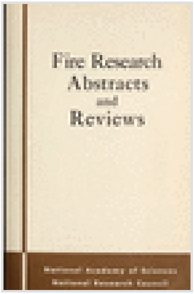

Fire Research Abstracts and Reviews, Volume 7 (1965)

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

Pages
274

Size
6 x 9

ISBN
0309309301

Volume 7 Number 1

Fire Research Abstracts and Reviews

Committee on Fire Research
Division of Engineering and Industrial Research
National Academy of Sciences—National Research Council

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
Washington, D. C.
1965

FIRE RESEARCH ABSTRACTS AND REVIEWS is published three times a year by the Committee on Fire Research 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 of the Department of the Army, the U. S. Department of Agriculture through the Forest Service, the National Science Foundation, and the National Bureau of Standards 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.

Library of Congress Catalog Card Number 58–60075 rev

Available without charge from the
Office of the Committee on Fire Research
National Academy of Sciences—National Research Council
Washington, D. C. 20418

FOREWORD

This issue marks the beginning of a new editorial regime for Fire Research Abstracts and Reviews.

The main hope of your new editor is that he will be able to uphold the high standards which Dr. W. G. Berl set in his initiation of FRAR. We feel that the fire research field owes a debt of gratitude to him for setting up and guiding the Abstracts to its position as an important positive force in the area. There is every reason to believe that we will be successful in the endeavor, because the editor can rely on the advice of Dr. Berl and the Committee on Fire Research; and the crucial factors of copy editing and literature searching remain in the same capable hands of D. W. Thornhill, the executive secretary of the Committee on Fire Research, and the editorial staff, Mrs. G. R. Fristrom and Mrs. E. J. Whipple. Constructive suggestions on the coverage and content of FRAR are always welcomed by the editor, particularly in this initial period.

In the past there have been complaints by fire research workers of a scarcity of suitable publication media. As a result the work has been scattered throughout the sciences in search of a suitable vehicle or simply not published. FRAR was organized to combat the first problem. It is a matter of debate whether the second problem, of inability to publish certain pieces of fire research, exists. Dr. Berl editorialized on this point in FRAR (Vol. 5, No. 3) and received from you a number of suggestions. He feels that the concensus was that, although a Fire Research Journal might be desirable in the future, it would be unwise to try to incorporate it into the present publication.

To try to establish whether this latter problem exists and to alleviate the situation if it does, we plan to try an experiment in the next two issues of FRAR, the publication of titles and abstracts of unpublished work in the Fire Research field. The proposal is simply this: If an author feels that he is unable to find a siutable medium for publication and that the paper contains material of interest in the fire field, he is requested to send twenty-five copies of the paper to FRAR. In each issue we will publish the titles of papers received and abstract those which the editor feels require further description. As a service, the editorial office will distribute copies of these papers to requesters who send *stamped* (10c) 8½″ × 11″ self-addressed envelopes. One copy will be retained in a file and, if the original copies are depleted, arrangements will be made to furnish microfilm to requesters at cost. This section will also include thesis titles and government reports of interest, though, of course, FRAR cannot undertake the responsibility for distributing copies of these latter documents. This new section will be called UNPUBLISHED FIRE RESEARCH and will be run as an experiment beginning with the next issue (FRAR, Vol. 7, No. 2) and continuing through 1965. At the end of the year we will evaluate the section and decide whether it should be retained. Comments by interested readers will be welcomed.

Several articles of special interest appear in this issue. One is Mr. Lawson's timely piece, "Fire Research in the Soviet Union." Mr. Lawson's comments on fire losses in the Soviet Union are particularly significant, since he is a relatively neutral observer. If the figures quoted have any significance, and there seems little reason to doubt their general order of magnitude, this country could stand improvement in its over-all fire program and should consider strengthening its fire research program as an urgent item. Since this is a public problem, the major burden probably must fall on the Federal Government, but it would be a mistake to depend solely on this source. It would be hoped that increases in government research would be matched or exceeded by public-spirited industries, individually, and through their fire-interested associations. This is an area where everyone benefits by improvements and where complacency is a mistake.

Other items of interest are a survey "A Review of Fire Weather Investigations in Australia" by H. E. Whittingham and an abstract of the "Directory of Fire Research in the United States."

The last item is a survey of the Fire Research program at the Tenth International Symposium on Combustion in Cambridge, England, August 1964. This was a major forum for fire research. To bring these important papers to the attention of the fire research public as soon