacle was mounted in the middle of the length of duct and ignition effected at the closed end. The effect of placing relief vents in the end near the ignition source was examined.

3) To determine the effect of various methods of distributing vents along the lengths of a duct on the maximum pressure and flame speed. Here the square section duct was employed, the vents being distributed along the top of the duct either as rectangular openings or as longitudinal slots. In this series of experiments the vents were closed at the moment of ignition by thin sheets of polythene clamped to the edges of the vent or by light covers held to the duct magnetically.

In view of the wide range and diversity of practical duct systems the results obtained by the authors are necessarily limited in their direct application. In certain cases it is possible to use the authors' results directly to calculate venting requirements, but in many circumstances their inevitable lack of generality makes prediction difficult. Nonetheless the paper should be very valuable to those concerned with the design of duct systems and contains many useful practical recommendations.

Subject Heading: *Explosions, in ducts, relief of.*

D. G. Martin

VIII. Model Studies and Scaling Laws

Gross, D. (National Bureau of Standards, Washington, D. C.) "Experiments on the Burning of Cross Piles of Wood," *Journal of Research of the National Bureau of Standards,* **66C,** 99–105 (1962)

Experiments were made on the natural convection burning of cross piles of wood with controlled conditions. The wood piles were geometrically scaled and in each case the sides of the pile D was ten times the thickness of its sticks b. The pile was constructed in the same manner as Folk[1] and consisted of N layers each containing n sticks, with successive layers laid crosswise.

The piles were ignited by burning normal heptane in a square pan one stick layer below the pile. The amount of normal heptane used in each case was 8 per cent or less of the initial weight of the pile.

The burning rate (weight lost per unit time) was determined by weighing the pile as it burned. A typical weight–time curve was included which illustrates three stages of burning: (1) The build-up or ignition stage; (2) the active combustion stage corresponding to a maximum and relatively constant weight loss rate; and (3) the decay stage corresponding to collapse of the pile into glowing embers and ultimate extinction.

Investigations revealed no appreciable effect on burning when horizontal shields of either a highly reflective or absorptive surface were placed at or below the base of the wood pile. Vertical shielding, on the other hand, reduced the burning rate over 50 per cent. The vertical shield was a square tube of black iron twice the height of the pile with 7.62 cm clearance on all sides of a cubical 12.7 cm pile.

A horizontally mounted radiometer measured the radiant flux from the burning piles. The maximum radiant intensity was shown to be directly proportional to the maximum rate of burning.

Bryan[2] in his experiments on the burning of wood cribs concluded that the burning rate depended on the 3/2 power of the scale size. The author lets $Rb^{1.6}$ represent the scale rate of burning where R is the rate of burning expressed in per cent per second. A plot of the scaled rate of burning as a function of pile size is given which shows a limiting maximum $Rb^{1.6}$ of 0.62 for three configurations of wood piles. Each configuration differed in approach to the maximum $Rb^{1.6}$ value. This was reconciled by replacing the pile size with a porosity factor ϕ given by

$$\phi = N^{0.5} b^{1.1} A_v / A_s,$$

where A_s is the initial total area of the sticks and A_v is the vent area of the pile, for simplicity, taken as the open area of the vertical shafts. A plot of $FRb^{1.6}$ as a function of porosity was given for all sizes and configurations of wood piles tested. The factor F is a ratio of the thermal diffusivity of Douglas fir to that of the wood under test. The plot could be separated into three combustion regions: (1) diffusion-limited combustion, where the scale burning rate is nearly proportional to ϕ; (2) free combustion where the scaled rate of burning is independent of ϕ; and (3) nonsustained combustion.

A dimensionless correlation was shown between the dimensionless flame height H/D and the modified Froude number N_{FR}. The rate of burning r was assumed to be directly related to the mass flow of gas,

$$r = \rho_1 v D^2 / k.$$

The density of the hot gas ρ_1 is taken to be 0.00028, the weight ratio of gas to solid fuel[3] k is 6.1, and the vertical velocity of the gas is represented by the symbol v. The modified Froude number is then written:

$$N_{FR} = (T_0/\Delta T)(k^2 r^2 / g \rho_1^2 D^4 h),$$

where T_0 is the cold gas temperature absolute, ΔT is the gas temperature rise, and h is the height of the pile. The plot of H/D as a function of N_{FR} agrees with data of Thomas.[4]

A condition for similarity for a flow system involving radiation is that the ratio of radiative to convective transport of heat shall be constant. This was expressed in a "radiation group", essentially the inverse of a group used by Thring,[5] namely,

$$N_{\text{Rad}} = J/krc_g \Delta T,$$

where c_g is the heat capacity of gas. The maximum radiant intensity J based on measurements at a single point was used since the integrated radiation was not measured. The "radiation group" was shown to vary by only a factor of 3 for a 100-fold change in the modified Froude number. Thus the ratio of radiative and convective transport of heat was essentially independent of the modified Froude number.

References

1. Folk, F.: *Nat. Fire Protect. Assoc. Quart.* **31**, 115–126 (1937).
2. Bryan, J.: Unpublished data, U. K. Ministry of Home Security, 1943.
3. Kawagoe, K.: "Fire Behavior in Rooms," *Japanese Ministry of Construction, Building Research Report No. 27*, Tokyo, September 1958.
4. Thomas, P. H.: *Combustion and Flame* **4**, 381–382 (Letters to the Editor) (1960).
5. Thring, M. W.: *Research* **1**, 492–500 (1948).

Subject Headings: ***Wood, burning, natural convective; Burning rate, of wood.***

W. L. Fans

X. Meteorological Interactions

Inoue, E. (National Institute of Agricultural Science, Tokyo, Japan) "Studies of the Diffusion Phenomena in the Atmospheric Surface Layer. Part 1. Diffusion of Smoke from a Continuous Fixed Source on the Ground Surface," *Journal of Agricultural Meteorology* **15**, 123–129 (1960)

Two methods are presented for dealing with the diffusion phenomena in the presence of temperature and mean wind velocity gradient. The first method is a direct extension of the Taylor method making use of Lagrangian correlation functions, allowing for effects of thermal stratification. The lifetime τ of coupling turbulons in the Lagrangian correlation function $\exp(-\xi/\tau)$ obtained on the assumption that the similarity theory of turbulence is applicable to the atmospheric surface layer, depends on height and thermal stratification in terms of stability length L defined by Monin and Obukhov. The explicit expressions for the lifetime are given through dimensional analysis by

$$\tau_u = l\frac{z}{V}\left(1-\alpha\frac{z}{L}\right), \qquad \tau_v = m\frac{z}{V}\left(1-\beta\frac{z}{L}\right), \qquad \tau_w = k\frac{z}{V}\left(1-\gamma\frac{z}{L}\right),$$

where l, m, n, α, β, and γ are constants, V the friction velocity. While l, m, and n are theoretically obtained as 3.6, 0.9, and 0.4, respectively, the values of α, β, and γ are not known. The root mean square of wind direction fluctuations σ_A which determines the diffusion angle at the source point depends on z/L and z, but the definite expression for σ_A is not obtained.

In this method it has been taken for granted that the Lagrangian correlation function in the stratified atmosphere has the same expression as that on similarity theory, hence it is applicable only to nearly isotropic turbulent flow. However, there is a need for a method applicable to the lowest layers of the atmosphere where temperature and mean wind velocity gradient become predominant. To meet this need the author adopts a temporary method, i.e., applying (1) the Taylor method making use of the Lagrangian correlation function on similarity theory for lateral diffusion which is considered nearly isotropic; and (2) the Monin method which is found to be inconsistent for lateral diffusion with the Taylor method for vertical diffusion. The following relations are obtained by this method under respective conditions of stability:

(a) Extremely unstable: $\langle Y^2\rangle^{\frac{1}{2}} \sim x$, $\langle z^2\rangle^{\frac{1}{2}} \sim x^{1.5}$, $\chi_p \sim x^{-2.5}$

(b) Neutral: $\langle Y^2\rangle^{\frac{1}{2}} \sim x$, $\langle z^2\rangle^{\frac{1}{2}} \sim x^{0.8}$, $\chi_p \sim x^{-1.8}$

(c) Extremely stable: $\langle Y^2\rangle^{\frac{1}{2}} \sim x^{1\sim 0.5}$, $\langle z^2\rangle^{\frac{1}{2}} \sim x^{0.5}$, $\chi_p \sim x^{-1.5\sim -1.0}$,

where x and χ_p denote the downwind distance and the maximum concentration of smoke, respectively. It is noticeable that the relation under extremely unstable conditions cannot be obtained by the Sutton theory. These are in good agreement with Cramer's (1957) empirical results obtained in the Project Prairie Grass.

Subject Headings: ***Diffusion phenomena, in atmospheric surface layer; Smoke, diffusion of, from continuous source on the ground.***

T. Kinbara

McArthur, I. K. H. (Price's (Bromborough) Ltd., Bebington, Wirral, Cheshire, England) "Cetyl Alcohol Monolayers for Water Conservation—Methods of Application and the Influence of Wind," *Research Applied in Industry* **15,** 230–238 (1962)

This paper deals with the principles underlying the formation of monolayers of cetyl and stearyl alcohols to reduce the loss of water by evaporation from reservoirs. Problems arise in the applying of the monolayer and maintaining it under the influence of wind.

When a long chain fatty alcohol is placed on the surface of water, the molecules spread out to form a condensed monolayer, a film of about eight grams per acre being sufficient to provide an evaporation barrier. On a large area the monolayer will move over the surface under the influence of wind or mechanical forces causing a reduction in surface equilibrium pressure, allowing evaporation of water to take place unless there is an excess of the alcohol to restore the equilibrium pressure. The rate of spreading the molecular film depends upon the chemical composition of the alcohol, the temperature of the water, the wind velocity, and the method of application; and the retention of the film under various wind conditions is of great importance in field work where savings as high as 35% of total water have resulted.

Two methods of application are in accepted use: (1) as a solution in a hydrocarbon solvent fed below the water surface; (2) as a finely ground crystalline solid spread upon the water surface. The results of field experiments in Scotland compared both powder and solution methods of application and the effects of water temperatures under a variety of wind conditions. Gusts or wind velocities in excess of 15 mph made observations unreliable. No significant differences were noted between powder and solvent applications but a solution of 2% cetyl alcohol in kerosene was recommended as generally suitable for large scale work based upon both technical and economic considerations.

Subject Headings: *Water, evaporation of; Cetyl alcohol, application for water loss prevention.*

D. Dembrow

XII. Instrumentation

Baumgartel, F. A. (Bailey Meter Company, Cleveland, Ohio) and **Hage, W. T.** (Babcock and Wilcox Company, Alliance, Ohio) "Combustion Monitoring of Large Flames from Flame Spectra," *ASME Paper No. 61-WA-299* (1961)

This paper describes the background research for the design of a commercial flame-failure detector ("Flamon" detector, Bailey Meter Co.). The need for this device originates with the increasing power demands of our technology. This situation leads to very large and automatically controlled combustion-heated utility boilers in which combustion failure or malfunction from any one of many operational conditions can result in a catastrophic explosion. The detector must respond reliably and quickly to flame failure or its incipient conditions and initiate corrective action.

In the experience of the authors it is preferable to monitor flame emission radiation than to use immersed sensors. A study of the origins of the emission spectrum characteristic of furnace flames leads to the conclusion that the discontinuous spectra in the ultraviolet, below 3500 Å, is particularly valuable for monitoring stable combustion of gaseous or oil fuels. This portion of the spectrum is free of interference from non-flame radiation sources, e.g., black-body emission from furnace walls, and permits examination of primary combustion reactions even in multiple burners. Experimental data shows, further, that the OH (hydroxyl) radical is a good index of combustion conditions. Its emission spectrum is most evident at the 2811 and 3064 Å band heads.

Selection of an ultraviolet detector for a reliable instrument was influenced by the need for high spectral sensitivity only below 3100 Å, high signal amplification with low background noise, long operational life in a temperature environment of 300°F, and a capability of being used remote from its circuitry.

Photosensitive Geiger–Muller counters were found superior to photomultipliers in the most critical of these considerations. A modified counter was developed which reportedly exhibits the desired features in conjunction with a simplified ac circuit. This design has undergone field tests in over 300 flame detector installations since 1960. No details are given of this field experience. Similarly, the technical details about the modified Geiger–Muller type detector are not presented.

Subject Heading: ***Combustion, monitoring of, by flame spectra.***

K. M. Foreman

XIII. Fire-Fighting Techniques, Equipment Design, Materials of Construction

Safety in Mines Research Establishment (Sheffield, England) "Safety in Mines Research, 1960" London: Her Majesty's Stationery Office

The research efforts in 1960 of the Safety in Mines Research Establishment dealt with explosives and blasting devices, explosion hazards due to coal dust and firedamp, fire hazards due to hydraulic fluids and coal dust, rescue apparatus, engineering and metallurgical research, and the pneumonoconiosis hazard, and a number of special services. The noteworthy study of methane roof layers has resulted in fundamentally based working rules which make it possible to choose the best fitted remedial method. It is sometimes impractical to eliminate methane roof layering by increasing the ventilation velocity; methane drainage is more beneficial. Recommended values of a layering number determine which course should be followed. This layering number is directly proportional to the ventilation velocity and proportional to the cube root of the ratio of the volume of methane emitted/width of the methane layer. Methane roof layering may also be reduced by increasing the ventilation velocity by means of baffles on the floor. Air ejectors placed in the roadway entraining methane from the roof layer and ejecting it near the floor is another approach.

The investigation of the mechanism of coal dust explosions is being pursued on a laboratory scale; much of the current effort has been directed toward devising a means of producing coal dust clouds with desired physical characteristics. At present, dust clouds are generated by allowing dust to fall vertically through a tube from a vibrated hopper. Concentration of dust is measured photoelectrically. Propagation of flame in coal dust–air mixtures was not obtained in a $2\frac{3}{4}$-in. diameter tube. Present estimates are that 6-in. diameter tubes are needed for flame propagation in coal dust clouds. Some work is being done using lycopodium dust to simulate the propagation of coal dust explosions in a large volume.

Study of the ignition hazard due to friction of sliding rocks has indicated that the rate at which mechanical work is changed into heat by friction determines whether ignition takes place. It is possible that the fall of a heavy mass of rock can cause firedamp to ignite when frictional heating is concentrated in a small area. Smears of very hot metal deposited by impact friction of rock surfaces may also cause ignition. Experiments to determine size and temperature of smears necessary for ignition have been devised. The area of hot surface required to ignite methane–air mixtures depends on surface temperature, concentration of methane, and whether the heated surface is on the floor, wall, or roof. Surface temperatures in the range of 1000° to 1300°C are required to cause ignition by smears of hot metal resulting from impact friction on rock.

Attention was also given to instrumentation for the detection of coal fires. Since coal dust can start to smolder at temperatures as low as 160°C, it is well to detect such smoldering before it becomes an open fire. The instrumentation is based on a lead sulfide photocell and suitable transistorized circuitry, making it possible to detect at three yards distance a 3-inch-diameter surface heated to 150°C. In a related study, examination was made of the possibility of using factory-type fire detectors in mines. When such fire detectors were used around burning trays of alcohol, the detector operated satisfactorily in still air 8 feet above the fire, but would not operate satisfactorily in a ventilation current of 100 feet per minute with the instrument 1 foot above the fire. Hot gases from the fire were flushed away by the ventilation current and the temperature profile was beyond the resolving power of the instrument.

The report discusses many other activities of SMRE and concludes with an abstract of current publications and a bibliography.

Subject Headings: *Explosions, methane and coal dust, in mines; Prevention and detection, of explosions, in mines.*

J. Grumer

Shoub, H. (National Bureau of Standards, Washington, D. C.) "Early History of Fire Endurance Testing in the United States," *American Society for Testing Materials, Special Technical Publication No. 301* (1961)

Testing of building structures for their endurance in fire, necessitated by the rise of skeleton-type construction, was started in the last years of the nineteenth century. But before this, there was an effort to provide fire resistant buildings by the use of noncombustible materials such as masonry walls, and iron columns, girders, and beams. A particular problem, and the basis of many early tests, was the design of floors. The need for a fire resistive covering for the protection of iron—and later steel—columns also became apparent. To impede the horizontal spread of fires, resistive partition constructions were developed. In addition to presenting a review of some early tests for fire endurance of these structures and a few concurrent tests of building materials, the paper describes the establishment of ASTM standards for such tests, under the cognizance of what is at present Committee E-5.

Fifteen literature references are given, all covering work done prior to 1925.

Subject Headings: *Fire endurance, tests of buildings; History, of fire endurance testing, of buildings.*

Author's synopsis

Feuer, S. S. and Torres, A. F. (Atlas Chemical Industries, Inc., Wilmington, Delaware) "Flame Resistance Testing of Plastics," *Chemical Engineering* **69**, 138–142 (1962)

In an attempt to develop lightweight, corrosion resistant, fire retardant fume ducts and hoods, the authors have undertaken a re-evaluation of various standard fire retardance test methods. Two special requirements for fume duct plastics were set: (1) the material should be non-flame spreading; and (2) the products of combustion should not interfere with extinguishment.

Of the six standard test methods evaluated, one was considered of limited value for screening fire retardant materials, namely, the Underwriters Tunnel Test (ASTM E 84–60 T); another, the Radiant Panel Flame Spread Test (ASTM E 162–61 T) was considered highly satisfactory for plastic duct evaluation. A correlation between the results of the latter test and the results from actual fires on various thicknesses of plastic ducts was deemed high. The presence of 5% antimony oxide in a fire retardant form of polyester resin was claimed to increase both corrosion resistance and fire retardance at low cost for polyester plastics suitable for fume duct applications.

Subject Headings: *Plastics, fire resistance tests.*

D. Dembrow

Hollington, M. R. (Cement and Concrete Association, London, England) "Fire Resistance of Concrete Structures," *Institution of Fire Engineers Quarterly* **22**, 244–252 (1962)

It is impractical to make buildings absolutely fireproof, but experience and tests show that properly designed reinforced or prestressed concrete structures have extremely good inherent resistance to fire. Elaborating upon this thought and without describing either experimental or theoretical programs, the author discusses aggregates having good fire-resistant properties, standard fire-resistance tests, and typical fire-resistance values of structural elements, including reinforced concrete columns, separating walls, reinforced concrete beams, and concrete floors.

In discussing the importance of aggregates, he mentions that dark-colored basic igneous rocks, such as basalts and dolerites, have very good fire-resistant properties as aggregates because they do not disrupt physically or chemically at elevated temperatures. It is also pointed out that high fire temperatures have an effect on the iron compounds that are present in most aggregates and the result is a marked change in the color of the concrete. The characteristic concrete colors are correlated against fire temperature to provide a useful method of assessing the strength of reinforced concrete buildings that have been damaged by fire.

Throughout, instances are cited where Codes may be improved by the adoption of revised fire-resistance values.

Subject Heading: *Concrete, fire resistance of.*

E. C. Woodward

---

van Hoogstraten, C. W. (Institute of Fire Prevention, The Hague, The Netherlands) **and van Sante, F. J.** (Ratiobouw Foundation, Rotterdam, The Netherlands) "Fire Protection of Buildings," *Institution of Fire Engineers Quarterly* **22,** 130–141 (1962)

This article, translated from the Dutch original, relates to the activities of Committee F 7 of the Netherlands Institution for Standardization, which drafts recommendations for the fire protection of buildings. When the wording of a recommendation of the Institution was being reviewed, the authors of the present article deemed it appropriate to analyze critically the basic elements of the recommendation; actually so far these had been based more on a certain tradition than on a strictly logical line of thought.

The authors compare the merits of the almost universally accepted "fire-load" concept to those of the "point" method of Boué and Geilinger.

In requirements to be satisfied by a building as regards fire prevention the following points are stated to be important:

(1) The safety of persons, and possibly animals, present in the building;
(2) Guarantee for the safety of firemen;
(3) Chances of the fire spreading to adjacent buildings;
(4) Restriction of damage within the building.

The remainder of the article is devoted to an elaboration of these four points in such a manner as to justify less stringent regulations wherever possible.

Subject Heading: *Building codes, fire protection by.*

E. C. Woodward

National Research Council, Division of Building Research (Ottawa, Canada) "Fire Studies of the Division of Building Research, Nos. 1–8"

Fire Study No. 1, "Fire Research Furnaces at the National Research Council" by G. W. Shorter and T. Z. Harmathy (July 1960)

The property of a construction that directly relates to its ability to restrain a fire within a compartment is called its fire endurance; it is measured in hours.

Test facilities have been provided in the new Fire Research Building of the Division of Building Research of the National Research Council, Ottawa, to determine the fire endurance period of walls and floors. These facilities have been designed to achieve maximum flexibility and utilization in order to render an efficient service to Canadian industry and to further knowledge in the use of building materials for structural fire protection.

The main equipment consists of two major units, one for carrying out fire endurance studies on walls, and the other for studies on floors and ceilings. Each of these units can further be divided into a furnace assembly, and a device for loading or restraining the test specimen in accordance with the test specifications. The report describes the facilities and their operation in considerable detail.

The immediate problems that are now being studied include the influence of load, restraint, and moisture content on the fire endurance period, and the correlation between the American and British fire endurance data.

Fire Study No. 2, "Fire Test of a Plank Wall Construction" by T. Z. Harmathy (July 1960)

This report describes a fire test of a specimen of plank wall construction representative of a wall construction widely used in the province of Quebec. The specimen was 12 ft by 12 ft by approximately 9 in. The surface exposed to fire was gypsum wallboard. The unexposed surface was brick. Additional data are as follows: (1) white pine lumber was roughly sawn; it contained from 9.0 to 9.2 per cent moisture on the day of the test; (2) gypsum wallboards complied, according to the manufacturer's statement, with Specification A82.27—1950 of the Canadian Standards Association; (3) bricks were of red clay from local source and their moisture content was less than 2 per cent on the day of the test; (4) mortar was of portland cement–lime–sand type and contained less than 2 per cent moisture on the day of the test; (5) galvanized metal ties were made from 20-gauge steel strips of 1-in. width. Overall length was $4\frac{3}{4}$ in.; (6) building paper was asphalt-saturated felt paper, approximately 15.0 lb per 100 sq ft; and (7) vapor barrier paper was duplex vapor seal paper, approximately 2.9 lb per 100 sq ft.

The specimen had aged for 32 days at the time of the test, which was carried out in accordance with ASTM Specification E-119.

After 47 minutes deterioration of the wall became more and more noticeable. The lumber structure began to buckle under the applied load and thus to exert a thrust on the brick veneer layer. The brick layer gradually separated from the lumber structure at the top half of the wall, especially at the upper right-hand corner. At 57 minutes the brick layer finally became unstable and overturned, pulling with it the remainder of the Canadian wood structure.

Fire Study No. 3, "Fire Test of a Wood Partition" by T. Z. Harmathy (October 1960)

This report describes a fire test of a specimen of wood partition construction representative of non-loadbearing wood partitions widely used in British Columbia. The specimen was 12 ft by 12 ft by approximately 4 in. Some additional information is as follows: (1) the Douglas fir lumber was of 2 in. by 6 in. nominal size and was "dressed," and it contained 7 per cent moisture on the day of the test; and (2) the gypsum wallboard conformed to the Specification for Gypsum Wallboard A82.27—1950 of the Standards Association as well as to ASTM C36–54.

The specimen was built in a restraining frame. To ensure perfect restraint, the specimen was wedged along all four edges. The specimen had been aged 38 days at the time of the test, which was carried out in accordance with ASTM Specification E119–58.

After a very complete discussion of the detailed test results, the author estimates that the partition failed after 1 hr and 20 min.

Fire Study No. 4, "Fire Research at the National Research Council 1960" by G. W. Shorter (February 1961)

The Fire Section of the Division of Building Research (National Research Council) was established approximately ten years ago with the object of conducting research aimed at a reduction in the life and property losses by fire in Canada.

Much of the work undertaken in the Fire Section is formulated within the Division itself as a result of general considerations of the fire situation in Canada. Many problems are brought to the attention of the Section from sources such as the Associate Committee on the National Building Code, fire officials, government departments, industrial companies and private individuals. Inquiries are also received both from the United States and overseas countries.

The report discusses the programming of research work as well as the Section's excellent staff and facilities.

Typical studies of the Section which are discussed in the report include: (1) Fire Fatalities; (2) St. Lawrence Burns Operation; (3) Fire Endurance; (4) Fires in Corridors; (5) Combustion; and (6) Fire Extinguishment.

Fire Study No. 5, "Fire Test of a "Tri-Seal" Floor and Ceiling Assembly" by T. Z. Harmathy (June 1961)

This report describes a fire test conducted on a "Tri-Seal" floor and ceiling assembly. Specifications of the parts and materials are: (1) reinforced frame, made from refractory castable; (2) concrete slab 2 in. thick, made from ready-mixed concrete of 2500 lb/sq in. nominal compressive strength; (3) clipped steel mat, fabricated in conformance to ASTM A184–37 from $\frac{1}{4}$-in. billet-steel bars (ASTM A15–54T) of structural grade, with 12- by 12-in. spacing; (4) metal floor forms with inverted V-shaped corrugation along both edges, made by cold pressing from No. 28 gauge high-strength low-alloy cold-rolled steel sheet (ASTM A374–54T), cut to 10-ft by approximately 17-in. sizes; (5) "Macomber Allspan" steel floor joists of 12-ft clear span, conforming to size No. 210A of Macomber Design Manual MA–59; (6) $1\frac{1}{4}$-in. galvanized roofing nails with $\frac{3}{8}$-in. diameter head; (7) bridging angle of $1\frac{1}{2}$- by $\frac{3}{16}$-in. sizes, conforming to AISI C1020; (8) $\frac{1}{2}$-in. by 2-in.hexagonal head bolts, with nuts; (9) "Tri-Seal Loop Channels" made from No. 25 gauge galvanized cold-rolled carbon steel strips, conforming to temper No. 4 of ASTM A109–49T; (10) galvanized double-strand tie wires of W and M gauge No. 18; (11) pieces of perforated gypsum lath, with the fiber of paper coverings parallel to the short dimension (commonly known as "Perforated Tri-Seal Lath"), in $\frac{3}{8}$- by 16- by 48-in. dimensions, conforming to ASTM C37–54; (12) cold-drawn steel reinforcing wires of W and M gauge No. 12, conforming to ASTM A82–34; (13) base coat, $\frac{9}{16}$-in. thick, made from mill aggregated plaster of a composition of 100 lb neat gypsum plaster and 2.2 cu ft perlite aggregate; (14) $\frac{1}{16}$ in. finish coat, made from standard lime putty–plaster of paris mixture; (15) expanded metal lath in 12-in. wide strips, approximately 2.5 lb/sq yd; (16) red clay bricks and mortar; and (17) asbestos wool.

The specimen had been aged 120 days at the time of the test, which was carried out in accordance with ASTM Specification E119–58.

The test results and observations are given in great detail and are compared with the Robertson-Ryan criteria.

Fire Study No. 6, "Fire Test of a Steel Column of 8 in. H Section, Protected with 4 in. Solid Haydite Blocks" by T. Z. Harmathy and J. A. C. Blanchard (February 1962)

This report describes a fire test conducted on a protected steel column. The column was one steel H section of 8-in. by 8-in. nominal sectional size (weight: 31.0 lb/ft) and of 8-ft 2.5-in. length. The steel was protected by a single thickness of Haydite blocks (dimensions: 4 in. by 8.125 in. by 14.625 in.) which conform to ASTM C331–53T.

The specimen had been aged 35 days at the time of the test, which was carried out in accordance with ASTM E119–58.

The report includes a brief account of the test results.

Fire Study No. 7, "Ottawa—Hull Fire of 1900" by G. W. Shorter (June 1962)

This report contains a well written, almost graphic description of the great fire of 1900 which all but destroyed the thriving municipalities of Ottawa and Hull—separated only by the Ottawa River.

A defective chimney igniting a wood-shingled roof appears to be the main source of ignition.

Discussions of early fire-fighting methods, construction, and spread of the fire are particularly interesting.

Fire Study No. 8, "Report on Conflagration in Lanark, Ontario 15 June 1959" by M. Galbreath and C. G. Burnett (May 1962)

The conflagration which occurred on 15 June 1959 in Lanark, Ontario, destroyed approximately 33 buildings representing almost the entire business centre of this village of 950 people. The fire started shortly after noon and spread rapidly down the main street in a southerly direction. It was brought under control at about 3:45 p.m. after involving both sides of the street for 1½ blocks and having started a large number of smaller fires throughout the village. The town hall, fire department headquarters, telephone exchange, hotel, stores and apartments were among the buildings lost. The Dominion Fire Commission's report on Fire Losses in Canada gives $738,420 as the estimated total loss.

The National Fire Protection Association has made a study of conflagrations and has listed the principal causes by frequency of occurrence. The five most frequent causes attributed by the NFPA during the period 1925 to 1950 are as follows: (1) wind velocity in excess of 30 mph; (2) inadequate water distribution system; (3) lack of exposure protection; (4) wood shingle roofs; and (5) inadequate public protection. All of these factors were present to some degree at the conflagration at Lanark.

Although it is not possible to assign to any one factor the development of the initial fire to the extent of the conflagration that took place in Lanark, a number of contributory causes are suggested.

Subject Headings: *Fire research, study of large-scale, fires, endurance tests of materials; Fire endurance, tests of materials and construction; Fires, study of large scale.*

E. C. Woodward

BOOK REVIEW

Diffusion Burning of Liquids. V. I. Blinov and G. N. Khudyakov, Izdatel'stvo Akademi Nauk SSSR, Moscow, 1961. 208 pp. 1.28 rubles.

A monograph in an important field of fire research has now been made available by the translation of "Diffusion Burning of Liquids" by V. I. Blinov and G. N. Khudyakov. To the best of the reviewer's knowledge this is the first published treatise that deals in a comprehensive way with the scientific and engineering problems of a specific fire situation. It is an important contribution, summarizing a great body of work published by the authors and their associates during the past 15 years (without neglecting the relevant non-Russian literature). While some of the work had previously been published in Soviet scientific periodicals much of it was only available up-to-now in inaccessible reports of the Central Fire-Fighting Research Institute, Moscow and its Baku affiliate, the Institute of Energetics and the Leningrad Institute of Aviation.

The book deals with the general problem of liquids burning from a "free" surface in tanks. It is divided into three parts: The first section discusses the "Flammability and Ignition of Liquids," a subject in which much empirical data has been published for many years. As presented by Blinov, (who is responsible for this section and is co-author with Khudyakov on the other two) the subject is treated from somewhat a novel point of view. Combustion principles are woven with care into phase equilibria and vapor pressure relations of liquid mixtures. The author, however, is careful not to stray too far from the more limited objective of discussing the ignition properties of liquids. After briefly defining flash point and ignition temperature and describing the applicable apparatus, the theories of auto-ignition and forced ignition of gases are reviewed with skill. Flame propagation is discussed, first in homogeneous gas mixtures, followed by a review of the work of Ipatov on flame propagation across the liquid–vapor interfaces. The remainder of the chapter is given over to the interpretation of ignition data for liquids and mixtures with various phase relationships and ignitabilities. Whenever possible theoretical formulations of the problem are attempted and presented together with the experimental results.

The most interesting part of the book is the second section dealing with the experimental and theoretical analysis of the "Burning of Liquids in Tanks." An impressive number of observations, mostly quantitative, are assembled and discussed. In a series of investigations the authors and their colleagues have systematically investigated the free surface burning over wide ranges of tank sizes, fuel types, oxygen content, wind, etc., and, in addition, have obtained important data on flame oscillation, burning rates, temperature distribution, flame radiation, preferential distillation, etc. This is followed by determination of the temperature distribution in the liquid (making due reference to

Translated by Research Information Service, Division of Pergamon International Corporation, 122 East 55th Street, New York, N. Y., for U. S. Army Engineer Research and Development Laboratories, Information Resources Branch, Translations Analysis Section, Fort Belvoir, Virginia. Copies available from Office of Technical Sciences, U. S. Department of Commerce, Washington 25, D. C. AERDL T–1490.

the important pioneering study of Burgoyne), an analysis of the applicable heat transfer arguments and a study of the propagation of a homothermal layer into the cold liquid. It concludes with a discussion of "boilover" of burning liquids. The entire section is liberally supplied with experimental data and numerous references to the original literature. Having available a large amount of experimental information, with tanks ranging in diameter from 4 mm to 229 000 mm, 24 liquids of wide-ranging volatility, tanks constructed of glass, quartz, aluminum, and copper (including the possibility of water-cooling) it was possible to disentangle many of the variables that affect the burning rate and the heat flow into the liquid.

The final section of the book discusses "Extinction Techniques." A series of studies are presented on the extinction by stirring, including model studies of the aero- and hydrodynamics of the mixing process inside tanks. The use of foams, of water sprays, and of the two used in conjunction is described. Based on the available data conclusions are drawn about the most desirable extinguishing techniques in particular circumstances. The authors conclude ". . . . we may point out that diffusion burning of liquids in tanks has been studied for only two decades, but that much experimental evidence has been accumulated. This evidence demonstrates a number of important principles and gives us a reasonably clear picture of the processes of ignition, burning, and extinction. All the same, it must be considered as only the first stage in the construction of a detailed theory of the processes."

The translation appears well done. Typography of the English text unfortunately is poor, consisting of a mediocre reproduction of a typed manuscript with unjustified right-hand margin. Figures and Tables have been taken directly from the original, with English terms written in when needed. 2500 copies of the original were printed at the cost of the equivalent of about $1.50.

Readers of Fire Research Abstracts and Reviews are familiar with the authors through the review [Fire Research Abstracts and Reviews *1*, 41 (1959)] by Professor Hottel of their paper on "Certain Laws Governing Diffusive Burning of Liquids". This paper, which plays a prominent part in the book, led to correspondence with Professor Blinov, during the course of which he made available a gift copy of the book when it was published in 1961.

To the reviewer this book represents a valuable contribution to an important field of Fire Research. It presents an account of a carefully conceived study which over a period of years has been vigorously pursued and documented. The interplay between experiment and analysis is refreshing and stimulating. There are all too few comprehensive reports of this kind in existence (only Akita's "Studies on the Mechanism of Ignition of Wood" comes readily to mind). One's only regret is that the flow of information between the USSR and the Western World is so meager that this program was hardly known to anyone in its earlier stages and that no estimate was possible of the quality and quantity of the work. The treatise, therefore, marks not only a summary of a well-thought-out research program but provides a long-needed insight into Fire Research activities in the Soviet Union.

W. G. Berl

COMMENTS AND DISCUSSIONS

Pennsylvania State University Meeting on Dust Explosions

R. H. ESSENHIGH

On September 4 and 5, 1962, a meeting was convened at University Park, Pennsylvania to discuss "Dust Explosions." Attended by 53 registrants (including 5 from Europe) representing 35 different organizations, it was organized by the Departments of Fuel Technology and Continuing Education under the joint sponsorship of the Pennsylvania State University and the National Science Foundation.

Objectives and Organization

The objectives of the conference, as listed for the participants in a set of 8 points, can be described as "strategic" rather than "tactical": that is to say, it was an attempt to determine how many organizations and industries were concerned with the problem of dust explosions; how serious the problem was; whether sufficient research was being carried out to be able to cope with, and to abate the explosion hazard; and if not, how much more research was required, and how this was to be organized and carried out. As a further guide to participants in the discussion, "An Appraisal" on "Dust Explosion Research" was circulated beforehand that set out in general terms some of the problems involved with an indication to solutions.

To cover the 8 points of the objectives, the discussion was organized into three Sessions, and closed with a final summary by the General Chairman for the Discussion, Prof. M. W. Thring, who was assisted by three cochairmen, one for each session, with opening speakers for each session prearranged.

As initiator of the discussion, Professor R. H. Essenhigh was named Conference Director and Reporter.

Summary

Summarizing this conference is by no means an easy task because of the diverse points of view presented. To reconcile these will clearly be the task of some future conference.

The original hope had been that the conference would result, at least, in a blueprint of action for cooperative research, even perhaps implement the blueprint with action itself. In the event, however, achievement fell far short of this for a variety of diverse and conflicting reasons.

To the extent, then, that the original objective of the conference—as originally conceived—was not achieved, to that extent the conference failed; but to the extent that an alternative objective was achieved—that of bringing to light all the obstacles to cooperative action, and indicating what action can now be taken—to that extent the conference succeeded.

The rest of this summary is, therefore, concerned with what appears to have been achieved; and what, therefore, should now perhaps follow.

The starting point at least was unchallenged. The annual loss from dust explosions was estimated to be in the region of $75,000,000 at least, which was about $1,000,000 per explosion. In absolute terms the rate of loss is rising year by year, though whether this represents a rise or fall relative to the increasing size of the industries concerned was not decided.

This loss occurred in all branches of industry where flammable dust was involved: coal mining, flour milling, feedstuffs and agricultural dusts, grain elevators, plastics and synthetic resin manufacture, power station boilers, and metals production and using industries such as aluminum and magnesium, etc. Of current incidents, about half were concerned with agricultural dusts (30%) and plastics (20%), but boiler explosions represent a currently significant hazard.

To cope with this, the organization, both for research and for collecting statistics, is somewhat haphazard. About 25 laboratories are known to be currently concerned with research, but without any central direction or central forum for periodic discussion the potentialities for overlapping research in one area while leaving gaps unstudied in another, is very large. The exception to this, of course, is the Bureau of Mines, with its special area of coal dust explosions underground. Collection of statistics, so that developing trends can be spotted and watched, is also open both to overlapping in one area with gaps in another so that the overall picture may be distorted.

The purpose of research is to obtain knowledge that then must be disseminated throughout industry. To carry this out, there stands between research and industry those who may be called the "field educators"; this somewhat amorphous but vital group is made up of such people as plant safety officers, insurance inspectors, and so forth.

In reaching industry, the field educators provide the channel of communication between research and industry; but this only splits the education problem in two: when the field educators are themselves fully informed, they are able to reach industry with the necessary information; but the first requirement is to educate the educators.

The technique of communication, therefore, has at least 3 aspects:

In the first place, the field educators must themselves be trained, e.g., by some appropriate course or set of courses in which research techniques, results and applications are fully explained.

Then, to maintain that training, new research results must be abstracted, interpreted, and cast into an appropriate form for immediate use by the field educators. There is no reason why they should be expected to do the necessary interpretation of original research results themselves.

Finally, to maintain communication, adequate methods of dissemination are required: at present the *Fire Research Abstracts and Reviews* fulfill this purpose admirably, at least as a technical channel. The only question might be whether

> it is at present slanted too much in the direction of those in research, with too little at present for those who have to apply results in the field.

A further problem concerns the audience; it does not necessarily follow that industry will wait upon the pleasure of the field educators. In the case of large firms which have experienced several incidents there is usually no problem as they have adequate safety precautions, supervised by safety officers. The trouble always is with firms who do not know of, or who do not believe in the explosion hazard. If they have never had an explosion they assume their operations must be intrinsically safe, and they see no point either in taking safety precautions or in supporting research (both of which cost money). Those that have had one explosion are inclined to attribute this to "bad luck"; they take precautions which they assume will be adequate, and also assume that their first explosion will also be their last. Again, therefore, they see no point in supporting research. Industry, therefore, is split into two groups: those who admit the explosion hazard; and those who do not.

Up to this point, those attending the conference were in general agreement: not unanimous, but adequate, and agreeing to differ merely on details. It was beyond this point that two marked dichotomies of thought appeared. The first can be described as an argument of "Education *versus* Research"; the second concerned the argument as to whether or not the different industries involved had a common ground in the subject of dust explosions, i.e., whether the problem was a single theme, with variations provided by the different dusts involved; or whether each dust represented an individual problem, the common ground between dusts being small or even negligible, tending to zero. These two arguments were never resolved by the conference; but they represent such extremes of thought that concerted action seems most unlikely until they are resolved.

On the Education question, no one present disputed the need for more; the split in thought was whether any further research was really necessary. Those favoring education at the expense of research were quite convinced that sufficient was now known about dust explosions for adequate precautions to be designed for any conceivable case that might arise; all that is now missing is the application of available knowledge. This, it was commented represents either great faith, or great wisdom, or great bravery. Those who disagreed with the proposition seemed to be mainly those most closely connected with research; the Reporter must be included among those who disagreed most profoundly. Also very relevant is the set of 8 practical problems which some of the field educators, at least, would like to have answered. Also relevant is the nomogram (obtained in research reported at the conference) that can be used to predict vent ratios required in practical, industrial systems by scaling up from laboratory tests. If this new knowledge is of any value, it can only mean that previous knowledge was inadequate and thus disproves the contention of sufficient knowledge, at least prior to the conference.

The other point on which participants split, that of common ground, requires little more amplification. As the basis of the belief was never explicitly stated—it appeared to be treated as being self-evident—it was never possible to refute it explicitly. It is, however, refuted implicitly by the Cochairman's opening address to Session II, in which he summarized the academic problems.

A further mode of thought that came to light was the expression of a belief that there must be some significant difference in quality of thought between scientific and engineering research. Again, being stated as a belief, it was not possible to refute it explicitly. Though only a minor point, it was still sufficiently significant to be antithetical to acceptance of common ground in the problem.

Conclusions

This set of opposed views is regarded by the Reporter as being largely a consequence of failure of cross-communication, leading to ignorance of others' points of view. To bring this out, therefore, justified the conference. What chiefly emerges from all this is:

(1) The need for a soundly-based training course for the field educators, covering all aspects of knowledge on dust explosions from the most fundamental to the most applied.

(2) Creation of some adequate, periodic forum of discussion, either formal or informal, at which all those concerned with research on combustion and explosion of all dusts can meet: only then will it be possible to decide whether dusts present a single problem with variations, or a set of totally unrelated problems.

(3) As a consequence of both the training course and the discussion forum, it is to be hoped that these will provide and promote the accurate and valid interpretation of past, present, and then future research results; with the byproduct, it is to be hoped, that well-presented interpretations of research results will become available for use by the field educators.

(4) Finally: should any future action be contemplated to amplify and extend current research activities, the discussion of Session II—with its survey of problems all the way from the most fundamental to the most applied—may provide the necessary ground plan for a properly balanced program.

INDEX OF AUTHORS

INDEX OF SUBJECTS

ABSTRACTORS

THOMAS C. ADAMSON, JR.
University of Michigan

GEORGE A. AGOSTON
Stanford Research Institute

JOHN J. AHERN
General Motors Corporation

THOMAS P. ANDERSON
Northwestern University

RAJAI H. ATALLA
Newark, Delaware

LOREN E. BOLLINGER
The Ohio State University

PETER BREISACHER
Aerospace Corporation

FREDERICK L. BROWNE
Madison, Wisconsin

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

HANS M. CASSEL
U. S. Bureau of Mines

WELBY G. COURTNEY
Texaco Experiment, Incorporated

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

GLADYS S. CUFF
Ethyl Corporation

DANIEL DEMBROW
National Aeronautics and Space Administration

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

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

R. H. ESSENHIGH
The Pennsylvania State University

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

FELIX FALK
Applied Physics Laboratory
The Johns Hopkins University

W. L. FONS
Southern Forest Fire Laboratory
U. S. Forest Service

K. M. FOREMAN
Republic Aviation Corporation

ALLEN E. FUHS
Aerospace Corporation

ARTHUR L. GOLDSTEIN
Ionics, Incorporated

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

BERNARD GREIFER
Atlantic Research Corporation

L. R. GRIFFITH
California Research Corporation

GEOFFREY L. ISLES
The University, Leeds (England)

OLIVER W. JOHNSON
Johnson-Williams, Inc.

WILLIAM C. JOHNSTON
Westinghouse Research Laboratories

J. RENE JUTRAS
National Research Council (Canada)

IRVING R. KING
Texaco Experiment, Incorporated

WILLIS G. LABES
Illinois Institute of Technology

JOSEPH B. LEVY
Atlantic Research Corporation

RONALD LONG
University of Birmingham (England)

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

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

D. G. MARTIN
Imperial College (England)

HOWARD N. McMANUS, JR.
Cornell University

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

C. C. MIESSE
Westinghouse Electric Corporation

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

A. E. NOREEN
Boeing Airplane Company

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

HENRY EDGAR PERLEE
U. S. Bureau of Mines

M. G. PERRY
University of Sheffield (England)

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

LOUIS A. POVINELLI
National Aeronautics and Space Administration

J. KENNETH RICHMOND
Boeing Airplane Company

DANIEL E. ROSNER
AeroChem Research Laboratories, Inc.

PETER A. ROSS
Boeing Airplane Company

WILLIS A. ROSSER, JR.
Stanford Research Institute

P. R. RYASON
California Research Corporation

R. H. SABERSKY
California Institute of Technology

R. G. SIDDALL
University of Sheffield (England)

JOSEPH M. SINGER
U. S. Bureau of Mines

PHILIP L. START
University of Sheffield (England)

ALEXANDER STRASSER
U. S. Bureau of Mines

K. SUMI
National Research Council (Canada)

CLAUDE P. TALLEY
Texaco Experiment, Incorporated

DONALD L. TURCOTTE
Cornell University

FORMAN A. WILLIAMS
Harvard University

HENRY WISE
Stanford Research Institute

E. C. WOODWARD
University of South Carolina

F. H. WRIGHT
California Institute of Technology

RICHARD W. ZIEMER
Electro-Optical Systems, Inc.

E. E. ZUKOSKI
California Institute of Technology

THE FIRE RESEARCH CONFERENCE

H. C. HOTTEL, *Chairman*	Director, Fuels Research Laboratory Massachusetts Institute of Technology
KEITH ARNOLD	Director, Division of Forest Fire Research Pacific Southwest Forest and Range Experiment Station
WILLIAM H. AVERY	Research and Development Supervisor Applied Physics Laboratory The Johns Hopkins University
J. S. BARROWS	Chief, Division Forest Fire Research Intermountain Forest and Range Experiment Station
L. M. K. BOELTER	Dean of Engineering University of California, Los Angeles
HORATIO BOND	Chief Engineer, National Fire Protection Association
B. P. BOTTERI	Wright Air Development Division Wright-Patterson Air Force Base, Ohio
MATHEW M. BRAIDECH	Director of Research National Board of Fire Underwriters
A. A. BROWN	Director, Division of Forest Fire Research U. S. Forest Service
C. C. BUCK	Assistant Director, Division of Forest Fire Research U. S. Forest Service
CLARENCE F. CASTLE	Chief, Services Division Properties and Installation Office Assistant Secretary of Defense
DEVER COLSON	Meteorologist, Meteorological Physics Section U. S. Weather Bureau
JAMES J. DUGGAN	Charleston, West Virginia
HOWARD W. EMMONS	Professor of Mechanical Engineering Havard University
W. L. FONS	Physicist Southern Forest Fire Laboratory
JOSEPH GRUMER	Project Coordinator, Flame Dynamics Explosives Research Laboratory U.S. Bureau of Mines

Fire Research Abstracts and Reviews, Volume 5
http://www.nap.edu/catalog.php?record_id=18854

ABSTRACTS AND REVIEWS

Arthur B. Guise	Technical Director, Research and Development Ansul Chemical Company
K. E. Klinger	Chief Engineer, Los Angeles County Fire Department
Harold E. Kuhlman	Chief Engineer, Oklahoma Inspection Bureau
Bernard Lewis	President, Combustion and Explosives Research, Inc.
J. B. Macauley	Assistant to the Director of Defense Research and Engineering Department of Defense
James E. Malcolm	Office of Chief of Engineers U.S. Army
Walter T. Olson	Chief, Propulsion Chemistry Division Lewis Research Center National Aeronautics and Space Administration
George J. Richardson	Silver Spring, Maryland
A. F. Robertson	Chief, Fire Research Section National Bureau of Standards
Vincent J. Schaefer	3 Schemerhorn Road Schenectady, New York
A. J. Steiner	Managing Engineer, Fire Protection Department Underwriters' Laboratories, Incorporated
Norman J. Thompson	Miller's Hill Road Dover, Massachusetts
Richard L. Tuve	Head, Engineering Research Branch Mechanics Division U.S. Naval Research Laboratory

Liaison

H. T. Hookway	United Kingdom Scientific Mission Washington, D.C.
G. W. Shorter	National Research Council Ottawa, Canada

D. W. Thornhill, Executive Secretary of Committee and Conference
Emma Jane Whipple, Administrative Assistant

Copyright © National Academy of Sciences. All rights reserved.

Volume 5 Number 2

Fire Research Abstracts and Reviews

Committee on Fire Research
and
Fire Research Conference

Division of Engineering and Industrial Research
NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
Washington, D. C.

FIRE RESEARCH ABSTRACTS AND REVIEWS is published three times a year by the Committee on Fire Research and the Fire Research Conference of the National Academy of Sciences—National Research Council, 2101 Constitution Avenue, Washington 25, D. C. It is supported by the Office of Civil Defense, Department of Defense, the U. S. Department of Agriculture through the Forest Service, the Department of Defense, the National Science Foundation, and the National Bureau of Standards under Contract OCD–OS–62–287. The opinions expressed by contributors are their own and are not necessarily those of the Committee on Fire Research and the Fire Research Conference.

Library of Congress Catalog Card Number 58-60075 rev

FOREWORD

Abstracts of two papers of more than usual interest are included in this issue of Fire Research Abstracts and Reviews. The first (A. O. Rankine, Experimental Studies in Thermal Convection, Proc. Phys. Soc., *63,* 417, 1950), despite its age, gives one of the most attractive presentations of a successful modeling experiment in the fire field. It deals with a World War II project (F.I.D.O.) in which buoyant diffusion flames were used for fog-removal at airfields, and shows clearly that thoughtful analysis of quite simple experimental data can lead to useful predictions of full-scale effects.

The second paper (Margaret Law, Heat Radiation from Fires and Building Separation, Fire Research Technical Paper No. 5, 1963), which also reports work done in England, refers to the application of results of investigations of several years' duration on the effects of flame radiation on ignition. This ambitious study comes up with far-reaching conclusions regarding the safe spacing of buildings. Comments on this paper are invited and will be published.

It is not too early to draw attention to the First Announcement of the Tenth International Symposium on Combustion, to be held in Cambridge, England (August 17–21 1964). Professor H. Emmons, Harvard University, who is the Chairman of a Discussion on "Fluid Dynamics in Combustion", intends to use a substantial part of the available time for topics that are related specifically to the fire problem. The Committee on Fire Research, National Academy of Sciences—National Research Council, will assist in the organization of this part of the Symposium program. Further information on the Symposium can be obtained from the Combustion Institute, Union Trust Building, Pittsburgh, Pennsylvania.

Walter G. Berl
Editor

CONTENTS

Volume 5 Number 2

IV. Diffusion Flames

V. Combustion Principles

VI. Radiation

VII. Suppression of Combustion

VIII. Model Studies and Scaling Laws

IX. Atomization of Liquids

X. Meteorological Interactions

XI. Operational Research Principles

XII. Instrumentation

XIII. Fire-Fighting Techniques, Equipment Design, Materials of Construction

XIV. Miscellaneous

COMMENTS AND DISCUSSIONS

REVIEW

[The following survey continues the plan to present the activities in the Fire field of various establishments in the United States and abroad. Previously, summaries have been published on *Fire Research in the United Kingdom* [*Fire Research Abstracts and Reviews* **1**, 149 (1959)], *Fire Research at the National Bureau of Standards* [*Fire Research Abstracts and Reviews* **1**, 159 (1959)], *A Survey of Fire Research in Japan* [*Fire Research Abstracts and Reviews* **3**, 1 (1961)]. It is hoped that the extensive effort of the Forest Service, U. S. Department of Agriculture, will be discussed in one of the forthcoming issues of *Fire Research Abstracts and Reviews*.—EDITOR]

Fire Research Activities at Factory Mutual Research Corporation

J. P. SMITH
Vice President, Factory Mutual Research Corporation

I. History of the Factory Mutuals

Mr. Zachariah Allen, owner of a cotton mill in Allendale, Rhode Island, founded the Factory Mutual System in 1835. He was a graduate of Brown University—author, inventor, of scientific inclination and ahead of his time. Convinced that a scientific approach to mill fire protection was needed, and with a strong economic incentive (fire insurance premiums were based on the theory that a mill would inevitably be destroyed by fire in from five to twenty years), he went to the fire companies that insured his mill. He could not interest them in fire protection. He thereupon persuaded about a score of cotton mill owners to join with him in forming the first Factory Mutual Company, "Manufacturers" in Providence, in 1835.

They devoted their efforts to seeing that each Factory Mutual member took standard precautions against letting a little fire grow into a big one. The first precautions were: ample water from fire pumps driven by water power through hose standpipes; reliable watchman service whenever mills were idle; good housekeeping, slow-burning brick-plank-on-timber construction; and most important, organization and training of management and workers promptly to detect and nip fires in the bud.

By the middle of the 19th century, perforated pipes, uniformly arranged in the beam bays of each room ceiling, were installed. These "sprinklers" were supplied by water under a head from the mill power dam or pumps. Watchman patrolled all rooms regularly. When they discovered fire beyond their ability to control, they went to a separate brick valve house, turned on the correct valve, and sprayed the whole room. Success depended mostly upon the watchman: his promptness in detecting fire, the correctness of his action in turning on the right valve, and his avoidance of prematurely shutting that valve.

The Factory Mutual idea caught on, and more Factory Mutual companies were organized in New England. Most high-type mill owners tried to qualify for admittance into the Factory Mutual System. Freedom from catastrophic fires and business interruption resulted in safer and steadier employment, more profits and reduced insurance costs.

Given this impetus by its founder, the Factory Mutuals could be expected to establish effective communication with the scientific community. Mr. Edward Atkinson of Boston, the leader in the Factory Mutuals during the latter part of the

19th century, turned to the Massachusetts Institute of Technology. He retained Professors John M. Ordway, Chemistry, and Gaetano Lanza, Applied Mechanics, to investigate fire properties of industrial petroleum oils and structural framing for mill construction, respectively. In 1878, Mr. Atkinson hired the first college-trained engineer to apply scientific principles to the problem of the hostile fire in mills. This man was Mr. C. J. H. Woodbury, MIT '73. He found himself working in a field ripe for applied science.

About 1870 a great advance in industrial fire protection was made when Mr. H. S. Parmelee invented the automatic sprinkler. This made automatic the discovery of fire and the initial turning on of water. Messrs. Atkinson, Woodbury, and others in the Factory Mutuals were the first, and for a long time the only group, to recommend automatic sprinkler protection, and they alone recommended its widespread installation in mills. Wherever installed, automatic sprinklers reduced fire loss by a whole order of magnitude.

Mr. Woodbury's book, "The Fire Protection of Mills," 1882, John Wiley & Sons, New York, is still the classic in industrial fire protection and won him the Alsatian Medal of the Société Industrielle de Mulhouse in 1883. Mr. Woodbury won the John Scott Legacy Medal of the city of Philadelphia on the recommendation of the Committee on Science and the Arts of the Franklin Institute in 1885, "for his apparatus and system of securing safety in the use of electric light in mills."

In rapid succession, the Factory Mutuals developed standard schedules of pipe sizes, sprinkler head spacing, and water supplies. In 1886 they established the first fire protection laboratory to make sure that equipment from various manufacturers met Factory Mutual standards. In 1887, the Bureau of Inspections was formed, consisting of a group of college-trained engineers who inspected the mills periodically and furnished advice regarding fire protection. The leader was John R. Freeman, MIT '76, who joined the Factory Mutuals in 1886 and carried on the work begun by C. J. H. Woodbury. Mr. Freeman's hydraulic investigations were reported in papers before the Boston Society of Civil Engineers. His work, "Experiments Relating to Hydraulics of Fire Streams," still provides the instrumentation and techniques for evaluating industrial water supplies. The paper was recognized in the year of its original presentation by the Norman Gold Medal of the American Society of Civil Engineers. He also designed the Underwriters steam fire pump and developed nationally used standards for sprinkler systems. Under Mr. Freeman's leadership the Factory Mutuals became the foremost group in applying science to the problem of the hostile fire in industry.

In 1905 a test station was established at Lowell, Massachussetts to make hydraulic experiments. This laboratory continued until 1922 at which time the facility was moved to the Inspection Department headquarters in Boston. A large-scale fire test station was first established in Everett, Massachusetts in 1922. It was moved to Norwood in 1943 and enlarged. A large 120×80 ft fire test building was erected at Norwood in 1946, and all of the laboratories moved into enlarged quarters in Norwood in 1951.

II. Factory Mutual Research Corporation

The Factory Mutual Research Corporation was incorporated in 1941 for research and experimentation in technical, scientific, and industrial fields. This was during World War II and was for the purpose of contracting mainly with the U.S. Government to help in the war effort. It is a not-for-profit organization, and its board of directors consists of the presidents of the Associated Factory Mutual Companies.

About five years ago, the Factory Mutuals recognized that FMRC could engage in contract work involving consulting engineering, research and development, of an advanced and exacting nature. By this means, FMRC could build up a cadre of elite fire engineers. These men, working extensively in the field of the hostile fire, could, in the long-range view, be expected to enhance the quality of fire protection engineering service available to Factory Mutual members.

The FMRC presently uses the physical facilities and personnel of the Factory Mutual Engineering Division's Standards and Laboratories Department. Eventually it will probably have its own.

These facilities and personnel consist of about 30 engineers who specialize in different sections of the hostile fire problem: hydraulics and sprinklers, ignition, fire growth, and fire properties of special combustibles, special fire protection and communications, and fire safety in building construction. These engineers regularly make field fire investigations to establish factors responsible for fire growth and for effective fire control. They do supplementary experimental research and engineering tests in the laboratories at Norwood, Massachusetts, to arrive at sound conclusions and practical remedies, to increase effectiveness of fire protection equipment, and to improve industrial processes, practices, and building materials, from the fire and explosion hazard standpoint.

III. Work Done

1. Recent Developments in Automatic Sprinkler Protection.—During the 1930's, the Factory Mutuals led in the development of modifications of existing designs to provide industry with economical and practical spray nozzles for fire protection.

In the 1950's, they developed the spray sprinkler, demonstrated its superiority experimentally, and had it adopted as standard by the fire protection industry.[1]

Several years ago, on the basis of a thorough experimental investigation, it was established that sprinkler spacings should be based on what is in the building rather than what the building is made of.[2] This recent development has resulted in more effective protection for industry.

During the past several years, the results of an experimental study of sprinkler temperature ratings and performance have shown that there are advantages to be gained from automatic sprinklers of intermediate temperature rating over sprinklers of ordinary temperature rating which have been used traditionally. (Results to be published in the near future.)

2. Insulated Metal Roof Deck.—In 1952, fire spread throughout a huge one-story manufacturing building in Livonia, Michigan, much to the dismay of fire protection engineers. They had supposed the roof to be noncombustible because it had modern steel decking instead of the older wood-deck roof construction.

By means of large- and small-scale fire tests by the Factory Mutual Engineering Division, sponsored partly by the Metal Roof Deck Technical Institute and the Insulation Board Institute, it was shown that this metal roof deck was indeed combustible construction. The asphalt adhesives and combustible insulation, installed on top of the sheet-metal deck and beneath the outer weather-proof membrane, volatilized when heated by fire in the building. These combustible volatiles, forced under pressure through the joints in the metal deck, created a self-accelerating fire inside the building.[3]

From this investigation, new insulated metal deck roofing construction of adequately reduced combustibility was developed and made available commercially.[4]

Factory Mutuals' construction materials calorimeter[5] is a new technique for determining on a small scale at a reasonable cost, whether the fuel contribution of a roof deck to a fire in a building has been satisfactorily minimized.

3. Flow of Carbon Dioxide for Fire Protection.[6]—The use of carbon dioxide as a fire extinguishing agent began on an empirical basis, first by total flooding of an enclosed space and then by directed flow on an unenclosed special hazard. As the systems grew in size and complexity, it became evident that fundamental knowledge of the flow of carbon dioxide through pipes and nozzles was needed. The FMRC in a project sponsored by a group of manufacturers of such systems, found the variables governing the successful extinguishment by directed jets and proved that some existing theoretical studies and data on small-scale experimental data on the two-phase flow of carbon dioxide through pipes and nozzles were indeed applicable to practical-size systems.

4. Protection Against Explosion Pressures.—The results of an investigation on the pressures produced by explosions in closed vessels and a method of controlling the maximum pressure by means of bursting discs was presented to an American Society of Mechanical Engineers conference in April, 1951.[7] Methods for designing discs to produce the desired result were included.

An earlier experimental study of Explosion Pressures in Industrial Piping Systems, a Factory Mutual Laboratory Research Project, was presented before the annual convention in Pittsburgh, Pennsylvania, of the International Acetylene Assocation in April, 1949.[8]

Factory Mutual Laboratory Research Project No. 11776,[9] was an investigation of the Explosion Hazard in Industrial Ovens and Furnaces from Over-Rich Combustion.

References

1. Thompson, N. J.: "Proving Spray Sprinkler Efficiency," *National Fire Protection Quarterly* **47,** 120–128 (1954).
2. Young, J. R.: "Spacing of Automatic Sprinklers," *National Fire Protection Quarterly* **54,** 120–128 (1960).
3. Wilson J. A.: "Insulated Metal Roof Deck Fire Tests," *National Fire Protection Quarterly* **49,** 92–105 (1955).
4. Wilson, J. A.: "Insulated Metal Roof Deck Construction," *National Fire Protection Quarterly* **56,** 267–274 (1963).
5. Thompson, N. J. and Cousins, E. W.: "The FM Construction Materials Calorimeter," *National Fire Protection Quarterly* **52,** 186–192 (1959).
6. Cousins, E. W.: "Extinguishing Agent Developments—Carbon Dioxide Extinguishment Tests," *National Fire Protection Association Quarterly* **54,** 164–172 (1960).
7. Cousins, E. W. and Cotton, P. E.: "The Protection of Closed Vessels Against Internal Explosions," *Paper No. 51-PRI-2.* Process Industries Conference, Baltimore, Maryland, of the American Society of Mechanical Engineers (1951).
8. Smith, J. B.: "Explosion Pressures in Industrial Piping Systems," *Proceedings of the International Acetylene Association 1948, 1949, and 1950*, 279–293 (New York).
9. Smith, J. B. and Jones, E. H.: "Recommendations for Minimizing Explosion Hazards in Ovens and Furnaces from Over-Rich Combustion," *Industrial Heating.* National Industrial Publishing Co. (October–November 1953).

ABSTRACTS

I. Ignition Phenomenon

Freiwald, H. and Koch, H. W. (German-French Research Institute, Saint-Louis, (Haut-Rhin) France) "Spherical Detonations of Acetylene–Oxygen–Nitrogen Mixtures as a Function of Nature and Strength of Initiation," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 275-281 (1963)

In this study, the authors have set out to determine for acetylene–oxygen–nitrogen mixtures, the composition regions wherein spherical detonations occur. To study the spherical detonations, they used self-luminosity photography involving streak camera, Kerr cell shutter, and high-speed camera. The consecutive shock waves produced by the spherical detonation were also investigated both on the streak camera records and via pressure–time records obtained with a condenser microphone.

The gaseous mixtures were contained in thin-walled transparent rubber balloons ranging from 15 to 500 liters. They were detonated at balloon center by a variety of methods: flame, hot wire, exploding wire, electric spark, impact of a flying projectile, by the detonation of lead azide or mercury fulminate–tetryl plus a PETN booster, and by a "linear" detonating mixture in a tube.

The results of this study demonstrate the influence of ignition energy on the detonation limits. In the study of ignition by detonation of lead azide, etc., a wide range of ignition energies was covered. The data are presented in a plot of ignition energy versus the maximum nitrogen content at which spherical detonation could still occur in near-stoichiometric acetylene rich mixtures. The nitrogen content increased asymptotically from 40 to about 77 per cent as the ignition energy was increased from about 10^2 to 10^5 joules.

Exploding wire studies indicate than an exploding wire is generally a more effective ignitor than an electric spark of the same energy. With spark ignition, deflagration always preceeded detonation. Minimum ignition delays observed were 50 μsec even for acetylene–oxygen mixtures and a spark energy of 5 joules. The results for spark ignition did not correlate with the extrapolation of detonation energies plotted versus per cent nitrogen, indicating that comparison is possible only between those ignition methods producing a detonation without an intermediate state of deflagration.

The transformation into spherical detonations, of linear detonations of gaseous mixtures propagating in a tube was also studied. The tube ended in balloon center and there was a critical tube diameter for each mixture. By expanding the diameter of the tube end from 28 to 120 mm, the domain of spherical detonation of acetylene–oxygen–nitrogen mixtures was also expanded. The maximum nitrogen content in near-stoichiometric acetylene rich mixtures was increased from 60 to 73 per cent.

The sequence of shock waves produced by the spherical detonation and by reflections was found to be independent of the nature of the gaseous mixture and was observed with mixtures of hydrogen, ethylene, and propane as well as with acetylene in oxygen and nitrogen. The geometry of the balloon solely determines the time of occurrence of the shock waves.

Subject Headings: *Ignition, of spherical detonation; Detonation initiation and stability limits.*

G. S. Cuff

Litchfield, E. L., Hay, M. H., and Forshey, D. R. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Direct Electrical Initiation of Freely Expanding Gaseous Detonation Waves," *Ninth Symposium* (*International*) *on Combustion*, New York and London, Academic Press, 282-286 (1963)

This study is devoted to the initiation of freely expanding gaseous detonation waves by electric discharge alone, principally exploding-wire discharge. The binary systems studied included mixtures of oxygen with ethylene, hydrogen, and propane, respectively. For each mixture, the variation of a minimum energy required to initiate detonation with mixture composition was determined. The data indicate that the ease of initiating detonation in the three systems increases in the order—propane, hydrogen, ethylene.

The pressure dependence of this well-defined minimum stored energy requirement was also studied. The relationship is apparently quite complex, permitting only one generalization. When a strong pressure dependence does exist, an increase in the mixture's initial pressure means a decrease in the required initiation energy.

The mixtures were contained in two spherical reaction vessels: a 1-liter bomb of about 12-cm diameter and a 14-liter bomb of about 30-cm diameter. Pressure-time histories were observed at the vessel walls with piezoelectric transducers, with outputs displayed on an oscilloscope. Electrical energy was stored on a capacitor. Discharge was usually accomplished with a three-element triggered spark gap.

The authors' criteria for judging a pressure–time record to indicate detonation were: the mean velocity of the combustion wave is supersonic, and no shocks are observed ahead of the main wave. They did observe transitions from deflagration to detonation in some circumstances but these transition records were not included in this investigation.

Wire composition, diameter, and length, switch characteristics, and electrode geometry are all very important in determining the stored energy required for initiating detonation. However, for a given gas composition and pressure, and range of wire parameters, stored energy is the controlling variable for producing detonation and within such a range of wire parameters, is sharp and reproducible to about 1 per cent.

The authors agree that their experimental arrangement is such that not all of the stored energy is delivered to the wire nor subsequently delivered from the wire to the gas. However, they believe three conclusions can validly be drawn from the data: (1) in the plots of stored energy versus mixture composition, the steep slopes exhibited by ethylene and propane represent the behavior of the gas and not characteristics of energy transfer from the wire to the gas; (2) ethylene is more sensitive to initiation of detonation than is propane; (3) there does exist for propane, a range of compositions of approximately equal initiation sensitivity and a range of compositions wherein initiation is insensitive to pressure changes.

Subject Headings: *Ignition, of spherical detonation; Detonation, ignition of.*

G. S. Cuff

Singer, J. M. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Ignition of Mixtures of Coal Dust, Methane, and Air by Hot Laminar Nitrogen Jets," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 407-414 (1963)

The technique of Vanpée and Wolfhard to study the ignition of gaseous mixtures by hot laminar jets, was modified for application to dust–gas mixtures. Nitrogen gas jets were used to determine ignition temperatures and limiting fuel concentrations for mixtures of coal dust (1 to 5 microns and approximately 37 per cent volatile matter), methane, and air. Four different coal dust concentrations were used (50, 86, 125, and 250 mg/liter) and the jet temperatures used were in the range 900° to 1200° C. The experimental data indicate that mixtures containing the stoichiometric concentration of coal dust (125 mg/liter) require the least added methane for ignition at all hot jet temperatures and that ignition temperatures are lower (at comparable fuel concentrations) when the hot jet contains 1.35 per cent of a 90 per cent CO + 10 per cent H_2 mixture. At sufficiently high nitrogen jet temperatures, 1220°C, and coal dust concentrations above stoichiometric to at least 250 mg/liter, no additional methane is required for ignition.

Gaseous halogenated hydrocarbons were added to the hot jet or to the coal dust–air–methane mixture to study inhibition effects. Data were obtained for admixture of bromotrifluoromethane and methyl bromide to the jet and to the mixture containing 100 and 250 mg/liter of coal dust. The effect of bromotrifluoromethane is compared with the effect of water vapor and CO_2 on the ignitibility of mixtures of coal dust (100 mg/liter), firedamp, and air. The data show that (1) the bromotrifluoromethane inhibits ignition much more effectively than water vapor or CO_2, (2) less bromotrifluoromethane than methyl bromide is needed for equivalent ignition suppression, both with and without CO and H_2 in the jet, (3) halogenated hydrocarbons are more effective ignition inhibitors when added to the hot nitrogen jet than to the mixture, (4) the concentration of halogenated hydrocarbon required to suppress ignition increases as the hot gas jet temperature rises.

The favorable ignition-suppression results obtained with halogenated hydrocarbons prompted further work in which the inhibitors bromine, methyl bromide, and bromotrifluoromethane were absorbed on inert powers and added in this form to the coal dust–air–methane mixtures. Activated charcoal, plus 28 per cent bromine, was chosen as a stable ignition-suppressing system. The absorbed bromine either completely prevents ignition or substantially increases the methane concentration required for ignition. These observations suggest that ignition suppressors, absorbed on the explosive charge itself, will reduce the ignition hazard of detonation products from explosives.

Subject Headings: *Ignition, by hot jets; Coal dust-methane–air mixtures, ignition by hot jets; Methane, coal dust–air mixtures, ignition by hot jets; Inhibition, of ignition by hot jets; Jets, ignition by.*

L. A. Povinelli

Scott, G. S., Perlee, H. E., Martindill, G. H., and Zabetakis, M. G. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Review of Fire and Explosion Hazards of Flight Vehicle Combustibles," *Technical Documentary Report No. ASD-TR-61-278, Supplement 1 Aeronautical Systems Division, Air Force Systems Command Contract AF 33(616)60-8* (October 1962)

This review is the second annual report on the fire and explosion hazards associated with organic solvents used in aircraft and missile systems. Previous studies[1] dealt with the combustibility of organic compounds in air only. This review considers the oxidation of organic liquids in air and in other atmospheres such as oxygen, nitrogen tetroxide, and nitrogen tetroxide/air mixtures at temperatures ranging from about 75° to 750°F. Since the bulk of the data of this review could be summarized in tabular form, Table I has been prepared to illustrate the effect of indicated oxidizing atmospheres on methyl alcohol, acetone, *n*-heptane, methylene chloride, and trichloroethylene. These data show the following:

I. Ignition Energy Requirements

1. The energy requirements for ignition are greater in nitrogen tetroxide atmospheres than in air or oxygen.
2. The quenching distance is larger in nitrogen tetroxide than in air and oxygen.

II. Flammability Limits

1. An increase in the temperature of the solvent vapor/oxidant mixtures tended to widen the flammable range of the solvent in each of the oxidants.
2. The amount of water vapor required to suppress flammability of all mixtures of solvent vapor and oxidant increased as the temperature of the mixture was increased prior to the ignition test. Conversely, the oxygen requirements for flame propagation decreased with an increase in temperature.
3. In changing from air to oxygen, the lower flammability limit of the solvents was changed slightly but not unidirectionally. The upper limit did change significantly, however, which gave rise to a much larger flammable zone for each of the solvents tested.
4. The data for trichloroethylene indicate that the flammable zone of solvents in contact with nitrogen tetroxide may fall between that for air and oxygen.
5. Methylene chloride has a flammable range in air at about 400°F.
6. Trichloroethylene has a flammable range in air at about 212°F. [ABSTRACTER'S NOTE: In the case of trichloroethylene, it should be noted that the existence of the flammable range does not alter other well-known points concerning this solvent, such as (a) the solvent does not have a flash point in closed or open flash cup tests, (b) in its principle use—vapor degreasing—the formation of combustible mixtures with air is extremely unlikely, and (c) the use of arc welding and cutting torches on closed containers of trichloroethylene should be discouraged unless the container is purged free of trichloroethylene vapors.]

III. Pool Burning Characteristics

Following the ignition of a pool of a combustible liquid, the flame spreads over the surface of the pool. The data show that acetone does not burn in an atmosphere of nitrogen tetroxide, but does burn in air and air/nitrogen tetroxide atmospheres.

TABLE 1

THE OXIDATION OF SOLVENTS IN VARIOUS ATMOSPHERES

Test Conditions: 1. Oxidizing atmosphere
A—Air; B—Oxygen; C—Nitrogen tetroxide; and D—Nitrogen tetroxide/air (60/40 vol ratio)
2. Test Systems at one atmos. unless indicated otherwise

Burning characteristics of solvents	Methyl alcohol				Acetone			
	A	B	C	D	A	B	C	D
I. *Ignition Energy Requirements*								
1. Min. ignition energy (millijoules)	0.26	—[a]	—	—	0.5	0.0024	—	—
2. Quenching Distance (mils)	76[e]	—	—	—	68[e]	10[c]	72	—
3. Combustible Content (vol %)	12	—	—	—	5–7	15–30	45	—
II. *Flammability Limits*								
1. Test temperature (°F)	—	*77*	*77*	—	—	*77*	*77*	—
Lower limit (vol %)	—	7.4	g	—	—	3.0	g	—
Upper limit (vol %)	—	—	g	—	—	—	g	—
2. Test temperature (°F)	*212*	*212*	—	—	*212*	*212*	—	—
Lower limit (vol %)	7	7	—	—	2.9	3.0	—	—
Upper limit (vol %)	36	93	—	—	11.3	61[e]	—	—
3. Test temperature (°F)	*392*	*300*	—	—	*392*	*300*	—	—
Lower limit (vol %)	6	6.9	—	—	2.3	3	—	—
Upper limit (vol %)	46	93	—	—	12.4	63	—	—
4. Test temperature (°F)	*752*	—	—	—	*617*	—	—	—
Lower limit (vol %)	4.5	—	—	—	0.9	—	—	—
Upper limit (vol %)	59	—	—	—	13.5	—	—	—
5. Min. conc. of water vapor (vol %) req. to suppress explosion of all solvent/oxidant mixtures at test condition 2.	43	—	—	—	31	—	—	—
3.	48	—	—	—	38	—	—	—
4.	52	—	—	—	49	—	—	—
III. *Pool-Burning Characteristics at 77°F*								
1. Max. flash-over rate (ft./sec.)	—	—	—	—	36	—	0	24
2. Liquid regression rate in 5″ diameter tray (in./min.)	—	—	—	g	~0.045	—	—	~0.07

TABLE I—Continued

Burning characteristics of solvents	Methylene chloride				Trichloroethylene				*n*-Heptane
	A	B	C	D	A	B	C	D	A
I. *Ignition Energy Requirements*									
1. Min. ignition energy (millijoules)	—	0.07[b]	0.5	—	—		—	—	—
2. Quenching Distance (mils)	—	—	200	—	—	200[c,d]	—	—	—
3. Combustible Content (vol %)	—	40	60–70	—	—	60[d]	—	—	—
II. *Flammability Limits*									
1. Test temperature (°F)	77	77	77	—	—	77	—	—	—
Lower limit (vol %)	j	15.5	34	—	—	9.3	—	—	—
Upper limit (vol %)	j	—	—	—	—	—	—	—	—
2. Test temperature (°F)	—	212	212	—	212	212	212	—	212
Lower limit (vol %)	—	13.4	18.5	—	11	9	16.3	—	1.1
Upper limit (vol %)	—	71	g	—	38	87[f]	67	—	6.9
3. Test temperature (°F)	392	300	—	—	392	300	—	—	392
Lower limit (vol %)	15.1	12	—	—	6	8.7	—	—	1.1
Upper limit (vol %)	18.8	72	—	—	41	87	—	—	8[i]
4. Test temperature (°F)	—	—	—	—	—	—	—	—	—
Lower limit (vol %)	—	—	—	—	—	—	—	—	—
Upper limit (vol %)	—	—	—	—	—	—	—	—	—
5. Min. conc. of water vapor (vol %) req. to suppress explosion of all solvent/oxidant mixtures at test condition	— 17 —	— — —	— — —	— — —	22 28 —	— — —	— — —	— — —	33 37 —
III. *Pool-Burning Characteristics at 77°F*									
1. Max. flash-over rate (ft./sec.)	0	—	12	0	—	—	—	—	—
2. Liquid regression rate in 5″ diameter tray (in./min.)	—	—	—	h	—	—	—	h	—

---

[a] Value not determined.
[b] Extrapolated value.
[c] Tentative value.
[d] Tests made at 95 mm of mercury.
[e] Interpolated value.
[f] Estimated value.
[g] Too reactive to determine.
[h] Flames were unstable.
[i] The upper limit for the cool flame was 25.5 vol. % of *n*-heptane.
[j] Nonflammable.

The converse situation prevailed for methylene chloride. Tests were also performed under an air/nitrogen tetroxide atmosphere with the solvents to determine the liquid regression rate while the solvent burned. The only reproducible data were obtained with acetone.

Additional information included in the subject review, but not contained in the table, include (1) the development of a method of studying the burning characteristics of heterogeneous flammable vapor mixtures of pentane in air, (2) the study of the effectiveness of flame arresters under laminar and turbulent gas flow conditions. In the latter case, a performance band was constructed for commercial wire gauze arresters using (a) oxygen–air mixtures with propane, ethylene, and pentane, and (b) air with methane and natural gas.

The performance band can be approximated by a straight line on log–log paper with the x and y intercepts (arrester diameter in inches, velocity of flame approach approach in ft/sec) of about 0.5 and 1, and 0.001 and 1,000. The arresters were effective for x, y values *under* the straight line relationship. Additional data showed that tube bundles in place of the gauze were more effective in the arresting of flames.

Reference

1. Coward, H. F. and Jones, G. W.: "Limits of Flammability of Gases and Vapors," *Bureau of Mines Bulletin 503* (1952).

Subject Headings: ***Solvents, ignition, flammability limits; Ignition, of solvents; Flammability, limits, of solvents.***

R. A. Gorski

Jacobson, M., Nagy, J., and Cooper, A. R. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Explosibility of Dusts Used in the Plastics Industry," *U. S. Bureau of Mines Report of Investigations 5971* (1962)

Data obtained by the Bureau of Mines on the dust-explosion hazard in air of materials used in the plastics industry are presented for over 300 samples. In general, most of the materials were found to present a strong to severe hazard. These include materials in the following classifications: thermoplastic resins and molding compounds (acetal, acrylic, cellulosic, chlorinated polyether, fluorocarbon, nylon, polycarbonate, polyethylene, polymethylene, polypropylene, rayon, styrene, and vinyl polymers and copolymers), thermosetting resins and molding compounds (alkyd, alkyl, amino, epoxy, furane, phenolic, polyester and polyurethane), special resins and molding compounds (asphalt, gilsonite, coumarone-indene, gums, lignin, rosin, shellac, cashew oil resin, natural and synthetic rubber), and a number of other ingredients and fillers. Information is given on ignition temperature of dust clouds and layers, minimum explosive concentration, minimum energy required for ignition, explosion pressure and rates of pressure rise, amount of inert dust required to prevent ignition and flame propagations, and, in some instances, on the limiting oxygen concentration in an atmosphere to prevent ignition by spark and by heated surface.

The effects of particle shape, additives, and resin structure on explosibility are discussed. Dusts composed of irregular particles present a greater explosion hazard than those composed of spherical particles. Addition of combustible materials tends to increase, and addition of inert fillers tends to decrease thee xplosion hazard. In general, the basic chemical structure of a resin governs its explosibility. Incorporation of the halogens, fluorides, and chlorides tends to decrease the hazard; substitution of a relatively nonflammable salt of a compound for the flammable compound reduces the potential hazard.

The relative explosibility of the materials was empirically defined as the product of ignition sensitivity and explosion severity. The ignition sensitivity was obtained from the ignition temperature, minimum energy and concentration for ignition. The explosion severity was obtained from the maximum explosive pressure and the maximum rate of pressure rise.

Subject Headings: *Dusts, explosion hazards; Explosion, plastic dust;Plastics, hazards of dust explosion; Ignition, temperature, of plastic dusts.*

C. P. Talley

Boddington, T. (University of Cambridge, England) "The Growth and Decay of Hot Spots and the Relation between Structure and Stability," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 287-293 (1963)

In condensed phase explosives, explosions occur frequently because of the rapid formation of localized regions of high temperature which are known as hot spots or temperature spikes. They can be produced under impact conditions or by irradiation with light, neutrons, and fission fragments or by a shock wave arriving at an impedance discontinuity.

Boddington presents two methods of estimating the critical conditions for the explosion to take place. The approximate analytical approach demonstrates the relative importance of the various parameters. An exact machine solution gave results which are in good agreement with those derived from the analytical method.

The formation of a hot spot is regarded as a purely thermal problem in which mass flow can be ignored. Therefore, an explosion occurs if self-heating in the hot spot exceeds the rate at which heat is conducted into the surrounding region. The temperature profile was assumed to be rectangular initially and to correspond to a slab, cylinder, or sphere at an elevated temperature T_s within an infinite, homogeneous, isotropic explosive mass at an ambient temperature T_0. Also, it was assumed that the explosive concentration followed an Arrhenius rate law.

Ignoring reactant consumption, the resulting differential equation is

$$\sigma c(\delta T/\delta t) = k \operatorname{divgrad} T + q\sigma\nu \exp(-E/RT)$$

where σ = density; c = heat capacity; T = absolute temperature; t = time; k = thermal conductivity; q = exothermicity; ν = pre-exponential factor; and E = activation energy. This equation cannot be integrated directly. If the second term of the equation is dropped, an equation corresponding to an adiabatic hot spot can be obtained which can be integrated approximately.

The decay of an inert hot spot is controlled by the Fourier equation obtained by dropping the last term of the equation. After making a few more assumptions and approximations, the result obtained describes the temperature evolution of any hot spot in terms of a dimensionless temperature x and a dimensionless time y. Physically, x is inversely proportional to the rate of heat evolution within the hot spot and y is proportional to the square root of time since inception.

Five separate cases of hot-spot conditions are considered. Also, an equation is developed which gives the time taken by the hot spot to reach infinite temperature. The author believes that most of the assumptions and approximations are demonstrably reasonable for conventional explosives provided that certain ratios are within specified limits. One assumption is difficult to justify; however, its influence is rather small. Results of the numerical method indicate that the developed equation is substantially correct.

The basic equations for a spherical hot spot were solved exactly with allowance for reactant consumption and without the use of Frank–Kamenetskii's exponential approximation. Results are shown in curves describing the evolution of a nearly critical hot spot in RDX and the critical temperature as a function of hot-spot size for AgN_3, HMX, PETN, RDX, tetryl, ethylenedinitramine, and ammonium nitrate.

Recent results for the azides are given in the attempts to show the general relationship between the electronic structure and the stability of explosive substances. The stability of the azides can be ascertained by a study of their optical and electrical properties. Most data are available over the range from liquid helium to room temperatures. Significant variation in properties occurs. At −30°C thallium azide undergoes a change to a more complicated structure. High-temperature properties of the azides must be studied to better understand the decomposition process.

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

L. E. Bollinger

Friedman, M. H. (Minnesota Mining & Manufacturing Company, St. Paul, Minnesota) "A Correlation of Impact Sensitivities by Means of the Hot Spot Model," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 294-302 (1963)

Explosions of most impact-sensitive materials are thermal in origin according to generally accepted theories. It is presumed that small regions of high temperatures are formed within the reactant. The hot spots then can act as nuclei from which more gross phenomena grow—decomposition, deflagration, and detonation.

The adiabatic compression of minute gas bubbles in liquids may form hot spots. In solids, gas may be trapped by the rapid mechanical crushing resulting from an impact. Explosions may be formed by the friction of particles or by the heat generated by the shearing of liquid or molten layers.

For a model Friedman used an infinitely large homogeneous sample of explosive at temperature T_1. Assuming negligible reactant consumption and heat loss and ignoring any dependence of the heat of reaction of the material with temperature, then a critical hot-spot size exists for any hot spot that is formed. When this value is exceeded, the temperature at the center of the hot spot will rise monotonically. For subcritical sizes, the central temperature will rise and then fall toward the ambient temperature.

For simplification in determining the critical hot-spot size as a function of the temperature of the hot spot and the ambient value, and the properties of the explosive, the hot spot is assumed to be a two-dimensional infinite slab of thickness two-dimensionally imbedded in an infinite mass of reactant. The resulting differential equation which determines the dependence of temperature on time at any point in the explosive when heat is transferred by conduction alone is

$$C\rho(\delta T/\delta t)=k(\delta^2 T/\delta X^2)+\rho QZ \exp(-E/RT) \qquad -\infty \leqslant x \leqslant \infty$$

for

$$T(x,0)=T_0(|x|<d)$$

$$=T_1(|x|>d)$$

where C = heat capacity; ρ = density; T = absolute temperature; t = time; k = thermal conductivity; x = distance; Q = heat evolved by decomposition; Z = frequency factor; E = energy of activation; and T_0 = hot-spot temperature.

Two digital computer programs were used to solve this equation. One treated the hot spot as a temperature perturbation while the other employed a second-order finite difference approximation. Critical dimensionless half-widths for the hot spot were obtained from integration. This correlation can be used to predict values of the critical hot-spot size for cases other than those given without additional computer work.

Results from integration for just-supercritical cases are: (1) the space-average heat generation rate within the hot spot changes relatively little prior to inflection; (2) before the inflection point is reached, not much heat is generated outside the hot spot.

After considering the reactant consumption prior to explosion to be finite, Friedman finds that (1) the times to explosion obtained from the computer integration agree with experimental data from impact sensitivity studies, (2) variations in C, k, ρ, and the heat of explosion have little effect on hot-spot stability, and (3) only a minor fraction of the heat flux through the explosive can be attributed to thermal radiation.

A final impact sensitivity correlation was developed to predict the experimental sensitivity of 16 diverse exothermic materials. Results of an impact test are of greatest value in ordering the impact sensitivities of a series of materials rather than in providing insensitivity numbers. Although the results do correlate well with experimental sensitivity data on a diverse collection of materials, the inherent limitations of the equation employed for the calculations must be kept in mind.

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

L. E. Bollinger

Carruthers, J. A. and Marsh, K. J. (British Petroleum Company, Ltd., London, England) "Charge Relaxation in Hydrocarbon Liquids Flowing through Conducting and Nonconducting Pipes," *Journal of the Institute of Petroleum* **48**, 169-179 (1962)

Carruthers, J. A. and Wigley, K. J. (British Petroleum Company, Ltd., London, England) "The Estimation of Electrostatic Potentials, Fields and Energies in a Rectangular Metal Tank Containing Charged Fuel," *ibid.* 180-189 and Discussion, 189-195 (1962)

In these two papers the authors derive and experimentally test simple mathematical expressions governing the behavior of charge relaxation and electrical field build up encountered in full-scale fueling operations. It is known that hydrocarbon fuels passing through filter/separators and delivery tubes to fuel tanks are subject to charge build up and subsequent relaxation. When the charged fuel is deposited in a fuel tank electrical fields in the tank may become adequate to cause electrical breakdown and subsequent explosion of the fuel vapor/air mixture.

In the first paper a simple one-dimensional model incorporating exponential charge relaxation laws has been used to predict the dominant parameters of interest and a simple overall relaxation law for pipes of prescribed conductivity. The theory predicts a universal relation between f, the fraction of charge unrelaxed, and two basic parameters λ and B. The first of these (λ) is the ratio of the residence time in the delivery system to the charge relaxation time characterizing the fuel. The second parameter (B) is the ratio of the liquid conductance (per unit length) to the liquid+pipe wall conductance (per unit length). In the experimental tests of this relation λ is changed by varying the fuel flow rate and by blending the fuel with a conductive additive. The parameter B is also varied by changing the delivery tube material (i.e., comparing copper to polytetrafluoroethylene). While a correlation of this type is experimentally observed, absolute values predicted by the theory are in considerable error, particularly when the relaxation times, τ, determined from independent conductivity measurements are applied to experimental data for full-scale equipment. Yet, if τ is determined directly from charge relaxation experiments, absolute values for laboratory-scale equipment are as predicted by the theory. The cause of the discrepancy for full-scale equipment may be current leakage in the experiments or shortcomings of the theory; however, the experimental correlation is good, suggesting that laboratory tests can be carried out which simulate charge production and relaxation in full-scale delivery systems. Expressions are also given for the voltage developed in insulating delivery pipes. Theoretical and experimental results indicate that conventional bonding wires (embedded in aircraft fueling hoses) do not significantly increase charge relaxation in the fuel at high fueling rates and may constitute a significant hazard if internal bond wire breaks pass undetected at the beginning of a fueling operation.

In the second paper expressions are derived and tested which (1) relate electrostatic field build up within rectangular fuel tanks with net current inflow and (2) allow rapid estimates of electrostatic quantities existing within a fuel tank from measurements made at a particular point in the tank, e.g., the tank roof. For partially filled, electrically grounded rectangular metal tanks, Poisson's equation is solved by the method of Fourier series expansions and simple one-term approximation formulae are presented for the maximum field, $E_{\max}$, existing in the vapor space, the total field energy in the vapor space, and the relation between $E_{\max}$ and a field measurement made at the tank roof. Field measurements presented indicate that theoretical predictions are conservative, being high by as much as a factor of about 3 for half-filled tanks. Calculations of the effects of surface charge and charged mists are also included. In certain circumstances the field produced by charged mists can be as great as those produced by charge uniformly distributed in liquid fuels.

A likely written discussion of these two papers is included in the journal and many improvements, both practical and theoretical, are suggested. One is left with the feeling that these contributions collectively represent a substantial stride in the process of replacing the mystery of costly fueling explosions by rational design and test procedures.

Subject Heading: ***Hydrocarbons, charge build up.***

D. E. Rosner

II. Thermal Decomposition

Eickner, H. W. (Forest Products Laboratory, U. S. Forest Service, Madison, Wisconsin) "Pyrolysis and Combustion of Wood," *Forest Products Journal* 12, 194-199 (1962)

The fundamental studies described, intended to aid the discovery of improved methods of "fireproofing" wood, began with a 2-year (1960–1962) grant by the National Science Foundation with Frederick L. Browne as principal investigator assisted by Walter Tang, Frances Baird, and John Brenden. A prior survey of the literature[1] revealed at least seven theories about the mechanism that imparts combustion resistance to wood of which the most promising is the redirection of pyrolysis toward production of more char, water, and nonflammable gases and less tar and flammable gases.

Wood is being investigated before and after impregnation with chemicals by five experimental procedures. (1) For static thermogravimetric analysis (TGA) the sample is heated at a constant temperature, either in vacuum or in inert gas, and its weight is charted continuously against time. Examining the results kinetically leads to pseudo reaction rate constants and activation energies. (2) For dynamic TGA the furnace temperature is raised at a linear rate and sample weight is charted against sample temperature. The results reveal the threshold temperature and temperature range of active pyrolysis and the yield of char. (3) For differential thermal analysis (DTA) the sample and a reference material are subjected simultaneously to linearly rising furnace temperature and the temperature difference between them is charted against sample temperature. The results show temperature levels at which different reactions occur, whether the reactions are exothermic or endothermic, and a crude estimate of their heat effect. (4) The heat of combustion of the volatile products of pyrolysis at its successive stages is estimated as the difference of heat of combustion (oxygen-bomb calorimeter) of a sample before pyrolysis and that of chars representing increasing extents of weight loss. (5) In a suitable furnace and train of cold traps, yields of char, tar, water, and fixed gases on pyrolysis in vacuum at constant temperature are obtained and more detailed analysis of the products by chromatography or spectroscopy is possible.

The thermogravimetric balance, its modification for differential thermal analysis, and the apparatus for product separation are described.

Preliminary experiments with samples in the form of dowels of different diameters and veneers of different thicknesses revealed a higher activation energy the smaller the dowel or thinner the veneer and for the larger dowels a dual activation energy with the activation energy lower above 330°C than below it. The duality is attributed to an undue temperature gradient and a resistance to escape of volatile products in the thicker specimens. Accordingly, subsequent TGA was done with veneers 0.005 inch thick.

The rest of the paper repeats results already published completely in *Fire Research Abstracts and Reviews*[2] dealing with static and dynamic TGA and DTA. Still further results will be released this spring.[3] Reports by Browne and Brenden on the heat of combustion of the volatile products of pyrolysis and by Browne and Baird on the effect of chemicals on the yields of major products of pyrolysis have not yet been released for publication.

References

1. Browne, F. L.: "Theories of the Combustion of Wood and Its Control," *Forest Products Laboratory Report No. 2136* (1958).
2. Browne, F. L. and Tang, W. K.: "Thermogravimetric and Differential Thermal Analysis of Wood and of Wood Treated with Inorganic Salts During Pyrolysis," *Fire Research Abstracts and Reviews* **4**, 76–91 (1962); presented in a Symposium on Fire Control Research at the Chicago, Ill., meeting of the American Chemical Society, Fuel Section, September 3–8 (1961).
3. Browne, F. L. and Tang, W. K.: "Effect of Various Chemicals on the Thermogravimetric Analysis of Ponderosa Pine," *U. S. Forest Service Research Paper FPL-6* (May 1963).

Subject Headings: ***Wood, pyrolysis; Wood, combustion; Combustion, of wood; Pyrolysis, of wood.***

F. L. Browne

Straus, S. and Madorsky, S. L. (National Bureau of Standards, Washington, D. C.) "Pyrolysis of Some Polyvinyl Polymers at Temperatures up to 1200°C," *Journal of Research of the National Bureau of Standards* **66A**, 401-406 (1962)

This paper provides an extension of earlier work by the same authors on the pyrolysis of polymers mainly at lower temperatures. Samples weighing 15 to 30 mg were heated in a platinum tube by quickly moving a preheated furnace into position so that it surrounded the sample.

Most of the results relate to pyrolysis in vacuum, but some represent pyrolysis in helium at atmospheric pressure. The residues were weighed and the volatile products were collected and fractionated into

1. a waxlike fraction, designated V_{pyr} volatile at the temperature of pyrolysis but not at room temperature,
2. a light fraction, V_{25} volatile at room temperature, collected in a liquid nitrogen cold trap,
3. a gaseous fraction, V_{-190}, not condensable at the temperature of liquid nitrogen,
4. a fraction, V_{-80} volatile at the temperature of dry ice was also collected in some cases.

The more volatile fractions V_{25}, V_{-80} and V_{-190} were analyzed in the mass spectrometer while V_{pyr} consisting of molecular fragments too large to be studied in this way, was investigated by a microcryoscopic method in which the average molecular weight was determined.

The polymers—polystyrene, polytetrafluoroethylene, poly(α methylstyrene), polypropylene, polyisobutylene and poly(methyl methacrylate)—were pyrolyzed at 500°, 800°, and 1200°C, respectively. Generally, the results from pyrolysis at 500°C resemble those obtained previously from the same polymer at lower temperatures. It is pointed out that at 500°C most of the pyrolysis takes place at or near the specified temperature, whereas at 800° and 1200°C where the rates of degradation are high most of the volatilizable part of a sample will be degraded and vaporized while the temperature is rising from room to final temperature. The results at 800° and 1200°C indicate a much greater fragmentation of the pyrolysis products than at lower temperatures. The yield of monomer from vacuum pyrolysis of polystyrene, for example, decreases with increase in temperature and in the case of pyrolysis in helium the decrease is so drastic that at 1200° only 0.6 per cent monomer is produced. The amounts of C_2H_2, C_2H_4, C_3H_4, C_6H_6 are considerably increased, however. Similarly, poly(α methylstyrene) yields 100 per cent monomer below 500°C but at 800° and 1200°C the yields are 88 per cent and 34 per cent, respectively. Also at the higher temperatures, pronounced amounts of H_2, CH_4, C_2H_2, C_3H_4, C_3H_6, C_4H_4, C_6H_6, C_4H_8, and C_8H_8 are formed.

The results of measurements of relative amounts of gaseous fractions and their chemical composition are said to reflect two principal mechanisms:

1. a primary thermal degradation, and
2. a subsequent degradation involving thermal and catalytic cracking reactions.

The results at 800° and 1200°C show an increased fragmentation of the degradation products and in the appearance of V_{pyr} fraction in some cases where such a fraction is absent at lower temperatures. Pyrolysis in helium also results in greater fragmentation due to the slower escape of volatile products from the hot zone.

Formation of C_6H_6 at the higher temperatures in the pyrolysis of polystyrene is discussed, but no mention is made of the mechanism by which the smaller amount of C_6H_6 arises in the pyrolysis of polypropylene or poly(methyl methacrylate) at the higher temperatures.

With polytetrafluoroethylene, the main product of pyrolysis at the lower temperatures is C_2F_4 with smaller amounts of C_3F_6 and CF_4. At the higher temperatures C_2F_4 is still the dominant product, but small amounts of HF appear. This polymer is believed to break up at free radical ends of chains by an unzipping process to yield mostly monomers. The overall reaction is first order, the unzipping process being preceded by a C—C bond scission giving free radicals; this is rate determining and of first order.

The mechanism of degradation of poly(α methylstyrene) is said to be similar and also of first order.

In the pyrolysis of polypropylene, the monomer C_3H_6 appears in small amounts below about 500°C. At 800° and 1200°C its yield is considerable. The reverse is true of V_{pyr} due to cracking into smaller molecules. Pyrolysis of polyisobutylene generally follows the same pattern as that of polypropylene.

Smaller amounts of monomer are obtained at the higher temperatures from poly(methylmethacrylate) than at lower temperatures due to decomposition of the monomer at the higher temperatures to yield considerable amounts of CO, CO_2, CH_4, C_2H_2, C_2H_4 etc.

Subject Headings: ***Pyrolysis, of polyvinyl polymers; Polymers, pyrolysis of polyvinyl.***

R. Long

III. Heat and Material Transfer

Sparrow, E. M. (University of Minnesota, Minneapolis, Minnesota), **Usiskin, C. M.** (Radio Corporation of America, Princeton, New Jersey), and **Hubbard, H. A.** (National Aeronautics and Space Administration, Cleveland, Ohio) "Radiation Heat Transfer in a Spherical Enclosure Containing a Participating, Heat-Generating Gas," *Journal of Heat Transfer* (Transactions of the ASME—Series C) **83**, 199-206 (1961)

This investigation is an attempt to calculate the temperature distribution in an absorbing-emitting gas confined within a black-walled spherical enclosure or in the space between two black concentric spherical enclosures. The heat transfer to the surrounding surfaces is also calculated.

The gas is assumed to be gray and have an absorption coefficient K, thereby removing most of the complexity which would arise with a real gas. Values of K have been chosen between the limiting cases of intense self-absorption and almost complete transparency.

Calculations with gray instead of black walls are possible but involve considerably more time.

The system chosen has radii R_1 and R_2, and an internal rate of heat generation of S per unit volume. The temperature of both surfaces are equal and uniform.

In order to calculate the temperature distribution, a heat balance is evaluated on an infinitesimal sphere of volume, dV:

> Heat absorbed by dV due to emission of gas + Heat absorbed by dV due to emission of surfaces + Internal heat generation = Heat emitted by dV.

This results in a general integral equation, containing two independent parameters KR_2 and R_1/R_2 and has been solved by an iterative technique. Solutions have been obtained for R_1/R_2: 0, 0.05, 0.5, 0.75, and 0.95 and KR_2: 0.1, 0.5, 1, and 2.

They are presented in graphical form using the above parameters, together with ordinates $(e_g - e_w)/SR_2$ or $(e_g - e_w)/S/K$ and abscissa r/R_2, where e denotes emissivity and r any radius.

It is noted that for a hollow sphere the variation of $(e_g - e_w)/SR_2$ is about 5 per cent when $KR_2 = 0.1$ but 60 per cent when $KR_2 = 2$. The level of gas temperature increases as the absorption coefficient decreases, so that if the lowest gas temperature possible is required, the gas having the highest absorption coefficient should be chosen.

As the spacing of the enclosure $R_2 - R_1$ increases, the temperature level increases, and the temperature distribution becomes nonuniform, since the resistance to heat flow increases with path length, and the amount of heat to be transferred also increases.

Again by means of a heat balance, the heat transfer to the bounding surfaces can be found:

> Net heat transferred to outer surface $\equiv\mathcal{Q}_2=$ Energy absorbed at surface due to gas emission $+$ Energy absorbed at surface due to emission at R_1- Energy emitted by surface.

This leads to an integral equation. The heat generation within the gas $\mathcal{Q}$ is obtained directly from the fixed rate of heat release S per unit volume, and hence $\mathcal{Q}-\mathcal{Q}_2$ is equal to the heat transferred to the inner surface. The results for similar values of KR_2 and R_1/R_2 have been tabulated in fractional form $\mathcal{Q}_2/\mathcal{Q}$, $\mathcal{Q}_1/\mathcal{Q}$, and $\mathcal{Q}/\frac{4}{3}\pi R_2^3 S$. The most important conclusion to be drawn is that little heat is transferred to the inner surface and when $R_1/R_2=0.5$ this fraction is only 15 per cent of the total.

The previous analytical technique can be approximated by an approach which assumes that the radiative flux can be given by $q=\frac{4}{3}K^{-1}\, de_g/dr$, and a relation which has the same form as a conduction equation. This gives temperature distributions which are from a few per cent to 20 per cent of the more accurate analysis, but are most correct for large spacing between the two surfaces and high values of K.

It is proposed to extend the work to the case where the two surfaces have different temperatures.

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

P. L. Start

Gibson, F. C., Murphy, J. M., and Burgess, D. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Evaluation of Radiant Heat Flux and Toxicity in Dyna-Soar—Titan II Destruct Tests," *Aeronautical Systems Division, Air Force Systems Command Technical Documentary Report No. ASD-TDR-62-221* (May 1962)

This report covers investigations conducted by the U. S. Bureau of Mines Explosives Research Laboratory in connection with two destruct tests of half-scale models of the Titan II missile fuel tankage systems.

Test 1 concerned the model second-stage propellant tankage system, and involved 14,000 lb of propellant mixture (5,000 lb of mixture of 50 per cent by weight unsymmetrical dimethyl hydrazine and 50 per cent by weight hydrazine, designated by the Aerojet General Corporation trade name of "Aerozine", and 9,000 lb of nitrogen tetroxide).

Test 2 concerned the model first-stage propellant tankage system, and involved 32,700 lb of propellant mixture (*ca.* 11,500 lb of the 50/50 per cent mixed hydrazine fuel specified in Test 1, and 21,200 lb of nitrogen tetroxide oxidizer).

The tests were undertaken since the Titan II was proposed for use in the Dyna-Soar (manned glider) program, and suitable methods for destruction of unused propellant charges in the event of malfunctions, were desired. The mixed hydrazine fuel and the nitrogen tetroxide oxidizer comprise a hypergolic system, i.e., they spontaneously ignite upon contact. However, since self-ignition occurs after initial diffusion and reaction at the contact boundary, during a finite "delay" time interval, in which the thermal energy required to initiate the flare combustion, is released, the extent to which combustion in an "open spill" type configuration might progress to completion before the reacting components are explosively dispersed, was subject to conjecture. These tests were conducted to observe in part the degree to which the reaction, upon mixture of the fuel and oxidizer components, could be expected to approach completion. In addition it was desired to determine the resulting radiant heat flux, and the extent and distribution of toxic vapors.

The test configuration consisted of vertically mounted propellant tanks, and mixture was accomplished by simultaneous removal, by explosive charges, of the bottom dome of the upper tank and the top dome of the lower tank. In Test 2, the upper tank contained nitrogen tetroxide and the lower tank contained the fuel mixture, and the assembly was 30 ft high and 5 ft in diameter, with fairing between the two vertically mounted tanks.

Instrumentation included use of thermal radiation detectors consisting of lamp-black-coated twelve-junction bismuth–silver thermopiles with calcium fluoride windows; gas sampling batteries at 10 and 60 foot elevation, located downwind from the tank site; photodetectors for combustion cloud opacity determinations; still photography using thermal radiation wavelengths above 5900 Å with densitometric analysis; and 16 frames-per-second motion picture coverage. No consideration was given to blast effects.

The completeness of the reaction was estimated in several ways. One concerned the comparison of measured thermal radiant energy output in the first 5–7 seconds to that calculated assuming the same degree of thermal radiation as experienced in unsymmetrical dimethyl hydrazine–air flames.[1] The determination of unreacted NO_2 in the combustion cloud, by means of still photographic densitometry and air sample collection enabled estimation of the quantity of nitrogen tetroxide involved in the combustion. In addition the fireball volume was estimated assuming complete fuel and oxidizer reaction, and compared with the observed fireball size.

The study found that:

1. In the 5–7 second period after mixing of propellants, approximately 5 per cent of the theoretical thermal output for complete reaction appeared as thermal radiant energy. During the first 2 second of Test 2, the cross section area of the fireball increased almost linearly with time, developing a peak radiant flux of about 20 kw/ft^2 at the boundary of the fireball, compared to 6 to 13 kw/ft^2 of luminous surface in unsymmetrical dimethyl hydrazine–air flames. At 4.6 seconds the radiant flux dropped to 8 kw/ft^2. The fireball size was nearly the same for the two tests, for example, being *ca.* 80 ft high and varying asymmetrically from 125 to 185 ft in width at 1.2 seconds after ignition.

2. In Test 2, based on the photographic densitometry, about 10,000 lb of the original nitrogen tetroxide appeared as NO_2 in the combustion cloud. From this observation it was estimated that the remaining 11,000 lb of nitrogen tetroxide reacted with no less than 3,600 lb (33 per cent) of the fuel mixture. Based on the radiation measurements, 14 per cent of the theoretical total reaction was achieved at the end of 4.6 seconds and at the end of 7 seconds, 20 per cent completion was estimated. In Test 2, instrumentation failure occurred at the end of 4.6 seconds.

3. Most of the unreacted NO_2 was dispersed in the upper air, and no measurable quantity of fuel vapors were detected.

Reference

1. A value of 28% was cited; *Fire Research Abstracts and Reviews* **3**, 159–176 (1961).

Subject Heading: ***Radiation, heat flux,*** **N_2H_4–N_2H_4–UDMH.**

J. E. Malcolm

IV. Diffusion Flames

Savage, L. D. (University of Glasgow, Glasgow, Scotland) "The Enclosed Laminar Diffusion Flame," *Combustion and Flame* **6**, 77-87 (1962)

The original model of the enclosed laminar diffusion flame[1] is discussed with reference to subsequent modifications and correlation with experimental results.

The idealized model consists of two concentric tubes with fuel flowing in the inner tube, oxidizer in the outer tube. The reactants are assumed to flow at equal velocities with lateral molecular diffusion constituting the only mixing mechanism. The coefficient of lateral diffusion is constant along the whole flame height, axial diffusion is negligible. The height of such a flame is then concluded to be proportional to the volume flow of fuel, independent of the geometry of the system.

Early experiments showed that the flame height was proportional to the square root of the fuel flow. This nonlinear behavior was attributed to variation of the coefficient of diffusion along the flame, in contrast to the assumption applied to the idealized case above.

Other workers have found that the degree or frequency of circular motion of gases at the mixing surface increases as the length of the flame. The overall effect would be an increase in the mean diffusivity resulting in mixing by a mechanism other than molecular diffusion.

Molecular diffusion can be achieved by maintaining parabolic velocity profiles prior to contact of the fuel and oxidizer streams. Experiments conducted under the latter conditions employing various geometrics and nonequal fuel and oxidizer flow speeds have shown that the nonlinear relationship of flame height versus fuel flow mentioned above seems to disappear.

The original theory was developed to describe the concentration profiles for the interdiffusion of two gases. The actual flame should coincide with the contour representing the stoichiometric ratio of fuel to oxidizer.

The system studied was butane–air. The large tube (2.1 cm diameter) was concentrically placed around fuel supply tubes 0.28 cm and 0.83 cm in diameter. The latter size tube delivered a parabolically defined velocity flow. The air flow was not parabolic in nature. Flame height was measured accurately with a cathetometer. Four flames were studied at four fuel flow velocities. Two clearly defined boundaries are discernible: the blue radiation zone just above the burner top; and the distinct onset of particle emission due to hot carbon particles.

The boundaries appear to occur at the same heights for the whole series of flames. Since the flame height is inversely proportional to the Reynolds number (Re) or more precisely is related to a definite value of y/R Re, where y is the distance above the burner, R is radius of the outer tube, then it is concluded that both radial and axial diffusion must enter into the mechanism. The role of the axial diffusion is important in the anchoring of the flame to the cool burner. As Re becomes smaller and is plotted versus y/L (L is fuel tube diameter) it is apparent that a nonlinear relationship exists for both sizes of fuel tube. It is concluded then that an axial effect due to the fuel tube is present in all diffusion flames and becomes more marked at lower flows. The results indicate that at $\mathrm{Re}=15$ the axial effects are dominant.

Two probable theories explain these observations. The concentration gradient of oxygen above the flame is such that it will diffuse against the fuel streaming velocity. The velocity will be inversely proportional to Re. The ratio of the oxygen diffusive velocity to the streaming velocity will give a measure of the flame height supression. In addition the products of combustion will flow against the fuel streaming velocity.

Variation of the air–fuel ratio from around 40 to 320 was studied at constant burner geometry and fuel Re. The richest mixture corresponds to the point where soot leaves the tip of the flame.

The variation of diameter ratio was analyzed by using earlier data.

The original solution proposed fails to take into account the effects of axial diffusion. Also the influence of burner geometry and air-fuel ratio affect the value of the Reynolds number correlation coefficient. The assumption that instantaneous reaction occurs subsequent to the encapsulation of a fuel molecule with enough oxygen to consume the latter fully is incorrect. The pyrolysis of methane in an open diffusion flame led to the detection of a large number of reaction intermediates. Thus several step pyrolysis reactions must occur.

Reference

1. Burke, S. P. and Schumann, T. E. W.: "Diffusion Flames," *Ind. Eng. Chem.* **20**, No. 10 (1928).

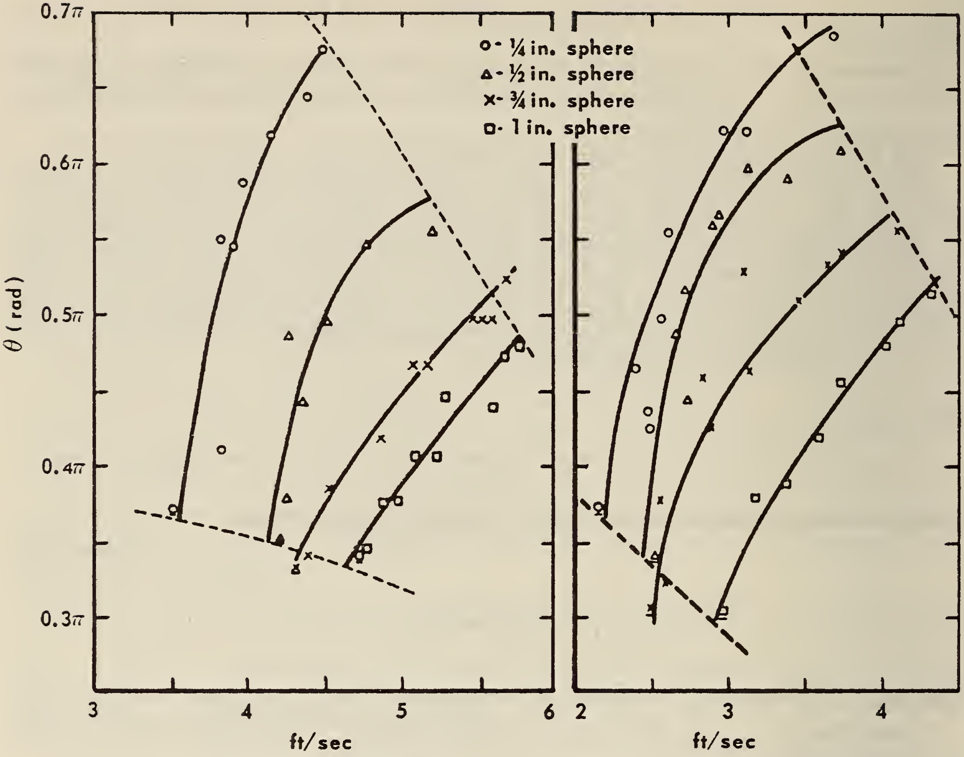
Subject Headings: ***Diffusion flame, study of variables; Flame, diffusion.***

P. Breisacher

Udelson, D. G. (Harvard University, Cambridge, Massachusetts) "Geometrical Considerations in the Burning of Liquid Drops," *Combustion and Flame* **6**, 93-102 (1962)

Following in the wake of Spalding[1]; Agoston, Wise, and Rosser[2]; and Tarifa and Millan,[3] who established the existence of the velocity-dependent envelope and wake flame configurations in the combustion of liquid spheres, the present author discovered a hysteresis effect whereby the high velocity wake flame is replaced by an intermediate velocity "side flame" as the velocity is decreased. Although the side flame can be induced artificially (by dextrous disturbance of the envelope flame) with increasing velocity, its natural incidence is observed only under conditions of decreasing air velocity. The angle θ, measured from the forward stagnation point, at which the leading edge of the side flame occurs, decreases as the velocity is lowered. For each size of droplet D there exists a critical angle θ_c corresponding to a critical free stream velocity U_c at which the side flame transforms suddenly to the envelope configuration. In order to account for free convection effects, two wind tunnel configurations were used, one with U vertically upward, and the other with U vertically downward. As demonstrated by Fig. 1, the experimental results are notably gravity-dependent. Lowest point on each curve specifies the critical angle θ_c and velocity U_c for the corresponding droplet diameter. Comparison of Figs. 1(a) and 1(b) reveals that U_c is greater for vertically downward stream, although author's Fig. 4 does not jibe with data presented in Fig. 1.

Theoretical analysis, based on third order Blasius series solution of appropriate boundary layer equations, plus the condition that boundary layer velocity equals flame speed at flame front, resulted in predicted values of θ_c which were 8 to 16 per cent higher than experimental data. Consideration of natural convection



(a) U vertically downward; (b) U vertically upward.

Fig. 1. Side flame angular positions.

effects by superimposing Jodlbauer's[4] experimental data for heated cylinders resulted in 8 per cent divergence from experimental data for one-inch spheres.

Since relative velocity of fuel droplets in combustion chambers is continually decreasing due to aerodynamic drag, the effect of flame configuration on burning rate should be of vital importance in determining performance characteristics. However, it is felt that much work needs to be done before the effects described in subject report can be included in performance calculations. Analytical method utilized in present report appears too cumbersome and inaccurate to provide a valid design tool.

References

1. Spalding, D. B.: "Experiments on the Burning and Extinction of Liquid Fuel Spheres." *Fuel* **32**, 169 (1953).
2. Agoston, G. A., Wise, H., and Rosser, W. A.: *Sixth Symposium (International) on Combustion.* New York: Reinhold Publishing Corporation, p. 708 (1956).
3. Tarifa, C. S. and Millan, G.: "The Combustion of Droplets. Influence of Forced Convection," *Instituto Nacional de Tecnica Aeronautica Esteban Terradas Report.* (Madrid, December 1956.)
4. Jodlbauer, K.: "Das Temperatur und Geschwindigkeitsfeld um ein geheiztes Rohr bei freier Konvektion." *Forsch. IngWes.* **4**, 157 (1933).

Subject Heading: ***Drops, burning of liquid.***

C. C. Miesse

Thomas, A. ("Shell" Research, Ltd., Chester, England) "Carbon Formation in Flames," *Combustion and Flame* **6**, 46-62 (1962)

Thomas describes the processes whereby molecules of hydrocarbon fuels are converted into particles of soot. He explains that what is required is a knowledge of the nature of the intermediates that grow to form the particles and also the species that add onto the growing intermediates. Any mechanism of soot formation must account for the variety of products, for the effects of additives, for the differences in smoking tendencies of fuels, for various spectroscopic observations and for certain features of flame structure.

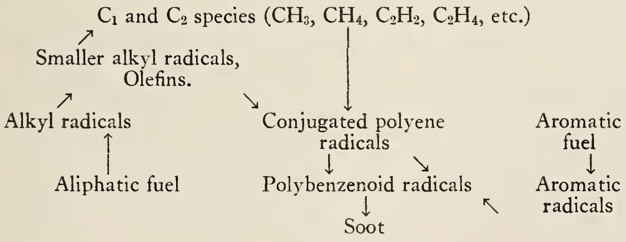
Soot (which is *not* carbon) has a hydrogen content which varies from 1 to 3 per cent by weight, i.e., approximately 12–36 per cent on an atomic basis—which is not negligible. The soot particles are built up of crystallites. Data are given on the mean dimensions of these particles varying from 47.5 A to 21 Å for one dimension across the planes and 13 Å in the other, which compares with 23.8 Å and 10 Å for the unit cell of circumanthracene. Distances between the planes are about the same for all soots and for circumanthracene.

Soots all give strong electron spin resonance signals indicating that they possess unpaired electrons and have a free radical nature. Consequently soot can be regarded as an agglomeration of very large polybenzenoid free radicals.

In a diffusion flame the conversion of simple fuel molecules into large aggregates containing 50,000 or so carbon atoms takes place in about 10 milliseconds and such fast reactions point to free radicals as intermediates. The carbon skeleton must survive high temperatures. Conjugated species, either conjugated polyenes or aromatics and polyaromatics, are considered. The skeleton must grow rapidly and conjugated species have the ability to undergo addition reactions of the Diels–Alder type.

Thomas considers that the nucleus should be able to add on fragments to form a new larger species just as reactive as the first and suggests that a conjugated free radical fulfils the requirements.

A reaction scheme proposed is:



Schalla and MacDonald who compared smoking tendencies of hydrocarbons found that the one with the lowest smoke point was butadiene, which fits in with the above scheme.

Additives that promote soot formation are mainly halogens or halogenated compounds which probably function by promoting dehydrogenation, making the process of olefin and polyene formation easier and assisting ring closure. The hypothesis of acetylene as an intermediate is considered briefly and it is pointed out that it may well be one of the species formed before the building up process starts.

According to Thomas, the compounds isolated from soot and often considered to be intermediates are not such but products of premature chain termination. They are the products not reactive enough to go on to form soot. From a list of the calculated reactivities to Diels–Alder additions of a number of polyolefins, linear bent polyacenes, it is concluded that butadiene and the linear polyacenes are of high reactivity but the bent polyacenes are of low reactivity and are, in fact, found in association with soot.

A general discussion follows this opening contribution to a one-day symposium and a number of participants discuss recent and, in some cases, unpublished work having a bearing on the topic.

Subject Headings: *Carbon, formation, in flames; Flame, formation of carbon.*

R. Long

Lee, K. B. (International Flame Research Foundation, IJmuiden, The Netherlands), **Thring, M. W.** (University of Sheffield, Sheffield, England), and **Beer, J. M.** (International Flame Research Foundation, IJmuiden, The Netherlands) "On the Rate of Combustion of Soot in a Laminar Soot Flame," *Combustion and Flame* **6**, 127-145 (1962)

A laminar diffusion flame that generated a thin cylindrical annulus of soot 5 mm in diameter and 0.5 mm thick is described. The burning away of this hollow soot column above the flame was investigated.

Air/O_2 mixtures were preheated to 200°C and the fuel used was calor gas. The flame and column of soot were enclosed in a quartz tube, the burner being a 10 mm diameter copper tube mounted concentrically with the quartz tube. The copper burner was movable vertically so that only a single sampling point in the quartz tube was necessary. Gas samples were taken using a 5 mm diameter stainless steel tube, while the total mass flow of soot was sampled through a 2 mm diameter copper tube. Temperature measurements with 0.1 mm Pt/Pt-Rh wire checked well with Kurlbaum measurements on the soot particles.

The column was sampled at 1 cm intervals for 6 cm downstream of the tail of the flame. Chromatographic analysis of the gases in initial experiments showed only nitrogen, oxygen, and carbon dioxide. No carbon monoxide could be detected. Subsequent gas analyses were therefore carried out in a modified Orsat apparatus. Since the velocities involved were too low for pitot tube measurement, they were calculated using the local gas temperature. Photographic checks of the velocities using dried soot particles were made, but no indication is given of the agreement. The size of the soot particles at the various points was found from electron micrographs. The results showed that the size at any point was uniform and that it decreased as combustion proceeded. Initially the particles were 400 Å, regardless of temperature or oxygen partial pressure.

An empirical equation for the rate of combustion is put forward:

$$\frac{\rho d_0}{p^{-1}\,6(m_0)^{\frac{1}{3}}\,(m)^{\frac{2}{3}}}\,\frac{dm}{dt}=\frac{k}{(T)^{\frac{1}{2}}\exp\,(E/RT)}$$

A regression analysis of the results gave the values for

$$E=39{,}300\text{ cal/g mole}\qquad\text{and}\qquad k=1.085\times 10^4$$

where m_0=initial mass flow g/sec; m=mass flow after time t g/sec; p=partial pressure oxygen atm; d_0= initial diameter of soot; and ρ=density of soot (28/cm). This equation was obtained by assuming surface reaction control. A calculation using Hottel and Parker's[1] simplified equation for diffusion control gave a very much higher rate of combustion than that found. This is hardly surprising since the form of Hottel and Parker's equation shows that at very small diameters, diffusion resistance becomes negligible. A calculation by your reviewer using the equation derived by Hottel and Parker[1] for surface kinetics gives a rate of combustion of 9.8×10^{-3} g/cm^2 sec for an oxygen partial pressure of 0.1 atm. This is two orders of magnitude greater than the experimental results. The explanation of this is not clear, but it seems likely that some further factor, possibly water vapor, needs to be taken into account.

Reference

1. Parker, A. S. and Hottel, H. C.: *Ind. Eng. Chem.* **28,** 1334 (1936).

Subject Headings: ***Soot, rate of combustion; Combustion, rate, of soot.***

M. G. Perry

V. Combustion Principles

Zel'dovich, Ya. B. (Institute of Chemical Physics, Moscow) "Chain Reactions in a Burning Flame—Approximate Theory of Flame Velocity," *Kinetics and Catalysis* **2,** 285-298 (1961) (Paper presented at the All-Union Conference of Combustion, January 10, 1961)

In the past few years the theoretical treatment of homogeneous flame propagation has been reduced to an exhibition of mathematical virtuosity. Numerous numerical and analytical procedures have been published differing predominantly in the approximations employed. The paper under review represents another attempt to develop an approximate theory of flame propagation which takes into account "model" mixtures undergoing symbolic chain reactions. The model mixtures exhibit transport properties with the Lewis number of unity and with no variation as a function of temperature or composition. The kinetics include unbranched chains of the type: $A+X\rightarrow 2B+X$ followed by $A+B\rightarrow C+B$ (where A is a reactant, B an active center, X a stable intermediate, and C a product); and chain branching of the type: $A+X\rightarrow 2B$ (chain initiation), $A+B\rightarrow 2B$ (chain branching); $A+B\rightarrow C+B$. Such a reaction sequence may be encountered in a real system such as

$$H+O_2\rightarrow OH+O;$$

$$O+H_2\rightarrow OH+H;$$

$$OH+H_2\rightarrow H_2O+H.$$

In essence the author desires to explore the effects of pressure and combustion temperature on flame speed. Basically the thermal theory of flame propagation is employed which yields effectively an exponential distribution in temperature T of the form

$$(T-T_0)/(T_b-T_0)=\exp\ (xu/D),$$

where T_b is the adiabatic flame temperature, T_0 the initial temperature, x the distance coordinate, u the flame speed (combustion rate), and D the thermal diffusivity. For the mass distribution profile an expression of similar form $A/A_0 = 1 - \exp(xu/D)$ is chosen, where A is the concentration of reactant A.

In the theoretical analysis that follows, various forms of the reaction-rate expressions are chosen to describe the reacting system. For example, for a simple monomolecular reaction the disappearance of reactant A is given by an Arrhenius expression of the form

$$-dA/dt = kA = A \cdot S \exp(-\mathcal{Q}/RT).$$

Under steady-state conditions the amount of A consumed in the burning zone is equal to the amount entering it so that

$$uA_0 = \int [-(dA/dt)]\, dx = \int A(x)\ S \exp[-\mathcal{Q}/RT(x)]\, dx.$$

An approximate evaluation of the integral[1] yields an expression for the flame speed

$$u = [DS \exp(-\mathcal{Q}/RT_b)]^{\frac{1}{2}} \cdot (RT_b^2)/[\mathcal{Q}(T_b - T_0)]. \tag{1}$$

This flame speed equation suggests that u is a function of pressure ($u \propto 1/p^{\frac{1}{2}}$) and also governed by the term $\mathcal{Q}/RT_b$ involving the activation energy and the flame temperature. Equation (1) also suggests that u is quite sensitive to the initial gas temperature, much more so than expected from experimental observations. Similar mathematical procedures are employed for the more complex reaction mechanisms and some generalizations are drawn. However, it is not apparent what advantages this approximate theoretical analysis offers to an understanding of the various kinetic steps in the combustion mechanism.

Reference

1. Frank-Kamenetzkii, D. A.: *Diffusion and Heat Exchange in Chemical Kinetics*. Princeton University Press, 1955.

Subject Headings: ***Flame velocity, approximate theory of chain reaction; Chain reaction, theory of flame velocity.***

H. Wise

Salooja, K. C. ("Shell" Research Ltd., Chester, England) "The Role of Combustion Promoters," *Journal of the Institute of Petroleum* **48**, 119-129 (1962)

The combustion behavior of a number of hydrocarbons, pure and in admixture with various promoters, was investigated in a flow system. The fuel/air mixture was about twice stoichiometric. Extensive results are presented as graphs of per cent carbon monoxide in the effluent gases from the reactor versus temperature.

Cyclohexane and *n*-heptane were oxidized more readily when the following promoters were used: isopropyl nitrate, cyclohexyl nitrate, ethyldigol nitrate, and *n*-decyl nitrate. The concentration of the promoter in the fuel was 5 volume per cent, except for isopropyl nitrate which was also used at 10 per cent by volume in *n*-heptane only. The lower figure (5 per cent) was preferred because the entire preflame region could be investigated. Methylcyclohexane was also examined using the above promoters, and in addition di-*t*-butyl peroxide and diethyl ether. The effect of promoter concentration was studied, using methylcyclohexane as fuel and cyclohexyl nitrate as the promoter, in a concentration range of 0.01–5.15 volume per cent. The extent of preflame reaction was increased by the promoters and the ignition temperature lowered. Diethyl ether, however, did not act as a promoter for methylcyclohexane. In the studies of the concentration effect, the effectiveness of cyclohexyl nitrate in promoting the oxidation of methylcyclohexane was found to be relatively less as the concentration was increased. This parallels the behavior of promoters in enhancing cetane numbers for diesel engine fuels. The promoters can be ranked in decreasing order of effectiveness: cyclohexyl nitrate, ethyldigol nitrate>*n*-decyl nitrate>isopropyl nitrate>di-*t*-butyl peroxide>diethyl ether.

The extent of preflame reaction of benzene was markedly increased by the addition of both cyclohexyl nitrate (5 mole per cent) and di-*t*-butyl peroxide (5 mole per cent). The ignition temperature of benzene was lowered from ∼700°C to ∼540°C by cyclohexyl nitrate and to ∼675°C by di-*t*-butyl peroxide. Cyclohexyl nitrate (5 vol per cent) in toluene, ethylbenzene, *iso*-octane and di-*iso*-butylene promoted preflame reactions and lowered the ignition temperatures for all these hydrocarbons.

Promoters increase the extent of reaction in all the preflame stages; in particular, the zone of negative temperature coefficient is diminished, and the magnitude of the coefficient is diminished. Promoters lower the ignition temperature. It is suggested the effectiveness of the different nitrate esters depends on the ease of oxidation of the hydrocarbon moiety of the ester. The relative susceptibilities of the various hydrocarbons are correlated with their blending properties in knock ratings in a gross way.

A possible mechanism is put forth for promoter action. It is suggested the nitrate ester decomposes to yield chain initiators:

$$RONO_2 \rightarrow RO\cdot + NO_2$$

The NO_2 is assumed to react in the sequence

$$RH + NO_2 \rightarrow R\cdot + HNO_2$$

$$HNO_2 + O_2 \rightarrow HO_2\cdot + NO_2$$

and

$$HNO_2 \rightarrow OH\cdot + NO$$

The decreasing effectiveness of the promoters as their concentrations are increased is ascribed to a recombination:

$$R\cdot + NO_2 \rightarrow RNO_2$$

This mechanism suggests nitrogen dioxide introduced in the air stream should serve as a promoter.

Subject Headings: *Combustion, role of promoters; Promoters, role in combustion.*

P. R. Ryason

Kaesche-Krischer, B. (Bundesanstalt für Materialprüfung, Berlin-Dahlem, Germany) "Mechanism of Combustion of Trichlorethene in Stationary Flames," *Combustion and Flame* 6, 183-191 (1962)

Chlorinated hydrocarbons, used extensively in the degreasing of metals, are not flammable in the presence of air. Use of some of these degreasing solvents in oxygen-enriched and oxygen atmospheres, however, require special precautions since some of these solvents support combustion under these conditions. Cited compounds as tetrachlorethene (perchlorethylene) and trichloromethane (chloroform) require an oxygen atmosphere to be combustible, while other compounds such as trichlorethene (trichlorethylene, the prime subject of this article), dichloromethane, and monochloromethane support combustion in oxygen-enriched atmospheres.

The combustion-mechanism studies of trichlorethene were based upon "burner" flames of premixed oxygen/nitrogen/trichlorethene gaseous mixtures and image photographs of the burner flames to determine the surfaces of the flame cones and flame velocities. These studies showed the following:

Measurement of the Trichlorethene ($CHCl=CCl_2$) *Burning Velocities*

Stable flames were obtained with mixtures of $CHCl{=}CCl_2/O_2/N_2$ when (a) the O_2/N_2 mixture contained at least 40 vol per cent O_2 and (b) in a mixture with this atmosphere, the $CHCl{=}CCl_2$ concentration was at least equal to that of the stoichiometric mixture, assuming CO_2, H_2O, and Cl_2 to be the sole products of the overall combustion. Under these conditions the burning velocity was low and the flame was unstable. Faster burning and stable flames were obtained with higher oxygen concentrations. The illustrated data showed that

(a) The flame velocity increased from 9 to 27 cm/sec for O_2 contents which increased from 40 to 100 per cent in the O_2/N_2 mixtures where the stoichiometric quantity of $CHCl=CCl_2$ and O_2 was held constant.

(b) The maximum burning velocity of the flames as a function of γ [the O_2/O_2+N_2 ratio] over the λ value range of 0.4 to 1.6 [the ratio of $CHCl=CCl_2/O_2$ divided by the stoichiometric ratio of $CHCl=CCl_2/O_2$] showed that the maximum burning velocity [$(v_n)_{\max}$] was a linear function of γ from *ca.* 0.21 (air) to 0.8 with $(v_n)_{\max}$ values of *ca.* 2 (extrapolated value) to 23 cm/sec. Above γ values of 0.8 to 1.0, $(v_n)_{\max}$ tended towards a maximum value of *ca.* 28 cm/sec.

Measurement of the Temperature of the Trichlorethene Flame Cones

As an extension of the above work, the temperature profiles of the two flame fronts were determined as a function of mixture strength ($\lambda =$ *ca.* 0.8 to 1.8) at a constant O_2/O_2+N_2 ratio ($\gamma=0.5$). It was shown the first flame front increased gradually in temperature from *ca.* 1100°C at $\lambda=0.8$ to 1400°C at *ca.* $\lambda=1.6$. At this approximate latter point, this first flame front "joined" with the second flame front and the temperature decreased from this point to *ca.* 1240°C at $\lambda=1.8$. The second flame front behaved normally by increasing rapidly in temperature from *ca.* 1500°C ($\lambda=0.8$) to a peak of *ca.* 1600°C ($\lambda=1.1$) and then dropping off in temperature as the mixture was enriched in trichlorethene.

Mechanism of Combustion in the Flames Cones

Based upon qualitative observations, a reaction mechanism was proposed which assumes that the first flame front is caused by the oxidation of $CHCl=CCl_2$ to chlorine monoxide (Cl_2O) and the second flame front is caused by the interaction of Cl_2O with carbon monoxide (CO). In addition, it was assumed that as the mixtures changed from lean to slightly rich trichlorethene mixtures ($\lambda \leq 1$ to $1.125 \leq \lambda < 1.5$), another product of combustion (water) gave way to the formation of hydrogen chloride. Further, when very rich mixtures were attained ($1.5 \leq \lambda < 2.25$), no more Cl_2O was formed due to the deficiency of oxygen. The following reaction mechanisms, as outlined by the author, summarize more completely the proposed mechanism of reaction:

Lean mixtures ($\lambda \leq 1$, $x \geq 2.25$):

$$CHCl{=}CCl_2 + xO_2 \xrightarrow[\text{reaction}]{\text{1st}} (x-2.25)O_2 + 0.5H_2O + 0.5Cl_2 + CO_2 + CO + Cl_2O$$

$$CO + Cl_2O \xrightarrow[\text{reaction}]{\text{2nd}} CO_2 + Cl_2$$

Slightly rich mixtures ($1.125 \leq \lambda < 1.5$, $2 \geq x > 1.5$):

$$CHCl{=}CCl_2 + xO_2 \xrightarrow[\text{reaction}]{\text{1st}} HCl + (4-2x)Cl_2 + CO_2 + CO + (2x-3)Cl_2O$$

$$CO + (2x-3)Cl_2O \xrightarrow[\text{reaction}]{\text{2nd}} (2x-3)(CO_2 + Cl_2) + (4-2x)CO$$

Very rich mixtures ($1.5 \leq \lambda < 2.25$, $1.5 \geq x > 1$):

$$CHCl{=}CCl_2 + xO_2 \longrightarrow HCl + Cl_2 + (2x-2)CO_2 + (4-2x)CO$$

Using this mechanism of reaction, the enthalpies of reaction were calculated from the lean to the very rich mixtures of the halocarbon in oxygen at a constant γ value ($\gamma = 0.5$). These changes in the enthalpies of reaction were plotted as a function of λ and were shown to be very similar to the corresponding changes in the measured flame temperatures. This similarity renders the proposed mechanism very plausible. In view of the approximate nature of the enthalpy calculations and the qualitative method of identifying the intermediate product of oxidation (Cl_2O), it has been suggested by the author that spectroscopic identification of the intermediate compound appears desirable.

Subject Headings: ***Trichlorethene, combustion of; Combustion, of trichlorethene.***

R. A. Gorski

Anagnostou, E. and Potter, A. E. (National Aeronautics and Space Administration, Cleveland, Ohio) "Flame Strength of Propane–Oxygen Flames at Low Pressures in Turbulent Flow," *Ninth Symposium* (*International*) *on Combustion*, New York and London, Academic Press, 1-6 (1963).

A combustion measurement, called "apparent flame strength," has been devised for the study of reactive fuel–oxidant combinations not easily handled as premixed systems. The measurement uses two opposed jets, one of fuel and one of oxidant. In the opposed-jet diffusion flame, as the mass flows of fuel and oxidant are increased, a critical flow is reached at which time the flame is extinguished in an area surrounding the jet axis. The average mass flow of fuel and oxidant at the jet axis when this occurs is defined as the apparent flame strength.

Measurements were made of the pressure and burner diameter dependence of propane–oxygen flames at Reynolds numbers above 2000, where a theory of Spalding[1] describing the opposed jet combustion situation is expected to be valid. Pressure was varied from 0.167 to 0.975 atm; burner diameter varied from 0.168 to 0.635 cm; and fuel Reynolds number from 2100 to 11,200.

The flame strength was directly proportional to burner diameter, which agrees with the prediction of Spalding's theory. The constant of proportionality was 2.3 gm/cm²-sec/cm of burner diameter at a pressure of 9.9 in. Hg and 1.7 gm/cm²-sec/cm of burner diameter at a pressure of 8.6 in. Hg.

The flame strength was found to be independent of Reynolds number. This agrees with the prediction of theory that the transport properties of the gaseous jets should have no effect on the flame strength.

The flame strength was shown to be represented by:

$$\text{Flame strength (gm/cm}^2\text{ sec)} = 10 \times [\text{Pressure (atm)}]^2.$$

The exponent should be close to the order of the reaction since, according to Spalding, the apparent flame strength is directly proportional to the maximum reaction rate in the flame. The exponent of 2 agrees well with the reaction order of 2.1 found from quenching distance experiments.

The maximum heat release rate was calculated using Spalding's theory and the measured flame strength. The result was 5.4 (10^4) cal/cm³ sec, which should be multiplied by a correction factor between 1.5 and 3 which accounts for viscous and density effects on the jet velocity. A similar calculation using a method based on Semenov's flame theory provided a heat release rate for propane–oxygen of 170 (10^4) cal/cm³ sec. The discrepancy indicates inadequacy in one or both of the theories.

This technique appears to have the potential of becoming, for impinging jet systems, a basic combustion measurement as useful as laminar flame speed has been for premixed systems. A necessary step is accumulation of extensive data on various fuel–oxidant combinations. This paper constitutes a good first step in that direction. The experimental set-up is sufficiently simple that further data could be derived by many investigators.

Reference

1. Spalding, D. B.: *ARS Journal* **31**, 763 (1961).

Subject Headings: *Flame, strength, of propane–oxygen; Propane, flame strength with oxygen.*

A. E. Noreen

King, I. R. (Texaco Experiment, Incorporated, Richmond, Virginia) "Recombination of Ions in Flames," *Journal of Chemical Physics* **37**, 74-80 (1962)

Using Langmuir probe and reactance ($\mathcal{Q}$) techniques King presents further experimental evidence that ion recombination downstream of subatmospheric hydrocarbon–air flames is primarily an ion-ion reaction rather than an ion-electron reaction. Considered in the light of current work in this field[1–4] it is suggested that H_3O^+ and OH^- are the most likely reactants, the latter being formed from OH by prior electron attachment.

King bases his conclusions mainly on the following observations:

1. The recombination of positive ions is second order, in the sense that the value of $1/n_+$ inferred from Langmuir probe traces increases linearly with

distance from the reaction zone. In contrast, reactance ($\mathcal{Q}$) measurements indicate a first order decay of electron concentration.

2. When streamwise ambipolar diffusion is neglected* and the apparent local ion number density is corrected for free path effects by the simple procedure outlined in Ref. 5, the second order recombination rate constant, α, for positive ion decay displays a $p^{-0.64}$ total pressure dependence (for subatmospheric propane-air mixtures) and α increases slightly with increased flame temperature.
3. The magnitude of the inferred second order recombination rate constant for positive ion decay decreases with the addition of small quantities of halogen containing compounds (e.g., $CHCl_3$) or nitric oxide. Halogenated additives also cause a marked decrease in the effective negative particle mobility of the flame gases.

With regard to the third of these observations King notes that these additive effects are qualitatively consistent with the classical Langevin treatment of ion-ion recombination since the decrease in recombination coefficient α would in each case simply reflect the decreased mobility of one of the dominant ionic reactants (Cl^- and NO^+, respectively). Dissociative recombination, which King apparently exludes as a possibility for ion–ion recombination, is also ruled out as being unlikely on the basis of the observed pressure and temperature dependence of α (cf. item 2, above).

While there now seems to be general agreement on the importance of electron attachment and ion–ion recombination in hydrocarbon–air flames, in several important respects King's detailed reasoning is by no means satisfying, as has been partially documented by Calcote in the printed discussion of Ref. 6.

The situation can be summarized as follows. First, it is not clear why King does not consider the possibility of a dissociative ion-ion recombination step such as

$$H_3O^+ + OH^- \rightarrow H_2O + OH + H \qquad (1)$$

although, admittedly, little is known about such reactions. Second, the reported pressure and temperature dependence of α in itself constitutes weak evidence for ruling out dissociative recombination since: (1) the pressure and temperature exponents may instead be a consequence of the Langmuir probe free-path correction procedure† or the systematic neglect of streamwise ambipolar diffusion, (2) the theoretical temperature dependence of any particular dissociative recombination is itself unknown and may depart considerably from the $-\frac{3}{2}$ power dependence frequently assumed; and finally, (3) a recombination coefficient, α, which depends on $p^{-0.64}$ (cf. King's Fig. 2) is apparently inconsistent with the basic second order (ion–ion) decay mechanism suggested in the same paper.‡

This work, with its uncertainites, points up the need for a detailed examination of negative ion profiles downstream of subatmospheric flat flames, as well as the need for a more detailed examination of the treatment of Langmuir probe data in such environments. In connection with the theory of Langmuir probes it should be noted

---

* Appreciable streamwise ambipolar diffusion would have caused nonlinearity in King's second-order plots; however, this was apparently not observed.

† Thus Calcote,[7] using a more elaborate free-path probe correction procedure, as well as a correction for streamwise ion diffusion, reports a value of α which is pressure independent, as one would expect for a second order kinetic process such as dissociative recombination.

‡ Actually, the data collected in King's Table I also suggests that α is pressure independent.

that the magnitude of the free-path, or diffusion, correction will strongly affect not only the apparent pressure–temperature dependence of α in any series of combustion experiments (such as those reported by King) but also the absolute value of the inferred second-order recombination coefficient in any one experiment. Thus, it would be of interest to re-examine existing Langmuir probe data in the light of the mathematically more rigorous probe theories recently developed by Su and Lam,[8] and Cohen.[9]

References

1. van Tiggelen, A.: "Ion Identification and Ionization Processes in Flames." Laboratory for Inorganic Chemistry, Universite Catholique de Louvain, 4 Rue Kraeken, Louvain, Belgium (May 1960).
2. Knewstubb, P. E. and Sugden, T. M.: *Proc. Roy. Soc.* (*London*) **A255**, 520 (1960).
3. Smith, H. and Sugden, T. M.: *Proc. Roy. Soc.* (*London*) **A211**, 31 (1952).
4. Calcote, H. F.: *Eighth Symposium* (*International*) *on Combustion.* Baltimore: The Williams and Wilkins Company, p. 184, 1962.
5. King, I. R. and Calcote, H. F.: *J. Chem. Phys.* **23**, 2203 (1955).
6. Calcote, H. F.: *Ninth Symposium* (*International*) *on Combustion.* New York: Academic Press, p. 622, 1963.
7. Calcote, H. F. and King, I. R.: *Fifth Symposium* (*International*) *on Combustion.* New York: Reinhold Publishing Corporation, p. 423, 1955.
8. Su, C. C. and Lam, S. H.: *Princeton University Aeronautical Engineering Department Report 605* (April 1962).
9. Cohen, I. M.: *Princeton University Plasma Physics Laboratory Report MATT-153* (November 1962) and *Report MATT-180* (March 1963).

Subject Headings: *Flame, recombination of ions; Ions, recombination in flames.*

D. E. Rosner

Maxworthy, T. (Harvard University, Cambridge, Massachusetts) "Flame Propagation in Tubes," *The Physics of Fluids* **5**, 407-417 (1961)

The paper discusses flame propagation in stationary fuel–air mixtures contained in long vertical tubes open at one end and closed at the other, with ignition taking place at the open end. The shape, and the velocity of uniform movement (U_∞), of such flames are known experimentally to depend on the tube diameter, the mixture composition, and on the direction of propagation relative to the gravitational field. For a given fundamental burning velocity S_u° the velocity of uniform movement depends principally on the ratio of the flame area A to the tube area, and both U_∞ and this ratio vary with the tube diameter and the direction of propagation.

For flame propagation in a tube the flame shape approximates to that of a semi-ellipsoid of revolution, convex towards the unburnt gas. Increased flame area is accompanied by greater eccentricity of the generating ellipse, and hence by greater flame curvature near the axis. This local increase in convexity towards the unburnt gas in turn reduces the local burning velocity, and so provides an effect which limits the area increase and which leads to a stable flame shape and area. In addition to this, viscosity effects in the gas modify the flame shape by affecting the gas velocities in the vicinity of the flame front. Both these effects are considered in order to obtain a solution for the flame shape. It is interesting to note that the curvature effect has been used by Markstein[1] in describing the formation of steady state cellular flames.

The calculated flame shapes are compared with shapes determined experimentally. For small diameter tubes agreement is poor, and this is ascribed to neglect of quenching effects at the tube wall in the calculation. For somewhat larger diameters (*ca.* $\frac{3}{4}''$ to $1\frac{1}{2}''$) agreement in the region away from the wall is regarded as reasonable, but the flame shapes near the wall were again modified. For very large diameters ($>2''$) agreement is again poor.

Comparison of calculated and experimental speeds of uniform movement also gives poor agreement.

Finally, modification of the ideal theory (valid far from a wall) by wall-quenching effects is considered in a qualitative manner and it is suggested that the central portion of a flame in a small diameter tube may best be approximated in the theory by performing the calculation for a diameter larger than the true tube diameter. For example, the central portion of an experimental flame in a tube of diameter 0.5 in. agrees very closely with the theoretical shape for a 0.55 in. diameter tube.

Reference

1. Markstein, G. H.: *Fourth Symposium on Combustion.* Baltimore: Williams and Wilkins Co., p. 53, 1953.

Subject Heading: *Flame, propagation, in tubes.*

G. Dixon-Lewis

Crowe, C. T. (United Technology Corporation, Sunnyvale, California), **Nicholls, J. A., and Morrison, R. B.** (University of Michigan, Ann Arbor, Michigan) "Drag Coefficients of Inert and Burning Particles Accelerating in Gas Streams," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 395-406 (1963)

Many solid rocket propellant formulations include metals. Upon combustion these produce metal oxide particles, which are carried out with the exhaust gases. These particles contribute to a specific impulse loss which is largely dependent on the gas-particle velocity and thermal lags.

The gas-particle velocity lag is a function of the particle drag coefficient, which in turn is a function of particle shape and orientation with respect to the flow, Mach number, and Reynolds number based on the relative velocity between the particle and the gas, acceleration modulus, roughness, burning rate, and the relative turbulent intensity of the gas stream.

The purpose of this study is the attainment of analytical and experimental values of drag coefficients for burning particles accelerating in a gas stream.

Since the particle is probably in a molten state for a considerable portion of its trajectory a spherical shape is assumed for the analysis. The Mach number and relative turbulence intensity are assumed small. Only Reynolds numbers greater than 200 are considered. The analytical approach consists of solution of the continuity and momentum equations written for the boundary layer of a spherical particle. This involves a large number of assumptions and introduction of some empirical values. The results of the analysis indicate that the effect of both burning and acceleration is to reduce the particle drag coefficient.

The experimental setup had to be capable of providing sufficient data to determine drag coefficients and burning rates for accelerating particles. To achieve this, particles were injected into a vertical shock tube above the test section and fell toward the testing region. A flame in the test section ignited the particles before a shock wave, coming from below, subjected them to a convective flow field accelerating them upwards. A high-speed camera took shadowgraph photographs of the particles, from which acceleration and burning rate data were obtained. The Mach number of the shock wave varied from 1.08 to 1.3. Both nonburning and burning particles were studied.

The results indicate a larger drag coefficient than the steady-state drag coefficient for a sphere. Reduced drag coefficients due to accelerative and burning effects were not detectable.

From this study, a steady-state drag coefficient for a sphere is applicable to particles found in rocket nozzles provided their Mach number, based on the relative velocity, is small. However the experimentally determined result

$$\log_{10} C_D = 2.586 - 1.705 \log_{10} \mathrm{Re} + 0.2501 (\log_{10} \mathrm{Re})^2$$

for

$$200 < \mathrm{Re} < 1600 \qquad \text{and} \qquad M \simeq 0;$$

where C_D is drag coefficient, Re is Reynolds number, and M is Mach number, would be appropriate should a more accurate drag coefficient be required.

Subject Headings: *Particles, drag coefficient of; Drag coefficients, of accelerating particles.*

A. E. Noreen

VI. Radiation

Sparrow, E. M. (University of Minnesota, Minneapolis, Minnesota), **Gregg, J. L., Szel, J. V., and Manos, P.** (National Aeronautics and Space Administration, Cleveland, Ohio) "Analysis, Results, and Interpretation for Radiation between Some Simply-Arranged Gray Surfaces," *Journal of Heat Transfer* (Transactions of the ASME—Series C) **83**, 207-214 (1961)

In order to simplify mathematical treatments of radiation heat transfer problems and provide practical solutions, three basic assumptions are usually made:

1. Surface reflection of radiant energy is diffuse,
2. Surface emission is diffuse,
3. Incident energy is distributed uniformly over the surface.

This article is concerned with the third assumption. Generally, the surface distribution will not be uniform and therefore the accuracy of overall heat transfer rates can be questioned. In addition, information may be required about the variation of local heat transfer over a surface, and on both these counts, the third assumption is invalid.

While such an extension of the analysis can become too complex, it is possible to evaluate simple geometric configurations and provide some results which are useful to the engineer.

Two systems have been considered:

1. Two planes, length L, infinite in the other direction and sharing a common edge, and
2. Two parallel planes, length L, infinite in the other direction.

The surfaces are gray, and have the same uniform temperature and emissivity, but consideration is also given to different temperature distributions and a radiating environment.

An integral equation is derived for the combined radiant flux per unit area and unit time leaving any position in the system, in terms of the temperature, emissivity reflectivity, and geometry of both systems (angle of adjoint planes, separation of parallel planes). Since the planes are infinite in one dimension, the analytical expression contains only two dimensions. From this equation the distribution of incident energy can be determined. Local heat transfer is calculated as the difference between the emitted and absorbed radiation, and expressed as a fraction of the radiation that the surface could emit to free space. Overall heat transfer rates are obtained by summation of local values.

The equations have been solved by numerical methods and the results presented in graphical form. Local heat transfer rate is given as a fraction and as a function of emissivity and dimensionless position along the plane.

For the parallel plane system when the separation (h) is smaller than the plane length (L) the nonuniformity of local heat transfer increases with increase in position ratio along the plane, and increases with increase in emissivity. As h/L decreases, the nonuniformity increases, such that when the emissivity is greater than 0.5, configurations with $h/L=0.05$ can be treated as semi-infinite gaps. For the adjoint planes, the fraction of maximum possible heat transfer increases with position ratio along the plane and the greatest nonuniformity occurs with the smallest angle (45° in this instance).

Overall heat transfer rates have been expressed again as a fraction of the maximum heat transfer possible. The overall heat transfer decreases with decreasing spacing and decreasing emissivity for the parallel plane system and decreases with decreasing angle with the second system.

Finally, these results have been compared with results obtained by a simplified approach which assumes uniform distribution of incident energy. The simplified theory gives less accurate values as the spacing ratio of the parallel plate system decreases, but these inaccuracies are small when the emissivity is high. In the case of adjoint planes, the simplified theory covers all the examples considered.

The authors discuss briefly the handling of the condition where the planes are at different temperatures, or the environment radiates to the system, or the emissivities differ. Combination of these possibilities can be treated by an additive approach. For example, if the surfaces are at T_1 and T_2, the solutions of radiant flux for the situation where the surfaces are at T_1 may be added to that for which the lower surface is at zero and the upper is at $(T_2^4-T_1^4)^{\frac{1}{4}}$.

The general equation can also cover the case of nonuniform temperature distribution.

Subject Heading: *Radiation, between gray surfaces.*

P. L. Start

Edwards, D. K. and Nelson, K. E. (University of California, Los Angeles, California) "Rapid Calculation of Radiant Energy Transfer between Nongray Walls and Isothermal H_2O or CO_2 Gas," *Journal of Heat Transfer* **84**, 273-278 (1962)

Combustion of hydrocarbons with atmospheric gases leads, as is well known, to water vapor and CO_2. The presence of H_2O and CO_2 increases the complexity of the radiant heat transfer problem. The degree of complication depends on the wall properties; e.g., a nongray wall necessitates summation of monochromatic contributions. In order to calculate the radiant energy exchange within an enclosure having nongray walls and containing absorbing gases a variety of data is required.

The adjective, nongray, describing the walls indicates that the variations of wall emissivity with wavelength are significant. The wall is defined by its temperature and spectral emissivity. Likewise, the gases of uniform temperature are characterized by the spectral emissivity. It is possible to replace the spectral emissivity by an average emissivity valid over an effective band width.

The geometrical relation between the walls and the intervening gas determines the set of linear algebraic equations[1] describing the radiant heat transfer and the mean beam length or optical path length.

Hottel's[2] graphs of total emissivity as a function of temperature and beam length are used. The fractional contribution of each vibration-rotational band is given in graphical form as a function of temperature. Knowledge of each band's contribution is required since the walls do not have constant emissivity.

An important element of the calculation is the estimation of the band widths. Guides for selecting the band widths are tabulated in the paper. Errors in estimating band width can cause large errors in calculated heat transfer.

In this paper the authors have outlined the method of calculating radiant heat transfer and have provided or indicated the source for the necessary data. Two numerical examples are given as illustrations.

The methods have application not only in combustion processes but in the geophysical problem of energy balances in the earth's atmosphere.

References

1. Oppenheim, A. K.: "Radiation Analysis by the Network Method," *Transactions ASME* **78**, 725 (1956).
2. Hottel, H. C.: "Radiation Heat Transmission," in *Heat Transmission*, edited by W. H. McAdams, 3rd edition. New York, N. Y.; McGraw-Hill Book Company, Inc., chapter 4, 1954.

Subject Heading: ***Radiation, transfer, nongray walls and gas.***

A. E. Fuhs

VII. Suppression of Combustion

Applied Physics Laboratory, The Johns Hopkins University "Flame Inhibition Research," *Quarterly Progress Report* (*1 February-30 April 1962*) (*TG376-6*) *ERDL Project No. 8M76-05-001-03*

This report is the sixth quarterly progress report on a program of basic research on the mechanism of the inhibition of hydrocarbon–air flames by halogenated compounds. The general approach in this work is to sample methane–oxygen and methane–oxygen-inhibitor flames using the micro-probe techniques developed in The Applied Physics Laboratory. Composition profiles so determined and temperature profiles determined by means of thermocouples will be used to interpret the effects of inhibitors on the flames.

A part of the effort is being devoted to the development of a "scavenger" technique that will allow the direct determination of atom and radical concentrations in the flame by a sampling technique. The method depends on the rapid reaction, within the sampling probe, of atoms or radicals with some stable "scavenger" molecule to yield a stable product whose concentration is an unambiguous measure of the particular atom or radical concentration. Attempts to scavenge H atoms with CCl_4 via $H+CCl_4 \rightarrow HCl+CCl_3$ were not satisfactory because atom recombination was too fast relative to the scavenging reaction. The determination of O atom concentrations by scavenging with nitrogen dioxide

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

has given satisfactory results. In the present report, further testing of the scavenging of O atoms has been performed. Comparison of the "scavenger" technique for O atom concentration with the gas-phase titration technique wherein nitrogen dioxide is also the reagent used but in a different way,[1] gave good agreement. Difficulties arising from the possible nonspecificity of the reaction for O atoms are considered but can be dealt with satisfactorily. Some discussion of factors affecting the gas-phase titration method is included.

In the experiments with the methane–oxygen flames, initially experiments were performed on a flat flame burner with methane–oxygen and methane–oxygen–hydrogen bromide, ambient pressure being 0.05 atm. Corrosion of the burner by the halogen compounds necessitated the design of a new Teflon glass-ceramic burner system which would be resistant to hydrogen bromide or other bromine-containing compounds that might be formed. Studies were then carried out with a spherical burner system, and flames of methane–oxygen with and without hydrogen bromide were examined. The results indicated that a significant amount of reaction was occurring on the ball surface. A further difficulty with the spherical burner is that the O atom concentration is substantially higher than the equilibrium one so that energy distributions in the flame front cannot be calculated. In the current report the difficulties arising from this nonequilibrium are discussed and the authors have decided to carry out future experiments with the flat flame burner. The new burner is described and experiments with it are planned for the next quarter.

Reference

1. F. Kaufmann: "Reactions of Oxygen Atoms," Paper No. 1 in *Progress in Reaction Kinetics*, Vol. 1, edited by G. Porter. New York: Pergamon Press, 4–16, 1961.

Subject Headings: ***Flame, inhibition of methane; Inhibition, of methane–air flames; Methane, inhibition of.***

J. B. Levy

Applied Physics Laboratory, The Johns Hopkins University "Flame Inhibition Research," *Quarterly Progress Report* (*1 November 1962–31 January 1963*) (*TG 376-9*) *ERDL Project No. 8M76-05-001-03*

This report is the ninth quarterly progress report on a program of basic research on the inhibition of hydrocarbon–air flames by halogenated compounds. The general approach in this program is to determine the microstructure of methane–oxygen and methane–oxygen-inhibitor flames using probe techniques developed in The Applied Physics Laboratory. From the composition and temperature profiles it is hoped that a detailed understanding of the mechanism of inhibition will be realized. A novel feature of the present probing experiments is the attempt to determine atom or radical concentration by "scavenging" such species with an appropriate reagent. Such a reagent must be able to react rapdily with the active species to yield a product whose concentration is an unambiguous measure of the radical concentration. So far it appears that nitrogen dioxide is a satisfactory scavenger for O atoms via

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

To date experiments have been performed with methyl bromide, hydrogen bromide, and iodine as inhibitors. Studies have been carried out using both a spherical burner and a flat flame burner.

Most recently profiles have been obtained in an all glass–ceramic flat flame burner showing the effect of hydrogen bromide and methyl bromide on a methane–oxygen flame at 0.05 atm pressure. These results have been programmed for computer analysis but the results have not yet been obtained. Preliminary experiments have been performed with methane–oxygen flames inhibited by trifluoromethyl bromide and trifluoromethyl chloride.

Another objective of the program is the development of a simple theory of flame inhibition. Burning velocity calculations of hydrogen–nitrogen–oxygen (0.1883: 0.7656:0.0460) have been made based on the Zeldovich theory[1] using estimated diffusivities of the gas mixture. The velocities calculated bracket the experimental velocity, the actual calculated value depending on the particular diffusivity value used.

In the computer program analyses have also been made on the effect of hydrogen bromide on the above hydrogen–oxygen–nitrogen flame. The results were that in the presence of hydrogen bromide the ignition delay was substantially increased, the reaction occurred at a higher temperature, and there was a small difference in reaction rates. These results are similar to those observed experimentally with the hydrogen bromide-inhibited methane–oxygen–argon flame.

A new feature of the program is the study of elementary reactions by the molecular beam technique. A discussion of the proposed experimental procedure is included in the present report. A technique is described for pumping the beam in which a porous nozzle is a basic feature. This allows the boundary layer to be pumped off in stages so that most of the material can be removed in the initial, high pressure part. Preliminary experiments have been performed with beams of sodium metal and methyl iodide with encouraging results.

Reference

1. Zel'dovich, Ya. B. and Barrenblaltt, G. J.: *Combustion and Flame* **3**, 9 (1960).

Subject Headings: *Flame, inhibition of methane; Inhibition, of methane–air flames; Methane, inhibition of.*

J. B. Levy

Skinner, G. B., Hedley, W. H., Ringrose, G. H., and Snyder, A. D. (Monsanto Research Corporation, Dayton, Ohio) "A Research Program for Understanding the Mechanisms of Flame Inhibition," Third Quarterly Progress Report (1 June 1962-31 August 1962) *Aeronautical Systems Division*, *Air Force Systems Command Contract 33(657)-7617* (September 1962)

This program of research is directed at the problem of the extinguishment of propellant fires. The systems currently being studied are the hydrogen–oxygen system and the hydrazine-nitrogen tetroxide system. In addition, the possibility of calculating flame system properties by means of a computer program is being investigated.

In previous work in this program on the hydrogen–oxygen system a large number of substances, both organic and inorganic, had been screened as potential inhibitors of this flame. More recently attention has been focused on ethylene as an effective inhibitor and on the study of its effect on the flame speeds and shock tube induction times to ignition for hydrogen–air mixtures.

In the present report, results are presented for flame speeds of hydrogen–air–ethylene mixtures at equivalence ratios of 0.95, 1.73 and 3.30 and for initial mixture temperatures ranging from about 380°–390°K to about 700°K. These results are presented in some detail in the form of tables and curves. The effect of ethylene was found to be a function both of the preheat temperatures and of the equivalence ratio.

In the shock tube studies, OH emission intensity measurements are being made and induction times have been defined as the time required for the OH emission intensity to reach 10 per cent of its maximum value. Induction times have been calculated by considering ten reactions as contributing and by making numerical integrations for various experimental concentrations and temperatures using known kinetic data. The ten reactions considered were:

$$H_2+O_2=2\,OH$$
$$H+O_2=OH+O$$
$$O+H_2=OH+H$$
$$OH+H_2=H_2O+H$$
$$H+O_2+A=HO_2+A$$
$$H+H+A=H_2+A$$
$$H+OH+A=H_2O+A$$
$$H+H+H_2O=H_2+H_2O$$
$$H+OH+H_2O=H_2O+H_2O$$
$$OH+OH=H_2O+O$$

Curves of the product of initial oxygen concentration and induction time vs. the reciprocal of absolute temperature have been plotted on the basis of these calculations for the systems: 4% H_2, 2% O_2, 94% A, P=1 atm; 1% H_2, 0.5% O_2, 98.5% A, P=1 atm; 1% H_2, 2% O_2, 97%A, P=1 atm; 8% H_2, 2% O_2, 90% A, P=5 atm. The temperature range considered was 800°–2500°K. The curves are compared with experimental data obtained in the present work and by others.

In another part of the program, the effect of halocarbons on the ignition induction times for H_2–O_2–A mixtures is being investigated. It has been found that CF_3Br and

1,2-$C_2F_4Br_2$ produce significant increases in these induction times. Analysis of the reaction products from the shock tube pyrolysis of these halocarbons in argon has shown that the chief product from CF_3Br is C_2F_6 and that from $C_2F_4Br_2$ is C_2F_4. Analysis of the products from the shock tube experiments with H_2–O_2–A inhibitor showed that the main product from CF_3Br under these conditions was CF_3H while that from $C_2F_4Br_2$ was still C_2F_4. In addition both halocarbons were consumed more rapidly in the presence of the hydrogen-oxygen mixture, than in its absence, supporting the hypothesis that under these conditions reaction occurred between them and flame species (presumably hydrogen atoms).

In the attempt to formulate a computer program by which the properties of the hydrogen–air flame could be computed, including effects of inhibitors, the program has been tested for the simple reaction $X \rightarrow Y$. The next step is to attempt to calculate properties of the hydrogen–air system with it.

In the studies of the hydrazine–nitrogen tetroxide system, the nonflame reaction of these two species is being studied using streams of argon-diluted reagents and the stirred-reactor technique. Product analyses were performed after constant temperature had been reached in the reactor. While with streams containing less than 2 per cent of reagents nitrous oxide was the chief product, with more concentrated streams (up to 4 per cent reagents) nitrogen was found in greater amounts than nitrous oxide. The increased concentration of reagents, of course led to higher temperatures which were responsible for the change in the nature of the products. Other products found were hydrogen, water, ammonia, and nitric oxide.

New phases of the program include studies of the effect of adding sodium vapor to the hydrogen stream in a hydrogen–air diffusion flame and the study of the low-pressure diborane–oxygen and pentaborane–oxygen flame systems. Both of these phases are still in preliminary stages.

Subject Heading: *Inhibition, of* H_2–O_2, N_2H_4–N_2O_4.

J. B. Levy

Skinner, G. B. (Monsanto Research Corporation, Dayton, Ohio) "Survey of Recent Research on Flame Extinguishment," *Technical Documentary Report No. ASD-TR-61-408*, *Supplement* 1, *Wright Air Development Command Contract AF 33(657)-7617* (December 1962)

This report surveys research that has been performed on chemical extinguishment of flames from April 1961 to August 1962, and that which has been performed on physical means of flame extinguishment from 1959–1962. Meetings, symposia, and the literature of journals and government reports are covered.

A brief discussion of the current state of flame theory is given. This is followed by sections devoted to chemical inhibition and physical extinguishment of flames.

Under chemical inhibition, inhibition of flames by hydrocarbons, halogen containing compounds, and finely divided solids is considered. In general the results in the first two cases are interpreted in terms of replacement of active chain-propagating atoms or radicals by less active or inert species as a result of interaction of the active species with the inhibition. The inhibition of flames by finely divided solids continues to be pretty much of a mystery as far as mechanism goes. The differences between various salts continue to be emphasized, but the bulk of the work in this area tends to be on the practical side.

Under the section on physical extinguishment recent work on the use of water spray and foams is described. This work too is largely devoted to practical applications. A section on fire-fighting systems describes new developments in automotic detection and extinguishment systems. The report concludes with a listing of various review articles recently published.

Subject Heading: ***Extinguishment, survey of research.***

J. B. Levy

Skinner, G. B., Miller, D. R., Katon, J. E., Hedley, W. H., Ringrose, G. H., and Snyder, A. D. (Monsanto Research Corporation, Dayton, Ohio) "Chemical Inhibition of the Hydrogen-Oxygen Reaction," *Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, Technical Documentary Report No. ASD-TDR-62-1042* (December 1962)

This paper is a far-reaching effort to study this much-discussed reaction from the flame inhibition point of view. Using as many techniques as could possibly be squeezed in, the authors begin to see a means of quantitative approach to the much sought after reaction rates for many reactions in the H_2–O_2 scheme. Flame velocity, flame temperature, emission and absorption spectroscopy, and shock tube ignition were among the techniques utilized.

Careful description is given of the many experimental setups. For the flame speed measurements, the conical flame of a bunsen burner was the subject. A schlieren system was used for photographing the cone. In the experiments involving spectroscopy, a porous metal flat flame burner was used. Care was taken to exclude ambient air so that the flame could be studied without significant exterior influences. A few flame temperature measurements were made with the flat flame burner. The hydrogen–air diffusion flame was also studied with sodium vapor being added to the preheated hydrogen gas stream. The shock tube was used for an attempted study of the reaction kinetics at near-flame temperatures. Gas samples were analyzed before and after reaction by gas chromatography. Induction time measurements were made in the shock tube by spectroscopically observing normal and excited OH radicals.

Induction times were calculated for ten reactions by numerical integrations at various concentrations and temperatures. Attempts were also made to calculate induction times of the combustible mixtures with inhibitors. Two examples of the calculated results are given for the hydrocarbon inhibitors, methane and ethylene. Measured values for these were 0.52 and 0.40 milliseconds, respectively; while the calculated results were 0.46 and 0.44 milliseconds. This is extremely good agreement. Because only one calculation at one temperature was carried out for each mixture, the authors believe that this agreement might be fortuitous.

The following reactions are responsible for radical production in the H_2–O_2 flame:

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

$$O+H_2 \rightarrow OH+H \qquad (2)$$

$$OH+H_2 \rightarrow H_2O+H \qquad (3)$$

The first reaction has the largest activation energy and the slowest reaction rate at low temperatures. Most of the work reported was performed with hydrogen rich flames, and Reactions (2) and (3) predominated. At temperatures below about 700°C, the products of Reaction (1) are replaced by the formation of HO_2. This is termed self-inhibition by H-atom removal, but when the HO_2 radical encounters higher temperatures it is decomposed returning the captured H-atom.

The authors conclude that in the fairly rich flames studied:

1. The inhibitors remove chiefly hydrogen atoms;
2. The inhibitors themselves deter the reaction, and not their decomposition products; and
3. There is little tendency for hydrogen atoms to react with fluorine in fluorocarbons as was shown by their shock tube experiments.

Subject Headings: *Inhibition, H_2–O_2 reaction; Hydrogen, inhibition of oxidates.*

C. O'Neal, Jr.

Grumer, E. L. and Burgess, D. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Experiments in Extinguishing Liquid-Fuel Flames with High-Expansion Foams," *U. S. Bureau of Mines Report of Investigations 6068* (1962)

High expansion foam[1] made with ammonium lauryl sulfate and water, having bubbles about 1 inch in diameter, was applied by means of a metal chute to test fires in a 1 foot diameter metal tray. Foam characteristics and rates were:

Expansion	Application rate	
	gal/sec	lb/sec
650	4.7	0.060
625	2.3	0.031
825	1.4	0.014

Fuels used were three hydrocarbons and acetone, unsymmetrical dimethyl hydrazine and methanol. Results were:

Fuel	Burning rate (cm/sec)	Seconds to effect extinguishment at rates (lb/sec)		
		0.060	0.031	0.014
Benzene	0.29	9.8	11.3	28.9
Xylene	0.18	8.0	15.2	36.3
Hexane	0.31	16.4	50.3	Failed
Acetone	0.25	125	Failed	Failed
UDMH	0.21	80	Failed	Failed
Methanol	0.098	113	Failed	Failed

The burning rates are comparable to those observed by other investigators, and, considering the scale factor, the application rates required for extinguishment of the hydrocarbon fires are also consistent with previous observations. An explanation was sought for the difficulty in extinguishing the fires supported by the second group of fuels.

The authors initiate discussion of the test results by computing a theoretical "water requirement for extinction" on the premise that the fuel vapor released at the observed burning rates could be "inerted" to suppress combustion if diluted with an appropriate amount of steam derived from the water in the foam. The observed rates of foam application actually required proved to be from $\frac{1}{2}$ to 10 times this theoretical rate, and the fuels with the lowest burning rates were the most difficult to control. It was concluded that this simple explanation is not wholly adequate.

It was observed that the flames of the hard-to-extinguish hydrocarbons were positioned close to the liquid surface, and thus able to transfer heat to the surface by convection, whereas the hydrocarbon flames, being more removed, must necessarily transfer heat largely by radiation. This situation favors the progressive screening of the surface by the advancing foam layer, with corresponding reduction in flame volume and radiation, and this was thought to account for the relative ease of extinguishing the hydrocarbon fuels.

Dilution of the surface layer of methanol by water from the foam is mentioned, but it is not indicated that this fact was considered significant. Actually water is soluble in all of the fuels found to be difficult to extinguish. It has long been known that the ordinary low expansion foam is relatively ineffective[2] on fires in alcohols, ketones, etc. This has been ascribed to water solubility. It might be that the high expansion foam used in this work shares this same difficulty.

The authors conclude: "There is an area of agreement between results with foams and those obtained with water sprays and fogs. Hydrocarbon fires, in which heat transfer to the fuel is most clearly radiative, are surprisingly easy to combat as compared, for example, with slow-burning methanol flames in which the heat transfer is largely convective."

References

1. Nagy, J., Murphy, E. M., and Mitchell, D. W.: "Controlling Mine Fires with High-Expansion Foam," *U. S. Bureau of Mines Report of Investigations 5632* (1960).
2. *National Fire Protection Association No. 11* "Standard for Foam Extinguishing Systems"; and *National Fire Protection Association Quarterly* 54, 137 (1960); and Nash, P. and French, R. J.: "Foam Compounds for Use Against Fires in Water-Miscible Solvents," Abstract: *Fire Research Abstracts and Reviews* 4, 201 (1962).

Subject Headings: *Foam, extinguishment of liquid-fuel flames; Extinguishment, use of foam, for liquid fuels.*

O. W. Johnson

Peterson, H. B. and Gipe, R. L. (U. S. Naval Research Laboratory, Washington, D. C.) "Discharge Characteristics of Potassium Bicarbonate Dry Chemical Fire Fighting Agents from Cartridge and Stored Pressure Extinguishers," *NRL Report 5853* (December 13, 1962)

Unsatisfactory field performance of Potassium Dry Chemical Fire Extinguishing Agent, Mil–F–22287, ("Purple–K" or "P–K–P") prompted an investigation to determine the cause of the poor discharge characteristics of fire extinguishers charged with this material. Caking of the chemical powders resulted in the discharge of only 25 to 50 per cent of the contents instead of the desired 90 per cent. It was discovered that all unsatisfactory field performance involved the powder manufactured by one company.

A detailed investigation was made of the discharge characteristics of the "Purple–K" dry chemical fire-extinguishing materials received from both Navy field supplies and the manufacturers of the dry chemicals. Several models of cartridge-type extinguishers and a stored pressure-type extinguisher were used to evaluate each of the four powders studied.

The effect of the packing of the chemicals inside the extinguishers on discharge characteristics was thoroughly studied. Field conditions were simulated by subjecting the charged extinguishers to controlled vibration before discharge. Additionally, extinguishers were tested immediately after being filled with powder, after a 10-day settling period, and after 10 days (1232 miles) on a moving vehicle.

Extensive laboratory tests on the dry chemical powders included moisture content, particle size and particle size distribution, hygroscopicity, apparent density, caking and lumping tendency, packed density, and specific surface area. No combination of these properties furnishes an adequate criterion for predicting the discharge properties of an extinguisher subjected to normal storage conditions.

The gas used and gas pressurizing action were found to be important factors in determining the performance of an extinguisher. An X-ray procedure was used to study the powder distribution and packing inside the pressurized extinguisher. It developed that a desired powder does not necessarily resist vibrational packing but that it must break up easily once packing has occurred. Further, it was established that vibration compaction was a less serious problem in extinguishers of the stored-pressure type.

Using information developed, a new laboratory test procedure was developed to simulate and evaluate performance of the charged extinguishers in field service. This test was made part of a recommended specification requirement.

All tests confirmed the field observations that one Navy stock source of "P–K–P" dry chemical was not satisfactory for use in extinguishers widely used by the Navy. Vibration and pressurization processes caused the powder to pack so that it was not discharged in a desired manner. Two of the extinguishers tested, which are presently in wide use by the Navy in aircraft fire-fighting operations, were found to aggravate the poor powder problem. These results showed the importance of good extinguisher design.

Subject Headings: *Potassium bicarbonate, discharge of; Extinguishers, discharge, of potassium bicarbonate.*

L. R. Griffith

VIII. Model Studies and Scaling Laws

Rankine, A. O. (Imperial College, London, England) "Experimental Studies in Thermal Convection," *Proceedings of the Physical Society* **63A,** 417-445 (1950)

The Guthrie lecture celebrating the 75th anniversary of the Physical Society described wartime research to develop a method of dissipating fog over airfield runways with heat from lines of gasoline flames. The purpose was to determine the pattern of heat flow downwind of a burning line across which winds of varied strength were imposed. Full-scale interpretation of such data would tell how much heat should be provided and the best position of the burning line with reference to the runway axis to dissipate fog for the required 100 feet above the runway. Even gentle wind sweeps the heated jet along close to the ground in the downwind direction while the upper edge of the jet makes an angle with the ground that diminishes rapidly as the wind increases. Above the edge no appreciable heat is imparted to dissipate fog. Near the ground heat is superabundant, higher up it is insufficient. To provide enough heat as far up as 100 feet heat must be wasted near the ground, the more so the stronger the wind. Full-scale tests at an airfield proved too time-consuming because atmospheric conditions were uncontrolled. Model experiments were therefore made at 1/30 to 1/60 scale in a wind tunnel built in Empress Hall, Earl's Court, London.

The wind tunnel was 100 feet long, 30 feet wide, 12 feet high, flared down starting 30 feet from one end first to a 12-foot square cross section and then to a circular channel 10 feet in diameter housing a 27 hp electric fan. A screen wire partition, 30 meshes per inch, placed 30 feet inside the open end of the tunnel rendered regular the air flow created by suction of the fan. Air speed from 0.5 to 5 feet per second was produced, which corresponded on the 1/60 scale to full-scale winds from 2.65 to 26.5 miles per hour. Air speeds at numerous points in the tunnel were measured by small electric anemometers based on the principle that an electrically heated wire, the temperature of which is measured by a nearby electric thermojunction, is cooled by moving air to an extent proportional to the velocity of the air. When there was no heating the horizontal air speed was essentially uniform over the cross section of the tunnel except for a distance of 15 to 25 inches upward from the floor and inward from the walls, where the speed was retarded by friction against floor and walls.

The rise in temperature of the air downwind above that of the air entering upwind of the burner line was measured at numerous downwind points by thermocouples made of copper and Eureka wire. Thermocouple potentials were observed with a Tinsley potentiometer. Anemometers and thermojunctions were distributed over cross sections of the tunnel spaced $3\frac{3}{4}$ feet, $7\frac{1}{2}$ feet, and 15 feet, respectively, from the burner line. Heat up to 5 therms an hour was supplied by burning butane gas in specially designed burners that provided small flames starting close to the floor in a line across the width of the tunnel, usually about midway between the wire screen and the plane where the cross section began to flare down to the fan. Heat input was calculated from the quantity of gas burned and its calorific power. The flames were nonluminous except for certain tests with luminous flames. Because turbulence produced variations in air speed and temperature at any one point, 50 readings were taken at each point. Several hundred thousand observations, sometimes as many as 2000 a day, were required. It was not always practicable to measure air speed and temperature simultaneously.

Results are reported in 30 tables with intervals small enough to permit interpolation by proportional parts. The rise in air temperature for heat input from 0 to 0.48 therms per yard per hour and with imposed air speed from 1.5 to 5.0 feet per second is tabulated at levels of 1.6, 8, 20, 40, and 60 inches, respectively, above the floor for each of the cross sections at $3\frac{3}{4}$, $7\frac{1}{2}$, and 15 feet from the burner line. Local horizontal air speed for heat input from 0 to 0.36 therms per yard per hour and imposed air speed from 1.5 to 5.0 feet per second is tabulated at levels of 4, 10, and 24 inches above the floor for the $3\frac{3}{4}$ foot cross section, and at 4, 10, 24, and 48 inches above the floor at the $7\frac{1}{2}$ foot cross section. For the 15 foot cross section the local air speed is given only for heat input of 0 and 0.12 therms per yard per hour and imposed air speed from 2.0 to 3.5 feet per second at 4, 10, 24, 36, 48, 60, and 72 inches above the floor.

Typical profiles show a sigmoid distribution of temperature rise with height above the floor with the upper part of the S stretched out more than the lower part. Increase in imposed air speed increased the maximum temperature rise at the "nose" of the curve (peak of the lower part of the S), brought the nose closer to the floor, decreased the temperature rise at higher levels, and decreased the height at which the temperature rise became inappreciable. The curve of local horizontal air speed versus height indicates an enhancement of air speed that was roughly proportional to the local temperature rise; the enhancement was emphasized both by reduction in imposed air speed and increase in degree of heating. Increase in heat emission at the burners increased the temperature rise at all heights and the increase augmented proportionally as the height increased. With increasing distance downwind from the burners the nose of the profile of temperature rise versus height became blunter, the peak temperature decreased, its height above the floor became greater, and the influence of heating extended to greater heights above the floor.

When the product of temperature rise by local air velocity was plotted against height above the floor, the area under the curve, density and specific heat of the air being known, yielded the quantity of convective heat passing downwind. This proved to be 80 per cent of the gross thermal energy developed by the burner line. The 20 per cent lost was made up of 5 per cent lost in heating the tunnel floor, chiefly within 3¾ feet of the burner line, and 15 per cent lost as thermal radiation, which is not available for dissipating fog unless it is converted by absorption into convective heat. Experiments with luminous in place of nonluminous flames showed that the additional loss by radiation reduced the convective heat flux to 64 per cent of the gross thermal energy supplied by combustion.

Comparison with full-scale tests made at the airfield at Staines, England, yielded excellent agreement when the data from the model tests were scaled on the principle that equal temperature rise, provided the rise is small in relation to the absolute temperature, should be obtained in model and full scale when $V_m/V_f = r^{\frac{1}{2}}$ and $H_m/H_f = r(r^2)$ in which r, the linear scale ratio, is L_m/L_f, with V denoting air speed at any point, H the convective heat generated per unit length of burner line, L any particular length, and subscripts m and f signify the corresponding parameters in model and full scale, respectively.

By reason of the disturbing effect of its roof, the tunnel can be used reliably as a model only for imposed air speeds greater than 1 foot per second.

Subject Headings: ***Convection, thermal, study of; Model, study of diffusion flames; Flame, model study.***

F. L. Browne

Putnam, A. A. and Speich, C. F. (Battelle Memorial Institute, Columbus, Ohio) "A Model Study of the Interaction of Multiple Turbulent Diffusion Flames," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 867-877 (1963)

The problem considered in this paper is that of determining the parameters that are significant in the change-over or merging of a number of individual flames into a mass fire. In fires fueled by liquids or solids that are stagnant, the physical transport of fuel, oxidant, and combustion gases takes place because of the resultant density gradients. The transport processes of a flame can be influenced by the thrust of the injected fuel when gases are utilized.

In this study the fuel velocity and nozzle diameter were adjusted so that the forces arising from buoyancy would be dominant relative to the forces established by the jet thrust. Under these conditions, the authors envision that data derived from gaseous-fueled flames could be correlated eventually with data from liquid- and solid-fueled flames.

A secondary objective was to investigate the influence of jet spacing, fuel flow rate, and the geometry of the jet array on the resulting flame configuration.

Preliminary results are presented of their efforts to establish modeling laws for flames that are partially and fully merged when gaseous fuels are employed.

The ratio of flame height to the initial diameter of the jet is one of the primary flame parameters investigated with gaseous jets. For thrust-controlled flames, this ratio is independent of the fuel flow rate. For buoyancy-controlled flames, however, this ratio is a function of the fuel flow rate. Therefore, their experimental and theoretical analyses are concerned with the determination of the dimensionless height and its dependence on the flow rate of the fuel. The theoretical analysis was extended to predict the flame height of multiple sources of fuel.

For a single-jet, buoyancy-controlled turbulent diffusion flame, two relations between jet diameter and flow velocity were considered. For the first relation, Reynolds numbers of the fuel jet were in excess of 5000 to ensure turbulent flow. Also, the ratio of the buoyancy force to the thrust was in excess of unity to ensure that the flame was buoyancy controlled primarily; that is, the Froude number was low.

Employing certain assumptions, the authors showed that

$$L/d_0 = K(\mathcal{Q}_0^2\ gd_0^5)^{1/5},$$

where L = height of flame array, K = constant, d_0 = nozzle port diameter, and $\mathcal{Q}_0$ = volume flux of injected fuel. Thus, the flame height for buoyancy-controlled flames should fall along a line whose slope is $\frac{1}{5}$ on a log–log plot. Deviation from this straight-line relationship at high flow rates would indicate that the flame becomes thrust controlled. Their experimental data for single flames broke away from the straight line at higher flow rates and the flame height tended to remain constant. For the buoyancy-controlled region, they found that

$$L/d_0 = 29(\mathcal{Q}_0^2/gd_0^5)^{1/5}.$$

For the single-jet study, the ratio of the flame height to spud diameter was large. Their other data are for large ratios too. Thus, d_0 can be eliminated in the correlating relation.

Considering the merging effects in arrays of flames where the multiple jets are very close together relative to the flame height, they showed that the height of the combined flame L' might be given as

$$L'/L^* = n^{2/5},$$

where L^* = height of single, unmerged flame and n = number of jets. When the jets are spaced apart by a distance S, the ratio might be given by

$$\frac{(L'/L^*)-1}{n^{2/5}-1}=\text{function [source-shape factor, } n, \ S/\mathcal{Q}_0^2/g)^{1/5}].$$

Here, the term $(L'/L^*)-1$ exaggerates small variations in the measurement of flame height.

The experimental data for multiple-jet burners do not correlate with the theoretical curves; a more rapid change in flame height was obtained. Possibly at close spacings the flame of each jet is aspirated, thereby decreasing the effective spacing between jets. The authors believe that mutual entrainment explains fully the rapid increase in flame height with a decrease in spacing, at the critical spacing distance.

Area fires and line fires were studied too. The results appear to show that the arrangement employed can be used to study the merging of individually acting fires into mass fires. Also, it appears that for a moderate number of jets, the array may be treated as a single extended fire, giving results correlating with those on stacks of wood and similar fire sources.

Subject Headings: ***Model, study, of diffusion flames; Flame, model study.***

L. E. Bollinger

Fons, W. L., Clements, H. B., Elliott, E. R., and George, P. M. (Southern Forest Fire Laboratory, U. S. Forest Service, Macon, Georgia) "Project Fire Model," *Summary Progress Report—II* (May 1, 1960–April 30, 1962)

This is a summary report on Project Fire Model, covering the period May 1, 1960 to April 30, 1962. Included in the introduction is a statement of the general objectives of the project and a rather detailed account of the experimental conditions under which the test fires were burned. The essential elements of the fire model are described to acquaint the reader with the physical arrangements and instrumentation methods used in the project.

Data from the experimental fires were analyzed to determine quantitative relationships between the several aspects of fire behavior, such as radiative and convective heat, flame dimensions, emissivity and rate of fire spread.

Appendix A of the report includes the experimental data used in the analyses of test fires; much of the data is also presented graphically in 13 figures and 3 tables within the body of the report.

The heat value was determined for five species of wood used in selected experimental fires. The procedure for calculating the low-heat value from the measured high-heat value is explained.

An equilibrium moisture content curve was established for white fir wood. This curve provided a means of selecting the relative humidity for a given test fire. Control of humidity in the combustion room to the specified level was essential to maintaining the moisture content of the crib material constant during experimental fires.

Previous test fires had indicated that rate of spread increased slightly with an increase in crib width. One test fire was burned in which half the crib length had the side open and the other half shielded with pretreated strips of brown wrapping paper. This arrangement made it possible to measure the effect of airflow through the sides of the crib on the rate of flame movement through the fuel bed. From this test, no change in spread was indicated as the fire moved into the shielded section of the crib.

Tests were continued to evaluate the effects of species of wood on rate of spread. Cribs of white fir, magnolia, basswood, sugar maple, and longleaf pine were burned at moisture contents of approximately 10.5 per cent. Longleaf pine, the only resinous wood tested, produced the lowest rate of spread of any of the fire species, suggesting that the resin content of the wood may not be as an important factor in rate of spread as previously thought. Basswood contains an oil rich in volatile fatty acids, and produced the higher rates of burning, indicating that chemical properties of wood may be as important as density in determining rate of fire spread.

A group of test fires were burned to determine the effect of specific gravity on rate of fire spread for fuels of different moisture contents. For fuels with specific gravities less than 0.45, spread increases rapidly with decreasing moisture content. These fuels are represented by litter, bark, moss, grass, and leaves in natural fuel communities and moisture content is the important factor in determining rate of spread. Lowering the fuel moisture content in fuels that have a specific gravity of 0.50 or more produces only slight increases in rate of spread.

The concept of flame dimension correlation and burning time correlation is explained and formulas for each factor are derived. Both appear to be important to a basic understanding of the fire model. Convective heat was measured from crib fires, and formulas for calculating the rate of convective heat are presented.

Radiation measurements were made on crib fires of the various species of wood to show the effects of instrument location on the amount of radiant energy produced by the fire. In one diagram, irradiance is shown as a function of rate of combustion. Results indicate that irradiance at the side and at the rear of the test fires are approximately equal. Irradiance at the front of the fire is approximately 60 per cent of the side and rear measurement.

Equations for calculating flame emissivity and a table of measured values are presented. Temperature measurements in the convection column were made to provide a spatial diagram of temperature structure of the column during burning. Temperature distribution in the convection column of the crib fires was similar to the distribution found for other heat sources.

Continuation of Project Fire Model was ensured on February 28, 1962, when a proposal was approved covering work ending June 30, 1963. The work proposed for this period included:

1. Continue investigations of fuel density, moisture content, and fuel size on free-burning fires.
2. Study effects of particle spacing in fuel beds on fire characteristics.
3. Develop scaling laws for prediction of fire behavior and properties of full-scale free-burning fires.

A complete listing of experimental nomenclature and literature references are included in the report. It is well to note that the foundation for much of the work described in this report was established and reported on in the previous Project Fire Model reports.

Subject Headings: *Model, study, of wood crib fires; Fires, model study of; Wood, model study.*

J. H. Dieterich

Bakke, P. and Leach, S. J. (Safety in Mines Research Establishment, Buxton, England) "Principles of Formation and Dispersion of Methane Roof Layers and Some Remedial Measures," *The Mining Engineer* 22, 645-669 (1962)

The authors present the main conclusions drawn from a series of investigations carried out at the Safety in Mines Research Establishment, England. Detailed account of the work, which was done in underground roadways as well as in laboratory on small-scale models, is not included. The paper is in two parts—one on the formation of layers and the other on preventive and remedial measures. The approach is both theoretical and experimental.

The main reason given for the formation of a firedamp layer at the roof of an underground roadway is the buoyancy of gas, and the effective dispersion of it is due entirely to the turbulent mixing of the gas with the ventilation air. The mixing process is, therefore, treated as one in which gas at the roof is being replaced by air and work is done by turbulence against gravity. Hence, the degree of dispersion depends on the level of turbulence, which in turn depends on the relative velocity between the gas layer and the air current.

Two simple properties of the movements of layers formed by firedamp emitted from single roof sources were observed:

1. The velocity of the layer attains a constant value not far from the source of emission.
2 For a given layer, the thickness increases linearly along the roof.

In this paper the layer thickness is defined as the normal distance from the roof to the "edge" of the layer, which is defined as the point at which the methane concentration is one hundredth of that at the roof.

It is to be noted that the layer thickness id different from the "depth" of layer usually referred to in literature. The latter is the distance from the roof to the point of a given methane concentration (say 5 per cent), and it is related to the hazard of the layer, while the former is related to the layer formation. It is also noted that the rate of increase of layer thickness can be referred to as the rate of mixing.

In considering general factors on which layering depends, the authors introduce a dimensionless group, named as the "layering number" (L) to describe the rate of mixing and the layer movement. This number is considered to be of fundamental importance as it provides a means of quantitative comparison on test results, and it takes the following form:

$$L=\frac{U}{\sqrt[3]{g(\Delta\rho/\rho)(V/W)}}=\frac{U}{37\sqrt[3]{V/W}} \quad \text{for methane.}$$

where U=velocity of ventilation (ft/min); V=emission rate of gas (cu ft/min); W=width of the layer (ft); g=gravitational acceleration; and $\Delta\rho/\rho$=relative density difference.

The authors discuss in detail test results obtained under various conditions of the roadway (inclination, smoothness of surfaces), of the ventilation air (velocity, direction), of the emission sources (rate of emission, single or multiple sources, position), in the light of the layering number in conjunction with the "length" of the layer. The layer length shows the hazard of the layer and is defined as the distance from the source of emission to the point at the roof at which methane concentration falls below 5 per cent.

While safe values of layering numbers for controlling layers are suggested, and from them, safe ventilation velocity for any specific case can be deduced, the influences of the above mentioned factors can be summarized as follows:

1. Any factor which increases the relative velocity between the layer and the air promotes mixing but effective mixing for the dispersion of the layer must be turbulent, i.e., large layering numbers. An extreme yet interesting case was observed, viz., in an ascensionally ventilated roadway, when the ventilation velocity was lower than that of the gas layer, either the smoother the roof surface, or the higher the road slope, or the slower the ventilation air, the better the mixing seemed to be. However, this case is in the region of small layering numbers where buoyancy of gas is important, and it is not surprising to see that all these measures are contrary to normal conception for good mixing.

2. For a given layer, ventilation velocity up to a certain value will not affect the layer length at all. In the intermediate range of the ventilation velocity, a slight increase of the velocity will shorten the layer length appreciably. When the velocity is further increased beyond a certain value, the layer length will continue to decrease but at a very much slower rate.

Although the authors stress the importance of the relative velocity on mixing and hence on the dispersion of the layer, the results are all presented in terms of ventilation velocity. In view of the fact that a layer attains a constant value not far from the source of emission, it would seem advantageous to express the velocity in relative terms, under which the influence of such factors as the inclination of the road, free or forced ventilation as well as its direction, and to some extent the emission rate of the source can be combined.

3. When the layering number is as large as that suggested for safe control of the layer, multiple sources distributed over a long length of the roof can be treated as a single source of combined strength for deducing an adequate ventilation velocity.

4. Side and floor sources are of much less hazard than the roof source of the same strength, as the gas will mix readily with air on the ascent and consequently form a layer with much lower initial methane concentration.

While considering the preventive and remedial measures, one is reminded of the importance of the time scale, which, involved in the layer formation, is in the order of few minutes or even fractions of a minute. The best course of remedy is by emission and velocity control and the action recommended to be taken is firstly, to reduce the emission rate of the gas as much as possible by such methods as methane drainage, and secondly, to increase the ventilation velocity to obtain the relevant value of layering number to ensure effective dispersion.

Two temporary measures are also recommended. One of them is the erection of "mixing baffle" which seals the lower part of the road and increases the local velocity at the roof. It is effective only when the locally increased layering number exceeds the suggested level. The other measure is to use "ejector" which removes the layer by arresting it in a trap at the roof, sucking the methane and large quantity of compressed air into a pipe and discharging the nonflammable mixture into the ventilation air at the floor level. Both measures are not effective for a long distance of the road and should be placed as close as possible to the source of emission of firedamp. They can be used for cases where emission and velocity control alone is difficult in practice, or where installations for adequate ventilation are awaited.

Subject Heading: *Methane, formation and removal of roof layers.*

A. S. C. Ma

IX. Atomization of Liquids

Hoffman, T. W. (McMaster University, Hamilton, Canada) and **Gauvin, W. H.** (McGill University, Montreal, Canada) "An Analysis of Spray Evaporation in a High-Temperature Environment II. Calculation of the Evaporative Load Distribution," *The Canadian Journal of Chemical Engineering* **40**, 110-118 (1962)

Calculations were made of the evaporative load distribution in a spray of droplets suspended in an absorbing gas medium contained in a cylindrical column after a temperature profile was assumed for the gas. Experimental data were obtained on the rate of evaporation from water sprays in a high-temperature environment.

Experimental data were obtained for water sprays in an 8-inch i.d. by 10-foot high pilot-plant atomized suspension reactor at wall temperatures up to 800°C. It was necessary to determine the drop size distribution and drop velocities near the nozzle in order to calculate the droplet evaporation in the column.

Experiments were conducted for wall temperatures of 650°, 700°, 750°, and 800°C for flow rates of feed water of 26.8, 38.5, and 49.2 lb/hr.

At high temperatures, the radiant heat transfer to the droplets may be important. Details of the calculation technique used to determine the radiation absorbed by individual particles will be discussed later in Part III of this series. For convective and conductive heat transfer to the spray, the first step is to assume an approximate profile for the longitudinal temperature and from it to calculate the evaporation of the spray as it proceeds down the column. An outline is given of the procedure employed to calculate the evaporation of the spray.

The same general temperature profiles were observed in all experiments; the temperature was quite low at the top of the column where most of the evaporation occurs. Here, highly turbulent mixing exists. For the same feed rate, the temperature in this zone increases as the wall temperature increases. Since the zone temperature comparatively was higher for the pneumatic than for the pressure atomizer, a greater heat flux in the zone is suggested which, in turn, could suggest a greater convective heat transfer coefficient since all other heat transfer rates should be the same approximately.

When the temperature profiles for two comparable pneumatic and pressure runs were studied, it was observed that the temperature gradient at any given temperature in the lower part of the column was greater for the pneumatic atomizer experiments. These results indicate that a small evaporative load may still exist in this portion of the column.

Because of different velocities and drag forces, the 130-micron and 170-micron size groups have the same calculated lifetime. The 70-micron group has the longest lifetime. Larger droplets evaporate faster because they proceed into the region of higher temperature.

Results show that reliable drag coefficient data are lacking, that the mechanism of heat transfer is incompletely understood, that the assumption of a uniform velocity profile in the reactor should be improved, and that complications are introduced by turbulence in the nozzle zone.

The general conclusions drawn are: (1) the gas temperature is relatively low at the top of the reactor; (2) radiation accounts for a large fraction of the heat transferred from the walls to the gas; (3) entraining action of the expanding spray increases the convective heat transfer coefficient near the nozzle; (4) a wide distribution of particle diameters and high injection velocities make the evaporative load more extensive; and (5) small droplets evaporate in a low-temperature gas atmosphere, and larger droplets evaporate in a high-temperature environment.

Subject Headings: *Sprays, evaporation; Evaporation, of sprays.*

L. E. Bollinger

Golovin, M. N. and Putnam, A. A. (Battelle Memorial Institute, Columbus, Ohio) "Inertial Impaction on Single Elements," *Industrial and Engineering Chemistry Fundamentals* **1,** 264-273 (1962)

A comprehensive review of inertial impaction of aerosol particles that compares theoretical and experimental results for spherical particles is presented. Target shapes considered include cylinders, spheres, infinite ribbons, and airfoils at various angles of attack.

The efficiency of inertial impaction is defined as the ratio of the number of particles flowing within the envelope of target-grazing trajectories to the total number of particles flowing through the target projected area. Basic parameters, derived by dimensional analysis, are the inertial impaction parameter

$$K=\rho D^2 U/g\eta D'=\text{stopping distance/target radius}, \qquad (1)$$

and the Reynolds number function

$$\phi=\mathrm{Re}^2/K=9(\rho^*/\rho)(\mathrm{Re}'), \qquad (2)$$

where ρ,ρ^* = density of particle, air; D,D' = diameter of particle, target; U = relative velocity; η = viscosity; and Re, Re′ = Reynolds number of particle, target. An additional correction term by which K is multiplied to allow for non-Stokesian slip, is defined by

$$k_m=1+(L/D)[2.46+0.82\exp(-0.44D/L)] \qquad (3)$$

where L is the mean free path of the gas molecules. Precise conformance with Stokes' Law (i.e., no slip effect) requires that $k_m=1.0$. For 1-micron and 5-micron particles in air at STP, k_m changes from 1.16 to 1.03. However, the mean free path L varies inversely as the square root of gas density, so that a tenfold decrease in ambient pressure combined with a fivefold increase in gas temperature (typical of jet engine combustors at high altitudes) results in a sevenfold increase in the mean free path and the magnitude of k_m becomes such that it can no longer be referred to as a "correction factor." It is noted here that, under such conditions of high temperature and low pressure, the evaporation rates of liquid particles are of the same order as the kinematic viscosity of the gaseous medium, so that the ballistics of evaporating droplets[1] must be considered in determining the droplet trajectories:

A comparison of theoretical and experimental variations of inertial impaction efficiency with the inertial impaction parameter K, for circular cylinders is shown in Fig. 1. The qualitative verification of the data of Ranz *et al.* for the theoretical curve ($\phi=0$) is noteworthy, although the wide scatter indicates the persistence of some uncontrolled factors (e.g., nonuniform drop size distribution) and the possible prevalence of other (noninertial) types of impaction. Comparison of the several sets of data indicates an improvement in the accuracy of experimental techniques, as time progresses.

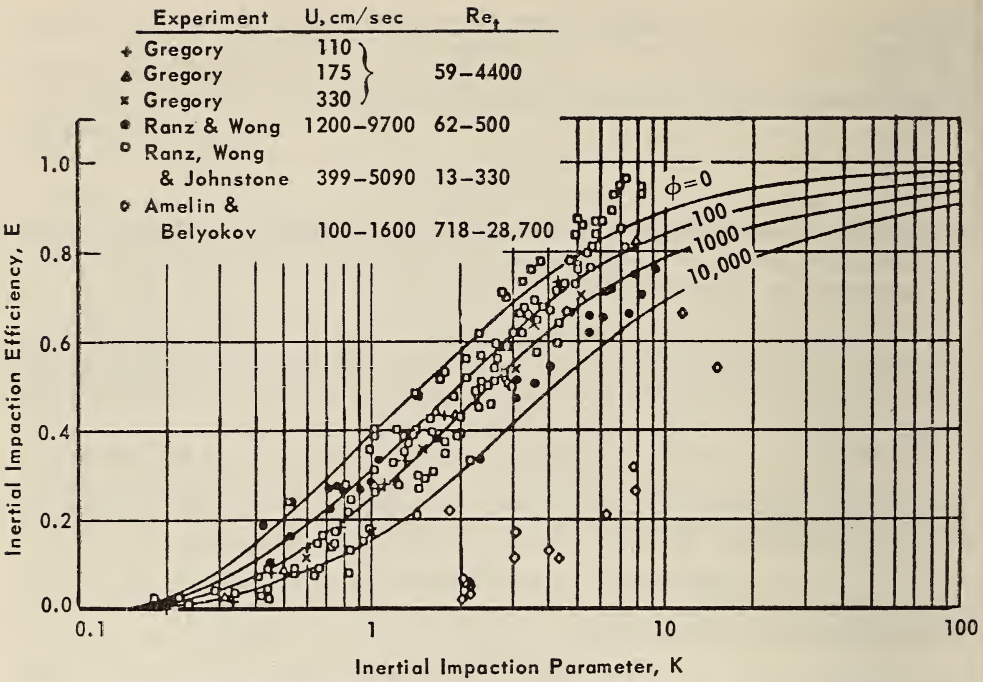


FIG. 1. Theoretical and experimental inertial impaction efficiencies, E, as functions of inertial impaction parameter, K, for circular cylinders.

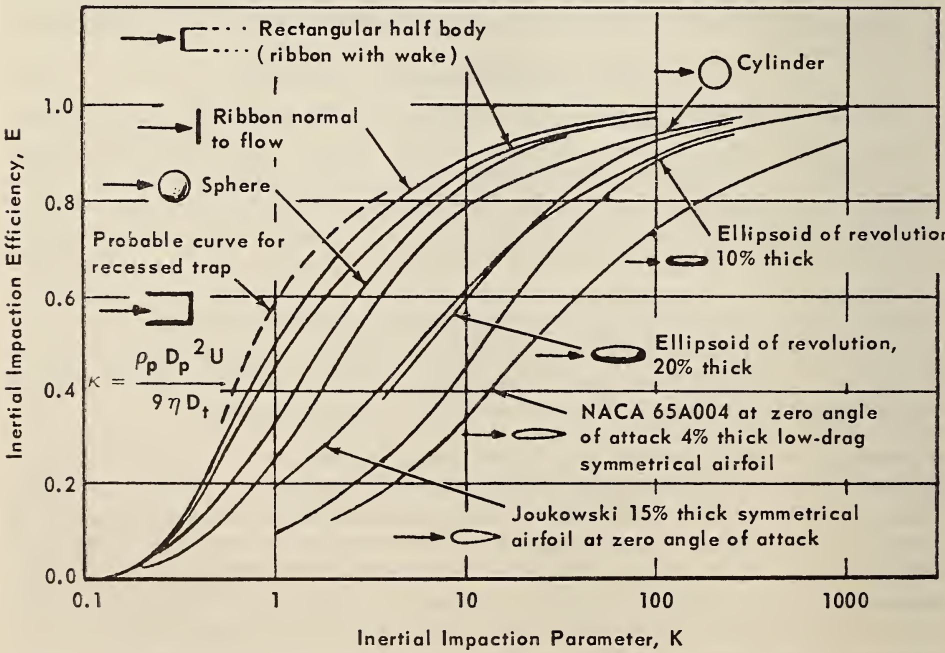


FIG. 2. Inertial impaction efficiency, E, as function of inertial impaction parameter, K, for a number of different target shapes.

Theoretical curves for other target configurations are shown in Fig. 2, although the absence of sufficient data for non-cylindrical shapes precludes further valid comparisons.

As a result of the survey reported above, it is concluded that theoretical variations appear to provide an adequate description of experimental results, and there is a crucial need for more refined experimental techniques (e.g., production of monodisperse aerosols).

Reference

1. Miesse, C. C.: "Ballistics of an Evaporating Droplet," *Jet Propulsion* **34**, 237 (1954).

Subject Headings: *Sprays, impaction of; Impaction, of aerosols.*

C. C. Miesse

X. Meteorological Interactions

Segel, L. A. (Rensselaer Polytechnic Institute, Troy, New York) and **Stuart, J. T.** (National Physical Laboratory, Teddington, Middlesex, England) "On the Question of the Preferred Mode in Cellular Thermal Convection," *Journal of Fluid Mechanics* **13**, 289-306 (1962)

This paper consists of corrections and clarifications of an analysis by Palm[1] concerning finite-amplitude cellular convection in a fluid with variable viscosity heated from below. A uniform temperature gradient is assumed to exist initially (at $t=0$) between two horizontal surfaces at which free boundary conditions are applied, and an attempt is made to deduce the motion of the fluid as $t\rightarrow\infty$. The method of attack consists in assuming that the asymptotic motion can, with sufficient accuracy, be characterized by the mutual interaction (and a consequent reinforcement) of two sinusoidal wave disturbances, which are chosen in such a way that the amplification rate predicted by linearized theory is maximized. Two second-order, ordinary differential equations (with constant coefficients), which are coupled through (nonlinear) quadratic and cubic terms involving powers and products of the two dependent variables, are obtained for the time development of the amplitudes of these two waves. The main part of the analysis is devoted to locating and characterizing the equilibrium points of these equations. Many conclusions and speculations concerning the shapes and other characteristics of the convection cells are derived from the results of the analysis.

It is shown that, depending upon the values of the parameters and upon the initial conditions, the solution may approach asymptotically a pattern resembling two-dimensional (roll) cells, hexagonal cells, and perhaps rectangular cells. Hexagonal cells (which have been observed experimentally) can be obtained only if the variation of viscosity with temperature is sufficiently great. Two-dimensional cells (which, apparently, are not observed experimentally) can be obtained regardless of the variation of viscosity with temperature. Speculative arguments to the effect that hexagonal cells should develop whenever possible are presented. Predictions, in agreement with experiment, concerning the dependence of the direction of motion at the center of a hexagonal cell upon the sign of the temperature dependence of the viscosity coefficient are obtained. Cases in which disturbances grow only for sufficiently large initial amplitudes are uncovered and are correlated (rather poorly) with experimental observations of columnar instability. Conceivably, this problem might have a remote bearing on convection above widely distributed fires.

Reference

1. Palm, E.: *J. Fluid Mech.* **8**, 183–192 (1960).

Subject Heading: **Convection, mode in cellular.**

F. A. Williams

Segel, L. A. (Rensselaer Polytechnic Institute, Troy, New York) "The Non-Linear Interaction of Two Disturbances in the Thermal Convection Problem," *Journal of Fluid Mechanics* **14**, 97-114 (1962)

The author considers the thermal convection problem of a horizontal layer of fluid slowly heated from below. While linear theory indicates that a fluid, originally at rest with a linear temperature distribution, becomes unstable undergoing cellular motion, it does not predict correctly the rate of increase of velocities with time, the preferred cell shape, or the shape of the spectrum of the disturbances. Yet it is known that due to interaction of disturbances all but a narrow band in the disturbance spectrum are damped. The author attempts to explain this phenomenon by considering the nonlinear interaction of two disturbances, both of which are linearly unstable. An idealized model consisting of a layer of fluid bounded by two free surfaces, with "roll" type disturbances periodic in one horizontal direction and independent of the vertical dimension, is assumed. Thus, the preferred cell shape problem is not studied. Disturbances are considered which are linearly unstable, but which finally achieve a finite amplitude equilibrium.

The Boussinesq approximation is used in deriving the governing equations. The solution is found in terms of a series expansion, in each term of which variables may be separated. Reference is made to a method of solution given previously by Stuart and by Watson, which results in obtaining a set of ordinary differential equations for the various series terms, including the amplitude functions, the time derivatives of which again require series expansions. A general solution of the latter equations is not possible, but an analysis of the equilibrium points and their stability is given. Essentially, then the problem reduces to the study of the amplitude functions, each associated with one of the interacting disturbances.

The general results indicate that when two linearly unstable disturbances interact, one of them may decay to zero while the other approaches an equilibrium value. The parameters of the problem, or the initial amplitudes of the disturbances determine which of the two disturbances decays. A mixed state consisting of both disturbances, which is also a possible equilibrium state for this model, will not occur if it is possible for either of the two interacting disturbances finally to decay to zero. A mixed state consisting of one linearly stable and one linearly unstable disturbance is another possibility since it is possible that the unstable disturbance changes the sign of the growth rate of the originally stable disturbance. The author discusses the possibility that the latter phenomenon may be an important mechanism in the transition from laminar to turbulent flow.

The general results are applied to the convection problem with various Rayleigh numbers. The analysis holds generally when the critical Rayleigh numbers based on the wave numbers of each of the two different unstable disturbances are close to the given Rayleigh number of the problem, although the most important conclusions are based on the situation where the actual Rayleigh number is only slightly above the minimum critical Rayleigh number. For this case it is shown that the mixed equilibrium case cannot exist, so that one disturbance decays. While experiment has indicated that one of many linearly unstable disturbances is selected for amplification, this is evidently the first theoretical model to illustrate this fact.

Subject Heading: *Convection, thermal, nonlinear interaction.*

T. C. Adamson

Pasquill, F. (Meteorological Office and Chemical Defense Establishment, Bracknell, England) "Some Observed Properties of Medium-Scale Diffusion in the Atmosphere," *Quarterly Journal of the Royal Meteorological Society* **88**, 70-79 (1962)

This paper reports an interesting set of diffusion experiments in the atmosphere. Tracer material was introduced continuously either at a fixed point on the ground or from an aircraft flying across the wind. The latter was equivalent to a line source. The tracer material was powdered zinc-cadmium sulphide (1–5 μ diameter). The tracer material was monitored at distances up to 85 miles downwind. Samples were collected from aircraft and at various heights along a cable attached to a balloon. For the point source the cross-wind spread of the tracer material along with the extremes and averages of the mean wind direction are given for various wind shears, altitudes, and distances from the source. For the line source the spread in the wind direction of the tracer material and the mean wind are given for various wind shears, altitudes, and distances from the source.

The feature of the data which the author emphasizes in his discussion is the small variation in height of the direction and speed of travel of the tracer material compared to the corresponding variations in height of the wind direction and speed. The conclusion that is drawn is that as a result of thorough vertical mixing the trace material has assumed a mean velocity which is approximately constant throughout the layer of mixing. The tendency for a cloud of particles to be sheared is not observed. This paper presents data on the horizontal spread of particles both cross wind and along the wind which can be used to correlate theories of atmospheric turbulent mixing as they become available.

Subject Heading: *Diffusion, medium-scale, in atmosphere.*

D. L. Turcotte

Scorer, R. S. (Imperial College, London, England) "The Effect of Thermal Convection on the Transfer Mechanisms in the Atmosphere," *Air and Water Pollution (An International Journal)* **6**, 101-111 (1962)

This paper gives a qualitative description of transport mechanisms in the atmosphere. Particular emphasis is given to the influence of thermals. The author provides lucid descriptions of the turbulent transport phenomena associated with the atmospheric convection of pollutants. No attempt is made to provide methods of computation or to discuss alternative theories. However, the reviewer would highly recommend this paper to anyone who is convinced that atmospheric convection problems are readily solvable.

A general description of turbulent transport in the atmosphere is given. The importance of the Richardson number is discussed. The role of the eddies is brought out and an excellent discussion of the flow of energy from large eddies to smaller eddies and finally to viscous dissipation is given. The importance of a three-dimensional description of turbulent transfer is convincingly illustrated. The effect of the turbulence generated by momentum transport on thermal and pollutant diffusion is discussed.

A detailed description of the structure of thermals is given. The overall motion of a thermal is shown to be much like that associated with a ring vortex. The importance of eddy motion in dissipating the energy of the thermal is described. The interaction of a thermal with a shear flow is discussed. The author concludes that it is incorrect to deduce the coefficient of diffusion for pollutants from momentum transport if buoyancy forces are present.

It would seem that this paper can best be summarized in the words of the author. "This (paper) is not a counsel of despair but an invitation not to ignore realities."

Subject Headings: ***Thermals, influence on convection; Atmosphere, effect of thermals on convection.***

D. L. Turcotte

Kuo, H. L. (Massachusetts Institute of Technology, Cambridge, Massachusetts) "On the Controlling Influences of Eddy Diffusion on Thermal Convection," *Journal of the Atmospheric Sciences* **19**, 236-243 (1962)

The object of this paper is to resolve the conflict involved in studies of the stability of a conditionally unstable atmosphere associated with hurricane formation. Previously, it had been found that all perturbations whose horizontal scales were shorter than a limiting length were unstable, while those with longer scales were oscillatory. When a Fickian type of diffusion mechanism was included, the very small perturbations were damped out, but the most favored perturbation remained of small scale, at most of the dimension of a cumulus cloud. Real atmospheric motions in a hurricane, however, are such that both large-scale circulation and cumulus convection take place simultaneously with the latter contributing its energy to the large-scale motion.

Important physical processes which restrict the growth of small-scale convection are: (1) exhaustion of moisture content of the ascending air by precipitation, (2) modification of the lapse-rate in the ascending region by convective upward heat transport, and (3) entrainment and detrainment of air in the ascending current. The third process is shown to be important in restricting the initial growth of small-scale convection. Entrainment is considered as having two effects on convection: increasing the mass of air being accelerated by the buoyancy force and at the same time reducing the buoyancy force per unit mass by cooling the moist ascending air. Both of these effects, stemming from the action of eddy diffusion, are treated by the introduction of nonlinear processes in the complete set of the dynamic and thermodynamic equations.

The dynamic equations are set up on the assumption that the mean motion is two-dimensional and symmetric about the vertical axis. Kinetic energy and thermal energy integrals are obtained by suitable manipulation of the dynamic and thermodynamic equations. An assumption in the dynamic equation is that the percentage density perturbation is small, which results in the simplifying of the continuity equation, while in the thermodynamic equation heating other than by conduction is neglected.

The analysis shows that by including quadratic diffusion terms in the description of convective motion maintained by unstable stratification, the solutions tend toward a steady equilibrium state in which the upward heat transfer is proportional to $(-\partial S_0/\partial Z)^{3/2}$ [S_0 is the horizontal average of log θ where θ is potential temperature. Z is the vertical coordinate] and also to k^{-4}, where k is the von Karman constant. The rate at which the equilibrium state is approached is proportional to $(-\partial S_0/\partial Z)^{1/2}$. On the basis of experimental and dimensional considerations, the heat transfer H may be considered proportional to $(-\partial S_0/\partial Z)^{4/3}$. This leads to the conclusion that k is an increasing function of $(-\partial S_0/\partial Z)$, and if this function is assumed to be a power law, the exponent will be about $\frac{1}{24}$ to $\frac{1}{20}$. The agreement between theory and average observed values is fairly good, although there is a large scatter in the observational data.

The author emphasizes that in dealing with problems of maintained thermal convection where physical instability is involved the effect of nonlinear eddy diffusion must be considered, and the most preferred motion will be that of larger horizontal dimension. Furthermore, because of the approach of the various disturbances to their equilibrium states, the more unstable fast-growing small-scale motions can be included in the study of large-scale motions, making it feasible to study problems of thermal convection by numerical integration of the dynamic and thermodynamic equations.

Subject Headings: *Convection, thermal, eddy diffusion on; Diffusion, effect on thermal convection.*

A. Strasser

Hall, W. S. (University of South Hampton, England) "The Rise of an Isolated Thermal in Wind Shear," *Quarterly Journal Royal Meteorological Society* **88,** 394-411 (1962)

The analysis given in this paper is based on previous work done on the isolated, axisymmetrical thermal rising through still surroundings. A plausible model for a thermal rising in a wind shear is developed by considering the immediate surroundings of the thermal to have a uniform velocity, with this velocity varying with altitude. Thus, the actual flow picture is replaced by a series of pictures in each of which a thermal is surrounded by air with different uniform velocities, and the thermal is affected by the velocity variation only through interaction with the surroundings. It is shown that the resulting flow model is that for a thermal with a bouyant force with two components: one is the usual vertical bouyant force and the other is a horizontal component dependent upon the time rate of change of the external velocity as the thermal rises. Since inertial effects are neglected, it is assumed, essentially, that the thermal is relatively unaffected by distorting forces.

The limits in applicability of this theory are reduced to a limiting angle to which the axis of the thermal can be inclined as it rises through the shear layer. Using a known value for the necessary parameter, the author shows that this angle cannot be less than 40° from the horizontal.

Calculations are carried out for three cases. First, the problem where the angle of inclination of the thermal axis is constant is considered. The velocity distribution necessary to produce this condition is calculated in closed form and presented in curves for various angles of inclination. Also, curves of time required to reach a given height, path of the thermal relative to the ground, size of the thermal as a function of height, and bouyancy variation as a function of height are given for various inclination angles.

Next, the case of a varying angle of inclination of the thermal axis is considered for various velocity profiles. Profiles with shear constant, increasing with height, and decreasing with height, are considered. A numerical solution is necessary for this case, with the same information as noted in the first case being presented. It is concluded that for a given initial bouyancy, the greater the total shear, the less distance a thermal will rise before breaking up.

Finally, the effects of changes in wind direction are considered. The conditions used for a numerical example are for a wind which changes direction linearly with height until it blows at 45° to the original direction. The time taken to rise to a given height and the size of the thermal are larger than those for the corresponding boundary conditions in the second case, but not significantly so.

Coefficients of momentum and heat transfer are calculated for both the constant inclination and varying angle of inclination cases. For the latter case, it is shown that momentum transfer coefficient is much smaller than the heat transfer coefficient. Based on experimental observations this result is opposite to that presented by other authors. However, the author points out that atmospheric conditions were far different from those assumed in this analysis and so the results are not comparable.

Subject Headings: *Thermals, rise in wind shear; Wind, rise of thermals.*

T. C. Adamson

Moses, H. (Argonne National Laboratory, Argonne, Illinois) and **Strom, G. H.** (New York University, New York, New York) "A Comparison of Observed Plume Rises with Values Obtained from Well-Known Formulas," *Journal of the Air Pollution Control Association* **11**, 455-466 (1961)

The predictions of six formulas of the height to which a stack effluent will rise in the atmosphere were compared with data produced by an experimental stack. Formulas tested were those of Holland,[1] Davidson and Bryant,[2] Sutton,[3] Scorer,[4] Bosanquet, Carey, and Halton,[5] and Bosanquet.[6]

The various equations are presented in detail. In addition, the Scorer technique is extended by the authors to provide an equation giving height of rise as a function of distance from stack, Scorer having given only the technique for calculating the height at which leveling off occurs.

Heights of plume rise, measured photographically at both 30 and 60 meters from the stack, were compared with maximum heights given by the Davidson–Bryant and the Holland equations, or the height at 30 and 60 meters as given by the others.

Comparisons among the various techniques were demonstrated in several ways. One remark of the authors is that when the observed heights are arranged in increasing order and compared with the highest and lowest calculated values, about three-fourths of the measured heights fall within the range of calculated values. The significance of this is not apparent, since if one were to include methods which predict extremely high and extremely low values, all of the measured heights would fall within the calculated range.

Another means of comparison was by display of histograms showing the frequency distribution of the differences between calculated and observed values. These indicated that at 30 meters distant from the stack, the Davidson–Bryant and the Holland formulas gave low values while the others were too high. At 60 meters, the Bosanquet formula with diffusion coefficient 0.17 also read too low.

The difficulties of prediction are well illustrated by the scatter diagram comparisons of observed and calculated values which are presented. In practically all of these the scatter is more evident than any correlation, although the correlation between calculated and observed values is better during stable conditions than during neutral or unstable conditions. The Scorer technique was applied only for the latter conditions and thus appeared poorer than the others for which values for stable conditions were also included. The calculated correlation coefficients at a distance of 30 meters varied from 0.64 to 0.71, while at 60 meters, the range was from 0.46 to 0.57. In both instances the Scorer technique is not included. The authors attribute some of the scatter to the fact that observing periods were only four minutes long and that eddies with time scales greater than this would influence the plume height more than some of the variables in the formulas.

Finally, it is concluded that "there is no one formula which is outstanding in all respects." The sources of error in the experiments and the necessary approximation in the development of the formula are such that all one can hope for is agreement within a factor of two or so. Sutton's formula and Bosanquet's with diffusion coefficient 0.09 are definitely the poorest. The others may be chosen on the basis of ease of calculation (Davidson–Bryant or Holland) or some other basis depending on the nature of the problem.

References

1. Holland, J. Z.: "A Meteorological Survey of the Oak Ridge Area," *U. S. Atomic Energy Commission Report ORO-99*, 554–559 (1953).
2. Davidson, W. F.: "The Dispersion and Spreading of Gases and Dust from Chimneys," *Transactions of Conference on Industrial Wastes, 14th Annual Meeting, Industrial Hygiene Foundation of America*, 38–55 (1949).
3. Sutton, O. G.: "The Dispersion of Hot Gases in the Atmosphere," *J. Meteorol.* **7**, 307–312 (1950).
4. Scorer, R. S.: "The Rise of Bent-Over Hot Plumes," *Advan. Geophys.* **6**, 399–411 (1960); Abstract: *Fire Research Abstracts and Reviews* **2**, 159 (1960).
5. Bosanquet, C. H., Carey, W. F., and Halton, E. M.: "Dust Deposition from Chimney Stacks," *Proc. Inst. Mech. Engrs.* **162**, 355–367 (1950).
6. Bosanquet, C. H.: "The Rise of a Hot Waste Gas Plume," *J. Inst. Fuel* **30**, 322–328 (1957).

Subject Heading: *Plumes, prediction of rise rates.*

A. Strasser

Halitsky, J. (New York University, New York, N. Y. "Single-Camera Measurement of Smoke Plumes," *International Journal of Air and Water Pollution* **4**, 185–198 (1961)

Observations of smoke plumes from chimneys have been used to determine diffusion characteristics of the atmosphere and to verify predictions of plume rise. The usual photographic technique for recording instantaneous plume shapes requires the use of two cameras operated simultaneously and arranged stereoscopically. In this paper the author describes a system in which a single camera is placed on the ground to the side of the plume and a wind direction recorder replaces the other camera. The means of minimizing perspective distortion is described.

The data correction method assumes that the instantaneous plume lies in a vertical plane which passes through the direction of the mean wind. With lateral wind fluctuations carrying the plume outside this plane, the author's method is used to estimate the error and supply the correction. One of the advantages of the method is that it is unnecessary to record any data during the test except the time each photograph is taken. The information necessary for data reduction consists of camera and projector constants, location of camera and mean wind direction, all of which may be obtained after the test if a wind direction recorder is used.

The procedure is to observe mean wind direction just before a test and select a camera site which gives approximately the appropriate plume angle with the camera axis. The camera is set up and photographs are taken at regular intervals during smoke generation. Since the mean wind direction is not necessarily the one in an individual photograph, a sufficient number of photographs should be taken to provide a statistically significant average.

Coordinates of interest are the plume rise above source, vertical thickness, local angle of expansion and angle of elevation of instantaneous plume at a given downwind distance. Correction equations for these quantities are derived in terms of two angles which are characteristic of a test run. These are the horizontal angle between camera axis and camera-source line and the horizontal angle between the film plane and the mean wind plane.

Derivation of the relationships is based on elementary geometric and trigonometric considerations. Following the derivation, a discussion of possible errors such as those due to omission of some correction as well as those due to lateral wind fluctuations indicates the rather wide applicability of the method. Errors can be even further minimized if the topography allows an appropriate choice of camera site and camera angle.

Subject Heading: ***Plumes, measurement of.***

A. Strasser

Powell, G. (Alabama Division of Forestry) "A Fire-Whirlwind in Alabama," *Fire Control Notes, U. S. Forest Service* **24**, 20–24 (1963)

Late in the afternoon of February 7, 1962, the author observed a whirlwind associated with a relatively small but intense control fire burning in logging slash in Covington County, Alabama. The lower half of the convection column tilted slightly to the southwest while the upper half, which terminated in a mushroom cap of water vapor, appeared to be vertical. From a distance the whirlwind resembled a long ribbon or narrow cylinder of white smoke. It appeared to extend downward from the mushroom cap over the convection column to make contact with the ground in the burned-over area (still smoldering) some distance from the main fire, which was spreading slowly toward the east.

A close-up examination showed that the cylindrical "funnel" was about 6 to 10 feet in diameter. Ash and particles of burned litter whirled vigorously in a counterclockwise direction. The base of the funnel moved slowly about in the burned-over area and caused smoldering logs to burst into flame. Mineral soil was exposed by the wandering funnel base but was covered again as the funnel moved away and deposited new ash in its path.

On stepping into the funnel, the author states that the intense wind filled his clothes with particles of ash and made his ears "pop" (this effect may have been due to the pressure drop).

Subject Headings: *Fires, whirlwind; Whirlwind.*

G. M. Byram

Reifsnyder, W. R. (Yale University, New Haven, Connecticut) "Weather and Fire Control Practices," *Proceedings of the Fifth World Forestry Congress* 2, 835-841 (1960)

The role of weather in forest fires and in fire control practices is presented in this paper.

Weather and climate influence the production, accumulation, and form of combustible materials in forested areas. The flammability of these materials is dependent on their moisture content, which is controlled by meteorological variables The author states that short-term climatic fluctuations may have little effect on forest type or fuel type but may have a measurable and important effect on quantity and flammability of available fuels.

The seasonal variation of atmospheric conditions is most important to the fire season concept and to the climatic controls of fire suppression practices The distribution of precipitation determines the duration of the fire hazard periods and also the type of fire control organization established The importance of synoptic-scale weather changes in relation to the drying of fuels is emphasized by the author. Diurnal changes in radiation and relative humidity, both of which control the equilibrium moisture content of fuels, are also emphasized Along with the time variation in flammability, the author also mentions the importance of space variation in fuel flammability due to topography.

Following the ignition of fuels and the start of a wildfire, the influence of weather on fire behavior must be considered along with other factors in determining the nature of the suppression effort and the development of an efficient organization. Ignition by lightning, which generally occurs in remote areas, has tremendous implications on fire control practices The detection of the fire and the rapid transport of men and equipment to these areas become imperative. The use of aircraft has radically changed the type of organization developed for combating lightning fires.

Surface wind is, in many ways, the most influential meteorological element in fire behavior. Aside from its effect on oxygen supply and direction of fire spread, the variability of wind in direction and speed is important in determining how a fire will spread and what control measures are needed. Because of this variability, the author stresses the importance of insuring the safety of suppression forces against sudden drastic changes in the direction and rate of fire spread.

Fire behavior can also be influenced by the variation of the vertical profile of wind speed and direction. The spread of many large fires has been primarily the result of spotting. On-the-spot measurements or estimates of the wind profile is stressed by the author as a means of alerting fire control personnel to possible blow-up conditions.

The thermal structure of the atmosphere and the resulting state of atmospheric stability can influence fire behavior through its effect on wind pattern. Detailed knowledge of existing and predicted wind and temperature distributions is necessary for adequate planning of suppression strategy.

Weather also affects the conduct of the fire suppression job by directly affecting the men engaged in suppression efforts. Exposure to high temperatures and insolation and, in many instances, to high altitudes produces a severe climatic stress on the human body. In extreme cases the individual may become completely incapacitated, while in others the efficiency of the individual and his power of judgment is lowered.

Meteorological factors also influence other fire control activities. Weather can affect visibility which is so important in planning detection systems. Increased use of aircraft in detection and suppression activities has resulted in increased attention to weather. The influence of weather on fire behavior determines to a great extent the strategy and tactics employed in suppression. Other activities such as those of logistics of service and supply and the distribution of control forces are also influenced by weather.

Methods of evaluating weather and climate influences are discussed in the last section of the paper. A brief history of the development of fire-danger rating systems is given. Brief mention is also made of special climatological techniques which have been developed for analyzing weather data. The use of fire-weather forecasting by various forestry services is briefly discussed.

Subject Headings: *Weather, influence on fire control; Fire control, influence by weather.*

W. Y. Pong

Countryman, C. M. (Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California) and **Schroeder, M. J.** (U. S. Weather Bureau, Berkeley, California) "Fire Environment—The Key to Fire Behavior," *Proceedings Fifth World Forestry Congress* 2, 860-863 (1960)

This article reviews the variables that affect the behavior of fire (weather, fuel, and topography), reports on two case studies where weather factors in combination with topography dominated fire behavior, and calls attention to the effects of cutting practices on fuels and microclimate. Information reported in this article is covered in greater detail in other publications.

Forest fires appear to burn in an erratic manner. Actually the fire behaves in response to differences in fuel, topography, and weather, i.e., the "fire environment." This environment is not static—the fuels change with the seasons from succulent in the spring to dead in the fall. But the most variable factor is weather, and meteorological conditions to 30,000 feet may be important to fire behavior.

Quantitative relations for predicting fire behavior are lacking. The authors are supplying some of the missing information by field studies of fuels, topography, and wind patterns in areas scheduled for prescribed burning for brush removal. Detailed observations of weather are also made during the actual burning when fire behavior is noted in detail. On a 1000-acre site designated for prescribed burning near Sonora, California, 20 weather stations were installed and observations were made for 8 days prior to burning. Surface wind patterns responded to changes in heating and cooling of the terrain as the day advanced. On the ninth day, actual fire behavior corresponded well with observed wind patterns. A large fire whirlwind even developed on a lee slope where eddies had been observed in the pre-fire wind patterns.

A similar study was made of a 500-acre area on the east-facing slope of the Coast Range north of San Francisco. There, morning upslope breezes gave way rather abruptly near noon to downslope westerly winds. These lasted through the afternoon reaching 15 to 18 mph by 1800 hours, gradually decreasing to normal downslope speeds sometime after sunset. Firing of this area had been planned without knowledge of the downslope winds, assuming topography would dominate. Set at 1100 hours, the resulting fire spread rapidly downslope before the wind and across prepared lines following behavior indicated by the average wind pattern for 1200 hours.

Not so easily determined are the effects of silvicultural practices, such as clear cutting, that greatly alter fuel arrangement, surface temperature, and exposure to wind. Partial cutting may increase chance of crown fire, while pruning of young stands reduces the likelihood of crown fires.

Wild land fire control depends on accurate prediction of fire behavior, which requires understanding of the fire environment: weather, fuel, and terrain.

Subject Headings: *Fires, environment effects on; Weather, effects on fire.*

O. P. Cramer

XI. Operational Research Principles

Nelson, R. M. (Southeastern Forest Experiment Station, U. S. Forest Service, Asheville, North Carolina) "Some Applications of Danger Ratings in Forest Fire Control and Management," *Southeastern Forest Experiment Station Paper* No. 129 (1961)

The avowed purpose of this publication is ". . .to summarize and explain the major uses of fire danger ratings and to present methods of analyzing fire and fire danger records." In principle the uses described apply wherever fire danger is measured. Examples and methodology relate to southern and eastern United States, where the Type 8 and Type 8–100–0 Forest Fire Danger Meters, developed by the Southeastern Forest Experiment Station, are used.

Appropriately, the text first tells what fire danger ratings are and what they mean in terms of fire occurrence and behavior. Subsequent major sections deal with uses of fire danger ratings in preparedness planning, dispatching, prevention planning, evaluating prevention and suppression accomplishments, guiding use of aerial detection, and rating the relative severity of fire seasons. Most of these sections deal adequately, although not exhaustively, with generally recognized applications of fire danger ratings by fire control organizations. "Danger Ratings in Fire Prevention Planning" is the weakest because it merely generalizes about broad prevention programs and policies instead of describing methods usable in the much-needed job of analyzing specific prevention problems preparatory to direct attack on them.

Interspersed with the sections that discuss actual uses of fire danger ratings are others entitled "Extreme Fire Behavior," "Fire-Weather Forecasting Services," and "A National Fire Danger System." These contain little or nothing of value on uses of fire danger ratings but rather appear to be "plugs" for three related ideas or programs. The inclusion of such off-the-subject material may be informative, but it weakens the main theme of the publication.

The description of methods for compiling records and making certain computations seems misplaced; logically it should appear either before or after all the sections on uses of danger ratings. A companion topic, which nevertheless occupies a separate location in the text, is that which emphasizes the need for accurate basic records. Understandably, compiling and computing techniques are covered only to the extent of showing how to arrive at fire occurrence rate, burned area rate, and occurrence in relation to fire danger and cause. Somewhat greater detail would be desirable in the sections dealing with specific uses of fire danger ratings. Each fire control situation has its own peculiarities, however, and each analysis its own goals. Therefore, relatively few basic techniques are broadly applicable; to go further each analyst or planner must develop the methodology that will yield the type of information he needs.

This publication merits attention not as a contribution to scientific knowledge, which it is not, but as needed effort to get existing knowledge into general use. Forest fire researchers and some fire control administrators already appreciate the advantages of using fire danger ratings and use them with considerable sophistication in designing, operating, and improving fire control systems. Too commonly, however, fire danger records and fire reports are filed and forgotten or used only sporadically, superficially, and even improperly. Nelson's description of a few rather obvious applications of fire danger ratings and his explanation of the simple methodology required to establish useful relationships should interest fire control administrators who are not using their fire and weather records to advantage. How much motivation the publication will provide remains to be seen.

Subject Headings: *Fires, danger rating, forest; Forest fires, danger rating.*

G. R. Fahnestock

XII. Instrumentation

Billetdeaux, A. C., Lawrence, R. W., and Freilino, R. S. (Mine Safety Appliances Company, Pittsburgh, Pennsylvania) "An Explosive Vapor Detector for Rocket Powered Aircraft," *Aeronautical Systems Division, Wright-Patterson Air Force Base Technical Documentary Report No. ASD–TDR-62-531* (October 1962)

A laboratory model of a some-day instrument for detecting explosive concentrations of flammable vapors in rocket-powered aircraft is described. An open path nondispersive infrared spectrometer monitors a volume of enclosing airframe, and sounds an alarm if the vapor concentration of JP–4, JP–x (40 per cent UDMH, 60 per cent JP-4), ammonia, or RFNA (red fuming nitric acid) exceed $\frac{1}{2}$ per cent by volume.

The design and construction of the laboratory model are described in explicit detail. Infrared radiation in the 2.0 to 4.5 micron region, from a 60-watt iodine cycle tungsten filament lamp in a quartz envelope, is gathered by a spun aluminum ellipsoidal collector mirror and focused along a folded 40-inch optical path to a condenser paraboloid having a sensitive gas-bulb detector at its focus. This detector measures incident infrared radiation as a pressure increase resulting from the thermal absorption; its action is selective and specific because it is filled with the vapor to be measured or a suitable simulant gas. The detector contains also a reference vapor having an absorption band near the wavelengths of the explosive vapors; the reference is acetylene, at 3 microns, in this case.

A rotating sector disc fitted with suitable filters modulates the infrared beam, passing alternately the sample wavelength and reference wavelength through to the detector. This modulation permits a capacitance-type pressure transducer in the detector to generate an a-c signal. This signal is amplified by a conventional negative feedback circuit and rectified by a phase-sensitive rectifier controlled by the modulator; it passes finally to a d-c voltage comparator where it triggers an alarm switch if it exceeds 3.0 volts.

The instrument is designed to operate between minus 65° and plus 160°F over an altitude range of 0 to 100,000 feet. Above 100,000 feet (the limit of pressure compensation in the amplifier circuit), the instrument functions as a leak detector, alarming if the mass of vapor in the absorption path equals the mass of vapor at the highest altitude for which a hazard exists. The pilot is warned, then, that when he descends he may encounter an explosive condition.

The sensitivity of the laboratory model to hydrocarbon vapors at room temperature and atmospheric pressure is high. One or two drops of lighter fluid several feet away, an ethane leak 15 feet away, automobile exhausts 100 feet away, all give alarms.

The sensitivity to ammonia vapor is very low, only one-thousandth the sensitivity to hydrocarbons. A different detector filling is required, probably ammonia itself.

Other performance requirements for the instrument are discussed: these include humidity tolerance, shock and vibration resistance, warmup and response times, calibration stability, and operation in sand and dust. It is revealed that the sensitivity and response tests called for in the specifications were not completed, largely due to lack of time. For example, the instrument itself was not tested to 1000,000 feet altitude (the electrical connectors arced at reduced pressure), only the vapor sample, which was contained in a sealed cell. Also, isobutane was used to simulate JP–4 fuel, and the other fuels were not evaluated with the finished laboratory model.

In spite of its shortcomings, the laboratory model confirms the suitability of the open path infrared approach for high altitude explosion hazard detection. Design of an operational explosive vapor detector awaits such detailed environmental information as the shape of the airframe and the exact location of the instrument in the aircraft.

Subject Heading: ***Explosion, vapor detector.***

B. Greifer

King, A. R. (Chemical Research Laboratories, Melbourne, Australia) "Compensating Radiometer," *British Journal of Applied Physics* **12**, 633-634 (1961)

An instrument for measuring radiant heat transfer was developed to meet the requirements of field measurements of forest fire flame fronts. The radiometer measures the heat absorbed by two identical planes, one of which is subjected to radiated and convected heat and the other to convected heat alone. These planes are disks (1 mm thick×1 cm diameter) of a silver–tellurium (1:2) alloy with circles of copper gauze attached thermally and electrically to each planar face. The heat flux to be measured flows in through one gauze circle and out through the other into a heat sink. A temperature gradient is established proportional to the heating rate, which generates an emf difference between the two junctions, gauze to alloy, which constitute thermocouples. The disks are mounted in opposite sides of a water-filled brass sphere, which acts as a heat sink. The disk intended to absorb both radiated and convected heat is painted black. The disk intended to absorb only convected heat is covered with bright aluminum foil.

The speed of response was 10 sec for 95 per cent full-scale when using a stepwise radiation change of 0.1 cal $cm^{-2}sec^{-1}$.

The effect of wind and instrument temperature on instrument readings are expected to be less than ±10 per cent in usual field measurements.

Subject Headings: ***Heat transfer, measurement of; Radiometer, design.***

A. E. Noreen

Ashton, J. S. (La Porte Chemicals, Luton, England) "Measurement of the Properties of Small-Scale Turbulent Jet Diffusion Flames," *Fuel Society Journal (University of Sheffield)* **13,** 28–37 (1962)

In order to facilitate operation of a small-scale flame tunnel by one worker, well-known techniques for the measurement of flame properties have been modified. The properties measured are temperature, velocity, soot concentration, and gas emissivity. A water cooled pitot tube is connected to a Beaudouin manometer described by Kissel[1] to measure fluctuating differential pressures of 0.001 inches water resulting from gas velocities of the order of 15 feet per second. Calibration procedures are described.

Temperature measurements are made by a shielded suction pyrometer, with the hot gases drawn past the platinum/platinum–13% rhodium thermocouple at about 500 feet per second. Under conditions of thermal loading applied, the error is about 80°C at 1500°C.

A number of methods for measuring gas emissivity are discussed with their relative advantages. It is concluded that under normal conditions the Schmidt method[2] is accurate to within 5 per cent. This method, depending on the assumption that the flame is gray, requires three readings: the radiation from the flame with a cold background, radiation from the flame with a hot background, and radiation from background alone. When recirculation takes place, emissivity of the gases surrounding the flame is calculated from the curves of Hottel and Egbert[3] and the equations are modified to take these into account.

Another method, useful for thick luminous flames such as those encountered in the Sheffield furnace, is an optical and total radiation technique which is based on the relationship

$$\epsilon = 1 - \exp\left[-f(kL, \lambda)\right],$$

where ϵ=spectral emissivity; k=an absorptivity factor; L=flame width; and λ=wavelength. Using published graphs of $f(kL, \lambda)$ and readings with a total radiation pyrometer and optical pyrometer, the flame emissivity and temperature are obtained.

Soot concentration is measured by means of a specially designed soot probe which is described. Reproducibility is ±3 per cent in regions of low soot concentration but this increases to ±7 per cent in the region of peak soot concentration where the pores of the sintered bronze filter in the probe become rapidly blocked, reducing the quantity of gas that can be sampled.

Although this paper describes no real innovations, it may be helpful as a source of information for an investigator about to embark on a study of flame characteristics in a small furnace.

References

1. Kissel, R. R.: *International Flame Research Foundation, Doc. No. 72/a/4.*
2. Schmidt, H.: *Ann. Phys.* 29, 998 (1909).
3. Hottel, H. C. and Egbert, R. B.: *Trans. ASME* 63, 297 (1941).

Subject Headings: *Flame, turbulent jet diffusion; Emissivity, measurement.*

A. Strasser

XIII. Fire-Fighting Techniques, Equipment Design, Materials of Construction

Shapland, J. D. (Foamite Ltd., England) "Fire-Fighting Installations in the Chemical Industry," *Chemical and Process Engineering* **43**, 5–8 (1962)

This article describes fire hazards in chemical processing and the types of automatic fire extinguishment installations appropriate for various classes of fire risks. Industrial fire risks are classified in three groups: (a) carbonaceous, (b) inflammables, and (c) electrical. Four methods for extinguishment are presented:

1. Removal of burning material from source of heat,
2. Reduction of surface temperature of combustible below flash point,
3. Retardation of chemical reaction, and
4. Reduction of oxygen concentration to level below that capable of supporting combustion.

For Class (a) fires, extinguishment by water is recommended; for Class (b), foam; and for Class (c), carbon dioxide or dry chemical powder. Typical automatic fire-fighting installations are described with accompanying sketches.

Recommendations are made for each system. For example, water sprays can be used for 1) fire extinguishment, 2) fire control, 3) exposure protection, or 4) fire prevention. For heavy oils or kerosene, extinguishment requirements are given; for volatile liquids control is recommended since extinguishment by water is impossible; for exposure protection, the required spray rate per exposed surface area is given. Foam extinguishment recommendations are given in detail, application rates of about 3 times critical being suggested to allow for adequate safety margins. The advantages and limitations of each fire extinguishment method are presented without bias.

Subject Heading: ***Fire extinguishment, methods.***

D. Dembrow

---

von Elbe, G. and Scott, H. T. (Atlantic Research Corporation, Alexandria, Virginia) "Hazards of Liquid Hydrogen in Research and Development Facilities," *Aeronautical Systems Division, Wright-Patterson Air Force Base Technical Documentary Report No. ASD-TDR-62-1027* (December 1962)

This paper reviews the hazards associated with the use of liquid hydrogen in research and development facilities and discusses the techniques by which these hazards can be prevented or controlled. Included among the hazards are pressure rupture of containers, formation of flammable mixtures by the release of hydrogen into the air, and explosion of hydrogen and entrapped oxygen under cryogenic conditions. As background for an understanding of the phenomena involved in possible hazards arising from the use of liquid hydrogen, the authors provide an excellent, although brief, review of the reaction mechanism controlling the combustion and detonation of hydrogen–oxygen mixtures.

Since the reaction of hydrogen and oxygen is not spontaneous under either cryogenic or normal ambient conditions it follows that any fire or explosion must result from ignition by an extraneous source, whether it be a hot spot, a shock wave, an electric spark, etc. It is also evident that the concentration and quantity of hydrogen involved determines to a great extent the nature and seriousness of the potential hazard. Thus, in reviewing the general considerations in evaluating and controlling these hazards the authors emphasize the following:

1. Elimination or minimization of areas where hydrogen may accumulate—either by burning excess gas, if practical, or by venting to a safe region.
2. Removal of ignition sources by grounding and bonding of metal parts and system components, by proper choice of electrical equipment, and by eliminating friction sparks.
3. Provision of an adequate ventilation system capable of maintaining hydrogen concentrations below flammable limits even in the event of a spill.
4. Provision of adequate pressure relief devices on every closed system. Consideration must be taken of the possibility of solidified air reducing the effectiveness of the devices.
5. Design of reaction and storage vessels for maximum pressures which may develop due to combustion or detonation.

In addition to the discussion of the general considerations outlined above, the authors present very practical information which should prove useful in the design and construction of test and storage facilities. As well as referring to design guides followed at various installations where liquid hydrogen is used, they also list some of the types of equipment proven to be most useful when working with liquid hydrogen. Procedures are outlined which have been demonstrated to be successful in minimizing potential hazards. These include the most acceptable techniques for purging and transfer. Reference is made to the available hydrogen-in-air and hydrogen fire detectors.

The paper concludes with a short section on areas requiring further research and development. Among these are:

1. Determination of the cause of ignition which usually occurs with rupture of pressure relief disks.
2. Study of the reaction between liquid hydrogen and solid oxygen including the sensitivity and modes of initiation and determination of yield.
3. Development of improved hydrogen-in-air detectors and measuring devices which have rapid response times, are specific for hydrogen, and do not introduce any additional hazard.
4. Development of hydrogen-fire detectors which can be effective at fairly long range.

This paper is valuable enough to consider it required reading not only for all people newly entering the liquid hydrogen field but also as a review for all experienced workers.

Subject Headings: ***Hydrogen, liquid, hazards associated with handling of; Ignition, of liquid hydrogen.***

F. Falk

Ryan, J. V. (National Bureau of Standards, Washington, D. C.) "Study of Gypsum Plasters Exposed to Fire," *Journal of Research of the National Bureau of Standards* 66C, 373–387 (1962)

This study was designed to examine the effects of mix, aggregate, and conditioning on the fire endurances, in terms of a limiting temperature rise, of gypsum plasters. It was not intended to examine the effects of large variations of thickness, nor was it felt that such was needed because of the published data from many standard fire tests and conclusions based thereon.

Under the conditions of specimen size and test conditions employed, the study showed that the mix ratio of gypsum to aggregate has little, if any, influence on the time to a 250°F temperature rise, for a single aggregate within the range of mixes ordinarily employed. The perlite and vermiculite aggregate plasters exhibited significantly longer temperature-rise times than did the sanded gypsum plasters. This was attributed in part to the differences between the aggregates and in part to the fact that the conventional mixes for sanded plasters correspond to quite different ranges of gypsum-to-aggregate ratios on a weight basis. Variation of the density of perlite aggregate over a range of about 8 to 13 $\mathrm{lb/ft^3}$ had no significant influence on the limiting temperature-rise time.

The effect of aging or conditioning was pronounced for the combination of very high relative humidity atmospheres and relatively short periods of aging. For perlite and vermiculite aggregate plaster specimens conditioned 30 days in atmospheres at relative humidities near 95 per cent and temperatures near 70° to 75°F, significantly longer times were observed than for equivalent specimens aged about

12 weeks under similar temperature and humidity conditions. Duration of aging beyond 30 days in atmospheres below 85 per cent relative humidity had no influence.

The data from the fire tests of neat gypsum, gypsum-perlite, and gypsum-vermiculite plasters served as bases for the calculation of estimates of the apparent thermal conductivities and thermal diffusivities of such plasters at temperatures in the range 1200° to 1500°F. Values of the same thermal properties were obtained for steady-state heat flow at about 120°F mean plaster temperature. No attempt was made to calculate values from the fire-test data for the range 200° to 1000°F because of the latent heat effects associated with calcination of gypsum early in fire-test exposures. However, the values for higher temperatures, although only estimates, should be useful in the prediction of the fire endurances of plastered structures by analog devices or computational procedures.

Examination of the data in terms of plaster thickness, over the small range of variation observed, showed agreement with the earlier findings from large specimen tests, so far as a limiting temperature rise is concerned. It is possible that large departures from the nominal 1-in. plaster thickness may affect the application of the high-temperature values of thermal properties, due to the effects resulting from the water in the hydrated gypsum.

Subject Headings: *Fires, effect, on gypsum; Gypsum, fire effect on.*

E. C. Woodward

Bird, G. I. (Joint Fire Research Organization, Boreham Wood, England) "Fire Resistance of Floors and Ceilings," *Joint Fire Research Organization Fire Note No. 1* (1961)

This report summarizes the criterion normally used to evaluate the fire resistance of structural members and the common methods of construction for ceilings and floors. Full-scale tests have been conducted to evaluate the characteristics of materials and configurations that are not included in the Fourth Schedule of the British Ministry of Housing and Local Government Model Byelaws for Buildings, 1935. None of the common ceilings will protect a timber floor against flame penetration for the desired time of one hour. Some representative materials and times are: $\frac{1}{8}$ inch hardboard, 5 minutes; $\frac{3}{8}$ inch plasterboard, 10 minutes; metal lath and $\frac{5}{8}$ inch plaster, 40 minutes. A four-hour fire-resistance is readily obtained with a floor of prestressed hollow box-section slabs, $6\frac{1}{4}$ inch deep, with $1\frac{1}{4}$ inch concrete screed on top, and a suspended ceiling of 1 inch vermiculite/gypsum plaster on metal lathing. A number of other construction techniques were tested. Openings for ducts and lights in noncombustible ceilings can not exceed 0.7 per cent of the area without seriously impairing the overall fire-resistance of the structure.

Subject Heading: *Fires, effect, on floors and ceilings.*

T. P. Anderson

Malhotra, H. L. (Joint Fire Research Organization, Boreham Wood, England) "Fire Resistance of Perforated Brick Walls," *The Builder* **202**, 513–515 (1962)

Perforated bricks show considerable promise as an external wall construction material, replacing conventional walls of face brick backed up by light-weight concrete blocks, in terms of weight, erection costs, and thermal insulation. These bricks have extruded clay sections with through perforations or cells in the vertical direction arranged in two groups connected by four webs. Fire tests were performed on 10 foot square load-bearing walls using three types of brick with different sizes and shapes of the perforations giving voids ranging from 50 to 60 per cent and weights from 6 to 8 pounds. The smallest cellular structure provided the best fire resistance, 1 hour for exposed brick and 4 hours when the exposed face was coated with ½ inch of vermiculite/gypsum plaster.

Subject Headings: *Fire resistance, of brick walls; Brick walls, fire resistance.*

T. P. Anderson

Ryan, J. V. and Bender, E. W. (National Bureau of Standards, Washington, D. C.) "Fire Tests of Precast Cellular Concrete Floors and Roofs," *National Bureau of Standards Monograph 45* (1962)

Experimental studies were conducted on floor and roof slabs assembled from precast planks of a gas-formed cellular concrete to determine the fire endurance of representative specimens and the effects thereon of variables such as amount of cover for reinforcing bars, overall thickness, amount and distribution of reinforecment, and density of the concrete. The nominal density of the planks for floor use was 44 lb/ft^3 and that of the roof planks was 31 lb/ft^3. Thicknesses of 5, 6, and 8 inches were used. Tests were conducted according to ASTM Standard E 119, although all of the tests were not terminated when the initial end point was reached.

Although most of the end point criteria are specific in interpretation, the load failure point is sometimes difficult to determine and an alternative critical value for both the deflection and rate of deflection is defined such that when both of these values are reached load failure can be considered to have occurred. Of the five panels tested under load, the performances of two were limited by load failure, two by exposed surface temperature rise, and one by ignition of cotton waste over a crack. In reinforced panels two additional criteria for end point definition are suggested; the time at which steel structural members or reinforcement members attain an average temperature of 1000°F and the time at which any point in the steel attains a temperature of 1200°F.

The results of these tests show that fire endurance is related to the $\frac{5}{3}$ power of the thickness, the same as for solid, essentially homogeneous walls. The results of the tests also show that cellular concrete slabs, made into precast planks, can be designed to provide fire endurances of 1 to 2 hours and probably up to 4 hours. The use of greater cover for the reinforcing bars, in the range of ¾ to 1¼ inch, even without increasing the total thickness will result in longer fire endurance. Within the density range of 35 to 50 lb/ft^3, slabs made of higher density concrete will provide longer fire endurance than those of lower density, both in terms of heat transfer through the slab and in terms of continued structural stability. The use of reinforcing bars of larger diameter and consequently greater ratio of reinforcement results in longer fire endurance than the combination of smaller bars plus shear reinforcement which was used in this study.

Subject Headings: *Concrete, fire tests; Fire tests, on concrete.*

T. P. Anderson

McGuire, J. H. and Ruscoe, B. E. (National Research Council, Ottawa, Canada) "The Value of a Fire Detector in the Home," *Fire Study No. 9 of the Division of Building Research, National Research Council, Canada* (1962)

The object of the work described in this report was to estimate the effect on the fire death rate of the installation of fire detectors in one class of residential property: unshared separate dwellings and small residences. The work was made possible by the authors having access to a card index system containing the factual circumstances in which 342 persons lost their lives in Ontario dwellings as a result of fire. Estimates were made of the likelihood that each person might have escaped had either one or another of two simple fire detectors been operating at the time. One detector was an extremely sensitive, ionization chamber, smoke detector and the other a fixed temperature (150°F) device. The latter was assumed to have a response typical of a bimetallic device with as low as possible a thermal-capacity/surface area ratio for such a type. The overall result was that the estimated saving of life would have been 41 and 8 per cent for the ionization chamber and thermal detectors, respectively. A significant secondary result is that the most sensitive fire detector available will only reduce the overall risk to a sleeping individual by a factor slightly above 2. Brief reference is also made to the economy of installing a fire detector with a view to reducing property damage.

Subject Heading: *Fire detector, value of.*

E. C. Woodward

Peterson, H. B., Gipe, R. L., and Tuve, R. L. (U. S. Naval Research Laboratory, Washington, D. C.) "The Development of a Combination Runway Foaming-Tanker Vehicle for Augmenting Naval Air Station Fire Fighting Operations," *NRL Report 5887* (January 31, 1963)

Previous reports[1,2] concluded that a foam layer on an aircraft runway can prove of value in decreasing the chance of ignition of fuel spilled during emergency landings made necessary by malfunction of landing gear. However, in recognition of the theoretical and operational problems[2] and particularly the reluctance to employ primary aircraft rescue and fire-fighting vehicles and the general unavailability of specialized auxiliary equipment to quickly and reliably foam a runway, widespread adoption of this technique has heretofore not been recommended.

The authors report more recent experience in which, in spite of the lack of specialized equipment, foam was applied by various means in 50 cases of emergency landings, with only one fire and this where the foam blanket was incomplete. By contrast, in 23 no-foam landings 13 fires occurred. Even taking into account the probability that circumstances which resulted in the decision not to apply foam, or inability to do so, may also have increased the chance of fire, these statistics were sufficiently convincing to stimulate work toward the design of improved foaming equipment.

Having developed a successful prototype runway foaming unit which can also serve as an auxiliary for the primary fire fighting and rescue apparatus, it has now been recommended that a standard policy on the use of foam on runways be established.

The development proceeded on the premise that equipment for runway foaming should be completely separate from the normally supplied crash fire-fighting equipment, in order that the ability to combat crash fires be not impaired. On the other hand, it was recognized that the present crash fire vehicles are limited in the time they can remain in action because of the requirement for extreme mobility, so that a vehicle which could act as a "nurse" to bring up additional supplies of water and foam concentrate would be very valuable.

Previously tried methods of foam spreading were reviewed. Turret and ground sweep nozzles were found to be difficult to control and to give poor distribution highly influenced by wind. Downward projection of foam from multiple outlets in a pipe close to the ground and extending transversely at the rear of the vehicle to give the desired spread was found promising and was selected for further development.

Because of general availability a 3000 gallon aircraft refueling unit was selected as the basis for the prototype. Removal of the fuel filters made space available at the rear for a 600 gpm 120 psig skid-mounted engine-pump unit, and a 200 gallon foam concentrate tank. A 6 per cent around-the-pump proportioner was used, the power take-off fuel-delivery pump was retained, and both this and the main water pump were piped and manifolded to discharge the truck contents by means of hoses during "nurse" operation. Controls were made accessible from an operators platform at the rear.

The folding foam spreader was mounted close to the ground at the rear, and consisted of a fixed 8-ft center section and two hinged outer sections to give a 24-ft spread. Foam was delivered into the spreader from 6 horizontally mounted aspirating nozzles of 50 gpm water capacity each, and was discharged downward through holes of graduated sizes spaced 2 in. on centers. Interior baffles were found necessary to provide uniform distribution (details given).

An engine tachometer provided an accurate means for regulating vehicle speed. At 250 feet per minute (2.9 mph) the foam blanket averaged 1.6-in. thick, and was ½-in. thick one foot from the edge of the 24-ft wide blanket. The 3000 gallons of water produced a blanket 1250 feet long in about 5 minutes. Foam had a 10.7 expansion, and a drainage time of 9.3 minutes after application, which was considered satisfactory.

The vehicle can discharge both water and foam concentrate at rates exceeding the requirements of a crash vehicle, and hence can serve as a "nurse" when not otherwise occupied, and can discharge water to assist in cleaning up after foaming.

The authors suggest that where surplus tank vehicles are available runway foaming units patterned after the prototype can be constructed locally.

References

1. Peterson, H. B., Jablonski, E. J., and Tuve, R. L.: "Studies on the Fuel-Ignition-Suppression Capability of Foam-Covered Runways for Aircraft," *NRL Report 5492* (June 1960).
2. National Fire Protection Association "Foaming Runways for Crash Protection," *NFPA No. 420M* (May 1961).

Subject Headings: *Fire fighting, use of foam; Foam, use in aircraft fire fighting; Aircraft fires, use of foam.*

O. W. Johnson

Fry, J. F. and Lustig, R. E. (Joint Fire Research Organization, Boreham Wood, England) "Fire Hazards of Electricity" *Technical Paper No. 3, Joint Fire Research Organization* (1962) and "Fires Associated with Kerosine-Burning Appliances in Dwellings, June 1960-May 1961," *Technical Paper No. 4, Joint Fire Research Organization* (1962)

Technical Paper No. 3—*Fire Hazards of Electricity*

This technical paper presents an analysis of special questionnaires, drafted by the Joint Fire Research Organization, with the collaboration of other responsible agencies, and completed by Fire Brigades in England, Scotland, and Wales. The Brigades submitted questionnaires on the fires deemed of electrical origin attended in the period 1 September 1957 to 31 August 1958. Nine thousand, three hundred and eighty-five questionnaries were received by the Joint Fire Research Organization. Two thousand, eight hundred and ninety-six referred to fixed installation fires, and six thousand, four hundred and eighty-nine referred to electrical apparatus and appliance fires. Data on electrical fires for 1955, 1956, 1957, and 1958 from other sources are compared with observations derived from the questionnaires.

Salient observations are as follows. Of the electrical installation fires reported, 44.1 per cent occurred in dwellings, and 64.5 per cent of the installation fires were caused by cable and wire failures, excluding fires occurring in lead wires to portable appliances. In calendar year 1958, wire and cable fires comprised 4.7 per cent of the building fires of record. The wire and cable fires were of lowest occurrence in industry, 2.6 per cent of all fires reported for 1958 in industrial occupancies as compared to the highest occurrence in clubs, hotels, and the like, i.e., 6.2 per cent of all fires reported for 1958 were in this latter type occupancy. Nonmechanical damage was cited as the cause of fire in 45.8 per cent of the fires occurring in cable and wiring, excluding fires in leads and cords to portable-type appliances. Mechanical damage was cited as the cause in 26.5 per cent of the fires in the fixed-type wiring and cables. In fires attributed to appliance leads, 30.7 per cent were designated to be of miscellaneous and unknown origin, and 29.5 per cent were caused by nonmechanical damage, whereas only 6.0 per cent were caused by mechanical damage.

Motor fires comprised 33 per cent of the electrical appliance fires in industrial occupancies, while in dwellings 32.7 per cent of the electrical appliance fires involved electrical cooking equipment, and 23 per cent were caused by electrical space heaters. In commercial premises, 32.5 per cent of the reported electrical appliance fires were caused by refrigerators, and 24.7 per cent were caused by lighting, largely of the fluorescent type.

Analyses of the results, and interpretations are presented. Electrical overloading was a relatively minor cause for installation fires. Diurnal and seasonal variations in electrical fire occurrences are shown and comparison of amateur versus professional labor in electrical installations with frequencies of fire occurrences are made. Deterioration with age and its effect on wire and cable failure, are also discussed.

It was concluded that some correlation existed between the age of electrical installations and the occurrence of fire, though not established as a direct cause and effect relationship. The importance of the proper use of portable appliances in prevention of fire and the possibility of improvements in appliance design and fabrication to eliminate features conducive to fires are cited.

Technical Paper No. 4—*Fires Associated with Kerosene-Burning Appliances in Dwellings*

Questionnaires were drafted and circulated to Fire Brigades throughout the United Kingdom concerning occurrences of fires in kerosene appliances during the period 1 June 1960 to 31 May 1961, inclusive. This paper presents the analysis of these questionnaires when completed.

Three thousand and fifteen completed questionnaires were received, of which two thousand six hundred and three concerned fires on private residential premises. Of the fires on private premises, two thousand three hundred and ninety-seven involved portable space heaters. Moreover, it was noted that 25 of the 85 cooking appliances involved in fires were actually being used as space heaters. The portable space heaters were for the most part of two types; 1446 were of the drip-feed type and 935 were of the wick-feed type. About 25 per cent of the reported fires in the wick-feed type heaters were attributed to the units being set with the flame too high. The causes (each contributing from 15 per cent to 18 per cent of the fires in the wick-feed heaters) were (a) the heater being overturned or dropped, (b) the heater being too near combustibles other than heater fuel, and (c) the heater being overheated or "flaring-up". This leaves 25 per cent of the wick-feed heater fires attributable to other causes, including 11 per cent caused by over-filling, or spilled fuel. Associated with the drip-feed type, 30 per cent of the fire incidents reported were attributed to overheating and flaring-up, 19 per cent to leakage or flooding, 13.1 per cent to fuel spilled or fuel tank overfilled, 10.8 per cent to the flame being set too high, and 8.6 per cent to being located too near combustibles other than fuel.

The authors make comparisons with experience in previous years. Correlations are drawn between fire occurrences and the parameters of appliance design, effect of draft, appliance age and condition, appliance location, frequency of use, incidents of improper fuel use, and casualties caused.

Based on the relative number of drip-feed and wick-feed heaters at risk, the authors consider the drip-feed heater to be about 3½ times as likely to cause a fire as the wick-feed type. However, it was noted that 40 per cent of the drip-feed heaters involved in the fires reported were installed in hearths, as opposed to only 12.7 per cent of the wick-feed types so installed. The number of fires with drip-feed heaters was greater than with the wick-feed type, but more drip-feed heaters were located in the hearth, a site of less risk, so that a lesser number of fires involving the drip-feed heaters spread beyond the room of origin. In addition, only 7.8 per cent of the the drip-feed heater fires produced casualties, compared to 11.8 per cent produced in fires involving the wick-feed heaters which, the authors point out, are more prone to be overturned.

The authors conclude that overheating and flooding are the greater dangers in drip-feed heaters, and that setting at too high a flame, and overturning were the greater dangers with the wick-feed heaters. They suggest that more attention be given to proper maintenance of the kerosene heaters.

Subject Headings: *Fire hazards, of electricity; Fire hazards, of kerosene stoves.*

J. E. Malcolm

Arne, F. (Associate Editor, *Chemical Engineering*) "Fire Retardants: Plastics' Entree to Building," *Chemical Engineering* **69,** 62-66 (1962)

Plastics producers are presented with a tempting target of a tenfold increase in the building materials market by 1970 through the development of improved fire-retardant plastics that meet revised and more stringent building codes. Anticipated growth could solve the current plastic over-production problem and conceivably capture 30 per cent of a potential fifteen billion dollar annual building material market. Increased fire retardance is attainable either by mechanical addition as in the use of self extinguishing agents incorporated within a plastic matrix or by chemical means in which a flame retardant element is incorporated into the molecular structure of the plastic.

Some plastics such as polycarbonates, nylon, fluorocarbons, phenolics and polyvinylchlorides are inherently self-extinguishing. Phosphate esters, halogens, and antimony trioxide constitute the prevalent fire-retarding constituents. Four to five per cent of phosphorus in a compound compares favorably with 25 per cent chlorine from a fire-retardant standpoint. Bromine compounds are several times more effective than chlorine but about five times more costly. Polyolefins are fire resistant in the form of chlorinated paraffins or with additives such as antimony oxide. Expanded polystyrene has been offered commercially in fire-resistant grades: one company uses organophosphorus esters; another, halogenated organic ester phosphates. Epoxies can be fireproofed with either Aroclors (chlorinated polyphenyls) or chlorendic anhydride, a hardener for epoxy resins. Even foams have been introduced that are fire-resistant: one company uses urethane and chlorendicacid polyesters; another, phosphorus-containing polyethers.

Subject Heading: *Fire retardants.*

D. Dembrow

XIV. Miscellaneous

Law, Margaret (Joint Fire Research Organization, British Department of Scientific and Industrial Research and Fire Offices' Committee, Boreham Wood, England) "Heat Radiation from Fires and Building Separation," *London: H. M. Stationery Office. Fire Research Technical Paper No. 5* (1963) 44 pages. 3 shillings. (British Information Services, 845 3d Ave., New York 22, New York—60 cents)

[The paper under review deserves thoughtful attention as an effort to recommend building separation distances on the basis of a reasonable heat-transfer model and radiation data obtained from part-scale experiments.

Two reviews of this paper are given, one factual, the other presenting, in addition, the viewpoints of an experienced fire protection engineer. It is hoped that readers of Fire Research Abstracts and Reviews will study its contents with care. Any technical comments on it are welcome for publication at a later date. EDITOR.]

Review I

Whenever a building is on fire there exists the danger that an adjacent building be set on fire by the flames of the first. It is the purpose of this discussion to determine a separation distance between adjacent buildings so that this danger becomes negligible. It is desired to present the information in such a way that it may serve as a basis for specifications in a building code.

The general problem may be subdivided into two broad aspects: the heat transfer rate necessary to cause a building to catch fire, and the heat transfer rate produced by a building which is on fire.

The heat transfer rate required to cause ignition will be considered first. In the problem at hand the heat transfer is principally by radiation and experiments show that for typical building materials a minimum radiation rate of 0.8 cal/cm^{2}sec (~3.0 Btu/ft^2 sec) is required for spontaneous ignition. To be conservative one must, however, recognize that firebrands from the burning building may aid ignition of the adjacent building, and under such conditions a radiation rate of only 0.3 cal/cm^2 sec (~1.1 Btu/ft^2 sec) has been found to cause ignition. Similarly the contents of a typical room may also be set afire by a radiation rate of about 0.3 cal/cm^2 sec. In arriving at this latter figure the presence of a small flame (such as a gas pilot flame) inside the room was assumed and no allowance was made for possible radiation protection which might be offered by unbroken window glass. On the basis of this information it was decided to specify 0.3 cal/cm^2 sec as a conservative upper limit of the radiation which may be allowed to fall on an adjacent building without causing fire.

Next let us consider the radiation emitted by a burning building. The radiation comes essentially from the flames only. Although flames may appear on the outside of the building, it is adequate to assume that only the "openings" of the building are filled by flames. The meaning of "openings" in this context includes not only windows but all portions of the wall of the building which cannot be considered fireproof. The radiation emitted per unit of flame surface now depends principally on the fuel and air supply which is available to the fire. The fuel supply depends on the burnable material per unit of floor area and the air supply may be discussed in terms of ventilation conditions. From experimental data obtained for various fuel supplies and ventilation conditions, it was concluded that a value of 4.0 cal/cm^2 sec (~15 Btu/ft^2 sec) will serve as a conservative estimate of the radiation emission from the openings of a burning building.

Having established a maximum safe radiation incidence rate of 0.3 cal/cm^2 sec (~1.1 Btu/ft^2 sec) and a radiation emission rate of 4.0 cal/cm^2 sec (~15 Btu/ft^2 sec), it is now possible to establish the necessary separation between two buildings. This separation distance is to be sufficiently large so that in case of fire in one of the buildings the adjacent one will not be set afire by the first. For the calculation of this distance the only additional information needed is the geometrical relationship between the two buildings. These relationships are generally fairly simple and may usually be approximated by superposition of the geometrical factors which apply between a rectangle and a point located opposite one of its corners. A graph giving this geometrical radiation factor for various rectangular shapes is included in the paper. Various approximate methods of calculation are discussed and several examples are presented. In one of these a separation distance of 44 ft is obtained for a building which is 60 ft wide, 20 ft high and for which 50 per cent of the frontal area is classed as "openings".

R. H. Sabersky

Review II

This paper has to do with the chance of a fire in one building spreading to a neighboring building. Fire protection engineers are required to appraise a very large number of variables in a decision on a specific case of building separation, so they will be grateful for the work done in this paper, which brings together certain facts and calculations that bear on the problem.

During World War II, some scientists felt that it should be possible to exactly say that if a building was a certain number of feet from another building, a fire in one would or would not spread to the other. Fire protection engineers could not then and still would probably not try to be too positive as to just what separations should be employed.

The scientific view is that it should be possible to calculate the radiation produced by a fire in a building and that it should be possible also to calculate the radiant heat intensities received at another building a certain distance away. This was given serious attention by some very competent people, notably Bevan and Webster,[1] the result of whose work was published in 1950. Their study duly presented the technical calculations, disposing of a lot of troublesome variables by calculation of a "configuration factor." This factor was not one which was greeted with very much satisfaction by fire protection engineers. The study, however, was a thoughtful one, and it has encouraged scientists at the British Fire Research Station to do further research on the factors involved in this problem.

This paper under review makes use of such results as the following, which have been developed in work at the British Fire Research Station and elsewhere:

1. At a certain degree of ventilation, temperatures in an exposing room fire reach a steady value not greater than 1100°C (2000°F).
2. A steady value of intensity of heat radiation from well-ventilated fires in exposing spaces is about 4 cal/cm^2 sec (885 Btu/ft^2 min) and may be taken as representative for most occupancies, experiments having produced this radiation intensity for fire loads of about 10 lb/ft^2 of ordinary combustibles.
3. Wood will ignite spontaneously at intensities above 0.8 cal/cm^2 sec (177 Btu/ft^2 min). If a subsidiary source of ignition is within $\frac{1}{2}$-inch of the surface, ignition will take place at intensities above 0.3 calories. Spontaneous ignition in the open has been observed to take place fairly quickly after exposure to radiation, and either occurs within about 2 minutes or not at all. When radiation is just barely enough, heating times of the order of 10 minutes are needed before pilot ignition can take place.
4. Material in an enclosure will ignite at a lower intensity than in the open, so that although the intensity of radiation falling on an exposed building may be below the minimum for pilot ignition in the open, there may still be a hazard to the contents of a room because of radiation coming through a window.
5. Data was available on experimental fires so that effect of ventilation could be related to shape and size of windows, but the experimental fires did not include compartments, the floor areas of which were many times the window areas.

The paper shows a way to employ some of the known factors in calculating how radiation from fires operates from one building to another. The author found it necessary to try to deal with the complexities of the problem by certain assumptions and simplifications.

Among assumptions made to produce the conclusions of the study, for example, were the following:

1. Conclusions for the behavior of timber on the exterior of buildings are taken as representative of a large variety of building materials. Exposed timber is assumed to be oven dried, unprotected by paint.
2. The availability of a fire brigade within 5 minutes for fire fighting is assumed.

3. Configuration factors for rectangular radiators are assumed since windows are almost invariably rectangular.

4. Exposed points are assumed to be on a vertical plane, parallel to the plane of the radiator.

5. Exposure at the facade of an exposed building is not significant below the minimum for pilot ignition of wood: 0.3 cal/cm^2 sec (66 Btu/ft^2 min).

6. Flame radiation from the exposing building may be neglected if the criterion of allowable exposure is below the minimum for pilot ignition of wood.

7. This same criterion makes it unnecessary to consider that material reached by radiant heat coming through a window may ignite more readily because it is in an enclosure and not in the open.

Simplifications employed in the preparation of the results included the following:

1. Fire load factors for ordinary combustibles are used in two values only: 10 lb/ft^2 and 5 lb/ft^2.

2. Intensity of radiation is taken in terms of fire load per unit window area which neglects surface area and arrangement of combustibles and the total size of the exposing compartment.

In a compartmented building, the exposure to other buildings is assumed to be the result of heat radiation from the compartment with the largest area of window openings.

Fire protection engineers would want to debate some of these simplifications, a fact which the author of the paper recognizes, particularly the conclusions about factors of fire loading, ventilation, and the contribution of flames outside of windows. In connection with the latter, gross errors are possible. A very gross error is introduced by neglect of wind effects.

A notable case of building exposure occurred in Chicago, March 15, 1922, when the top seven floors of the 15-story, fire-resistive Burlington Building were burned out as the result of an exposure from a 7-story building across an 80-foot street. The construction of the exposing building was one with brick outside walls but wood floors and roof. There was no significant exposure to the lower eight floors of the Burlington Building, but severe exposure to the upper seven floors. The exposure was not alone in the form of radiation from flames extending above the roof of the exposing building, but due to the effect of flying brands, convection and wind.

As a result of the Burlington Building fire, a committee of the National Fire Protection Association presented a report in 1924 containing a suggested practice for the protection against exposure of openings in fire resistive walls. This report has been available in publications of the Association since that date.[2,3]

The NFPA 1924 report outlined minimum requirements for the protection of window openings in an exposed building against exposure from buildings with wood frame combustible outside walls, buildings with brick noncombustible outside walls but combustible interior construction, and fire-resistive buildings with noncombustible structure but combustible contents. Exposing buildings of varying height, ground floor area, and width of side toward the exposed building were enumerated. It recommended that the window and other wall openings in the exposed building be protected by one or more of the following:

a. Automatic rolling shutters.
b. Swinging shutters.

c. Windows of steel frame with wired glass.
d. Outside sprinklers (British idiom, "drenchers").

At some distances of separation, the report pointed out that either shutters or wired glass windows should be employed for exposure protection. For severe exposure, it recommended that wired glass windows *plus* shutters be employed or either shutters or wired glass windows *plus* outside sprinklers. At least two forms of window protection are considered necessary when the exposure is through a combustible roof of a building lower than the exposed building. It is considered necessary to protect windows in a building so exposed for three to six floors above the level of the building from which the exposure will develop.

The paper under review calls attention to the practical reasons wanting more exact information as to appropriate distance separations. Requirement of unnecessary separation is of economic importance where land is extremely valuable or where a site area is restricted by other use. The author produces the configuration factors applying to heat radiation between buildings. Arithmetical methods of calculating the size of a single radiator representative of exposing windows in walls are given. About these, there is little question. Separations can be calculated using a log–log plot of configuration factors against a factor derived from the dimensions of the assumed radiator and the separation. Log–log plots are also given from which the separation distance can be determined. The distance cannot be read directly but, knowing the radiator dimensions, it can be computed from a point on a curve for percentages of window openings in the assumed radiating area.

There are two plots given, one for fire loads greater than 5 lb/ft^2, and the other for fire loads 5 pounds or less per square foot. Using the former, since it applies to "ordinary" fire hazard occupancies, one seems to get examples of the following order:

Exposing building, wood frame, one story, exposing face about 60 feet wide, height of radiator taken as about 10 feet, window openings treated as 100 per cent, separation distance 40 feet.

Exposing building, brick walls with wood-joist floor and roof construction, four stories, exposing face about 60 feet wide, height of radiator taken as about 50 feet, window openings assumed 50 per cent, separation distance 65 feet.

Exposing building, fire-resistive walls, floor and roof construction, four stories, exposing face about 60 feet wide, height of radiator taken as about 50 feet, window openings assumed 50 per cent, separation distance 65 feet.

If figures such as these are used, gross errors are involved. The separation distance for fire-resistive buildings is greater than usually required by fire protection engineers, and that for wood frame buildings much less. In the case of brick-joisted buildings, exposure from fire coming through a combustible roof would be considered. The described method ignores this. Much greater weight would be given to occupancy factors in the exposing buildings and to their total size. Moreover, it is simply incorrect to dismiss wind effects which transfer heat by convection and transmit flying brands.

No objection can be properly raised to learning as much as possible by laboratory fire studies, but these alone are insufficient on which to offer a method, as this paper does, for the use of regulative authorities. Before the latter is justified, the recommended separation distances should be compared with distances over which fire spread has occurred in representative fires.

The economics of the problem are better reflected in the NFPA report mentioned in this review, but which was not included in the bibliography of the study. The NFPA study shows how inadequate separation distances can be made tolerable if window openings are protected by shutters or wired glass in metal window frames.

Two other factors need extended discussion in a treatment of exposure factors. If either the exposing building or the exposed building, or both, are protected by automatic sprinklers, the exposure conditions are radically modified. The variability of capabilities of fire departments must also be given consideration. The fire departments of the largest cities, such as London or New York, can put a large force of men and apparatus to work on a fire in 5 minutes. The force available in 5 minutes is strictly limited in suburban and small cities, and a much longer time is necessary before a force would be present to affect the exposure factor.

References

1. Bevan, R. C. and Webster, C. T.: (British Department of Scientific and Industrial Research, Building Research Station, Garston, Watford, Herts.) "Investigations on Building Fires, Part III. Radiation from Building Fires," *London: H. M. Stationery Office National Building Studies Technical Paper No. 5* (1950) 28 pages. 1 shilling. (British Information Services, 845 3d Ave., New York 22, New York—20 cents).
2. Committee on Protection of Openings in Walls and Partitions (National Fire Protection Association, 60 Batterymarch Street, Boston 10, Massachusetts): "Suggested Practice for the Protection Against Fire Exposure of Openings in Fire Resistive Walls," *NFPA 80A* (1925) and (1960 Reprint). 8 pages.
3. The problem was recognized in numerous articles of an earlier date, notably Blauvelt, Albert: "Debarment of City Conflagrations," *Quarterly, National Fire Protection Association* 8, No. 1, 21–33 (July 1914), and was supplemented by a study of exposure factors in 897 fires reported in an article "Protection Against Exposure Fires," *Quarterly, National Fire Protection Association* 25, No. 2, 190–228 (October 1931).

Subject Headings: *Radiation, effect of, on building separation; Fires, radiation from.*

H. Bond

Joint Fire Research Organization, Boreham Wood, England "Fire Research 1961"
London: Her Majesty's Stationery Office

This publication is a joint report of the Fire Research Board and the Director of of Fire Reseach for the year 1961. For convenience of presentation this review is carried out under the same headings as those used in the original report.

Studies of Outbreaks of Fires

This section deals mainly with outbreaks of fires on domestic premises. The figures show:

1. The particular need for fire protection in kitchens in blocks of high flats which are inaccessible to fire brigade ladders.
2. That the rate of incidence of fires with electric blankets has been increasing in recent years, approximately half of those reported being due to misuse. This points to the need for higher quality protective devices on electric blankets.
3. How guards on electric heaters reduce the likelihood of fires involving both clothing on persons and other textile materials.

4. That in a comparison between cooking appliances the electric oven is between 7 and 18 times as likely to be the source of ignition of fire as a gas oven. The reason for this is not obvious but it may be due to differences in construction and ventilation. The chance of an electric hotplate being the source of ignition is only between 3 and 4 times as great as that of a gas ring. The comparative safety of the gas ring is due to the fact that fat may pass through the flame without igniting. It is also found that the likelihood of clothing becoming ignited is greater with a gas cooker although the possibility of nonfatal burns is about the same for both types.
5. That for experimental fires, a fully developed fire in a room can be extinguished with about 9½ gallons of water per 1000 ft^3 of room volume. Fire Brigade reports (which do not contain information on the size of rooms involved or the state of fire on arrival) show that about half the fires need less than 15 gallons, three quarters need less than 30 gallons, and 95 per cent of all fires need less than 100 gallons. Allowing for the fact that brigades use rather more water than is used in an experimental extinguishing, it follows that in a large portion of fires which are confined to the room of origin the quantity of water used in practice is of the same order of magnitude as the experimental values.

The small quantity of water needed to extinguish the bulk of the fires points to the possible advantages that might result in residential areas from supplementing the usual fire brigade equipment with small fast vehicles carrying limited quantities of water.

Ignition

a. *Hazards of unstable compounds.* A study is being made of the slow decomposition which takes place in unstable compounds and which may at some stage be accompanied by an evolution of heat leading to a risk in temperature and eventual explosion. For example, benzoyl peroxide gives a mild explosion when a 9 gm sample is maintained in the neighborhood of 80°C for a few days in a furnace provided with explosion reliefs, even though this temperature is well below the melting point of the pure substance. When slightly larger amounts are used the explosion can shatter the container. The observed effects appear to be associated with an accumulation of decomposition products in the peroxide.

b. *Fundamental significance of gaseous flammability limits.* It has been suggested previously that the divergence between the measured and predicted properties of flammability limits may be due to a number of factors such as:

1. Wall effects in the case of tube flames.
2. Unforseen heat losses due to the shape of a real flame.
3. Aerodynamic disruption of the flame front.

One aim of the work described is to investigate the role of such effects for fuel/air mixtures.

Direct cine photographs are taken of a flame which is induced to fail within the field of view by adjustment of the mixture strength. Attempts are being made to trace the gas movement near the flame by the use of particle tracking techniques. Observations show that a methane/air flame fails in a particular manner with the head of the paraboloidal flame vanishing first, followed by the sides, provided there are no great variations in temperature in the tube wall and that the gas is adequately mixed.

Growth of Fire

a. *Rate of burning of wood.* Continuously weighed specimens of fiber insulating board have been subjected to different levels of radiation (below the minimum for spontaneous ignition) and different atmospheres for a period of time. The results indicate little difference in the rate of loss of weight whether nitrogen, air by forced convection, or air by natural convection is used as the atmosphere provided that the rate of supply is the same in each case. This suggests that it would be practical to apply results obtained in free air to fires in the interior of compartments.

In order to test if the reactions responsible for self-heating have a correspondingly important role in burning, some specimens were preheated at 1600°C for varying periods of time to drive off some volatile materials. Increasing the time of preheat to about 48 hours appears to produce a significant effect on the subsequent rate of burning.

b. *Fires in compartments.* Experiments confined to the situation where the fire is fully developed and burning at an approximately constant rate (corresponding to the period when most structural damage occurs in buildings) have been carried out as a preliminary to the object of building up a general theory of fires in compartments. The final aim is to be able to predict fire behavior from such properties as window size, fire load, and the thermal properties of the walls. The experimental results provide a basis for a qualitative theory which satisfactorily predicts actual behavior. In particular it shows that fires in compartments can be divided broadly into two types according to whether the window is large or small. When the window is small the rate of burning is proportional to the rate at which air can enter through the window which in turn depends upon the window size. With large windows fires behave similarly to fires in the open with rate of burning substantially independent of window size but being roughly proportional to the surface area of the fuel. The problems remaining to be solved before the theory can be placed on a quantitative basis are the separation of flame and wall radiation and convection in the experimental results.

Measurements have been made to find the rise in temperature at different depths beneath the surface of the structure of a compartment containing a fire. The results show that radiation measurements provide a rather better measure of structural temperature than the temperature measured 3 inches from the ceiling with bare thermocouples (a technique often used previously to give estimates of structural temperatures in full-scale fire tests in buildings).

Size of Flames

a. *Flames from windows.* The heights of flames from wooden cribs burning in cubical compartments with one side open were found to be related to the rate of burning by the equation

$$L/D = K(R^2/D^5)^{\frac{1}{3}},$$

where L = flame height measured from the base of the box, D = compartment size, and R = mass rate of fuel flow (i.e., the rate of burning of the crib in the early stages when only volatiles are burning).

b. *Flames in the open* (*still air*). The following equation adequately represents experimental results on both flames from a burner and flames from wooden cribs

$$L/D = K(R^2/D^5)^{0.30},$$

where in this case D is a characteristic crib or burner dimension.

c. *The effects of wind on flames.* This work represents part of a study of the rate of spread of fire in forest and heathland materials. The results should also be applicable to the spread of fire in built-up areas. Statistical analysis of the results obtained from wooden cribs burning in a wind (speed up to 15 ft/sec) in the direction of the shorter side (length D) gave

$$L/D = K(m^2/g\rho^2 D)^{0.43}\ (U^2/gD)^{-0.11},$$

L being the flame length, U the wind speed, ρ a density, m the rate of burning per unit base area, and g acceleration due to gravity.

Venting of Fires in Single-Story Buildings

A hydrodynamic analogue has been used to provide a demonstration of the use of roof vents for obtaining a layer of clear cool air near the floor of a large single-story building. The model is immersed in brine and the hot gases produced by a fire are simulated by colored water with a lower density, which is injected through perforations in the floor. Approximate similarity with full scale is achieved by keeping the model flow turbulent. Results show that for a fire in a building with a vented roof the opening of low level inlets or doors by firemen would provide a clear path to the fire enabling easy entry and access for fire-fighting purposes. Nonograms have been prepared which relate the height of the clear layer to the area of vents in the roof and inlets at low level for different sizes of fire (expressed in terms of area).

Extinction and Inhibition of Fire and Study of Explosions

a. *Extinction of wood fires in compartments.* Wood cribs were burned in a 1-ft cubical compartment fitted with a 1-ft-square door to control the ingress of oxygen for combustion. The crib was first ignited and allowed to burn with the door fully open until a predetermined weight of wood had been consumed (the "preburn" period). The door was then closed and the rate of loss of weight recorded while hot volatiles escaped through a small outlet in the door. After a time the door was opened to see whether the fire would rekindle when ventilation was re-established. By varying the time at which the door was opened the minimum closure period required to extinguish the fire was determined. The results show that the amount of cooling necessary to extinguish the fire increases rapidly with preburn in the range investigated. Measurement of the decomposition rate at the time of extinction suggests that it decreases linearly with increasing preburn.

b. *Surface application of foam to burning petrol.* In the extinction of fires of burning petrol by the surface application of foam the three main aspects considered were:

1. The ability of the foam to control (i.e., reduce the radiant intensity to some stated proportion of its original value) the fire rapidly. This is particularly important with small spill fires.
2. The minimum rate of application of foaming solution per unit surface area of fire necessary to control the fire (i.e., the critical rate of application).

This is of importance when equipment and supplies are limited in relation to the size of the fire.

3. The ability of the foam to provide a protective blanket on the petrol surface. This is important with multiple, obstructed, or large fires.

The experimental results for many proprietary stabilized foam compounds gave the following relationship:

$$t=18+2.7S/R,$$

where t is the time in seconds to reduce the intensity of radiation of the fire to one-third its original value (i.e., two-thirds control), S is the critical shear stress (lb/ft^2), and R the rate of application (gal ft^{-2} min^{-1}). This equation is independent of the type of compound, the compound concentration in solution, and the foam expansion.

The critical rate of application was related to the rate of drainage and the rate of evaporation by the equation

$$R_c=R_D+R_E.$$

Measurements showed that both R_c and R_D increase in a similar manner with a reduction in critical shear stress, and tend to reach constant values at higher critical shear stresses. The rate of evaporation (R_E) was found to be substantially independent of the critical shear stress of the foam applied.

The stability of the foam blanket (measured as the quantity of solution remaining in the foam 10 min after the start of application) was found to be largely dependent on the critical shear stress, the drainage decreasing as the critical shear stress increased. It was found to be independent of the type of compound and the expansion.

It is known that normal protein-based foams break down rapidly with alcohol and other water-miscible solvents. Normal foams were tested on petrol containing 20 per cent methylated spirit by measuring the time to control the fire at various rates of application. It was found that when the foam was applied gently to the surface by an applicator the critical rate was approximately 3 times that for alcohol free petrol, and that when it was applied by jet the factor could be as large as 8.

c. *The caking and flow properties of dry powders.* The ease with which a powder can be fluidized and discharged from an extinguisher depends upon the cohesive forces between particles. Investigations have been carried out to find the effects of small amounts of very finely ground additives coated on to particles (magnesium stearate on to sodium bicarbonate). The cohesive force was measured (1) by determining the crushing strength of a pellet of standard volume and density (to simulate the condition of powder stored in an extinguisher), and (2) by disrupting by air pressure a bed of powder which was packed by vibration (to simulate powder which has packed a discharge hose and has to be cleared by air pressure). The effect of the stearate on the water adsorption properties of the powder was also investigated. The results show that while the moisture adsorption properties are greatly improved by the addition of 0.1 per cent of stearate, 0.5 per cent addition is necessary to give a similar improvement in the flowing and anti-caking properties.

d. *Magnesium fires.* In the search for a reliable fire-fighting agent for aircraft constructed with magnesium alloys polvinyl-chloride/borax powder was finally chosen and produced for trial use by Service departments. This compound has the advantages of being nontoxic, moisture-repellent and easily available from inexpensive components.

e. *Extinguishing fires in large buildings by jet engine.* Tests have been carried out using humidified exhaust gases from a jet engine for extinguishing fires in buildings to investigate ways of injecting the gas, extinction of fires in the atmosphere produced in the building, and the conditions under which firemen could work in the atmosphere. The tests were conducted in a building 250,000 ft^3 in volume and 40 ft high with gas injected at a rate of 45,000 ft^3/min at 120°C. Breathing apparatus teams wearing normal fire service uniforms, with some protection of exposed skin, found it possible to work in the highly humid atmosphere at ground level for 15 min or so. At head level the temperature was 60° to 65°C and the atmosphere was just capable of extinguishing flaming combustion. Condition were intolerable 12 to 15 ft above ground level (75° to 80°C) due to pain on exposed skin.

Such an inert gas system would be expected to work best in compartments of smaller height and, of course, in basements. For compartments with ceilings as high as 30 to 40 ft the combined use of an inert gas system and a high expansion foam produced by the same appliance is being considered. The inert gas would prevent flaming at roof level and the high expansion foam would extinguish the fire at ground level.

Subject Headings: *Fires, extinguishment of; Fires, growth of; Fires, inhibition of; Fires, outbreak of; Fires, venting in structures; Ignition; Wood, rate of burning; Flame, size of; Foam, application of; Powders, application of; Wind, effect on flames; Extinguishment, of fires; Inhibition, of fires.*

R. G. Siddall

Safety in Mines Research Establishment (Sheffield, England) "Safety in Mines Research, 1961," *London: Her Majesty's Stationery Office*

In 1961, the Safety in Mines Research Establishment continued its research on explosives and blasting devices, explosion hazards due to coal dust and firedamp, fire hazards due to timber in mine roadways, rescue apparatus, dust measurement in connection with the pneumonconiosis hazard, and engineering and metallurgical research.

A study of the effect of shock waves on explosive materials was required because of short delay shot-firing techniques. Tentative values were obtained for critical shock pressures required to initiate detonation which indicate lower values for powder explosives than for gelatin dynamites. An oscilloscopic technique for measuring rate of movement of the explosive material has been developed.

In the study of the mechanism of ignition of methane-air by explosives, confirmation was obtained of earlier findings that stronger explosives caused local ignition of gas before the whole cartridge had detonated. The hazard of explosion of coal dust has been attacked by a study of aerosols for binding the dust. Binding agents and wetting agents are incorporated into a water aerosol and discharged into the ventilation current. The ratio of total liquid to dust had to be at least one for efficient binding to take place. Study of the aerodynamics of dust explosions shows the variability in results which may occur when different galleries are used or the results extrapolated to mines. Laboratory investigation of flame propagation in dust clouds has culminated in a report in which concentration limits have been determined for flame propagation for upward propagation of flame in coal dust clouds.

Experiments with methane roof layers has continued, with emphasis on multiple sources at intervals along the roadway instead of a single source. Results indicate that control for multiple sources is similar to that for a single source provided total methane emission rate remains constant. The study of methane layering has been facilitated by using a model consistency of a small water tube with a brine floor layer. This model is used to study the effect of mixing baffles. Much work has been done on the pressure drop due to these baffles as it effects ventilation flows.

Work on the detection of methane has been directed to the development of elements called "pellistors" in which a reaction causes a temperature change in a heating coil embedded in a pellet. It is claimed that commercial instruments reading to ±0.1 per cent methane for concentrations up to 1¼ per cent methane should be feasible. In addition to this device, several models of flame safety lamps for detection of layers of firedamp are described.

Studies have continued on the ignition hazard from rocks and metals with the conclusion that the mechanism involves formation of a patch of fused rock large enough and hot enough to ignite the gas.

Ignition by electric sparks has been studied by use of breakwire apparatus which gives consistent results.

New work on the thermal decomposition of wood to determine the rate of evolution of volatile matter under controlled heating conditions is reported. A two-stage decomposition is hypothesized.

Finally, it is reported that a foaming agent effective with very hard water has been developed so that the foam plug method of fighting mine roadway fires can be applied more widely.

Many other activities of SMRE are also described. Abstracts of recent publications and a bibliography conclude the report.

Subject Headings: ***Ignition, of methane, by explosives; Wood, decomposition of; Foam.***

J. Grumer

"Forest Fires"—Session D of the *Proceedings of the Fifth World Forestry Congress, Seattle, Washington*, 971–1005 (August 29 to September 10, 1960)

The nine papers contributed from seven countries discuss most of the broad categories of problems of forest fires including: (1) causes; (2) factors of fuel, weather, and topography that influence ignition and spread; (3) policies and general methods of organization and action in prevention, detection, and suppression; (4) prescribed use of fire for fuel reduction and improvement of the site or environment for establishing a new crop of trees; (5) economics of fire control; (6) research needs, programs, and progress. The papers generally were not intended to release new information or results but rather to give an international view of problems and progress in forest fire control. Some of the papers touch on most of the above categories while others are restricted to one.

Meeting Protection Objectives in Difficult Years—R. H. Luke (New South Wales Forestry Commission, Australia)

This paper discusses the need to plan and organize for occasional control of fires much larger and the kind that spread much faster than the worst fires of the average year. Under some conditions a forest or grass fire may develop a major conflagration within a few minutes, but under other conditions (which may continue for long periods) fires will spread slowly or will not start. Large numbers of firemen can not economically be kept ready for a fire throughout such periods. In most forest regions, burning conditions vary greatly from year to year as well as between seasons in the same year. A succession of years requiring little fire control skill and force produces a cumulative loss of skill, especially among those who are not professional firemen. Forest fire services should, therefore, develop sufficient flexibility to meet the needs of difficult years, and should ensure ability to recognize these difficult years before, or as, they develop.

To aid in recognizing severe fire seasons, forest fire services should compile detailed fire history, including weather conditions, for a period of at least 10 years in the given area. The services should determine quantity of fuels (such as grass) that vary with previous moisture supplies, and should know the progress of curing or drying as the season progresses. They should study weather factors related to winds, especially dry winds of high speed. They should study behavior and rate of fire spread as related to fuels, weather, slope, and other factors. Simple graphs or tables should be prepared giving the manpower and mechanical equipment needed for given categories of fuel and weather conditions.

An example is given for a pine plantation fuel type in New South Wales. It shows relative frequency of days of low, moderate, high, etc. danger in years classed as either mild, moderate, or severe. The numbers of such years expected in each 10 in the example are 4, 4, and 2, respectively. The class in which a year belongs can be determined from descriptive definitions. A tabulation of 10 years, 1949–58, for New South Wales shows classification of each year, fire occurrence, area burned, and expenditures. Percentage of total area of state forests burned in severe years exceeds that in mild years by 25 times or more.

The author discusses the general organization of a forest service to meet fire emergencies. Frequency and relative severity of fire seasons require first consideration. In Australia, only 2 per cent of full-time staff are fire control specialists. Men normally engaged in other forestry activities are the primary force organized to prevent and control fires as needed. All staff members should receive training each year to supervise untrained reinforcements. If a "difficult" season can be forecast, training should be intensified. Emergency plans should include transferring equipment from districts whose high fire danger occurs in a different part of the year. Plans should include inventories of, and arrangements to borrow, special or large equipment owned by other agencies.

If the forest manager recognizes that a difficult season is developing, he should begin the measures especially planned for prevention, detection, and cooperation in a difficult year. The financial plan should provide a reserve fund for fire fighting in difficult years.

Aerial Support of Ground Fire Fighters—A. W. Greeley (U. S. Forest Service, Washington, D. C.)

The author describes the principal ways in which the U. S. Forest Service now uses aircraft in fighting wildland fires. Numerous other federal, state, and private fire-fighting organizations use many of the same methods. Principal uses of aircraft in supporting firefighters are for fire detection, transportation of smoke-jumpers, cargo dropping, dropping of chemical fire retardants, scouting, on-the-line personnel transport, and behind-the-line transport of personnel and supplies. Types and names of aircrafts in each use are listed.

For efficient detection of fires, airplanes fly at predetermined time intervals over routes designed to give adequate seen-area coverage; these two factors must satisfy time standards for fire discovery under the given forest and weather conditions. Principles of route planning and looking are mentioned. Smoke jumpers differ from other well-trained fire fighters only in method of travel. During 20 years 18,491 jumps have been made to fires, and as many more for training, etc., without a fatality.

In 1959 the Service applied 3,300,000 gallons of retardants with aircraft to reduce heat or retard spread of fires. They used mostly slurries of either sodium calcium borate or sodium bentonite clay. The "borate" is almost as effective after it dries as it is when wet. The water-holding capacity of bentonite, which makes it effective, is lost in 2 or 3 hours. About four pounds of retardant are mixed with one gallon of water. The slurry should be dropped from airplanes through very large gates in the tanks and from 75 to 150 feet above the fuel. Only specially trained pilots under careful supervision on the fire can safely and effectively drop retardants.

Helicopters, used for most of the same purposes as airplanes, work more efficiently for inspecting fires, transporting fire fighters to points inaccessible by road, and for laying hose 1,000 feet or more per minute where vegetation or topography make hand-laying impractical.

The author discusses the training and coordination required for the best use of aircraft. Smoke jumpers require precise training and equipment to land safely in forest cover and mountainous topography. Pilots likewise require special training for low-level mountain flying. On a large fire where numerous aircraft scout the fire, carry men and supplies, or drop retardants a special line of supervision is described to improve safety and efficiency.

Study on Outbreak and Spread of Forest Fires in Japan—K. Inoue (Hokkaido Branch, Government Forest Experimental Station, Japan)

This paper discusses current studies of flammable materials and effects of climate and site or location. Average annual loss of forest area in Japan, 1953–57, was about 24,000 hectares (60,000 acres) or 0.1 per cent of the forest area. Lightning set few fires. Studies of fuels include: (1) statistics for each fire on area burned classified by tree species, tree spacing, number of dead trees; (2) experiments in moisture content by species, rate of drying, relation of moisture content to temperature and humidity, turpentine content, ignition according to species and moisture content, ignition by live charcoal, and temperature of ignition. Post-mortem studies of fire spread include direction of spread indicated by greater height of char on the lee side of a tree trunk. Records of the usual climatic factors are studied and related to moisture content of fuel and to fire occurrence and behavior. Where no communication facilities exist, low humidity is indicated by color change of dried cobalt chloride on paper. Downslope winds cause low humidity in some localities. The number of fires first increases with wind speed, then decreases.

Research in Forest Fire Control—J. C. Macleod (Department of Northern Affairs and National Resources, Ottawa, Canada)

The author discusses the need for and the development of forest fire research, and gives examples of current problems. If the present rate of increase in world demand for forest products continues, current fire losses will be intolerable. Fortunately, the need for better knowledge of how to protect forests from fire is now recognized. The first full-time investigators in North America began work in the 1920's. The number increased slowly before 1940, but in 1960 there were about 60 in the United States and 16 in Canada. The greatest change in concept has been the provision of laboratories for use of a variety of specialists and concerted cooperative attacks on problems. Increased emphasis is being given to fundamental research.

Examples of current problems of prevention research include: lightning reduction and other weather modification studies, applied tests of saturated publicity prorams, psychological approaches, and methods of reducing fuel hazards. Presuppression problems include: methods of measuring or rating burning conditions as related to fuels and weather, forecasts of weather, and classification of fuels. Detection problems include: improvement of lookout structures, infrared radiation and television detectors, and the efficient ratio of aerial vs. ground watchers. Suppression problems include: equipment for applying water, water additives, and use of helicopters. Economic problems include: best distribution of available funds among prevention, presuppression, detection, and suppression needs; evaluation of damages; and procedures for applying the theory of holding costs and losses to a minimum.

Methodes et pratiques de protection contre les incendies de forêts (Methods andPractices of Protection Against Forest Fires)—General Directorate for Economy (Mountains and Forests), Rome, Italy

This special paper briefly discusses the causes of forest fires in Italy, the forest factors affecting their ignition, the damage, and the means of preventing and extinguishing them. Ten per cent are set intentionally, 50 per cent are set through human carelessness, and 40 per cent are caused by other things such as railroad trains. In the period 1950–59, 14,440 forest fires covering 420,000 acres, or 3 per cent of the forest area, occurred in Italy.

Progresos Obtenidos en la Defense y la Lucha contra Incendios—E. Benito (Spain)

This describes recent advances in fire control in Spain. New detection methods and fire-fighting techniques introduced in 1956 have reduced burned areas to 0.148 per cent of the total forest area, or a rate less than in Poland, Switzerland, and Ireland where more favorable weather occurs. Spain applied to its peculiar topography and climate methods already tested in other countries. In detection work, Spain has begun to use fire danger indicators, lookout stations, and radio telephones. In fire fighting they use backpack extinguishers with water and detergents, all-terrain vehicles with fire pumps, and chemical retardants.

Ecological Effects of Fire on North Swedish Forests—E. Uggla (Forest Research Institute of Sweden, Stockholm, Sweden)

This describes fire temperatures and effects of controlled fires on raw humus. Fire is used increasingly as a silvicultural treatment, especially in Northern Sweden. It is generally agreed that properly applied fire on ground not too dry is the most efficient method of activating the humus and reducing difficulties of planting.

Alkalies of the ash can be absorbed by humus in an accessible form, nitrogen metabolism increases, and conditions for most microorganisms are ameliorated. Increased surface temperature from sun on the black humus favors germination. Fire favors birch and aspen invaders, and their leaves contribute to the soil. On poor, dry soils, uncontrolled fires can have devastating effects. There the activating effects of fire soon disappear.

A graph of temperature during a controlled burning shows readings at 5 cm above the surface and at 3 and 5 cm below the surface. Although it reached 540°C above the surface, it showed no increase at only 3 cm below. This is partly explained by condensation of water vapor formed during burning of organic material. The sweating zone immediately below the fire prevents deeper penetration of fire. High temperature during a controlled burn usually does not last long enough for the moisture in the sweating zone to evaporate.

Records of temperatures upward along tree trunks during controlled burning show that sufficient wind will keep the hottest (or yellowish-brown to black smoke) below the foliage, but if it strikes the foliage the tree will die. Chemical changes in the humus cover after a fire show for the decomposition layer a great increase in pH and considerable increase in Ca, K, and P but a decrease in total N. A few months later pH and Ca had decreased. Subsequently, total N had increased. On old burns it equalled that on other areas before burning, but pH remained above normal about 25 years.

The Significance of Fire to World Forestry—A. A. Brown (U. S. Forest Service, Washington, D. C.)

This paper discusses the need for (1) more detailed knowledge of fire processes to enable understanding of blow-up fires, and (2) applied research in use of fire as a tool and in rating fire danger. Each year a small proportion of fires become blow-up fires which cover 80 to 90 per cent of the total area burned in the United States. At best, a small percentage of such fires is inevitable. Effective control depends on predicting their behavior. The great quantity of debris left after logging in Douglas-fir forests is usually burned to reduce hazard. Research should help to improve techniques of burning. The second applied research need is a current study to unify and, if possible, improve the present eight regional fire danger rating systems.

Test of Sodium-Calcium Borate in Controlling Lake States Forest Fires—G. A. Hesterberg (Michigan College of Mining and Technology, Houghton, Michigan)

This describes six different kinds of unreplicated field tests that were evaluated subjectively by four experienced men. The purpose was to determine effectiveness of "borate" in retarding fires burning in the most hazardous fuels of the region. The tests required two days. Fire danger on those days was classed very high. About 30 acres of dense jack pine and brush was burned in the tests. Pine slash was added to these fuels for four of the tests. The observers reported that borate made an effective firebreak. In four-foot-high windrows of dry pine slash it effectively fireproofed the fuel. A two-foot strip of borate-treated fuel stopped a surface fire in dense bracken, blueberry, sweetfern, and pine slash. Treated stumps and other large fuels on the ground would not burn amid running surface fires in dense brush. In dense young pine 2 to 6 inches d.b.h. treated the previous day, a crown fire was checked so that it could be controlled and extinguished. A two-foot strip treated with borate served well to establish and hold a backfire line in light brush with scattered slash.

Subject Headings: ***Forest fires; Fires, forest.***

W. G. Morris

Tall Timbers Research Station (Tallahassee, Florida) "*Proceedings First Annual Tall Timbers Fire Ecology Conference*," (March 1–2, 1962)

The Tall Timbers Research Station, headquartered at Tall Timbers Plantation near Tallahassee, Florida, has a small technical staff dominated by one family and nominally headed by the Station's "angel", the owner of the Plantation. Research and public education are undertaken on various, essentially nonrevenue-producing aspects of natural resource conservation. The strongest leanings are toward ornithology and fire ecology, i.e., the place of fire in the ecology of the native flora and fauna. The research, mostly observational rather than experimental, appears to be a sideline or hobby for most of the staff, since they have other paid employment.

The program of the First Annual Tall Timbers Fire Ecology Conference included consideration of the history of fire occurrence, effects and use in the forests of southeastern United States, the ecological basis for using fire, and the employment of controlled fire in modern wildland management. Although interesting, the papers were understandably less complete than publications already available on most of the subjects. Treatment ranged from narration of a layman's observations on early use of fire in the Southeast to a researcher's technical description of a controlled experiment in prescribed burning. The topics and speakers are listed for each program section and followed by a section summary.

Historical Section

Fire Impressions	H. L. Beadel
The Use of Fire: An Historical Background	E. V. Komarek, Sr.
Historical Notes on the Relation of Fire to Forests	Roland M. Harper
Use of Fire in Pine Forests and Game Lands of the Deep Southeast	H. L. Stoddard, Sr.
The Florida Forest Service and Controlled Burning	R. A. Bonninghausen

Early travelers in southern United States encountered widespread forest fires and found evidence that burning had strongly influenced vegetation. Many ascribed salutary effects to the fires. Prior to exploitation of the timber, cattlemen set low-intensity fires to keep forest range free of brush and to encourage growth of grass. This type of burning benefited quail by preventing "jungles", encouraged food plants, and controlled some enemies.

The forestry movement, which followed clear cutting of the virgin timber, was dominated by men who, from experience elsewhere, considered fire universally destructive and therefore set out to exclude it from southern forests. Also, as forestlands became more valuable, owners did not want them burned indiscriminately. Thus foresters and landowners came into conflict with local custom, and malicious burning began to occur.

Scientific experimentation proved that fire, properly used, was an effective tool for managing timber, grazing, and game lands. Public forestry agencies were somewhat slow to accept these findings but now both burn on their own lands and, in some instances (e.g., the Florida Forest Service), help private owners plan and execute prescribed burning by accepted methods. However, indiscriminate burning by unqualified, irresponsible people is not compatible with today's resource values and population density.

Ecological Section

Fire and Vegetation in the Everglades	William B. Robertson
Fire and Vegetation of Arid Lands	Walter S. Phillips
Fire Ecology	E. V. Komarek, Sr.

Periodic disturbance, chiefly by fire and hurricane, has produced the present confused pattern of plant communities in southern Florida and prevented approach toward a regional climax. Four of the six broad vegetational types are subject to modification by fire. Depending on its intensity, fire can slightly alter or completely destroy pine forests and hammocks, thus either maintaining the fire subclimax or setting back plant succession to an earlier stage. Burning changes marsh (Everglades) vegetation appreciably only for about a year after the fire. Lightning always caused enough fires to account for the vegetation pattern, but fire frequency probably has increased since the advent of first the Indian and then the white man.

In arid lands of western North America, Australia, and South Africa, fire formerly held woody plants in check and permitted grass to occupy large areas that otherwise would have been woodland or scrub. The vegetation that follows fire varies with season of burning. Substitution of grazing for burning has caused woody vegetation to increase at the expense of grass. The change can be reversed by use of fire in conjunction with mechanical or chemical treatment.

Widespread observation strongly suggests that fires have always occurred in nature wherever dead vegetation accumulated and became dry enough to burn. Man learned to use fire by watching it and playing with it; even the primitive Australian aborigine uses fire to drive game. The general effect of fire in nature is to set back or prevent the occurrence of decadent, unproductive, late successional stages.

Application Section

The Use of Prescribed Fire in the Silviculture of Loblolly Pine	Thomas Lotti
Use of Fire on Southeastern Wildlife Refuges	Lawrence S. Givens
Forest Land Management and the Use of Fire	R. A. Bonninghausen
Some Techniques of Controlled Burnings in the Deep Southeast	H. L. Stoddard, Sr.
Is Prescribed Burning Paying Off?	Robert W. Cooper
Forest Service Policy for Controlled Use of Fire	Glenn A. Thompson

In the flatwoods loblolly pine type periodic burning with low-intensity fires reduces fire hazard, controls hardwoods and brush, reduces logging costs, and prepares a good seedbed for regeneration without apparent harm to the soil. Fires during the growing season are more effective than winter fires. Methods and costs vary with size of area, time of year, and stand characteristics. Many thousands of acres are prescribe-burned annually in southeastern United States.

Fire is being used extensively in other southeastern forest types—on State Forests in Florida, on the National Forests, and on private lands of various descriptions. The prescription must meet the need. In general, burning should be done when the soil is moist, the most flammable areas must be burned when burning conditions are least severe, and burning of large blocks should begin after flammability has begun to drop for the day. Intense fires are frequently used for reclamation, or type conversion; low-intensity fires, sometimes backfires or night fires, for maintenance of existing conditions. U. S. Forest Service policy authorizes use of fire to accomplish 16 different goals of protection and management in situations where it is known that burning will not damage soil and watershed values. Research is underway to determine whether prescribed burning can be done safely on still other areas. When used properly, prescribed burning definitely is paying off in terms of reduced damage from wildfire, improved flora and fauna, and easier management.

Subject Headings: ***Fires, controlled burns; Ecology, effect of fires.***

G. R. Fahnestock

COMMENTS AND DISCUSSIONS

A Critique of the Present State of Knowledge of The Mechanism of Cellulose Pyrolysis

A. BROIDO AND F. J. KILZER
Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California

This critique reviews several divergent theories of cellulose pyrolysis, raises questions about experimental results obtained prior to the recent recognition of the importance of trace impurities, and indicates the need for sufficient detail in the reaction mechanism to permit a better prediction of the action of fire extinguishing and flame retarding chemicals.

The phrase "reaction mechanism" generally refers to a description of the stepwise processes by which one set of atoms or molecules changes into a different set. As this description becomes more detailed, it becomes of increasing value in predicting and directing the course of chemical reactions. Growing recognition of the unlimited potential of such detailed studies has led to an almost revolutionary expansion of the field of physical organic chemistry in the past generation. Such interest has led to the development of much new apparatus and techniques, which in turn have stimulated much more detailed investigations. As with other problems in this field, studies of the mechanism of the pyrolysis and combustion of cellulose are becoming increasingly refined. Thus, they can be expected to be increasingly useful in predicting and directing the course of the reactions involved.

Early studies of the pyrolysis of cellulose were confined to determination of such gross fractions as gas, tar, and char and to simple observation of how the combustibility of the sample varied with the relative proportions of these fractions. Such studies clearly established that the production of a large proportion of "tar" favors high flammability.[1,2]

As early as 1918, Pictet and Sarasin[3] isolated a crystalline substance from the tarry volatile products formed when they distilled cellulose in a vacuum. They named the substance "levoglucosan" in keeping with its formula ($C_6H_{10}O_5$), its negative optical rotation, and the fact that acid hydrolysis converted it to glucose. Josephson[4] determined that this substance was 1,6-anhydro-β-D-glycopyranose (see Fig. 1). These observations can be expressed crudely as

$$(C_6H_{10}O_5)_n \rightarrow mC_6H_{10}O_5 + \text{other products.}$$

Since this early report, investigators into the pyrolysis of cellulose have questioned: (1) the importance of levoglucosan in the combustion process; (2) the mode of levoglucosan formation; (3) the subsequent fate of the levoglucosan; (4) the nature of the "other products"; and (5) the mode of formation of these other products. The effect of inorganic salts and substituants on cellulose pyrolysis has also been recognized and investigated. Despite much excellent work, particularly since the early 1950's, the exact mechanism of the thermal decomposition of cellulose has remained highly controversial.

It has been well established[5] that levoglucosan constitutes a major component of

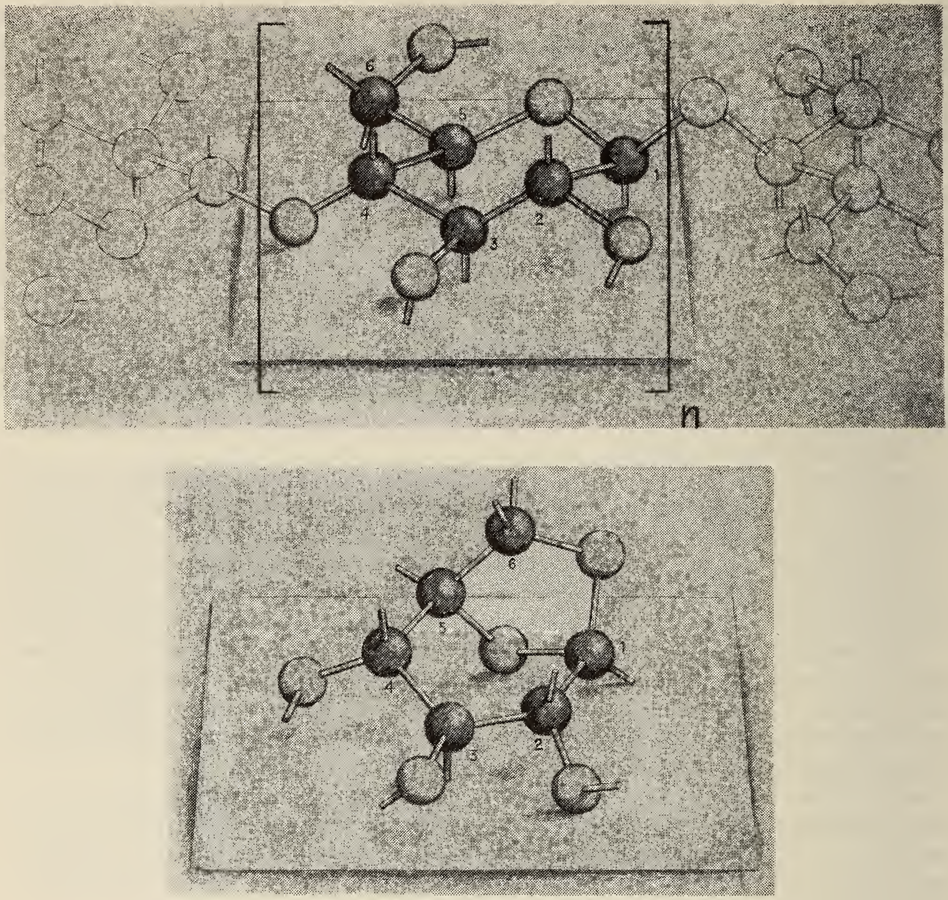


Fig. 1. Structure of cellulose (upper) and levoglucosan (lower).

Cellulose $(C_6H_{10}O_5)_n$, is a nonbranching polymer, formed from glucose by splitting off one molecule of water between the C–1 position of one glucose and the C–4 position of the next. Levoglucosan $C_6H_{10}O_5$, is a bi-cyclic derivative of glucose, formed by splitting off one water molecule between the C–1 and C–6 positions of the same glucose molecule.

the "tar" fraction of cellulose pyrolysis and thus is a major factor in the combustion of cellulose. Other data contributing to the development of a satisfactory theory are coming from such general measurements as are made by gasometry and thermogravimetry[6] and from the determination of intermediate products of pyrolysis or combustion, using such analytical techniques as infrared spectroscopy,[7] paper chromatography,[8,9] and gas chromatography alone[10] or coupled with mass spectrometry.[11]

The extent of detail in the several theories which have been proposed is quite variable. Thus, Schuyten, Weaver, and Reid[12] in their review paper on the flameproofing of cellulose did not discuss the thermal decomposition of pure cellulose; they suggested that successful flameproofing agents are Lewis acids or bases which catalyze the dehydration of cellulose to a "high carbon content . . . difficulty combustible" residue. Parks *et al.*[13] proposed that in the pyrolysis of cellulose a first order depolymerization to levoglucosan is the first and rate-determining step. On this basis, Schwenker and Pacsu[14] concluded that modifying cellulose at the C–6 position to minimize levoglucosan formation would markedly diminish flammability. The structures of cellulose and levoglucosan contravene the possibility that chain-breaking results from a direct displacement step initiated by the C–6 hydroxyl attacking the C–1 position of its own glucose ring. Instead, a prior elimination or displacement step is required.

Madorsky, Hart, and Straus[15] suggested a mechanism based upon two simultaneous random processes: dehydration (presumably similar to that suggested by Schuyten, Weaver, and Reid) and thermal scission of the C—O bonds anywhere in the polymer chain. They suggested that scission of the appropriate bond may result in the production of levoglucosan by the double displacement mechanism which McCloskey and Coleman[16] used to describe the base-catalyzed genesis of levoglucosan from β-D-glycosides. However, the fact that in Madorsky's experiments less levoglucosan was produced from cellulose in the presence of bases tends to discourage this analogy.

In 1956 Golova *et al.* began to publish results of their research into cellulose pyrolysis and oxidation. In their first paper[17] they concluded that hydrolysis, oxidation, and dehydration are all side reactions in the thermal destruction of cellulose. According to them, the main pyrolysis path involves a break at the C–1 position into fragments which isomerize into levoglucosan. Among other observations, they noted that adding glucose to cellulose reduced the yield of levoglucosan obtained on vacuum pyrolysis.

The following year, Golova and Krylova[18] reported the results of a more detailed study. In pyrolyzing cotton cellulose, they found that the original cellulose molecules first break down randomly into chains of about 200 anhydroglucose units. These chains then decompose by "unzipping" completely to produce levoglucosan. They did not speculate about the reason for the apparent stability of the cellulose molecule with degree of polymerization (DP) of 200, nor did their results establish whether the DP of 200 represented an average over a broad spectrum or was indeed a critical size for a cellulose molecule.

Additional papers by this research team presented their results on the yield of levoglucosan upon pyrolysis of such model compounds as β-D-glucose[19] and cellobiose,[20] described the isolation of such compounds as 1,6-anhydro-β-D-glucofuranose from cellulose pyrolysate[21] and of 2,3,6-trimethyl-1,4-anhydro-β-D-glucopyranose from trimethyl cellulose pyrolysate,[22] and showed that their samples of cotton cellulose and cellulose hydrate deocmposed by two different mechanisms.[23] However, more recent publications[24,25] describe drastic changes in results when the ash content of the materials are lowered from a little above to a little below 0.1 per cent. In fact, it appears that the only results they do not have to attribute, at least in part, to the effect of impurities in their samples, are those which led to their reported mechanism for the thermal decomposition of cotton cellulose.

Broido[26] also has observed that as little as 0.15 per cent "ash" markedly alters the pyrolysis and combustion behavior of cellulose papers.

These findings raise questions about all previous work in which the presence of such small amounts of ash was not considered. Where chemical modification of cellulose was accomplished by a process which may have altered the purity of the material (for example, in the work of Schwenker and Pacsu[14]), it becomes important to separate the effect of the change in purity from the effect of the actual chemical modification of the cellulose.

None of the theories yet proposed has been sufficiently detailed to predict or even provide an explanation for the rather startling differences in the combustion behavior of a number of saccharides. For example, they do not explain why a chemical which extinguishes flaming in cellulose and starch also "catalyzes" the combustion of sucrose.[27]

Golova's results confirm that some initial reactions can produce shorter but still nonvolatile polymer chains. Pictet[28] and Wolfram *et al.*[29,30] have shown that some of the volatile products of primary reactions can recombine to form nonvolatile products. Thus, experiments that simply measure weight loss or gas evolution, while useful, cannot even give the true rate of reaction of the starting material. In order to permit better prediction of the course of the pyrolysis and combustion of cellulose and to better indicate useful methods of modifying this course, the mechanisms for these reactions must be described in much greater detail than they yet have been. As Hine put it in describing the recent growth of physical organic chemistry[31]:

> "In reactions where earlier investigators may have been satisfied to learn what intermediate was being formed in the rate-controlling step, many physical organic chemists are currently trying to learn much more: to determine the intermediates in all of the steps and the relative heights of the various energy barriers; to learn as nearly as possible the geometrical location of every atom throughout every stage of the reaction; and to learn how changes in reactant structure, solvent, and other reaction conditions affect the enregy barrier heights and molecular geometries."

By such criteria, the reaction mechanisms of carbohydrate pyrolysis are very poorly defined. Until these mechanisms are better understood, the gross effects of fire-extinguishing and flame retarding chemicals may be observed, but detailed prediction of their action will remain subject to considerable question.

References

1. Coppick, S.: *In* Flameproofing Textile Fabrics, R. W. Little, ed. Reinhold, New York: *ACS Monograph 104,* 410 pp. (1947).
2. Tamaru, K.: "Pyrolysis and Combustion of Cellulose in the Presence of Inorganic Salts," *Bull. of the Chemical Society (Japan)* 24, 164–168 (1951).
3. Pictet, A., and Sarasin, J.: "Distillation of Cellulose and Starch in Vacuo," *Helv. chim. acta* 1, 87–96 (1918).
4. Josephson, K.: "Constitution of Levoglucosan," *Chem. Ber.* 62B, 313–316 (1929).
5. Holmes, F. H. and Shaw, C. J. G.: "The Pyrolysis of Cellulose and the Action of Flame Retardants," *J. Appl. Chem.* 11, 210–216 (1961).
6. Cerniani, A.: "The Comparative Thermal Decomposition of Some Monosaccharides, Oligosaccharides, and Polysaccharides," *Ann. Chim. (Rome)* 41, 455–464 (1951).
7. Urbanski, T., Hofman, W., Ostrowski, T., and Witanowski, M.: "Infrared Absorption Spectra of Products of Carbonization of Cellulose," *Bul. acad. polon. sci. Ser. sci., Chim., geol. et geograph* 7, 851–859 (1959).
8. Schwenker, R. F., Jr. and Pacsu, E.: "Pyrolytic Degradation Products of Cellulose," *Chem. Eng. Data Ser.* 2, 83–88 (1957).
9. Honeyman, J.: "A Fundamental Study of the Pyrolysis of Cotton Cellulose," *Project UR-E29-(20)-9, Annual Progress Report. Manchester: Shirley Institute,* 41 pp. (1960).
10. Greenwood, C. T., Knox, J. H., and Milne, E.: "Analysis of the Thermal Decomposition Products of Carbohydrates by Gas-Chromatography," *Chem. Ind. (London)* 1878–1879 (1961).
11. Broido, A. and Martin, S. B.: "Effects of Potassium Bicarbonate on the Ignition of Cellulose by Radiation," *Fire Research Abstracts and Reviews* 3, 193–201 (1961).

12. Schuyten, H. A., Weaver, J. W., and Reid, J. D.: "Some Theoretical Aspects of the Flameproofing of Cellulose," *In Fire Retardant Paints. Advan. Chem. Ser.* 9, 7–20 (1954).
13. Parks, W. G., *et al.*: "Mechanism of the Pyrolytic Decomposition of Cellulose," *Abstracts 127th Meeting American Chemical Society* 6E–7E (1955).
14. Schwenker, R. F. and Pacsu, E.: "Chemically Modifying Cellulose for Flame Resistance," *Ind. Eng. Chem.* **50**, 91–96 (1958).
15. Madorsky, S. L., Hart, V. E., and Straus, S.: "Pyrolysis of Cellulose in a Vacuum," *J. Res. Natl. Bur. Std.* **56**, 343–354 (1956).
16. McCloskey, C. M. and Coleman, G. H.: "A Proposed Inversion Mechanism for the Formation of Levoglucosan from Phenyl β-D-glucoside and Trimethylglucosylammonium Compounds," *J. Org. Chem.* **10**, 184–193 (1945).
17. Ivanov, V. I., Golova, O. P., and Pakhomov, A. M.: "Main Direction of Reaction in the Thermal Decomposition of Cellulose in a Vacuum," *Izvest. Akad. Nauk. SSSR, Otdel. Khim. Nauk*, 1266–1267 (1956).
18. Golova, O. P. and Krylova, R. G.: "Thermal Decomposition of Cellulose and its Structure," *Doklady Akad. Nauk. SSSR* 116, 419–421 (1957).
19. Golova, O. P., *et al.*: "Transformation of Cellulose at Elevated Temperatures. III Formation of Levoglucosan from β-D-Glucose," *Izvest. Akad. Nauk. SSSR, Otdel. Khim. Nauk*, 389–391 (1957).
20. Golova, O. P., *et al.*: "On the Mechanism of the Thermal Decomposition of Cellulose under Vacuum and the Formation of 1,6-anhydro-1,5-glucopyranose," *Doklady Akad. Nauk. SSSR* **115** (6), 1122–1125 (1957).
21. Golova, O. P., Merlis, N. M., and Volodinu, Z. V.: "Preparation of 1,6-anhydroglucofuranose by the Thermal Decomposition of Cellulose in Vacuum," *Zhur. Obshchei. Khim.* **29**, 997–1000 (1959).
22. Pakhomov, A. M., Golova, O. P., and Nikolaeua, I. I.: "Thermal Degradation of Trimethyl Cellulose in a Vacuum," *Izvest. Akad. Nauk. SSSR, Otdel. Khim. Nauk.* 521–523 (1957).
23. Golova, O. P., Krylova, R. G., and Nikolaeua, I. I.: "Mechanism of Thermal Decomposition of Cellulose in Vacuum. I and II." *Vysokomolekul. Soedin.* **1**, 1295–1308 (1959).
24. Golova, O. P. and Krylova, R. G.: "Thermal Depolymerization of Cellulose," *Doklady Akad. Nauk. SSSR* **135** (6), 1391–1394 (1960).
25. Golova, O. P., Epshtein Ya V., and Durynina, L. I.: "Effect of Inorganic Components on C–C Cleavage During Thermal Degradation of Cellulose," *Vysokomolekul. Soedin.* **3**, 536–540 (1961).
26. Broido, A.: "Thermogravimetric and Differential Thermal Analysis of Potassium Bicarbonate Contaminated Cellulose," (manuscript in preparation).
27. Broido, A.: "Effect of Fire Extinguishing Agents on Combustion of Sucrose," *Science* **133**, 1701–1702 (1961).
28. Pictet, A.: "Transformation of Levoglucosan into Dextrin," *Helv. chim. acta.* **1**, 226–230 (1918).
29. Wolfram, M. L., Thompson, A., and Ward, R. B.: "The Composition of Pyrodextrins. II Thermal Polymerization of Levoglucosan," *J. Am. Chem. Soc.* **81**, 4623–4625 (1959).
30. Wolfram, M. L., Thompson, A., Ward, R. B., Horton, D., and Moore, R. H.: "The Composition of Pyrodextrins. III Thermal Polymerization of Levoglucosan," *J. Org. Chem.* 26, 4617–4620 (1961).
31. Hine, J. "Physical Organic Chemistry," *Chem. Eng. News* 38 (19), 101–106 (1960).

INDEX OF AUTHORS

INDEX OF SUBJECTS

ABSTRACTERS

THOMAS C. ADAMSON, JR.
University of Michigan

GEORGE A. AGOSTON
Stanford Research Institute

JOHN J. AHERN
General Motors Corporation

THOMAS P. ANDERSON
Northwestern University

LOREN E. BOLLINGER
The Ohio State University

PETER BREISACHER
Aerospace Corporation

FREDERICK L. BROWNE
Madison, Wisconsin

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

HANS M. CASSEL
U. S. Bureau of Mines

WELBY G. COURTNEY
Thiokol Chemical Corporation

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

GLADYS S. CUFF
Royal Oak, Michigan

DANIEL DEMBROW
National Aeronautics and Space Administration

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

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

R. H. ESSENHIGH
The Pennsylvania State University

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

FELIX FALK
Applied Physics Laboratory
The Johns Hopkins University

W. L. FONS
Southern Forest Fire Laboratory
U. S. Forest Service

K. M. FOREMAN
Republic Aviation Corporation

ALLEN E. FUHS
Aerospace Corporation

ARTHUR L. GOLDSTEIN
Ionics, Incorporated

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

BERNARD GREIFER
Atlantic Research Corporation

L. R. GRIFFITH
California Research Corporation

GEOFFREY L. ISLES
The University, Leeds (England)

OLIVER W. JOHNSON
Johnson-Williams, Inc.

WILLIAM C. JOHNSTON
Westinghouse Research Laboratories

IRVING R. KING
Texaco Experiment, Incorporated

WILLIS G. LABES
Illinois Institute of Technology

JOSEPH B. LEVY
Atlantic Research Corporation

RONALD LONG
University of Birmingham (England)

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

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

D. G. MARTIN
Imperial College (England)

HOWARD N. McMANUS, JR.
Cornell University

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

C. C. MIESSE
Westinghouse Electric Corporation

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

A. E. NOREEN
Boeing Airplane Company

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

HENRY EDGAR PERLEE
U. S. Bureau of Mines

M. G. PERRY
University of Sheffield (England)

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

LOUIS A. POVINELLI
National Aeronautics and Space Administration

J. KENNETH RICHMOND
Boeing Airplane Company

DANIEL E. ROSNER
AeroChem Research Laboratories, Inc.

PETER A. ROSS
Boeing Airplane Company

WILLIS A. ROSSER, JR.
Stanford Research Institute

P. R. RYASON
California Research Corporation

R. H. SABERSKY
California Institute of Technology

R. G. SIDDALL
University of Sheffield (England)

JOSEPH M. SINGER
U. S. Bureau of Mines

PHILIP L. START
University of Sheffield (England)

ALEXANDER STRASSER
U. S. Bureau of Mines

K. SUMI
National Research Council (Canada)

CLAUDE P. TALLEY
Texaco Experiment, Incorporated

DONALD L. TURCOTTE
Cornell University

FORMAN A. WILLIAMS
Harvard University

HENRY WISE
Stanford Research Institute

E. C. WOODWARD
University of South Carolina

F. H. WRIGHT
California Institute of Technology

RICHARD W. ZIEMER
Electro-Optical Systems, Inc.

E. E. ZUKOSKI
California Institute of Technology

THE FIRE RESEARCH CONFERENCE

H. C. HOTTEL, *Chairman*	Director, Fuels Research Laboratory Massachusetts Institute of Technology
KEITH ARNOLD	Director, Division of Forest Fire Research Pacific Southwest Forest and Range Experiment Station
WILLIAM H. AVERY	Research and Development Supervisor Applied Physics Laboratory The Johns Hopkins University
J. S. BARROWS	Chief, Division Forest Fire Research Intermountain Forest and Range Experiment Station
L. M. K. BOELTER	Dean of Engineering University of California, Los Angeles
HORATIO BOND	Chief Engineer, National Fire Protection Association
B. P. BOTTERI	Wright Air Development Division Wright-Patterson Air Force Base, Ohio
MATHEW M. BRAIDECH	Director of Research National Board of Fire Underwriters
A. A. BROWN	Director, Division of Forest Fire Research U. S. Forest Service
C. C. BUCK	Assistant Director, Division of Forest Fire Research U. S. Forest Service
CLARENCE F. CASTLE	Chief, Services Division Properties and Installation Office Assistant Secretary of Defense
DEVER COLSON	Meteorologist, Meteorological Physics Section U. S. Weather Bureau
JAMES J. DUGGAN	Charleston, West Virginia
HOWARD W. EMMONS	Professor of Mechanical Engineering Harvard University
W. L. FONS	Physicist Southern Forest Fire Laboratory
JOSEPH GRUMER	Project Coordinator, Flame Dynamics Explosives Research Laboratory U.S. Bureau of Mines

ARTHUR B. GUISE	Technical Director, Research and Development Ansul Chemical Company
K. E. KLINGER	Chief Engineer, Los Angeles County Fire Department
HAROLD E. KUHLMAN	Chief Engineer, Oklahoma Inspection Bureau
BERNARD LEWIS	President, Combustion and Explosives Research, Inc.
J. B. MACAULEY	Assistant to the Director of Defense Research and Engineering Department of Defense
JAMES E. MALCOLM	Office of Chief of Engineers U.S. Army
WALTER T. OLSON	Chief, Propulsion Chemistry Division Lewis Research Center National Aeronautics and Space Administration
GEORGE J. RICHARDSON	Silver Spring, Maryland
A. F. ROBERTSON	Chief, Fire Research Section National Bureau of Standards
VINCENT J. SCHAEFER	3 Schemerhorn Road Schenectady, New York
A. J. STEINER	Managing Engineer, Fire Protection Department Underwriters' Laboratories, Incorporated
NORMAN J. THOMPSON	Miller's Hill Road Dover, Massachusetts
RICHARD L. TUVE	Head, Engineering Research Branch Mechanics Division U.S. Naval Research Laboratory

Liaison

H. T. HOOKWAY	United Kingdom Scientific Mission Washington, D.C.
G. W. SHORTER	National Research Council Ottawa, Canada

D. W. THORNHILL, Executive Secretary of Committee and Conference
EMMA JANE WHIPPLE, Administrative Assistant

Volume 5 Number 3

Fire Research Abstracts and Reviews

Committee on Fire Research
and
Fire Research Conference

Division of Engineering and Industrial Research
NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
Washington, D. C.

FIRE RESEARCH ABSTRACTS AND REVIEWS is published three times a year by the Committee on Fire Research and the Fire Research Conference of the National Academy of Sciences—National Research Council, 2101 Constitution Avenue, Washington 25, D. C. It is supported by the Office of Civil Defense, Department of Defense, the U. S. Department of Agriculture through the Forest Service, the National Science Foundation, and the National Bureau of Standards under Contract OCD–PS–64–34. The opinions expressed by contributors are their own and are not necessarily those of the Committee on Fire Research and the Fire Research Conference.

Library of Congress Catalog Card Number 58–60075 rev

FOREWORD

Together with the Committee on Fire Research of the National Academy of Sciences—National Research Council, I had the stimulating experience of a visit to the Northern Fire Research Laboratory of the U. S. Forest Service and to the just-opened Forest Fire Laboratory at Riverside, California. At the former, research and development programs directed toward the understanding and control of Forest Fires were discussed at length, while at the latter Fire problems engendered by the nuclear age were emphasized.

Both presentations were marked by the sophistication and breadth of view of the attack. No less impressive was the infectious enthusiasm with which the Forest Fire problems are being tackled. This augurs well for the future. The intelligent and prompt application of the tools of technology, aided by an increased appreciation of the factors that enter into the understanding of Fire problems, has already led to spectacular results in some areas.

A word of warning, however, is due. The means for exchanging information of lasting value among the professional investigators are not adequate. The Fire field, requiring inputs from a number of scientific disciplines, suffers from excessive fragmentation. There is an abundance of Station Papers, "Final" Reports, Technical Notes, etc., generally of limited distribution and with widely varying editorial standards of excellence. At present, there is no journal of wide circulation and acceptance which would publish promptly and extensively those contributions in research and development that should be brought to the attention of people with a professional interest in the advancement of Fire research. This cannot fail but have a depressing effect on the research workers who should be no less well served than their counterparts in other fields; on newcomers who have to familiarize themselves with established principles but have difficulty finding the original sources; and on the trained observers who wish to stay abreast of the progress and the problems in the Fire field. This dilemma must be resolved, in large measure through joint action by the Fire research investigators themselves, so that the burgeoning research effort does not find itself needlessly handicapped.

W. G. Berl
Editor

J. F. K.

1917–1963

WALLACE L. FONS

1899–1963

". . . dedicated his professional life to the study of Fire problems at a time when it had little glamour or momentum or assistance from sister sciences. He had to think his way into a virgin field and extract those problems that could profitably be worked on in the laboratory rather than in the field. He has now been taken away at a time when the field of his choice is experiencing an encouraging growth. He will not be able to enjoy the satisfaction of participating in the resolution of some of the problems with which he was personally so deeply involved. He will be greatly missed."

CONTENTS

Volume 5 Number 3

VIII. Model Studies and Scaling Laws

IX. Atomization of Liquids

X. Meteorological Interactions

XI. Operational Research Principles Applied to Fire Research

XII. Instrumentation

XIII. Fire-Fighting Techniques, Equipment Design, Materials of Construction

XIV. Miscellaneous

REVIEW

[The following article first appeared in "Air, Space and Instruments (S. Lees, ed.)," as part of a collection of papers dedicated to Professor C. S. Draper. The McGraw-Hill Publishing Company, New York, has graciously given permission to have it reprinted in its entirety.—Editor]

Fire in the Forest

HOWARD EMMONS

Gordon McKay Professor of Mechanical Engineering, Division of Engineering and Applied Physics, Harvard University

Introduction

An uncontrolled fire sweeping through a forest presents an awesome picture of power and destruction. Men's efforts at control appear puny by comparison and, in fact, sometimes are. When an exceptionally dry summer season is followed by an autumn of strong dry winds, the stage is set for fires that man can start but only nature can stop. It wasn't O'Leary's cow that burned a third of Chicago and cost 250 lives. It was an exceptionally dry summer and fall and a very strong dry wind on October eighth and ninth of 1871. Nature had loaded the cannon; the cow merely lit the fuse.

And while Chicago was being prepared for burning, so were the forests of Michigan, Wisconsin, and Minnesota. While the Chicago fire got all the publicity, another fire, the Peshtago fire, destroyed many acres of forest on both sides of Green Bay and wiped out the lumbering town of Peshtago, Wisconsin, including most of the people. This fire, which occurred the same day as the Chicago fire, cost 1,500 lives—the greatest loss of life by a single fire in the history of the United States.

Man doesn't put out such fires; the fire runs out of fuel (at the shore of Lake Michigan or Lake Superior), or the weather changes, the wind dies, and it rains. Fortunately only rarely is nature so severe. Often it is possible to stop a forest fire by direct action with shovels, brushes, and man-carried water on the windward side of a fire. On the flanks, a firebreak prepared by hand or by bulldozer can usually be held. In the lee of the fire there is real trouble. Smoke hampers all operations, firebreaks must be widened by a back fire, and many men must be available to extinguish fires spotted across the firebreak by fire brands.

The art of fire fighting is well advanced. The science of fire fighting has hardly begun. Under these conditions, there are those who ask a quite proper question—why bother with the science at all? There are several good reasons in addition to the ever-present reason of curiosity.

First, there are a number of phenomena encountered in forest-fire fighting that are not well enough understood to be adequately controlled. There is the fire blowup. A small or sometimes large section of the advancing front suddenly rushes ahead. Every year a dozen firemen are lost by failure to predict such occurrences. There is the fire tornado. A section of the rising column of hot gases begins to swirl, and as the swirl grows it pulls in adjacent flames and embers and raises them high in the air. The scale of the vortex may be a few inches in diameter and 10 ft high, to hundreds of feet in diameter and 1,000 ft high. Many new fires are spotted over a large area of forest by the burning embers carried aloft and often the entire vortex column moves off in a seemingly independent way, marking its path with a line of ignition. There are many other less spectacular but important effects dependent in an obscure way on local forest properties, local weather, local topography, etc., which if more accurately predictable would make the work of the fire fighter easier and less dangerous.

Second, there is the ever-present and generally justified hope that with an increased understanding will come an increased power to control. Are there trigger mechanisms in the process of spread of a fire which man with his small available energy could manipulate to affect in a major way the future course of a fire? Are there novel approaches to fire extinguishment not yet recognized?

The Mechanisms of Forest-Fire Spread

The simplest problem to examine with scientific care would seem to be the steady movement of a long fire front through a homogeneous "forest" on a large plane. In fact the first step would appear to be to examine available data on the velocity of fire-front movement. Alas, there is almost none available! Fire reports filled out after the fire is over by men whose primary duty was to put out the fire are very unreliable. The few controlled fire tests that have been made are interpreted and presented as rate of increase of fire perimeter—in chains per hour. The perimeter increase is important because of its relation to manpower and equipment required, but doesn't help much in a fundamental understanding because of the averaged effect of the wind. What data there are merely confirm what could have been guessed; namely, the fire front moves faster in dry fuels than in wet ones, and moves faster with a wind present than without one.

Clearly, a careful collection of fire-front velocity data and related fuel and weather information is of highest priority.

With such profound ignorance of essential quantitative knowledge, we might conclude that this paper should terminate here pending correction of the deficiency. While this might be true for many publication media, it is certainly not true of the Draper anniversary volume. When was Stark Draper ever deterred from action by lack of data or apparent hopeless complexity? Instead of termination, let us proceed to do what we can to identify the nature of the forest-fire spread problem and to examine a simplified model for the guidance it can give us.

In Fig. 1 we see a section through the fire front in a forest. As the trees to the

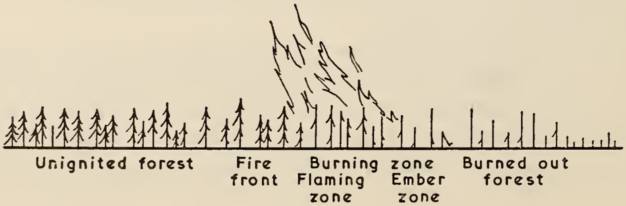


FIG. 1. A burning forest.

left ignite, flames rise high in the air. Behind the flaming front is a region of burning embers and this is followed by the burned-out forest. Let us examine each of these regions to see what is happening there.

The unignited forest consists of trees of various sizes and various spacings. The crowns may be closely packed or widely separated, but in either case the leaves and twigs constitute finely divided fuel containing more or less moisture, depending upon the health of the tree and the local weather conditions. Below the crowns there is usually a layer of tree trunks with little fine fuel. Green tree trunks can only with difficulty support their own combustion. In this layer, then, the fire danger is low except for an occasional young tree or a snag—a standing, dead, generally branchless tree. Nearer the ground may be a layer of growing grass and brush. This layer, from a few inches to 6 or 10 ft in depth, contains, in addition to a more or less dense leaf and branch complex, various dead and fallen trees in various states of decay. In fact, very near the ground the predominant fuel is the litter of branches, leaves, and other fallen materials. Finally, between the litter and the mineral soil is a layer of duff, organic matter of all kinds from centuries past in a decaying state, ranging from recognizable plant remains to dark brown homogeneous soil filled with plant roots seeking water and nutrients.

It is clear from this description that the progress of a fire front involves many minor events. The ignition of one leaf by its neighbor, the fluctuation of a flame in the forest wind turbulence, the hot gases rising from the brush to dry and ignite the crowns, the falling of burning embers into unignited fuel, ignition by radiation from flames and embers, the flashover of combustible vapors pyrolized from irradiated fuel—all play their separate and interrelated parts. If the location of every leaf in the forest must be specified in order to calculate quantitatively the effect of every one of the above mechanisms of ignition, the fire-spread problem is indeed a hopeless one. What is needed is some kind of statistical description of the forest and a selection of the major fire-ignition mechanisms for quantitative representation.

The statistical description will have to describe the amount, fineness, and horizontal distribution of fuel at various levels above the forest floor. The most common forest fire runs through the brush and litter with heating damage to tree trunks and crowns, but without actual crown burning. On rare occasions with wet litter but sun- and fire-dried crowns, a wind may sweep a fire through the crowns without burning the underbrush. This emphasizes the need to consider a fire front as two-dimensional, width and vertical depth, rather than a one-dimensional statistically homogeneous phenomenon. Hottel and Morton have recently suggested that an adequate description may be attained by considering two one-dimensional fire fronts at different levels with interaction terms describing the thermal relations between them.

The average properties of a forest will probably not be sufficient because of the large fluctuation about that average over a horizontal distance comparable to the fire-front thickness. Again, few data are available, but a recent vacation in the Tetons provided an opportunity to make a few measurements in the evergreen forests of that region.

The only simple measurements to get are tree counts. Such counts were made on three typical wooded areas. Figure 2 shows the distribution of tree sizes. These areas are of different ages since last lumbered (or burned over). In each case about $\frac{1}{4}$ acre was counted. In the case of the Timbered Island, the count was made by

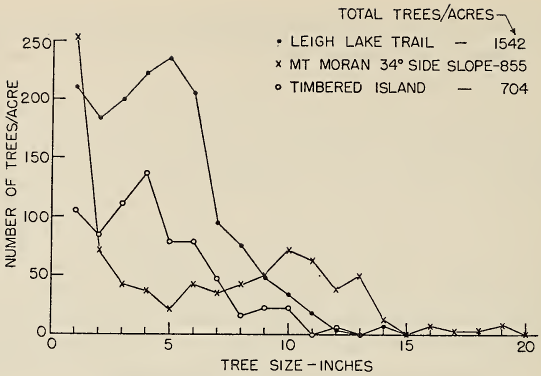


Fig. 2. Forest tree size distribution.

20 ft square subareas, thus providing the additional statistics of Fig. 3. We note the large variation of trees per acre from one 400 sq ft section to the next.

To give some idea of the low-level foliage, some rough measurements of tree height were made. Figure 4 shows these results and makes clear that young trees must grow very rapidly, to 50 ft or so, if they are to be successful in the competition for sunlight. Thus, above an underbrush of a few feet in height there is very little fine fuel up to 20 ft or so, with the major heavy foliage between 35 and 55 ft.

Much more extensive measurement would be needed to determine the mass of fuel in each layer and its pertinent geometric distribution factors. This information is not currently available, and in fact it is not at present clear just what form such data should take.

As the fire front moves toward a given section of unignited forest, heat transfer by radiation from flames and glowing embers heats the available forest fuel. The first effect of this heating is to dry surface moisture. This is followed by the evaporation of moisture soaked into the fuel or combined more intimately in the growing tissues. Further heating causes pyrolysis which supplies large amounts of steam and gradually more and more combustible gases. Unless the wind above the forest is very strong, it would be expected that these gases would be drawn into the fire by the fire-induced convection. The absorptivity of these gases for thermal radiation

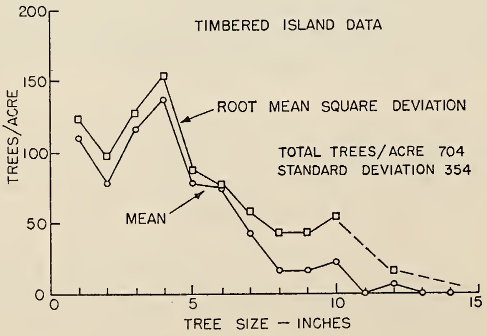


Fig. 3. Deviation from mean tree distribution

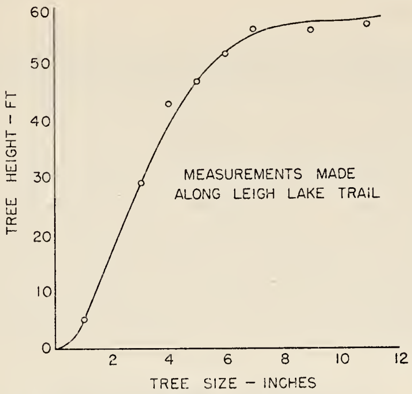


FIG. 4. Tree height–trunk size relation.

reduces to some extent the energy radiated to the unignited fuel. The fire convection, however, introduces a more important effect in the convective cooling by the inducted cool air.

Eventually the surface of the fuel is heated close to the ignition condition when one of the ignition mechanisms mentioned above tips the scales and this surface becomes part of the fire front.

In the active burning zone, the pyrolysis of fuel continues rapidly. The gases may burn where produced to the extent that oxygen is available, but most of the gases rise with the thermal convection to burn with air far above their source. The gases are not only those directly produced by pyrolysis but include some hydrogen and carbon monoxide produced by the reaction of water with the hot solid carbon present.

The burning gases and solids liberate and heat a large volume of gas which rises above the forest by natural convection. If the atmosphere is stable, these gases and smoke rise to a considerable height and then spread horizontally, masking the fire from aerial view. The rising gases in any case serve to draw air into the fire, thus serving as the pump to supply combustion air. At the same time the flames supply by radiation a probably large, but unknown, fraction of the heat required to dry and preheat the as yet unignited fuel. If there is a wind, or the fire is on an upslope, the flames tend to lean over the unburned trees and thus propagate the fire faster.

Behind the flaming region, there is a zone of glowing combustion. All the fine fuels have been burned out and all the gases have been removed from the hot surface layers of the large-size tree trunks both green and dead. The width of this zone will depend upon the relative amount of dead and green material and the absolute amount of fuel per acre. If only green tree trunks are present, the fire soon goes out, leaving many ghosts in the form of snags to support a new fire 10 or 20 years later. If the lumber was ready to cut, the snags can be used, as only an inch or so has been affected by the fire.

In the burned-out area we find the standing charred trunks of the larger trees, and on the forest floor we find more or less the duff, depending upon the intensity of the fire and the soil moisture. Generally there is enough soil left to support new tree growth, although reseeding will probably be necessary.

A Simple Fire-Spread Model

From the above description of a forest and the many phenomena which enter into fire propagation, it is clear that a complete quantitative description is for the present out of the question. In fact, in the present crude state of knowledge, the first quantitative predictions should attempt only to cover the most important effects as suggestive of general fire behavior, rather than to produce any precise predictions. For this purpose, we attempt a fire spread model in which the fire produces an energy flux $\mathcal{Q}(x)$ horizontally into the unburned fuel. This heat is absorbed by the unignited fuel which is thus heated to its ignition point.

We must now devise suitable approximate relations for the generation of $\mathcal{Q}(x)$ and for its absorption. Since radiation is probably the major heat transfer mechanism in a forest fire, let us choose as a single mechanism one that is well adapted to radiation transfer.

Let the heat flux $\mathcal{Q}(x)$ be absorbed in fraction α per unit length. Thus, in Fig. 5, the rate of energy absorption in an element dx at position $-x$ is

$$dE_a = -\alpha \mathcal{Q}\, dx \tag{1}$$

The factor α will depend most importantly on the fuel surface exposed to heating in the element dx. For radiant heating of black surfaces, α is equal to the total surface per unit volume. In the case of a forest, corrections would be needed to account for radiation loss to the sky, emissivity of nonblack surfaces, and angularity of radiation input from flames. Only experimental measurements or a more complete theory can finally show how accurate the present model can be made by an α selection.

Again, for simplicity the mechanism of production of $\mathcal{Q}(x)$ will be chosen to agree with radiation heat transfer. We suppose the burning zone to be made up of surfaces of emissivity ϵ and at a burning temperature T_b. Thus each unit of surface emits energy at the rate $\epsilon\sigma T_b^4$ through 2π steradians. The fraction $\mathcal{Q}(x)$ of this radiation which moves toward the unburned fuel depends upon the amount of radiating surface per unit volume and the radiation loss to the sky. These factors are the same as for the absorption process. We will therefore use the same factor α in spite of the fact that much of the fine fuel is burned rapidly, thus greatly reducing the surface-volume ratio. This reduction is, however, partially compensated by radiation from flames. Thus the rate of energy flux production by element dx' at x' in the burning zone is

$$dE_p = \alpha\epsilon\sigma T_b^4 h\, dx' = \alpha \mathcal{Q}_b\, dx' \tag{2}$$

The energy $\mathcal{Q}$ entering the element at $-x$ differs from that at the origin by absorption in intermediate elements

$$\mathcal{Q}(-x) = \mathcal{Q}_0 e^{\alpha x} \tag{3}$$

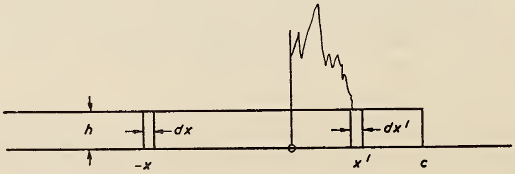


FIG. 5. Fire-spread nomenclature.

while the energy at the origin follows from Eq. (2) observing that some of the energy emitted by each element is absorbed by the fuel lying between it and the origin. Thus

$$\mathcal{Q}_0=\int_0^c e^{-\alpha x}\,dE_p=\mathcal{Q}_b(1-e^{-\alpha c}) \tag{4}$$

where c is the width of the burning zone, Fig. 5.

For steady fire propagation at velocity u the unignited fuel moves toward the origin from $-\infty$ and in so doing acquires the heat necessary to raise it to the ignition temperature (an ignition temperature is assumed to be an adequate criterion of the commencement of active combustion in this simple model).

$$Mc_p(T_i-T_0)u=\mathcal{Q}_b(1-e^{-\alpha c}) \tag{5}$$

where M is the mass of fuel that will be burned per unit area of forest floor.

If w is the average burning rate per unit area of forest floor, then the characteristic time required to burn a given element of forest can be computed in two ways.

$$\tau_0=M/w=c/u \tag{6}$$

Equation (5) now gives

$$\frac{wc_p(T_i-T_0)}{\alpha\mathcal{Q}_b}\,\frac{\alpha Mu}{w}=1-e^{-\alpha Mu/w} \tag{7}$$

This equation plotted in Fig. 6 gives the relation between the fire-front velocity group $\alpha Mu/w$ and the burning characteristic

$$P=[wc_p(T_i-T_0)/\alpha\mathcal{Q}_b] \qquad \text{non-dimensional,} \tag{8}$$

which sets the slope of the line representing the left-hand side. We see that for small characteristics $P<1$ there is one and only one solution as at a for line A. If $P>1$, there is no real solution at all as for line C. The tangent line B, for $P=1$, is the limit characteristic that will burn. Figure 7 shows the solution. The abscissa also represents the width of the burning zone by Eq. (6)

$$\alpha c=\alpha Mu/w \tag{9}$$

We see that as the burning characteristic increases, the fire front slows down and

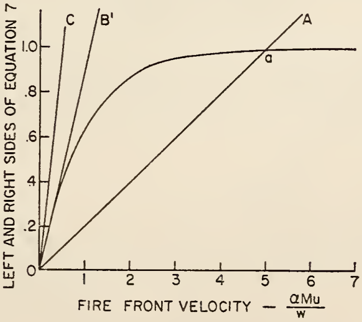


Fig. 6. Graphical solution of fire-spread rate.

becomes narrower. As expected, an increase of the heat required to heat the fuel to the ignition condition, either by raising the ignition temperature or adding moisture to the fuel, raises the burning characteristic and slows the fire front. Similarly, raising the heat transfer $\mathcal{Q}_b$ from the burning zone by either raising its temperature or effective emissivity ϵ decreases the burning characteristic and thus increases the burning zone thickness and speeds its progress through the forest.

The effect on the fire of the tree density α and the burning rate are more complex. First, we note that an increase of burning rate w or a thinning of the forest (decrease of α) raises the burning characteristic and hence decreases the fire-front speed group $\alpha Mu/w$. This is very important because this is the direction of change which tends to put the fire out. To put the fire out requires raising the burning characteristic above 1. This sounds correct so far as thinning the forest is concerned. For the burning rate w, however, this sounds reversed—make the fuel burn faster to put the fire out. The cause for this is, of course, the fact that by burning faster, the characteristic burning time τ_0 is decreased and the width of burning zone c is decreased.

Further interesting effects can be noted by examining Eq. (7) for high values of $\alpha Mu/w$,

$$\frac{c_p(T_i-T_0)Mu}{\mathcal{Q}_b}=1 \tag{10}$$

Thus, for low burning characteristic, the fire front moves at a rate independent of the burning rate w and inversely with the fuel loading M.

One important aspect of the burning characteristic P should be observed. The burning rate w would be expected to depend upon the burning zone temperature by

$$w \propto e^{-E/RT} \tag{11}$$

while the heat transfer $\mathcal{Q}_b$ would depend upon T_b to some power between 1 and 4 since both convection and radiation play their parts. The burning characteristic P dependent upon $w/\mathcal{Q}_b$ would vary with the burning temperature as

$$P \propto T_b^{-n}\, e^{-E/RT_b} \tag{12}$$

a function which rises from zero at $T_b=0$ to a maximum and then falls again to zero. The maximum might or might not raise P above 1, the fire-out value. Furthermore, if P can be raised above 1 by adjustment of the burning temperature, a fire-extinguishing agent should affect an increase or decrease of burning-zone temperature depending upon whether the initial forest fire is below or above the maximum.

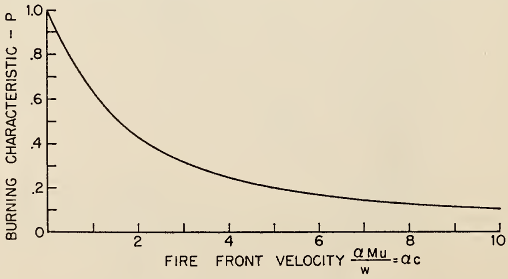


Fig. 7. Fire-front velocity.

Considerable study combined with experiment will be necessary before these complex burning relationships can be understood in a practical way. The complexity in connection with chemical factors is in line with experiments on the conflicting effects of inhibitors.

The Firebreak

Probably the major fire-control device in the forest after the use of water is the firebreak. By clearing a path down to mineral soil, no fire can pass unless the heating of fuel across the break is sufficient to raise it to its ignition point or a fire brand carries fire over the top. The simple fire model of the previous section can be used to discuss firebreak needs.

In Fig. 8, a firebreak of width g is shown in fuel of height h. The fire moves from far to the right toward the break and the question to be answered is "Does the fuel to the left of the break begin to burn before the fuel to the right of the break burns out?"

The heating of the fuel at the left of the break must be considered in two parts:

1. The fire front is at distance x from the break $0<x<\infty$.
2. The fire rear is at distance x from the break $0<x<c$.

The total energy which flows into the break from the fire is for part 1

$$\mathcal{Q}_1=\int_0^\infty \mathcal{Q}_b(1-e^{-\alpha c})e^{-\alpha x}\,dt=\int_0^\infty \frac{\mathcal{Q}_b(1-e^{-\alpha c})e^{-\alpha x}\,dx}{u}$$

$$=\frac{\mathcal{Q}_b}{\alpha u}(1-e^{-\alpha c}) \qquad (13)$$

and for part 2

$$\mathcal{Q}_2=\int_0^c \mathcal{Q}_b(1-e^{-\alpha x})\,dt=\int_0^c \frac{\mathcal{Q}_b(1-e^{-\alpha x})\,dx}{u}=\frac{\mathcal{Q}_b}{\alpha u}(\alpha c+e^{-\alpha c}-1) \qquad (14)$$

where use has been made of the fact that the fire front moves at the constant rate u right up to the break, and since τ_0 is constant, the rear of the burning zone moves at the constant rate u also. The total energy entering the break from the right is

$$\mathcal{Q}=\mathcal{Q}_1+\mathcal{Q}_2=\mathcal{Q}_b c/u \qquad (15)$$

Only a certain fraction B of this heat gets across the break; the remainder is lost to sky and ground. Of the heat that gets across, fraction $\alpha\,dx$ is used to heat the fuel in the strip dx wide along the left of the break. The fire will ignite across the break

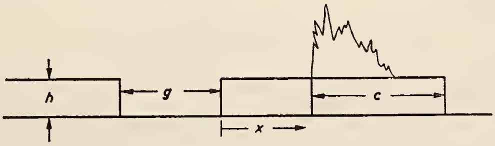


FIG. 8. Firebreak nomenclature.

if the heat required to ignite the fuel is less than or equal to that absorbed. Thus

$$Mc_p(T_i - T_0) \leq \frac{\alpha B \mathcal{Q}_b c}{u} = \frac{\alpha B \mathcal{Q}_b c}{u} = \frac{\alpha B \mathcal{Q}_b M}{w}$$

or

$$B \geq \frac{wc_p(T_i - T_0)}{\alpha \mathcal{Q}_b} = P \tag{16}$$

Before this relation becomes useful, B must be evaluated in terms of g/h, the break width ratio. Since the heat transfer across a firebreak is largely radiative, we estimate the firebreak heat ratio B by approximating the forest on each side of the break as vertical solid radiators.

$$B = [1 + (g/h)^2]^{\frac{1}{2}} - (g/h) \tag{17}$$

When Eq. (17) is computed, we discover that the functions $(1+x^2)^{\frac{1}{2}} - x$ and $\frac{1}{2}x(1-e^{-2x})$ [see Eq. (7)] differ by less than about 6 per cent over the entire range $0 < x < \infty$. In view of the approximation made in the present theory, this 6 per cent difference is negligible, and the firebreak jump criterion can be expressed

$$g/h \geq \alpha M u/w \tag{18}$$

This is a most simple and directly useful relation. Some relatively simple facts about the fuel in the forest $\alpha M/w$ and an observation of the rate of fire-front advance u determine the required firebreak width. Thus a knowledge of how long it takes to build a break of the required width and the present location of the fire serves to locate the possible positions in which a suitable firebreak can be built with the available fire-fighting force.

Another way of using this firebreak information is illustrated in Fig. 9. Suppose the fuel in the forest has a known characteristic distribution as shown in the graph at the right of Fig. 9. Equation (16) now relates the curves on the left and right such that for any chosen firebreak width, the fraction of the break length that will be breached is shown by the shaded area. Thus, again, it is clear how many men must be available if a break of a given size width is to be held.

These graphs thus answer in an approximate way the question "Can the fire be stopped by a firebreak here?" If the break is too narrow, too many men are required to hold it. If the break is too wide, there will not be enough time to build it. Thus

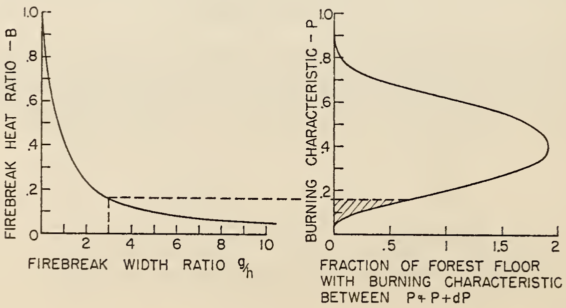


Fig. 9. Firebreak performance.

there is an optimum break width to build and an essential minimum number of men (and facilities) required for building and holding. If the minimum are not available, the break must be built at a greater distance from the present fire location.

Fire Buildup

It is well known that a fire on first ignition does not spring immediately into the large phenomenon it will become as a steady propagating front. This is most important because for a considerable period after first ignition a small force of men can control the blaze. Furthermore, the fires that spot across a firebreak are much easier to handle than the original fire front. Finally, a still easier problem is the holding of a firebreak against a newly set-back fire since it starts as a small fire and takes time to build up to full size.

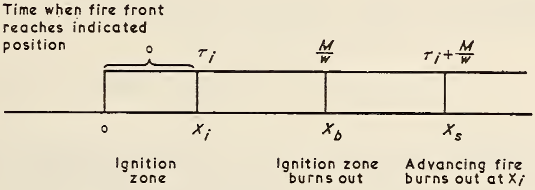


FIG. 10. Fire buildup nomenclature.

In Fig. 10, the notation for the fire buildup is defined. The section between 0 and x_i is supposed to be simultaneously ignited. After a heating period τ_i the fire front moves forward from x_i. At time M/w the ignition zone burns out while the advancing front has reached x_b. Next, while the fire front advances to x_s, the rear of the fire does not move until time M/w has elapsed since its ignition. After time τ_i+M/w there is an advancing burning zone which travels, however, at a nonuniform rate.

The initial stages of this process can be solved and are given below. The later stages are more difficult and have not yet been solved analytically, but the nature of the solution is indicated.

First find the time τ_i at which the fire front begins to move.

$$Mc_p(T_i-T_0)=\alpha\int_0^{\tau_i}\mathcal{Q}_b(1-e^{-\alpha c})\,dt \tag{19}$$

Thus,

$$\tau_i w/M=P/[1-e^{-\alpha x_i}] \tag{20}$$

The front will not advance at all unless ignition occurs before ignition zone burn-out, i.e., $\tau_i w/M\leq 1$ or

$$\alpha x_i\geq -\ln(1-P) \tag{21}$$

Figure 11 shows the required minimum distance along with the steady propagating fire-zone width for comparison. If the burning characteristic of the fuel P is low, only a very narrow ignition strip is required. If P is high, a strip much wider than the steady burning width c must be ignited if the fire is to go.

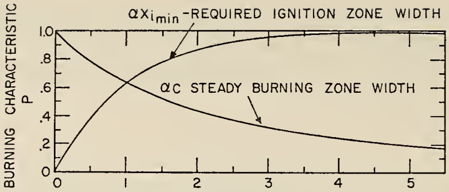


FIG. 11. Ignition- and burning-zone widths.

If the Front is at x between the Ignition Zone x_i and the Ignition Burn-out Location x_b. The fuel in dx at x must be heated to the ignition point by the time τ at which the fire front arrives. $x_i<x<x_b$. Thus

$$Mc_p(T_i-T_0)=\int_0^{\tau}\alpha\mathcal{Q}(x)\;dt=\alpha\mathcal{Q}_b(1-e^{-\alpha x_0})\;e^{-\alpha(x-x_0)}\tau_i$$

$$+\int_{x_i}^{x}\frac{\alpha\mathcal{Q}_b[1-\;e^{-\alpha x_f}]\;e^{-\alpha(x-x_f)}]\;dx_f}{u(x_f)}\tag{22}$$

where the first term on the right is the heat received from the ignition zone in the period before the front starts to move, while the second term is the heat received from the entire burning zone while the fire front at x_f moves from x_i to the ignition element at x. This form of accounting for the heat transfers has the advantage over others in that the first term on the right immediately simplifies using Eq. (20). Thus

$$P\{1-\;e^{-\alpha(x-x_0)}\}=\int_{x_i}^{x}\frac{[1-\;e^{-\alpha x_f}]\;e^{-\alpha(x-x_f)}\alpha\;dx_f}{\alpha Mu(x_f)/w}\tag{23}$$

By inspection, the solution to this integral equation for $u(x)$ is

$$\alpha Mu/w=(1-e^{-\alpha x})/P\qquad x_i<x<x_b\tag{24}$$

which gives the fire-front velocity for positions x between the ignition zone and the time of ignition burn-out. If we denote the steady fire-front velocity of Eq. (7) by u_s, we get

$$u/u_s=(1-e^{-\alpha x})/(1-e^{-\alpha c})\qquad x_i<x<x_b\tag{25}$$

Figure 12 shows this velocity ratio as a function of αx and αc. The steady-state burning-zone width αc is, in a sense, a characteristic of the fuel and is related to the burning characteristic P by Eqs. (7) and (9) as in Fig. 7. The dashed line on Fig. 12 shows the required ignition region. If a zone width is ignited which falls to the left of the dashed line, the fire will go out as soon as the ignited fuel burns out. If a zone width is ignited which falls to the right of the dashed line the fire will burn in the ignition zone for time τ_i; then the fire will start to move forward at the rate given by the αx_i, αc point of Fig. 12. Furthermore, we note that the fire front does not start slowly and then move faster and faster. It starts at a finite rate that may be either larger or smaller than the steady-state rate. In fact, the fire-front speed after it starts moves along a c constant curve. Hence, even if it starts at its steady-

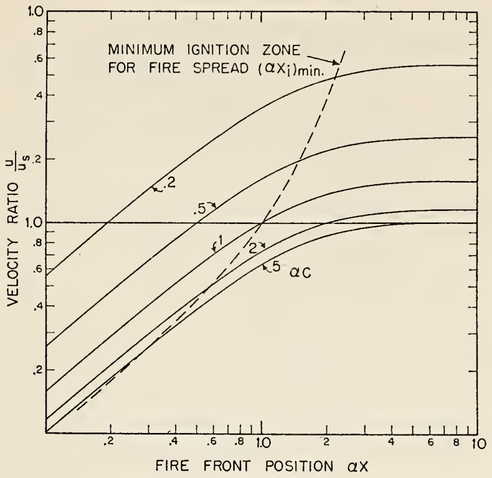


Fig. 12. Velocity of buildup fire front.

state speed, it immediately speeds up. In any case, the speed-up continues until the ignition zone fire burns out.

To find the flame front position x_b at the time M/w when the ignition zone burns out, we note that the time can also be computed from the front speed.

$$\tau_b = M/w = \tau_i + \int_{x_i}^{x_b} dx/u(x) \tag{26}$$

On substituting from Eqs. (20) and (24), we get

$$g(\alpha x_b) = A^{-1}[1 - e^{-\alpha x_i}]^{-1} + g(\alpha x_i) \tag{27}$$

where

$$g(\beta) = \beta + \ln(1 - e^{-\beta})$$

The function $g(\beta)$ is drawn as Fig. 13 and with its aid and Eq. (27), Fig. 14 was

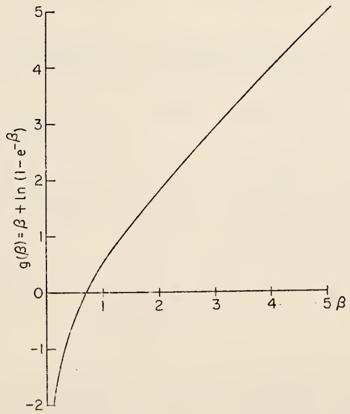


Fig. 13. The fire-spread function $g(\beta)$.

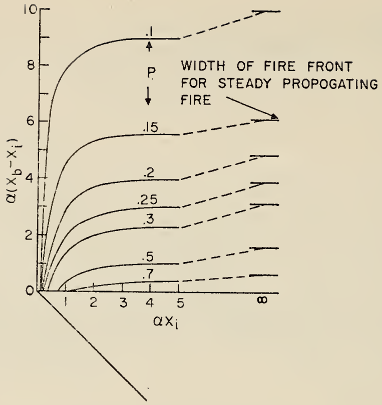


Fig. 14. Fire-front position at ignition burn-out.

drawn showing how far the fire will have progressed by the time the ignition zone burns out. The 45° line below the axis is a reference ignition-zone width line. For any chosen abscissa, the fire extends from the 45° line up to the appropriate curve just before the ignition zone burns out. Immediately thereafter, the burning-zone length drops to the portion above the x_i axis.

If the Fire Front x is between Ignition Burn-out Location x_b and Position x_s (x_s is the fire-front position at the time the fire rear burns out at x_i). The derivation follows exactly parallel to that for Eq. (24) and results in a front speed given by

$$\frac{\alpha u M}{w} = \frac{1 - e^{-\alpha(x - x_i)}}{A} \tag{28}$$

or

$$\frac{u}{u_s} = \frac{1 - e^{-\alpha(x - x_i)}}{1 - e^{-\alpha c}} \qquad x_b < x < x_s \tag{29}$$

Also, the location x_s is found in the same way as x_b [Eq. (27)]:

$$g[\alpha(x_s - x_i)] = [1 - e^{-\alpha x_i}]^{-1} + g[\alpha(x_b - x_i)] \tag{30}$$

The fact that the velocity integral equation was easily solved for each section above suggests that it might be solved in general. This proves to be true for a forest of uniform properties. The integral equation is

$$P = \int_{\alpha x}^{\infty} \frac{\{1 - e^{-\alpha[x_f - x_r(x_f)]}\}\, e^{-\alpha(x - x_f)}\, d(\alpha x_f)}{\alpha u(x_f) M / w} \tag{31}$$

where the integration extends from the front position αx to ∞ in order to get all contributions to the heating. Actually, the integration must be taken piecewise since there are discontinuities at x_i, x_b, x_s, and an infinite succession of other points reflecting the presence of each of the previous ones. To solve this equation, differentiate both sides with respect to (αx).

$$0=\frac{1-e^{-\alpha[x-x_r(x)]}}{\alpha u(x)M/w}-\int_{\alpha x}^{\infty}\frac{\{1-e^{-\alpha(x_f-x_r)}\}\,e^{-\alpha(x-x_f)}\,d(\alpha x_f)}{\alpha u(x_f)M/w} \tag{32}$$

But the integral here is the original integral and equals P; hence

$$\frac{\alpha uM}{w}=\frac{1-e^{-\alpha[x-x_r(x)]}}{P} \tag{33}$$

To compute the fire-front velocity from this equation requires the computation of the fire-rear position x_r. In Eqs. (24) and (28), the fire-rear position was known and fixed. These earlier results are special cases of Eq. (33).

If the fire-front position $x(t)$ were known, the fire-rear position would be given by

$$x_r=x[t-(M/w)] \tag{34}$$

Thus,

$$\frac{\alpha uM}{w}=\frac{1-e^{-\alpha[x(t)-x(t-M/w)]}}{P} \tag{35}$$

This equation is best solved numerically or graphically.

The buildup of fire-front velocity (and position) is shown for a particular example as Fig. 15. The case chosen has a burning characteristic $P=0.5$ and an initial ignition strip of $\alpha x_i=1.0$. The fire has several discontinuities in velocity (at x_i and x_b), and discontinuities in higher and higher derivatives at reflected positions of x_i and x_b. (The nth derivative is discontinuous at $x_s^{(n-1)}$ and $x_b^{(n)}$.) After the first few

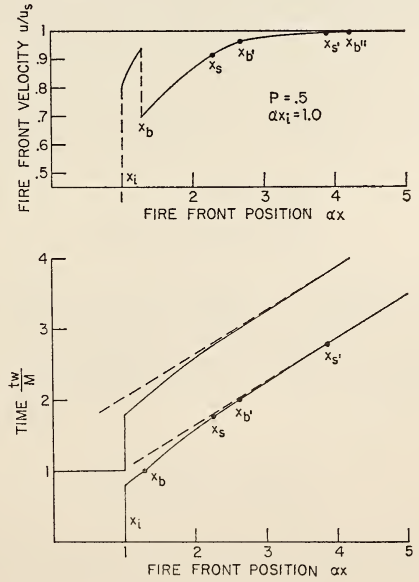


FIG. 15. Backfire buildup.

discontinuities the curve is smooth enough to use a linearized solution of Eq. (35) found by setting

$$x\left(t-\frac{M}{w}\right)=x(t)-x'(t)\frac{M}{w}+\frac{1}{2}x''(t)\frac{M^2}{w^2}\cdots$$

$$=x(t)-u(t)\frac{M}{w}+\frac{1}{2}\frac{M^2}{w^2}\frac{du}{dt}\cdots \qquad (36)$$

and

$$u(t)=u_s+u'(t) \qquad \text{with } u'\ll u_s \qquad (37)$$

The first-order solution is

$$\alpha Mu'/w=(\alpha Mu'/w)_0\, e^{-2(1-Pe^{ac})tw/M} \qquad (38)$$

The corresponding fire-front position is easily computed.

It is clear that the model of fire-front movement is capable of answering many of the important fire-spread problems. Further mathematical work with this simplified model has, however, been carried far enough in the present paper to make two other studies of next essential importance. These are:

1. A careful experimental study of fire-front movement in fuels of carefully measured properties.
2. A careful analytical study of a more complete mathematical model of the fire spread. This should be directed toward the two ends of finding a model which includes directly all the important known processes and of determining the degree of precision of the simple theory of this paper. By the judicious determination of α, M, w, etc., as related to the real forest fire, it may be possible to attain adequate description without a more cumbersome treatment.

The practical problems raised by the forest fire are of a nature that a modern scientific approach to their solution offers much promise.

ABSTRACTS

III. Heat Transfer

Hausen, H. and Binder, J. A. (Technische Hochschule, Welfengarten 1a, Hannover, Germany) "Simplified Calculation of Heat Transfer by Radiation from a Gas to a Wall," *International Journal of Heat and Mass Transfer* 5, 317–327 (1962)

In this paper the authors derive two approximate procedures for determining the radiant transfer of thermal energy between a hot tube wall and a moving gas phase. One of the authors, Binder, has previously conducted a similar exact numerical calculation of this radiant transfer by use of a digital computer. Since such exact numerical solutions of these equations are, in practice, unwarranted, the authors have attempted to obtain a reliable approximate analytical procedure. The authors assumed that the radiant transfer of thermal energy can be equated to the temperature difference between the wall and the gas and a strongly temperature-dependent proportionality factor. It is then assumed that it is only necessary to determine the average value of this proportionality factor to obtain an approximate solution to the problem. Therefore, equating this linear expression to the usual radiant energy expression involving the fourth power dependence of temperature and taking average values one obtains:

$$C_s\epsilon_{gw}(T^4-T_w^4)_m=a_{sm}(T-T_w)_m,$$

where C_s is the black body radiation constant, ϵ_{sw} the heat exchange relation between gas temperature T and wall temperature T_w, a_s is the proportionality factor and the expression $(T-T_w)_m$ is as usually understood as the logarithmic average of T_1-T_w over T_2-T_w. The subscript m indicates average values. To evaluate the fourth power expression in the above equation, the authors define a new average temperature T^* such that $T^*=T_2+0.36\ (T_1-T_2)$ where T_2 and T_1 are the exit and entrance tube gas temperatures, respectively. Thereby one can obtain the following expression:

$$a_{sm}=C_s\epsilon_{gw}\frac{T^{*4}-T_w^4}{(T-T_w)_m}.$$

If the wall temperature is assumed constant, an average value of a_s is found and a solution to the radiant heat transfer problem readily follows. The authors derive a second more accurate approximation method wherein a temperature dependence of ϵ_{gw} can be considered. From the basic heat balance equations the following expression is readily obtained,

$$\int_{T_2}^{T_1}\frac{dT}{a\Delta T}=\frac{T_1-T_2}{(a\Delta T)_m}$$

where now it becomes necessary to evaluate the integral appearing on the left hand side of the expression: $\Delta T = T - T_w$. Gauss has shown that if y is a quadratic function of x then

$$\int_{x_1}^{x_2} y dx \doteq \tfrac{1}{2}(x_2 - x_1)(y_1^* + y_2^*),$$

where

$$x_1^* = x_1 + 0.211\ (x_2 - x_1)$$

$$x_2^* = x_2 - 0.211\ (x_2 - x_1).$$

Using this same quadrature technique on the foregoing integral, the authors arrive at an average value of $1/(a\Delta T)_m$,

$$\frac{2}{(a\Delta T)_m}\ \frac{1}{(a\Delta T)_1^*}\ \frac{1}{(a\Delta T)_2^*},$$

where

$$T_1^* = T_1 - 0.211\ (T_1 - T_2),$$

$$T_2^* = T_2 + 0.211\ (T_1 - T_2),$$

and $(a\Delta T)_1^*$ is the value of $(a\Delta T)$ at T_1^* and similarly for $(a\Delta T)_2^*$. Thereby an average value of $(a\Delta T)$ has been obtained and subsequently the average value of the radiant transfer of thermal energy. The authors have shown that these approximate expressions are in favorable agreement with the exact numerical expressions of Binder.

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

H. E. Perlee

IV. Diffusion Flames

Pandya, T. P. and Weinberg, F. J. (Imperial College, London, England) "The Study of the Structure of Laminar Diffusion Flames by Optical Methods," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 587–596 (1963)

Methods based on refractive index measurements have been used to study the temperature distribution in a flat premixed flame. This method, which makes possible the measurement of heat releases in the flame, is limited at atmospheric pressure to near-limit mixtures. Flames whose burning velocity is less than about 12 cm/sec can be studied by this method, especially if the flames are at lower pressures or near the rich or lean limit.

Diffusion flames which are not premixed can be studied in a counterflow opposed jet burner. The flow is divided into two equal streams, one O_2+N_2 and the other $C_2H_4+N_2$, such that each flow is properly metered. Then the $C_2H_4+N_2$ flow is introduced at the bottom of a water-cooled glass tube such that it flows upward through a bed of glass beads and through a matrix of corrugated cupronickel strips wound in a spiral. At the same time and in the same manner, the O_2+N_2 flow enters the top of another glass tube and flows downward in a similar fashion. The two tubes are placed the one above the other coaxially. Thermocouples are used to measure the temperature of the stream. The flow patterns were determined by photographing particles illuminated by interrupted light.

The temperature pattern was determined either by deflection mapping of the area or by a modified interferometry technique. The former method is most sensitive for large thermal gradients since it measures the slope of the temperature lines, while the latter method is best suited for measuring the absolute temperature values. A discussion of the merits of deflection mapping for temperature readings and the sodium line-reversal method is given.

In order to make a complete analysis of the flame the following data are necessary: (1) The distribution of temperature in both r and z (the radial and axial directions) of the flame. The change in the refractive index is caused mainly by the change in temperature. Smaller effects due to composition changes are noted and can be corrected. (2) The distribution of flow velocity in r and z. The flow velocities are used to calculate burning velocities and reaction rates. (3) Calculation of local values of thermal conductivity, density and enthalpy. Composition changes due to diffusion are taken into account.

The following conclusions may be drawn: (1) A method of stabilizing large, flat diffusion flames in an equal-volume, counterflow regime has been established. (2) Instrumentation to measure the distribution of flow velocities and the approach stream temperatures has been set up. (3) Two optical methods, one based on deflection mapping and the other on interferometry, have been developed for the measurement of the distribution of refractive index and hence of temperature. (4) Their use is illustrated by a complete temperature map of a flame in two dimensions. (5) The approach for analyzing flame structures to deduce heat release rates is discussed. Results of such analyses will be published.

Subject Headings: ***Flame, optical study of structure; Diffusion flame, study of.***

W. C. Johnston

Burgess, D. and Zabetakis, M. G. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania "Fire and Explosion Hazards Associated with Liquefied Natural Gas," *U. S. Bureau of Mines Report of Investigations No. 6099* (1963)

In this report the authors present the results of a program undertaken to evaluate the fire and explosion hazards associated with the storage of liquefied natural gas. The characteristics of fuels related to their fire and explosive hazards are discussed. Previously available data concerning these characteristics for liquefied natural gas and methane (the principal constituent, 90 to 95 per cent, of liquefied natural gas) were analyzed, and the results provided guidance for planning the experimental program reported here. The results of the previous study were also compared with the data obtained in the currently reported experimental investigation.

The experimental investigation comprised tests to determine vaporization rates of liquefied natural gas, mixing rates of the resulting vapors with air, the effect of temperature and nitrogen dilution on the flammable limits of methane in air, the burning rate of the liquefied natural gas in pool configurations, as well as corresponding rates for other hydrocarbon liquids, the fraction of the heat of combustion generated and dissipated by radiation, and the feasibility of liquefied natural gas fire extinguishment using dry-powder fire extinguishing agents.

Based on the results of the tests, the authors conclude that liquefied natural gas may be safely stored in appropriate above-ground containers, surrounded by earthen berm walls or dikes, in much the same manner employed for gasoline storage, and that separation distances between tanks and adjacent buildings should be of the same order of magnitude as for gasoline storage. (The NFPA Code 30, of 1961, was cited in reference to gasoline storage configuration requirements.)

Salient test observations included:

1. In the event of large spills of liquefied natural gas, flash vaporization can produce flammable vapor mixtures at appreciable distances downwind from the point of spill for a period of about one minute following the time of spill.
2. Following the transient condition cited above, the zone of flammable mixtures is restricted to the immediate spill area. This characteristic reflects the critical function of confining berms or dikes in controlling the hazard of stored liquefied natural gas spills.
3. Spillage of liquefied natural gas with simultaneous ignition of the ensuing vapors produces a flash-type combustion, but no over-pressure wave or splashing of fuel, followed by steady-state burning.
4. Delayed ignition of liquefied natural gas spills results in steady-state combustion.
5. Burning rates, on a weight basis per unit burning liquid surface area, for liquefied natural gas pools following the initial flash vaporization from the pool filling, and the fraction of the heat of combustion dissipated by radiation approximate the corresponding values for gasoline.
6. In connection with spills of liquefied natural gas in air (conducted in the Lake Charles, Louisiana test area), the flammable vapor concentrations were always observed to occur within the confines of the resulting condensed water-vapor cloud. No data specifying the relative humidity at the times of the tests were presented, however.
7. Extinguishment of liquefied natural gas fires was accomplished using a sodium bicarbonate-type dry-powder fire extinguishing agent applied at a rate of about 0.14 lb sec^{-1} ft^{-2}. The authors recommend that the extinguishing agent be applied as rapidly as possible over the entire burning liquid surface, since the agent falling directly into the liquefied fuel, or through the flames, increases the rate of vaporization and the volume of flammable vapors available to support combustion.

Data presented from previous investigations defining the combustion characteristics of methane, compared with corresponding values for other fuels, included:

1. Temperature for spontaneous ignition by heated surfaces, 537°C.
2. Temperature for ignition by a heated 10 mm diameter nitrogen gas jet, 1325°C.
3. Limiting oxygen concentration, corresponding to the dilution of a stoichiometric mixture of methane in air by nitrogen to the point of no longer supporting combustion, 12.1 per cent by volume.
4. Flammable concentration range in air, 5.0 to 14.0 per cent by volume (lower and upper flammability limits).
5. Minimum ignition energy, 0.3 millijoules.

6. Approximate fraction of the heat of combustion in quiet air that is dissipated by radiation, 0.23 (a fraction of 0.25 was estimated for liquefied natural gas).
7. Laminar burning velocity in air, 39 cm $\sec^{-1}$.

The thermal output per unit liquefied natural gas burning surface area was estimated to be 3.2 kcal cm^{-2} min^{-1}, based also on previous work.

In the experimental program currently reported, "steady-state" rates of liquefied natural gas vaporization in 30 in. diameter trays, and 5 by 5 ft pits, 1 ft depth were determined to be 0.016 in. min^{-1} and 0.02 in. min^{-1}, respectively (following the initial flash vaporization, with an exponential-type decay, experienced immediately after pouring fuel into the tray or pits). The pertinent vaporization rate equation was cited as:

$$v=\frac{K}{\rho L}\,\frac{T_1-T_0}{(\pi ut)^{\frac{1}{2}}}$$

where v = vaporization rate, cm $\sec^{-1}$; u = thermal diffusivity, cm^2 $\sec^{-1}$; T_1-T_0 = the temperature difference between ground and liquefied natural gas, °C; ρ = density of liquefied natural gas, gm cm^{-3}; L = latent heat of vaporization of the fuel cal gm^{-1}; K = thermal conductivity of the ground soil, cal cm^{-1} $\sec^{-1}$ $°\text{C}^{-1}$; and t = time, sec.

The Bakke dispersive mixing parameter, $\psi=U/(gV\Delta\rho/\rho W)^{\frac{1}{3}}$ was also discussed, where $\psi\geq 4$ indicates turbulent gas mixing; $\psi\leq 3$ indicates nonturbulent condition, or stability of vapor boundary layers downwind from spills; V = wind velocity; g = gravitational constant; $\Delta\rho$ = difference in density, methane vapor and air; W = width of vapor layer resulting from spill; ρ = density of air; V = volume flow rate of methane vapor.

In the discussion, it was noted that a definite value for $\Delta\rho$ could not be assigned because of ground warming effects on the fuel vapor.

Lower flammable limits for methane in air at various reduced temperatures, and flammable limits of methane-air-nitrogen mixtures were determined at 28°C and −130°C. A modified Burgess–Wheeler relationship was presented for the correlation of lower flammable limits of methane in air with temperature, i.e.,

$$L_T=5.0+0.0035\ (25-T)$$

where

L_T = per cent by volume of methane at temperature T °C corresponding to the lower flammability limit
T = temperature, °C.

Burning rates of liquefied natural gas were experimentally derived and correlated with the burning liquid surface area (pool diameter). Previous studies yielded the relationship

$$V=V_\infty(1-e^{-kd}),$$

where V = liquid burning rate (volume of liquid burned per unit surface area in unit time) e.g., cm min^{-1}; V_∞ = liquid burning rate in pool of infinite diameter (i.e., upper limit of burning rate) cm min^{-1}; k = unit constant, *ca.* 0.03 cm^{-1} where d is expressed in cm, or 0.9 ft^{-1} where d is expressed in ft; d = pool diameter expressed in cm or ft as noted above; V_∞ is related to the fraction of the actual heat of combustion which is absorbed in the liquid fuel to maintain vaporization, that is,

$V_\infty(\text{cm min}^{-1}) = 0.0076L/V$, where L = net heat of combustion per unit weight and V = heat for vaporization of the liquid fuel, per unit weight.

The tests to determine fuel burning rates, and radiation outputs were conducted in pools from ½ ft diameter to dimensions of 20 by 20 ft, under various wind velocities. Fuels investigated included liquefied natural gas, hexane, benzene, and gasoline. With liquefied natural gas, fractions of thermal energy released which were radiated were observed as high as 0.34, and as low as 0.14 in the tests reported (compared to the anticipated value previously cited of 0.25, and the more generally observed range in the reported tests of from 0.20 to 0.27). It was noted that V_∞, the upper limit of the burning rate (i.e., 0.66 cm min^{-1}) exceeded the value anticipated from previous studies. The effect of wind velocity was, however, difficult to assess quantitatively. Energy radiated per unit burning liquefied natural gas surface area ranged from 37 to 75 kilowatts per square foot (40 to 82 watts cm^{-2}).

Data were presented and discussed in 21 figures, and 10 tables. Twelve references were cited, including two from FIRE RESEARCH ABSTRACTS AND REVIEWS: Volume 3, 159–171 and 171–192.

Subject Headings: ***Natural gas, fire and explosion hazards; Fires, of liquified natural gas; Explosion, associated with liquified natural gas; Methane, liquid combustion, characteristics of.***

J. E. Malcolm

Millikan, R. C. (General Electric Research Laboratory, Schenectady, New York) "Non-Equilibrium Soot Formation in Premixed Flames," *Journal of Physical Chemistry* **66**, 794–799 (1962)

Soot deposition was studied in a series of premixed ethylene–air flames burning on large flat porous metal burners. The onset of soot deposition in certain ethylene–air flames was observed for mixtures with a carbon to oxygen atom ratio as low as 0.58. If equilibrium prevailed, soot would not be set free until this ratio exceeded 1. Such non-equilibrium behavior has been observed before and for a variety of fuels. The purpose of this work was to collect sufficient experimental data on a well-defined system, to find an explanation for the occurrence of non-equilibrium soot deposition, and to elucidate the mechanisms involved.

The flames studied were burned on porous metal burners of the type developed by Kaskan.[1] Burners used ranged from a 2.5×5 cm rectangular one to circular ones 7 cm in diameter. All flames were shielded by N_2 gas. Optical and probe sampling techniques were used to give the spatial distribution of C_2H_2, CH_4, OH, and soot concentrations as functions of burned gas temperature.

It was found that acetylene and methane (in smaller amounts) are produced in the reaction zone of the flame and survive to form about 1 per cent of the burned gases. Next above the reaction zone is a dark space which turns out to be a region of high oxidizing power due to the OH concentration in excess of equilibrium. Following the dark zone is the appearance of a soot zone. The critical mixture ratio at which soot appears is temperature dependent.

A soot deposition process which qualitatively accounts for all of the observations is given involving reasonable kinetic parameters for the reactions involved. The conclusions drawn are these:

1. The hydrocarbons found in the burned gases of rich flames in amounts in excess of equilibrium are produced in the reaction zone, well before the region of soot deposition.
2. The dark space lying between the reaction zone and the soot zone is an oxidizing region due to the concentration of OH in excess of equilibrium.
3. Non-equilibrium soot formation results from thermal decomposition of the acetylene and, to a much lesser extent, the methane produced in the reaction zone. This pyrolysis is opposed at some stage by an oxidation reaction involving mainly OH as the oxidizer. It is the balance between these two reactions which determines whether or not soot is set free.
4. The critical mixture ratio at which soot first is observed is temperature dependent. With certain assumptions, this temperature dependence leads to a value of 34±10 kcal/mole for the activation energy of the soot deposition reaction. This value is in agreement with shock tube results on the pyrolysis of acetylene-argon mixtures.

Reference

1. Kaskan, W. E.: *Sixth Symposium (International) on Combustion.* Reinhold Publishing Corporation, New York, 1957, p. 134.

Subject Headings: ***Flame, soot formation; Soot, formation in flame.***

W. C. Johnston

V. Combustion Principles

Fristrom, R. M. (Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland) "Radical Concentrations and Reactions in a Methane–Oxygen Flame," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 560–575 (1963)

The methane-oxygen flame has been under study in the author's laboratory by micro-probe and thermocouple techniques wherein composition and temperature profiles have been obtained. In the present paper composition profiles for radicals have been determined for a spherical methane–oxygen flame ($CH_4=0.078$, $O_2=0.92$, $P=0.05$ atm). A recently-developed "scavenging" technique has been applied wherein atoms or radicals react in the sampling probe with a stable species to produce another stable species whose concentration gives an unequivocal measure of the original radical concentration. This technique has been used here to determine O atom concentrations via the reaction $O+NO_2 \rightarrow O_2+NO$; some information on H atom concentration has similarly been determined using the reaction $H+CCl_4 \rightarrow HCl+CCl_3$. Hydrogen atom concentrations were actually estimated assuming that oxygen disappeared by reaction with hydrogen atoms. Hydroxyl radical concentrations were derived from the rate of carbon dioxide formation, the carbon monoxide profile and the experimental rate constant of the reaction $HO+CO \rightarrow CO_2+H$. Values so obtained were in agreement with values determined elsewhere spectroscopically.

With this information composition profiles for the present flame can be drawn for H_2O, CH_2O, O_2, CO_2, CO, CH_4, H, OH and O. From these profiles, the temperature profile and experimental rate constants, the author concludes that the following two schemes are self-consistent descriptions of the reactions occurring in the flame:

Mechanism 1

$$\begin{array}{c} \mathrm{3O_2+3H\rightarrow 3OH+3O} \\ \mathrm{CH_4+OH\rightarrow H_2O+CH_3} \\ \mathrm{CH_3+O\rightarrow OCH_2+H} \\ \mathrm{OCH_2+OH\rightarrow H_2O+HCO} \\ \mathrm{HCO\rightarrow CO+H} \\ \mathrm{CO+OH\rightarrow CO_2+H} \\ \mathrm{O+O+M\rightarrow O_2+M^*} \\ \hline \mathrm{CH_4+2O_2\rightarrow 2H_2O+CO_2} \end{array}$$

Mechanism 2

$$\begin{array}{c} \mathrm{2O_2+2H\rightarrow 2OH+2O} \\ \mathrm{CH_4+OH\rightarrow H_2O+CH_3} \\ \mathrm{O_2+CH_3\rightarrow OCH_2+OH} \\ \mathrm{OCH_2+O\rightarrow HCO+OH} \\ \mathrm{HCO\rightarrow H+CO} \\ \mathrm{CO+OH\rightarrow CO_2+H} \\ \mathrm{2OH\rightarrow H_2O+O} \\ \mathrm{2O+M\rightarrow O_2+M^*} \\ \hline \mathrm{CH_4+2O_2\rightarrow 2H_2O+CO_2} \end{array}$$

Seventeen reactions occurring in this flame are tabulated and the Arrhenius parameters for the forward and reverse steps are given where known. In addition the compositions and net rates of production of CO_2, CH_2O, CO, H_2O, CH_4, H_2, NO, O_2 and O, and the temperatures are tabulated as a function of distance for the given flame.

The author discusses various features of the results. The data obtained in the present work for the rate of the reaction

$$\mathrm{OH+CH_4\rightarrow H_2O+CH_3}$$

are in good agreement with earlier results from the present laboratory at a higher temperature and yield a frequency factor of 1.4×10^{14} sec^{-1} and an activation energy 6.5 kcal $mole^{-1}$ for the temperature range of about 1200° to 1800°K.

Oxygen atoms are the most abundant radical with a maximum concentration of 0.015 mole fraction. As seen above they disappear mostly by reaction with methyl radical or formaldehyde.

Although methyl radical concentrations could not be determined directly, it was assumed that the most probable way in which they were consumed in the probe was by reaction with oxygen to give formaldehyde. This placed an upper limit on the methyl radical concentration of 10^{-3} mole fraction, which was the formaldehyde concentration. Evidence for the methyl radical reactions written in the above two schemes is given.

Some discussion is given of the recombination region in the flame, roughly beyond about 9 mm from the burner surface, where atom and radical recombinations are important. It is pointed out that the rate of disappearance of oxygen atoms is too great to be explained by the direct three-body recombination. The presence of nitric oxide in the flame, presumably as a result of air impurities, makes it possible to write the reactions

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

which serve to explain the observed rate of oxygen atom disappearance.

Subject Headings: ***Methane, radicals and reaction in flame; Flame, methane–oxygen radicals and reaction.***

J. B. Levy

Blackmore, D. R. and Hinshelwood, C. (University of Oxford, Oxford, England) "Inhibition and Acceleration of Paraffin Decomposition by Nitric Oxide," *Proceedings of the Royal Society* **A268**, 21–35 (1962)

This paper is a very detailed exploration of the mechanism of paraffin decomposition with and without inhibitor. A very extensive review of previous work is given with pertinent comments during the summary. To begin, the authors state that paraffin hydrocarbon decomposition proceeds by a free-radical chain mechanism and that inhibitors reduce the rate by reacting with the chain-carrying radicals. Secondly, increasing amounts of inhibitor reduces the rate to a limit rather than to zero. Thirdly, NO is an effective inhibitor and with large amounts of this reagent, the rate increases again—linearly with inhibitor pressure. The limited rate of the inhibited reaction is called the rate of the "maximally inhibited reaction." The accelerated reaction associated with large amounts of NO is termed the "induced reaction." An "inhibition curve" is defined as a plot of the rate of decomposition of the paraffin as a function of inhibitor pressure. Now, we can follow the careful study of the induced reaction and its relation to other parts of the mechanism.

A great deal of attention is given to the method of rate measurement. Whether the initial rate or the steady-state rate should be used has been a question in the past. Of the several explanations for the "initial burst," the authors believe that the initial rate is the true rate; and its subsequent decrease is the result of secondary polymerization of olefinic products. In this case, both the initial and steady rates are valid measures of decomposition, provided one uses the correct stoichiometric conversion factor. This case is shown to be the most probable by experiments performed with neopentane. These studies showed that the initial burst was somewhat dependent on surface conditions, but the steady state was unaffected. The addition of isobutene (10%) also left the steady state undisturbed, but completely eliminated the initial rate. Variation of surface/volume ratio had no effect on the steady rate, but lowered the initial rate to some extent when isobutene was added. On adding 15% NO and 10% isobutene, the steady rate remained unchanged while the initial rate was decreased. These results indicate that both rates are characteristic of homogeneous processes.

With the arguments presented above, the authors chose the "reciprocal-time" method as a valid measurement of the rate. The quantity used is the reciprocal of the time, in seconds, for ΔP to change from 10 to 20 per cent of the initial hydrocarbon pressure. As a result of measurements for the three isomeric pentanes (normal, iso-, and neo-), the authors report some pertinent observations. Normal and iso-pentane behave similarly, but the neo- compound differs considerably from them. For the latter the rates are lower, the maximum extent of inhibition is less, and much more NO is needed for a given fractional inhibition. Inhibition curves are presented for the three compounds and are analyzed separately.

In a discussion of the induced reaction and the maximally inhibited reaction, the authors show that the latter is influenced to some extent by the former. In support of the assumption that the maximally inhibited reaction is a molecular process, close examination of inhibition curves for *n*-pentane and neo-pentane show that the slopes of the rising portion of the curves (induced reaction) are in a ratio of 5 to 1. Neo-pentane has primary hydrogen atoms only, while *n*-pentane has numerous secondary hydrogen atoms making it susceptible to H-atom abstraction by the nitric oxide.

In discussing the mechanism of the induced reaction, it is assumed that a molecular reaction takes place along with the generally accepted free-radical chain process. The molecular reaction is believed to predominate in the maximally inhibited reaction. The true rate of the induced reaction is the total measured rate at a given [NO] less the rate of the molecular reaction. First-order rate constants are tabulated over a range of pressure for each hydrocarbon. Also, a table of rate constants for the induced reaction is presented. In the latter k_{induced} is seen to be very nearly steady over a considerable pressure range.

The authors conclude that the three parts of the inhibition curve should be considered in relation to each other and not piecemeal. In the region of the induced reaction the rate is proportional to [RH][NO] and the consumption of nitric oxide amounts to one molecule for each molecule of hydrocarbon decomposed. The most plausible interpretation of this is an initial hydrogen abstraction by NO, yielding HNO.

Subject Headings: ***Hydrocarbons, decomposition, influenced by nitric oxide; Inhibition, of paraffin decomposition, by nitric oxide.***

C. O'Neal, Jr.

Blackmore, D. R. and Hinshelwood, C. (University of Oxford, Oxford, England) "Derivation of Rate Constants for Steps in the Free-Radical Chain Decomposition of Paraffins," *Proceedings of the Royal Society* **A268,** 36–45 (1962)

This paper is a follow-up of the paper discussed in the abstract immediately preceding this one.

Here the authors attempt to deduce specific rate constants for the many reactions involved in the scheme from the measured results given in the previous paper. Propane and the three pentanes were studied in the first report and the decomposition reaction was found to be very nearly first order. The three octanes were added in the present work, and they exhibited first-order behavior also.

The six reactions following represent the mechanism of the paraffin decomposition and also the starting point for separating the individual rate constants.

(1) $RH = R' + CH_3$

(2) $CH_3 + RH = CH_4 + R$

(3) $R = CH_3 + \text{olefine}$

(4) $CH_3 + R = \text{end product}$

(5) $CH_3 + NO = \text{end product}$

(6) $R + NO = \text{end product}$

Let $CH_3 = X$, $R = Y$, $RH = a$, and $NO = b$. Then

$$dx/dt = k_1a - k_2ax + k_3y - k_4xy - k_5bx = 0$$

$$dy/dt = k_2ax - k_3y - k_4xy - k_6by = 0.$$

The rate of hydrocarbon consumption r is $r = k_1a + k_2ax$. When the chains are long enough $r = k_2ax$. When inhibitor concentration is zero, the equations above predict a first-order rate constant. i.e.,

$$k_{\text{chain}} = (k_1k_2k_3/2k_4)^{\frac{1}{2}}. \tag{1}$$

Equations involving the variation of rate with nitric oxide concentration are inconvenient to manipulate. So, by using the initial rate of decomposition velocity with small increases in inhibitor concentration, the authors arrive at the following equation:

$$\frac{-4(\text{rate})/\text{rate}}{b} = \frac{k_5(k_3/k_4)}{ak_{\text{chain}}} + \frac{k_6(k_2k_4)}{k_{\text{chain}}}. \tag{2}$$

Of the six constants involved in the total reaction scheme, four appear in Eq. (1) and five appear in Eq. (2). k_{chain} is an experimental quantity, $k_{\text{chain}} = (k_0 - k_\infty)$, where k_0 is the rate constant of the uninhibited reaction, and k_∞ is that of the maximally inhibited reaction. Now, we have the "tools" with which to untangle all the rate constants involved.

The next several pages show in great detail with very appealing logic how the six rate constants are obtained. Tentative relative values were first assigned through the use of the k ratios appearing in Eqs. (1) and (2). With assumptions about activation energies and steric factors, the authors tabulate the calculated constants for the isomeric pentanes and octanes. All six rate constants are examined in the homologous series from octane down through propane. Definite trends are observed for all compounds. k_1, for example, is lowest for the normal compound in each series and highest for the most branched. On the other hand, k_3 is highest for the straight-chain compound and lowest for the most branched. These observations tell us that the most stable heavy radical comes from the parent hydrocarbon which most readily suffers an original carbon–carbon split.

After the fruitful encounter with assigning relative rate constants, the authors attempt to assign approximate absolute values. In adjusting the relative values of the constants, the authors warn that the adjustments are limited by fairly stringent kinetic laws. The k ratios are fixed by experiment, thus the raising or lowering of a particular constant can be done only within its lawful range. From the adjusted constants are calculated Arrhenius parameters for Reactions 1 and 3. For example,

$$k_1 = A\exp(-E_1/RT) \qquad \text{and} \qquad k_3 = A\exp(-E_3/RT).$$

Activation energies are tabulated for propane, pentane, and octane using various values of A.

The authors conclude that the individual rate constants arrived at are rather rough; but as a whole, they offer a coherent picture of rate constant variation with hydrocarbon structure. Indeed, considering the two papers, this work does much to elucidate the kinetics of hydrocarbon decomposition by a free-radical chain mechanism.

Subject Heading: ***Hydrocarbons, decomposition rate constants.***

C. O'Neal, Jr.

Lee, T. G. (National Bureau of Standards, Washington, D. C.) "Electron Attachment Coefficients of Some Hydrocarbon Flame Inhibitors," *Journal of Physical Chemistry* **67**, 360–366 (1963)

To test the hypothesis that the effectiveness of flame inhibitors is associated with their ability to capture electrons[1] Lee has measured the electron attachment coefficient of some 27 halogenated hydrocarbons at S.T.P. as a function of mean electron energy in an energy range (0.1 to 1.2 eV) bracketing that of interest in flames. With few exceptions a qualitative correlation could be found but the exceptions indicate that high attachment coefficient alone is not necessarily indicative of high effectiveness as inhibiting agent. It is remarked that all of the effective inhibiting agents were found to have higher attachment coefficients than O_2, with CF_2Br_2 having the highest coefficient of the compounds studied.

The experimental technique makes use of the electron pulse produced by a collimated, 5.3 meV α-particle in a parallel-plate ionization chamber. The chamber is filled with a carrier gas and a small amount (typically 1 to 2000 ppm) of inhibitor. Electrons produced in the wake of the α-particle drift under the influence of a small imposed electrostatic field and the basic measurement is then the time variation of the electrostatic potential at the electrodes. The relation between observed pulse height and electron attachment coefficient given by Bortner and Hurst,[2] has been used in this study. Mean electron energy is varied by varying the applied potential at the electrodes, keeping the total chamber pressure constant.

Unfortunately for the flame kineticist, values of the attachment coefficient reported have somewhat awkward units: attachment probability per centimeter of electron travel in the field per unit concentration (ppm) of attaching gas in the non-attaching carrier. However, the data reported are extensive and reveal important trends as to the variation of attachment coefficient with electron temperature as well as the type and number of halogen atoms present in the molecules tested. For example, it has been observed that (1) for a given alkyl group the effect of a halogen atom is in the decreasing order $I > Br > Cl > F$ and (2) the greater the number of Br or Cl atoms substituted in the alkyl group the higher the probability of electron attachment. The attachment coefficient for most compounds examined decreases as the electron temperature increases above 1500°K; but, again, this dependence is not without important exceptions (e.g., CF_4, $C_2F_4Cl_2$). As anticipated, observed attachment coefficients (as defined above) were independent of the concentration of the attaching gas in the chamber. This was tested for 3 halogenated compounds at several values of E/p over as much as a hundredfold variation in concentration. Qualitative agreement is reported between the results of the electron swarm technique and electron beam,[3] as well as mass spectrometer[4] measurements. Since the electron swarm technique has proven itself capable of covering millionfold variation in attachment coefficient, it would appear to represent a powerful tool for future research on electron attachment rates.

References

1. Creitz, E. C.: *J. Res. Natl. Bur. Std.* 65A, 389 (1961).
2. Bortner, T. E. and Hurst, G. S.: *Health Phys.* **1**, 39 (1958).
3. Hurst, G. S., O'Kelly, L. B. and Bortner, T. E.: *Phys. Rev.* **123**, 1715 (1961).
4. Hickam, W. M. and Berg, D.: *J. Chem. Phys.* **29**, 517 (1958).

Subject Headings: ***Inhibition, attachment coefficients; Hydrocarbons, inhibitions, attachment coefficient.***

D. E. Rosner

VI. Radiation

Hottel, H. C. (Massachusetts Institute of Technology, Cambridge, Massachusetts) "Radiation as a Diffusion Process," *International Journal of Heat and Mass Transfer* **5,** 82–83 (1962)

The paper "On the Regularities of Composite Heat Transfer" by Konakov, appearing in the March 1961 issues of the Journal, is in the opinion of Hottel quite misleading in suggesting that combined conduction and radiation in absorbing–emitting–conducting bodies may be so treated as to obtain a simple explicit solution of the problem which is valid over the full range of variation in body dimensions—measured in mean free paths. Konakov recommends equations purporting to give the flux from hot to cold wall due to radiation and conduction acting together, for the three cases of a diathermanous medium in steady state between hot and cold parallel plates, between concentric cylinders or concentric spheres. Hottel shows that Konakov's recommendations for parallel walls are easy to test, since several authors have treated that case rigorously. A graph adequately supports the generalization that radiative flux is expressible as a diffusion process $D_r(d\phi dx)$ only where $d\phi/dx$ is constant for several mean free paths on either side of the plane of interest. Here D_r is the diffusivity of photons and ϕ is the radiation density of local space. Konakov does distinguish between molecular temperature T and radiation temperature T_{Av} but the equations he finally recommends do not permit the distinction. It is clear on physical grounds that where KL (the number of mean free paths between walls) is small there is no dodging the solution of an integral equation or its equivalent.

The Konakov analysis also makes use of what the present author believes is an incorrect value of D_r, namely $cl_s/4$ instead of $cl_s/3$, where l_s is the mean free path of a photon or $1/K$ (K is the absorption coefficient).*

---

* This difference is discussed by the present author in a lecture entitled "Some Problems in Radiative Transport" presented at the International Heat Transfer Conference, Boulder, Colorado, August 1961.

Many problems of practical interest lie in the KL range 0 to 3 where, as Hottel's figure indicates, Konakov's proposed approximation has negligible value. When KL is large the technique of adding λ_c and $16\sigma T_{Av}^3/3K$ to obtain λ_T, where λ_c is the true thermal conductivity and λ_T is the effective or "total" conductivity due to conduction plus radiation, is well known.

Subject Heading: ***Radiation, diffusion process.***

H. E. Perlee

VII. Suppression of Combustion

Halpern, C. (National Bureau of Standards, Washington, D. C.) "Effect of Methyl Bromide Additions on the Flame Speed of Methane," *Journal of Research of the National Bureau of Standards* **67A,** 71–77 (1963)

Halogenated hydrocarbons have been used to extinguish fires and the effect of these combustion inhibitors on various combustion parameters has been studied. Limits of flammability, quenching distance, and laminar flame speed have been found to be affected by these inhibitors. The inhibiting effect of methyl bromide on the flame speed of methane is the chief topic of this investigation.

A description of the apparatus and method used to measure flame speeds is presented.[1] The apparatus consists of a drying and metering system for air and fuel, and a nozzle, the exit of which is the burner port. Means are provided to control the temperature of the combustible mixture issuing from the nozzle. Flame speeds are determined by a total-area method, which is based on the measurement of the area of an enlarged photograph of the schlieren image of the flame. It was decided to prepare mixtures of air and methyl bromide of the desired strength and to meter these mixtures, rather than to set up a third measuring system for the methyl bromide.

Mixtures of 0.1, 0.2, 0.3, 0.4, and 0.5 per cent by volume of methyl bromide in air were prepared. For each mixture, the variation of flame speed with mixture ratio, by weight, of methane to air plus methyl bromide was determined, gas velocity at the exit of the nozzle being constant. The ratio, by weight, of methane to air plus methyl bromide was varied from 0.054 to 0.072 and the gas velocity at the port of the nozzle was varied from 3 to 6 ft/sec. Control of the temperature of the combustible mixture was such that the maximum change in temperature during a single run was about 3.7°F. Correction of flame speeds to 75°F was accomplished using the value 0.00328 ft/sec F°.

The outer mantle of the flames was colored brown by the formation of free bromine and the odor of bromine was noticeable. It is probable that hydrogen bromide is the original product and is converted to bromine by the over-all reaction

$$4HBr+O_2\rightarrow 2Br_2+2H_2O.$$

Apparently in a rich flame there is insufficient oxygen for complete conversion of hydrogen bromide.

Theoretically, the velocity with which combustible gas issues from a burner should have no effect on the flame speed. In practice, some variation of flame speed with gas velocity is noted.[1] In this investigation a small decrease of flame speed with increasing gas velocity, amounting to about 2 per cent, was found. Hence the data are reported at four different gas velocities.

The results are given as curves and in tabular form. In general, the addition of 0.5 per cent methyl bromide reduces the flame speed to 70 per cent of its former value.

In the method used for determining flame speeds, photographs of the schlieren and visible images of the flame are taken simultaneously on the same film. The schlieren image which depends on the change in density and thus on the change in temperature marks the position where chemical reactions begin in the flame. The visible image indicates the region in the flame where reactions are completed. Hence, the separation between the two images is a measure of the thickness of the reaction zone.

It is found that the thickness of the reaction zone varies with flame speed; the greater the flame speed, the less the thickness of the reaction zone. The thickness of the reaction zone is given for the ratios of different mixtures and is roughly 0.020 inch. When various amounts of methyl bromide are added, the reaction zone becomes thicker. For example, 0.5 per cent methyl bromide will increase the thickness from 0.025 to 0.036 inch.

Small amounts of methyl bromide added to methane–air mixtures have a large effect on the flame speed. Maximum flame speed is reduced proportionally to the amount of methyl bromide added. Flame speed of rich mixtures is much more reduced than that of lean mixtures. Reaction zone thickness is increased by the presence of methyl bromide.

Reference

1. Halpern, C.: *J. Res. Natl. Bur. Std.* **60**, 535 (1958).

Subject Headings: ***Flame speed, effect of methyl bromide on methane; Methane, methyl bromide effect on flame speed; Methyl bromide, effect on flame speed.***

W. C. Johnston

Kazakov, M. V. "The Problem of Investigating the Stability and Insulating Properties of the Air-Mechanical Foam," Russian Book: *New Methods and Means of Extinguishing Flames of Petroleum Products*, 135–147 (1960) Translated by A. Pingell, U.S. Naval Research Laboratory, Washington, D.C. (NRL Translation No. 915)

Fire extinguishing foams are the principal means for combatting highly flammable liquids. The principal factors considered at the present time as having an effect on the termination of the burning process are: (1) The cooling of the heated layer of a petroleum product by the liquid drained off the foam during its decomposition; and (2) The insulation of combustible vapors against the flame zone by a layer of foam. The term "insulation" means both the retardation of the diffusion of the combustible vapor by means of the foam layer as well as the resistance or stability of this layer to vapor break-through.

In the past few years the problem of foam stability and its insulating properties has been considered by many with unsatisfactory results. One of the reasons for this is that the behavior of the foam was considered separately from the behavior of the combustible liquid. Therefore, in connection with this present work, the investigation was carried out in two directions: (a) The stability of the air mechanical foam obtained from a 2 per cent solution of the foam former PO–1 was determined with respect to a number of flammable liquids. The flammable liquids were heated to different temperatures and the stability of the foam was judged by the accretion of liquid from the foam. (b) The capacity of a foam with different degrees of stability to insulate the combustible vapors was determined.

The extinguishing of highly flammable liquids is accomplished, in any case, according to a unique scheme. There is a definite critical temperature of the surface layer of a liquid, above which the foam will not produce any insulation. In the beginning, it is necessary first to cool the highly flammable liquid down to the critical temperature, and only after that will the factor of insulation come into action. In this initial stage of extinguishing, the stability of the foam has no great significance, and only after the temperature of the surface layer of the liquid has been reduced to the critical value, will the stability of the foam acquire a decisive role.

Determination of the foam stability was accomplished in an apparatus previously described.[1] The stability of foam with regard to different highly flammable liquids was determined by the rate of syneresis (accumulation of liquid from the foam). Benzene, toluol, *n*-xylol, hexane, heptane, octane, gasoline, and kerosene were used as the combustible liquids. It can be said that the decomposition of the foam at a particular temperature is not dependent on the vapor pressure of the liquid, but is wholly dependent on its individual properties and, in part, on the chemical structure.

The insulating property of the foams was studied in an apparatus which consisted of a metallic vessel placed into a water or glycerine bath. The liquid to be studied is poured into the vessel where it is kept at the required temperature. The top surface of the liquid is covered with a certain layer of foam and the upper surface of the foam is tested by a spark jumping between two electrodes. The insulating capacity of the foam is characterized by the time which has elapsed between the moment the foam was deposited on the surface of the liquid and the moment its vapors ignited.

The following conclusions may be drawn:

1. It is indicated that the stability of a foam is affected by its quality, chemical composition, and temperature of the heated layer of the combustible liquid.
2. A method has been developed for determining the insulating capacity of foams.
3. It has been determined that the insulating capacity of a foam is dependent on the structure of the liquid, temperature of the heated layer and, in connection with it, on the vapor pressure of the combustible liquid.
4. Critical temperatures of the insulating capacity of foam have been determined for the highly flammable liquids investigated.

Reference

1. Losev, V. P. and Kazakov, M. V.: *Otchet TsNIIPO, MVD, SSSR* (Report of the Central Scientific Research Institute of Fire Protection, Ministry of Internal Affairs, USSR), 1958.

Subject Heading: *Foam, properties of.*

W. C. Johnston

VIII. Model Studies of Scaling Laws

Spalding, D. B. (Imperial College, London, England) "The Art of Partial Modeling," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 833–854 (1963)

Modeling is the practice of predicting the likely result of one experiment by way of the interpretation of the result of another experiment, the second experiment only being performed once the experimenter is satisfied that its predictions are reliable. The first experiment, the full-scale experiment, is the object of interest, but is often prohibitively expensive of time, money, or material. In these circumstances the technique of modeling is often employed to obtain a relatively cheap prediction of the results.

In order to model successfully it is necessary that certain rules are obeyed in setting up and interpreting the results of the experiment. These rules are obtained by dimensional analysis or by study of the governing differential equations, and usually take the form of specifying which dimensionless quantities must have the same value in the model as in the full-scale experiment. In simple cases, where the number of dimensionless quantities is small, it is often possible to obey all the rules for correct modeling and accurate predictions can be obtained relatively easily. In more complicated cases, however, it is impossible to obey all the rules since the number of rules to be obeyed may greatly exceed the number of degrees of freedom at the disposal of the experimenter. Fortunately, however, although many factors may influence the outcome of an experiment, some of these influences are much weaker than others, and provided that these weaker influences can be identified, experience has shown that their neglect does not entirely invalidate the experiment, so that useful results can be obtained. Model experiments in which only some of the rules are obeyed are "partial models" and the central problem of "partial modeling" is to identify which of the modeling rules need not be obeyed. The solution of the problem is largely a matter of physical insight and inspiration.

The combustion process is a complex of a variety of processes such as chemical reaction, mixing, heat transfer, aerodynamic, etc., and in the first part of the paper under review the author lists some of the rules which would have to be obeyed in order to model the combustion process completely, and shows that these are so numerous that it is impossible to comply with all of them. Partial modeling of the combustion process has, however, been widely practiced for many years and it is with the art of this technique that the majority of the paper is concerned. The paper was written to introduce the "Colloquium on Modeling Principles" held during the course of the Ninth Symposium (International) on Combustion in 1962, and constitutes for the most part a sophisticated review of some of the more notable examples of partial modeling of the combustion process, and mentions the physical facts which underlie their success. The author includes a discussion of analogues but excludes a study of mathematical models.

The art of partial modeling is rendered possible, at least in part, by the fact that it is never necessary to make a complete prediction about the outcome of a full-scale experiment and that often only a few pieces of information are of interest. Accordingly, interest is often restricted to particular aspects of the combustion process. For example, it may be desired to know the flow pattern of the gases in a furnace, and here it is the fluid mechanical aspects of the process which are of interest, or it may be that the temperature distribution at outlet from an aircraft gas turbine chamber to fly at low altitude is sought, in which case it is the mixing processes which are of interest. Fortunately it appears that in many cases the component processes of mixing, fluid mechanics, chemical reaction, etc., which together make up the combustion process do not interact to any very great extent. For this reason it is often possible to neglect these interactions when devising models for the prediction of particular aspects of the behavior of the full-scale experiment, thus giving a very considerable reduction in the number of modeling rules which have to be obeyed. In his paper the author considers the various examples of partial modeling according to the various restricted interests which they are able to serve. Thus he considers models useful when interest is restricted to

a) fluid mechanical features of the process,
b) mixing,
c) gross effect of chemical kinetics.

For each he discusses the features of the full-scale experiment that can be predicted and the modeling rules that experience has shown may be neglected. Among the techniques discussed are:

1. The use of water models for the study of steady flow combustion systems.
2. Methods of accounting for the effect of combustion produced density variations in models of the combustion process.
3. The study of the mixing processes by model experiments using tracers.
4. The use of analogues to predict some of the effects of the chemical kinetics.
5. The use of water injection into a combustion chamber operating at atmospheric pressure to predict the effect of combustion chamber operation at reduced pressure.
6. The partial modeling of flame propagation in spark ignition engines.

The paper is well written, desirable reading for all those interested in modeling the combustion process, and should help to establish a proper attitude of mind toward models and modeling.

Subject Heading: ***Models, in combustion research.***

D. G. Martin

Fons, W. L., Clements, H. B., and George, P. M. (Southern Forest Fire Laboratory, U. S. Forest Service, Macon, Georgia) "Scale Effects on Propagation Rate of Laboratory Crib Fires," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 860–866 (1963)

An experimental investigation of crib fires was conducted to determine the effect of fuel and fuel bed properties on fire behavior. The quantitative results of the investigation were used to determine the several governing dimensionless groups to allow scaling.

The model used consisted of a crib of wood sticks mounted on a movable table which could be moved at a controlled rate so as to hold the flaming zone at a fixed position. Three banks of thermocouples were mounted above the combustion table to permit determination of the temperature of the convection column. Fire radiation was measured by thermopile radiometers. Ignition was effected at one end of the crib and the fire allowed to progress to the other. The use of a long crib mounted on a movable table provided a means of studying a line fire in the "steady state."

The effect of specific gravity of wood and wood moisture content was investigated in six series of tests. The crib size was 9.25 inches wide and 35.5 inches long. The flame length data from this series of tests was correlated by using the dimensionless grouping derived by Thomas *et al.* The gas velocity in the Thomas relation was expressed in terms of the properties of the combustion system and by plotting of data and taking the slope, the following relation was obtained for flame length

$$L/D=4.5(C^2G^2/\rho_g{}^2gD)^{0.43},$$

where L is flame length, D is fire depth, ρ_g is gas density, C is combustion gas produced per mass of fuel, G is fuel consumption rate, and g is gravitational acceleration. The exponent value of this relation is in agreement with the value for line fires. Since the ratio of flame zone depth to fire width is less than 1, and the correlation obtained here agrees with that for line fires, it is concluded that this type of crib fire can be used to study line fires.

Data previously obtained by the authors were used to correlate the burning time. The definition of burning time can be stated as the time required for the flame zone to pass a reference point in the crib, or equivalently, the residence time of a fuel particle in the flaming zone. The exponents of the various groups were determined by use of data from 106 fires. A comparison of the burning time correlation obtained from the propagating flame model of this work with the stationary flame model of prior work indicated excellent agreement.

In addition to the conclusions already stated the authors indicate that individual effects of fuel and fuel bed parameters can be studied, and that this work leads to a better understanding of some of the aspects of the burning of wildfires.

It is indicated that studies of local slope, wind, and crib material spacing on the burning characteristics is contemplated.

Subject Heading: ***Fires, scale effects on propagation rates.***

H. N. McManus, Jr.

Thomas, P. H. and Heselden, A. J. M. (Joint Fire Research Organization, Boreham Wood, England) "Behavior of Fully Developed Fire in an Enclosure," *Combustion and Flame* 6, 133–135 (1962)

An experimental study was made of the combustion rate of a fire in a model enclosure with a single opening, simulating a fully developed fire in a small room in a building. Measurements were made with a calorimeter of the rate of heat release within the model enclosure as a function of the "window" size and the supply rate of fuel, town-gas. It was observed that when the window is small the burning rate is limited by the air supply and supplying additional fuel has little or no effect. However, if the supply of fuel becomes very large, the efflux of volatile fuel reduces the inflow of air reducing the combustion rate and part of the combustion occurs outside the enclosure, thereby causing a further reduction of heat released within the room. If the window is large so that sufficient air is available by natural convection, the burning is primarily dependent upon the surface area of combustible material within the enclosure. These are the general effects observed in actual building fires.

The above effects were measured quantitatively in the tests. For a given ratio of window area to enclosure volume, the measured heat release rapidly increased as fuel rate was increased, until a maximum was reached. Further increase in fuel flow caused the rate of heat release to diminish at about half the rate as the initial increase and then continued to decrease but at a lower rate. As the window area is made smaller, the magnitude of the maximum decreases and the fuel rate at which the maximum occurs shifts to lower values.

Experiments were also made in which the window, originally the full width of the enclosure, was progressively blocked by vertical strips. The results showed that the ratio of the rate of fuel released (the rate of decomposition in a wood fire) to the fraction of the window remaining open, was nearly a constant. This results from the rate of decomposition being dependent upon the heat release rate within the enclosure which is in turn dependent upon the availability of air.

From these data, the effects of restricted ventilation on the intensity of a fire within a cubicle can be semiquantitatively evaluated.

Subject Heading: ***Fires, behavior in enclosure.***

R. W. Ziemer

IX. Atomization of Liquids

Hinrichs, B. R. (Polytechnic Institute, Karlsruhe, Germany) "Atomization of Water in Multi-Purpose Nozzles at Pressures up to 355 psi," *VFBD Forschung und Technik im Brandschutz*, **12**, 14–17 (1963)

The effect of pressure drop on the atomization of water in multipurpose nozzles was investigated experimentally and compared with both empirical and theoretical results by other investigators. The numerical average drop size was found to decrease for each of three nozzles as the pressure drop increased from 40 meters water head to 250 meters (57 psi to 355 psi gauge). Comparison with the experimental data reported by Fraser and Eisenklam[1] indicated qualitative agreement, although quantitatively of a different order of magnitude since Fraser's data were obtained with oil nozzles of much smaller flow rate. Fuel oil data obtained by Joyce[2] evidenced similar behavior, with drop sizes increasing with the flow number.

A final comparison was made with the theoretical curve for maximum droplet diameter obtained by Troesch[3] for atomization which is theoretically independent of nozzle size or geometry:

$$\left(\frac{T}{\rho_L V^2 d_{\max}}\right)\left(1+10^6\frac{\mu_L^2}{T\rho_L d_{\max}}\right)^{1/12}[1-0.5(\rho_A/\rho_L)]$$
$$=W^{-1}[1+10^6(W/R^2)][1-0.5(\rho_A/\rho_L)]=4.8\times10^{-5}, \quad (1)$$

where T=surface tension of liquid, V=velocity (relative) of liquid jet, $d_{\max}$= maximum droplet diameter, ρ_L=liquid density, ρ_A=air density, μ_L=liquid viscosity, W=Weber number, and R=Reynolds number.

Application of the similarity principle and probability concept to Troesch's theory resulted in the following equations for drop size distribution (n_i/N) and

Sauter Mean Diameter, respectively:

$$n_i/N = \frac{e^{-b/x}(1+b/x)}{e^{-b}(1+b)}, \tag{2}$$

and

$$d_m = d_{\max}\cdot b[(-e^{-b}/b\cdot \mathrm{Ei}(-b))-1], \tag{3}$$

where n_i = number of drops in ith size range, N = total number of droplets, $x = d_i/d_{\max}$ = relative diameter in ith size range, b = arbitrary constant, approximately equal to 0.35, $\mathrm{Ei}(-x)$ = exponential integral of x, d_m = Sauter Mean Diameter.

Direct comparison of the author's data with Troesch's theoretical results is shown in Figs. 1 and 2, which reveals a wide difference in maximum diameters, and close correlation of size distribution data.

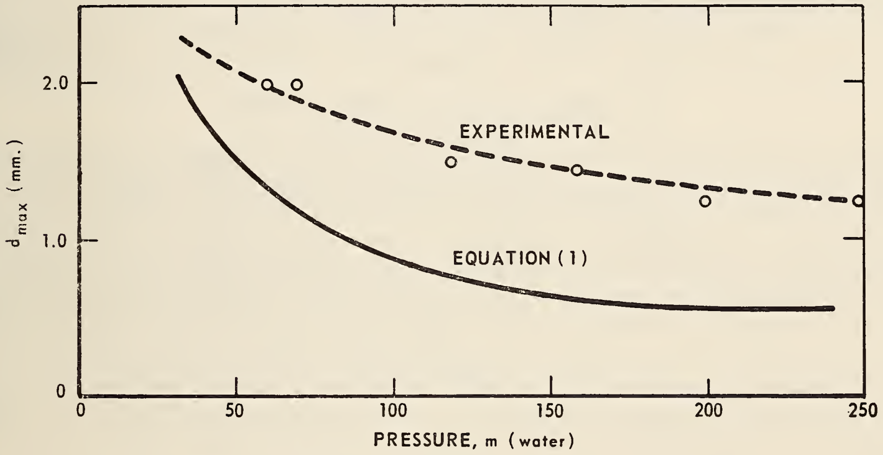


FIG. 1. Variation of maximum droplet diameter with nozzle pressure.

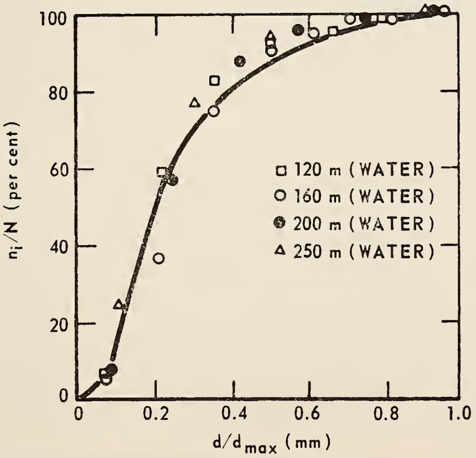


FIG. 2. Comparison of experimental size distribution with theoretical curve [Eq. (2)] for $b = 0.35$.

Close fit of the size distribution curves is exceptional, but wide divergence of drop size variation with pressure drop is to be expected:

1. Troesch's Eq. (1) predicts maximum drop size to vary inversely with pressure, which is characteristic of secondary atomization.[4]
2. Author's maximum drop size varies inversely as the 0.3 power of pressure, which is characteristic of pressure jets[5] for which drop size is strongly dependent upon nozzle dimensions.

References

1. Fraser, R. P., and Eisenklam, P.: *Trans. Inst. Chem. Engr.* **34**, 294 (1956).
2. Joyce, J. R.: *J. Inst. Fuel* **22**, 150 (1948).
3. Troesch, H. A.: *Chem. Ing. Techn.*, **26**, 311 (1951).
4. Lane, W. R.: *Ind. Eng. Chem.* **43**, 1311 (1951).
5. Scheubel, F. N.: "On Atomization in Carburetors," NACA TM 644, 1931.

Subject Headings: *Water, atomization of; Atomization, of water.*

C. C. Miesse

X. Meteorological Interactions

Morton, B. R. (University of Manchester, Manchester, England) "Model Experiments for Vortex Columns in the Atmosphere," *Nature* **197**, 840–842 (1963)

Convergence into thermal convection columns may amplify existing ambient rotation about the vertical to provide a mechanism for the generation of vortices in the atmosphere. To investigate the amplification of vorticity through the action of turbulent thermal convection, jets of dyed liquid were directed along the central axis of a tank of water which was in solid rotation. The angular velocity of the tank (75 cm in diameter and 150 cm deep) ranged from 0.3 to 4.5 radians per second. The buoyancy of upward jets of alcohol, or downward jets of salt solution, was taken as positive. The buoyancy of downward jets of alcohol, or upward jets of salt solution, was considered negative. Jets of water were neutral.

A jet with positive buoyancy released in a tank of rotating fluid produces a rotating column with an angular velocity two to ten times that of the tank. When the jet is stopped the rotating column wanders slowly about the tank and usually subdivides into two or three persistent vortices of comparable strength. A negatively buoyant jet generates a number of rotating columns with an angular velocity smaller than that of the surrounding water. A neutral jet produces no appreciable effect on the uniform solid rotation of the ambient fluid.

The effects produced by the three jets are explained in terms of the distortion of mean vortex tubes. When a vortex tube is stretched, the associated angular velocity increases. When the tube is shortened, the angular velocity decreases. In the interior of the jet there is a continuous shortening of mean vortex tubes parallel to the axis. Ambient vortex tubes convected into the jet by the slow inward radial flow are at first stretched as they are drawn through the outer surface of the jet. Turbulent diffusion throughout the two regions rapidly averages the plus and minus angular velocity changes. The net angular velocity change is positive for the positively buoyant jet, negative for the negatively buoyant, and zero for the neutral jet.

Subject Headings: *Models, of vortex columns; Atmosphere, models of vortex columns.*

G. M. Byram

Turner, J. S. (C.S.I.R.O. Radiophysics Laboratory, Sydney, Australia) "Model Experiments Relating to Thermals with Increasing Buoyancy," *Quarterly Journal Royal Meteorological Society* **89,** 62–74 (1963)

In previous laboratory experiments dealing with buoyant elements released from rest in a fluid, the total buoyancy F was either constant or its magnitude was decreasing with time. However, in an ascending atmospheric cloud, F may be increasing owing to the buoyancy created by the release of latent heat. This paper presents the first results of some new laboratory experiments involving buoyant elements, or "clouds" for which F increases as the element travels upward. A chemical reaction between one reagent dissolved in a large tank of liquid and another in the injected fluid (about 150 cc) was used to produce a large number of gas bubbles whose total volume increased with time. The mean density variation throughout the cloud of small bubbles thus resembled that which could occur in an atmospheric cloud. Two simple cases of the upward motion of the bubble cloud were studied; one for constant acceleration a and the other for constant velocity w.

For a buoyant element the total buoyancy is $F=V\Delta$, where V is the volume of the element and

$$\Delta=g(\rho-\rho_1)/\rho, \tag{1}$$

where ρ and ρ_1 are the densities inside and outside the element and g is the acceleration due to gravity. [As written, Eq. (1) applies to an element which is heavier than the surrounding fluid. However, if $\rho-\rho_1$ (or $\rho_1-\rho$) is small compared to ρ, it applies also to elements lighter than the surrounding fluid.] For the two cases studied in this investigation, as well as for the case of the ordinary thermal with constant F, the following equations hold

$$w=C(r\Delta)^{\frac{1}{2}}$$

and

$$r=\alpha z, \tag{2}$$

where z is the height to the top of the thermal, or cloud, r is its radius, and C and α are constants. For each of the three cases it is informative to write Eq. (2) in terms of the quantities which remain constant. For the ordinary thermal with constant F it follows from Eq. (2) that

$$w\propto F^{\frac{1}{3}}z^{-1}$$

or

$$\Delta\propto Fz^{-3}.$$

If the acceleration a is constant, then $a=\beta\Delta$. Hence Δ is also constant and proportional to a. The constant β must be determined experimentally. In terms of Δ, it follows from Eq. (2) that

$$w\propto z^{\frac{1}{2}}\Delta^{\frac{1}{2}}.$$

If the velocity w is constant during the motion, then Eq. (2) gives

$$\Delta\propto w^2z^{-1}.$$

For all three cases $r=\alpha z$ although α may be slightly different for each case.

To a close approximation Δ may be written as

$$\Delta = g(v/V),$$

where V is the volume of the buoyant cloud, and v is the total volume of the gas bubbles within it. Δ can thus be determined from measurements of v and V. The volume v proved to be difficult to determine at any given instant and the author feels that the experimental estimates of Δ may be too low and those for β too high. However, for those tests in which the measured acceleration was constant during any one experiment, there was a linear relationship between a and Δ as the dimensional analysis predicted.

For constant acceleration the mean value of α was 0.20 as compared with a value of 0.27 which previous investigators had obtained for elements with a constant F. Measured value of r and V indicated that for constant acceleration the bubble cloud was nearly spherical.

For clouds with a constant w, the mean value of α was 0.23 which was intermediate between the values for clouds having a constant a and thermals having a constant F. In this case the shape of the bubble clouds was an oblate spheroid similar to thermals with a constant F.

For accelerating clouds the circulation K varies as $z^{\frac{3}{2}}$ and for clouds of constant velocity K varies as z. Hence in the two types of buoyant clouds described in this paper, the distribution of buoyancy and therefore the details of the mixing process must be very different than for a thermal element for which K is constant.

Subject Headings: *Thermals, model experiment; Models, of thermals.*

G. M. Byram

Lilly, D. K. (U. S. Weather Bureau, Washington, D. C.) "On the Numerical Simulation of Buoyant Convection," *Tellus* **14,** 148–172 (1962)

The turbulent thermal convection generated by an instantaneous line heat source in a calm, dry, isentropic atmosphere was investigated by the use of numerical models for simulating fluid motions. Machine solutions to a complete set of Eulerian equations, with varying computational approximations, constitute a series of "numerical experiments." The problem of nonlinear computational instability was solved by the inclusion of turbulent eddy exchange terms. Owing to the complex nature of the eddy exchange process, simplifying assumptions and a considerable amount of empiricism were needed to obtain the numerical solutions.

In the two-dimensional numerical formulation of the equations, a space–time staggered grid network is set up such that, if the grid points are considered as centers of squares on a checkerboard, all dependent variables are defined at a given time on the black squares, and for one time interval later, on the red squares. For the low resolution experiments, two-dimensional motions were confined to a slab 3750 meters high and 7500 meters wide divided into grid squares 250 meters on a side. The time steps were one second. In the high resolution experiments the slab (3875 meters high and 11,750 meters wide) was divided into grid squares 125 meters on a side. Time steps were one-half second. The symmetrical initial disturbance to the density and potential temperature fields was confined to a slab 1000 meters high and extending 1000 feet on either side of the central line "source."

In the similarity stage the relationships between some of the basic variables are compared to the general relationships which dimensional analysis requires. Also certain parameters were selected for comparing the results of the numerical method with those of laboratory experiments. The agreement might be described as qualitatively good in most cases. Probably the significance of this paper is not so much in what it contributes to an understanding of convection processes, but more in what it reveals about the nature of the method and general approach. Although its present state of development leaves much to be desired, it may be that the numerical method will become an effective tool for studying complex problems in fluid flow.

Subject Heading: *Convection, simulation of buoyant.*

G. M. Byram

Wasko, P. E. and Moses, H. (Argonne National Laboratory, Argonne, Illinois) "Photogrammetric Technique for Studying Atmospheric Diffusion," *Photogrammetric Engineering* **27**, 92–98 (1961)

A photographic technique is described for measuring the rate of atmospheric diffusion and dispersion of smoke at altitudes of about 100 ft. A plume of fog–oil smoke emanating from a stack is simultaneously photographed from three ground positions. Two cameras face each other approximately equidistant from and at opposite sides of the plume, 400 ft apart, with their optical axis 30° above the horizontal plane, and the other camera is placed 40 ft from the stack below the plume with its axis vertical. A series of photographs are taken at 1 to 15 second intervals. At the same time meteorologic measurements are made including wind speed and direction, temperature, dew-point, solar radiation, net radiation, soil temperature, precipitation and pressure.

The crux of the technique lies in the analysis of the data. Images from photographs taken with the opposing cameras are projected onto a translucent screen with positions duplicating the geometry of the camera locations. The screen is mechanically moved perpendicular to its plane until a corresponding point of the projected images coincide. A marker is also driven across the screen to the location of the image point under consideration. Mechanical counters attached to the driving mechanisms measure the values of x, y and z coordinates. The image from the vertically oriented camera is projected independently onto another screen.

The coordinate measurements are then punched on IBM cards and processed on an IBM 650 computer. From the analysis is determined the horizontal width of the plume, the thickness of the plume in a plane normal to the plume axis which is not necessarily horizontal, the cross-sectional area of the plume in a plane normal to the plume axis, and the height of the plume axis.

The above technique is limited to regions close to the stack where the plume remains intact and its boundary is relatively distinct, and to altitudes corresponding to the height of the stack, a few hundred feet at the most.

Some typical data are presented which show several interesting characteristics. For example, the rate of increase of the plume cross-sectional area, which is a measure of the concentration of the smoke, drops from a very high value to a low and nearly constant rate at about 13 stack diameters from the source. Additional data are being taken and future measurements will include the effect of temperature of the smoke on dispersion.

Subject Headings: *Diffusion, photogrammetric study; Atmosphere, photogrammetric study of diffusion.*

R. W. Ziemer

XII. Instrumentation

Pengelly, A. E. S. (The United Steel Companies, Ltd., Rotherham, England) "New Equipment for Flame and Furnace Research," *Journal of the Institute of Fuel* 35, 210–219 (1962)

In recent times, research into industrial flames and furnaces has progressed by the development of several new techniques. Instruments have been developed which enable measurements to be made much more quickly and reliably than hitherto. More information can be obtained about a particular process to make a mathematical and physical analysis possible, and certain techniques can form the primary elements of automatic control systems.

Of new equipment which is fully developed and in current use, brief mention is made of gas velocity and temperature measurement, gas and solid sampling, radiation measurements, and furnace control instruments.

The use of transducers to measure the differential pressure across a pitot tube has enabled high speed traverses of gas velocity to be made. The addition of a refractory tip to the pitot tube has enabled measurements to be made in fume or dust laden gases. The concentration of solid matter in gas streams can be measured by drawing a known volume of gas through a weighed porous metal filter in a water-cooled probe, such that the gas is cooled to 120°–300°C prior to the filter. The filter is allowed to cool before reweighing. This technique has been adapted for continuous waste gas analysis on production furnaces by the addition of a compressed air purge to clean the filter, when the differential pressure across it exceeds a preset value. For the collection of gas samples, the use of flexible plastic bags inside rigid perspex boxes instead of glass containers has proved valuable when a large number of gas samples are required in a short time and under difficult conditions.

Many of these new techniques lend themselves to form the primary elements of automatic control systems; for example, the transducer and furnace pressure control and continuous gas analysis for control of combustion conditions.

A number of new devices are being developed that at present may be considered specialist or research tools rather than tools suitable for regular use.

In many combustion systems, the measurement of gas velocity is made more difficult by nonaxial flow, and an attempt has been made to measure velocity and direction in cases where the gas stream flows at less than 45° to the axis. The pitot tube has been modified to incorporate a water-cooled spherical end three-fourths inch in diameter with an axial pressure hole and four holes arranged on the forward curved surface of the sphere. The direction of flow and gas velocity can be evaluated from four separate differential pressures taken from the five holes with transducers and calibration constants.

The venturi pneumatic pyrometer has been developed to overcome the major disadvantages of the suction pyrometer for gas temperature measurement, namely, response time and maximum service temperature of the thermocouple. Basically, the pyrometer consists of two venturi-type restrictions in series. The stream of gas drawn through the probe creates two differential pressures which are measured by transducers. The gas stream is cooled along the probe to 150°–200°C to avoid condensation, and the temperature after the second venturi is measured by a resistance thermometer. A computer takes in the signals from the venturi and resistance thermometers, and evaluates the temperature at the first (hot venturi) in terms of a proportionality constant which is set at ambient temperature and is therefore known.

Combustion gas analysis can now be performed by chromatographic means. Using helium as the carrier gas, and two separating columns, an analysis of a sample for the six most common components can be made in five to six minutes. Details of the column materials and promotors, the detectors, and the operating procedure are given in detail.

The use of the mass spectrograph for rapid gas analysis is being appraised at the present time. It should be possible to scan a given sample for mass numbers, 12–45 in less than 1 minute. From a sample injected at about 15 cc/min, a portion is ionized and accelerated and depending on the resultant charge on the ions and their mass, the ions are deflected to an electrometer probe. Problems arise when components have the same mass number, CO and N_2, but variations of operating technique (higher ionization) should overcome this.

Finally, instruments are described which measure total heat arriving at a surface (heat flow meters). Constructional details are given of two types, which when used in conjunction enable the total heat to be separated into radiation and convection.

Subject Heading: ***Furnaces, instruments for research.***

P. L. Start

Cramer, O. P. (Pacific Northwest Forest and Range Experiment Station, U. S. Forest Service, Portland, Oregon) "Predicting Moisture Content of Fuel-Moisture-Indicator Sticks in the Pacific Northwest," *Pacific Northwest Forest and Range Experiment Station Research Paper 41* (May 1961)

Fuel-moisture indicator sticks provide an important tool for predicting burning conditions in Region 6 of the Forest Service. The fire control agencies in the Pacific Northwest rely a great deal on this and other danger rating aids to indicate to them periods of low fire danger, days when prescribed burning can be safely done, and critical periods of weather under which area closures may be affected.

Fire control agencies welcome any means by which they can predict, and predict with a high degree of accuracy, the burning conditions for the immediate period ahead—be it 8, 16, or 24 hours in advance. This paper describes some fuel moisture prediction aids that will permit accurate estimates of fuel moisture to within 1 per cent of the correct value 90–96 per cent of the time.

The standard fuel moisture sticks are manufactured from carefully screened ponderosa pine sapwood. They are trimmed to weigh exactly 100 grams ovendry and are exposed to full sunlight and weather 6 inches above the ground.

Three charts or aids that may be used are presented. These include an afternoon composite chart for predicting the following afternoon fuel moisture for any station location; a morning chart for predicting mountain peak station fuel moisture for the same afternoon; and a morning chart for valley stations for predicting fuel moisture for the same afternoon.

Detailed instructions are given for using the three aids mentioned above. When special weather (precipitation) is expected, the values obtained from the aids need to be adjusted and instructions are included for doing this.

In order to make refinements in the use of these fuel moisture aids, a verification program is suggested for each individual station using the charts. This, in effect, increases the accuracy of the fuel moisture prediction for the particular station and results in more reliable estimates of fuel moisture. If the verification procedure indicates that the established curves and the plotted data are nearly identical, the original or standard charts may be used. If there is a large difference between the established aid and the verification aid, the new data should be used.

It is obvious to the reader that an accurate prediction of fuel moisture is directly dependent upon an accurate forecast of relative humidity for the period in question. If the humidity forecast is not accurate within rather narrow limits, the resulting fuel moisture prediction will be decreased in accuracy accordingly. Consequently, the fuel moisture aid is only as reliable as the weather forecast for the specific area.

Subject Heading: ***Moisture, prediction, in indicator sticks.***

J. H. Dieterich

Iwama, A., Yamazaki, K., Kishi, K., Aoyagi, S., and Kozuki, I. (Aeronautical Research Institute, University of Tokyo, Tokyo, Japan) "Burning Rate Measurement of Solid Propellants by Means of Photo-Transistors," *Kogyo-Kagaku Zasshi* **65,** 1218 (1962)

A modified method of measuring the linear burning rate of solid rocket propellants is developed. Measurements are carried out by using the train of two photo-transistors having two horizontal slits located in a suitably fixed distance along the test strand, instead of using the timing fuse wires embedded in or wound around the strand as in the conventional Crawford method.

The photo-transistors catch the signals of radiation from the burning surfaces through the slits at the instant of the passage of a regressive burning surface. As a result, occasional inhibition or promotion effects on the burning rate caused by being in contact with other materials is avoided. Thus, the linear burning rate can be accurately obtained from photo-electric time signals while the strand has burned for the prefixed distance between upper and lower transistors.

Subject Heading: ***Burning rate, measurement by photo-transistors.***

T. Kinbara

INDEX OF AUTHORS

INDEX OF SUBJECTS

CUMULATIVE INDEX OF AUTHORS

CUMULATIVE INDEX OF SUBJECTS

ABSTRACTORS

THOMAS C. ADAMSON, JR.
University of Michigan

GEORGE A. AGOSTON
Stanford Research Institute

JOHN J. AHERN
General Motors Corporation

THOMAS P. ANDERSON
Northwestern University

RAJAI H. ATALLA
Newark, Delaware

LOREN E. BOLLINGER
The Ohio State University

PETER BREISACHER
Aerospace Corporation

FREDERICK L. BROWNE
Madison, Wisconsin

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

HANS M. CASSEL
Silver Spring, Maryland

WELBY G. COURTNEY
Texaco Experiment, Incorporated

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

GLADYS S. CUFF
Ethyl Corporation

DANIEL DEMBROW
National Aeronautics and Space Administration

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

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

R. H. ESSENHIGH
The Pennsylvania State University

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

FELIX FALK
Applied Physics Laboratory
The Johns Hopkins University

K. M. FOREMAN
Republic Aviation Corporation

ALLEN E. FUHS
Aerospace Corporation

ARTHUR L. GOLDSTEIN
Ionics, Incorporated

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

BERNARD GREIFER
Atlantic Research Corporation

L. R. GRIFFITH
California Research Corporation

GEOFFREY L. ISLES
The University, Leeds (England)

OLIVER W. JOHNSON
Johnson-Williams, Inc.

WILLIAM C. JOHNSTON
Westinghouse Research Laboratories

J. RENE JUTRAS
National Research Council (Canada)

IRVING R. KING
Texaco Experiment, Incorporated

WILLIS G. LABES
Illinois Institute of Technology

JOSEPH B. LEVY
Atlantic Research Corporation

RONALD LONG
University of Birmingham (England)

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

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

D. G. MARTIN
Imperial College (England)

HOWARD N. McMANUS, JR.
Cornell University

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

C. C. MIESSE
Westinghouse Electric Corporation

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

A. E. NOREEN
Boeing Airplane Company

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

HENRY EDGAR PERLEE
U. S. Bureau of Mines

M. G. PERRY
University of Sheffield (England)

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

LOUIS A. POVINELLI
National Aeronautics and Space Administration

J. KENNETH RICHMOND
Boeing Airplane Company

DANIEL E. ROSNER
AeroChem Research Laboratories, Inc.

PETER A. ROSS
Boeing Airplane Company

WILLIS A. ROSSER, JR.
Stanford Research Institute

P. R. RYASON
California Research Corporation

R. H. SABERSKY
California Institute of Technology

R. G. SIDDALL
University of Sheffield (England)

JOSEPH M. SINGER
U. S. Bureau of Mines

PHILIP L. START
University of Sheffield (England)

ALEXANDER STRASSER
U. S. Bureau of Mines

K. SUMI
National Research Council (Canada)

CLAUDE P. TALLEY
Texaco Experiment, Incorporated

DONALD L. TURCOTTE
Cornell University

FORMAN A. WILLIAMS
Institute of Defense Analysis

HENRY WISE
Stanford Research Institute

E. C. WOODWARD
University of South Carolina

F. H. WRIGHT
California Institute of Technology

RICHARD W. ZIEMER
Electro-Optical Systems, Inc.

E. E. ZUKOSKI
California Institute of Technology

THE FIRE RESEARCH CONFERENCE

H. C. Hottel, *Chairman*	Director, Fuels Research Laboratory Massachusetts Institute of Technology
Keith Arnold	Director, Division of Forest Fire Research Pacific Southwest Forest and Range Experiment Station
William H. Avery	Research and Development Supervisor Applied Physics Laboratory The Johns Hopkins University
J. S. Barrows	Chief, Division Forest Fire Research Intermountain Forest and Range Experiment Station
L. M. K. Boelter	Dean of Engineering University of California, Los Angeles
Horatio Bond	Chief Engineer, National Fire Protection Association
B. P. Botteri	Wright Air Development Division Wright-Patterson Air Force Base, Ohio
Mathew M. Braidech	Director of Research National Board of Fire Underwriters
A. A. Brown	Director, Division of Forest Fire Research U. S. Forest Service
C. C. Buck	Assistant Director, Division of Forest Fire Research U. S. Forest Service
Clarence F. Castle	Chief, Services Division Properties and Installation Office Assistant Secretary of Defense
DeVer Colson	Meteorologist, Meteorological Physics Section U. S. Weather Bureau
James J. Duggan	Charleston, West Virginia
Howard W. Emmons	Professor of Mechanical Engineering Havard University
Joseph Grumer	Project Coordinator, Flame Dynamics Explosives Research Laboratory U.S. Bureau of Mines

ARTHUR B. GUISE	Technical Director, Research and Development Ansul Chemical Company
K. E. KLINGER	Chief Engineer, Los Angeles County Fire Department
HAROLD E. KUHLMAN	Chief Engineer, Oklahoma Inspection Bureau
BERNARD LEWIS	President, Combustion and Explosives Research, Inc.
J. B. MACAULEY	Assistant to the Director of Defense Research and Engineering Department of Defense
JAMES E. MALCOLM	Office of Chief of Engineers U.S. Army
WALTER T. OLSON	Chief, Propulsion Chemistry Division Lewis Research Center National Aeronautics and Space Administration
GEORGE J. RICHARDSON	Silver Spring, Maryland
A. F. ROBERTSON	Chief, Fire Research Section National Bureau of Standards
VINCENT J. SCHAEFER	3 Schemerhorn Road Schenectady, New York
A. J. STEINER	Managing Engineer, Fire Protection Department Underwriters' Laboratories, Incorporated
NORMAN J. THOMPSON	Miller's Hill Road Dover, Massachusetts
RICHARD L. TUVE	Head, Engineering Research Branch Mechanics Division U.S. Naval Research Laboratory

Liaison

H. T. HOOKWAY	United Kingdom Scientific Mission Washington, D.C.
G. W. SHORTER	National Research Council Ottawa, Canada

D. W. THORNHILL, Executive Secretary of Committee and Conference
EMMA JANE WHIPPLE, Administrative Assistant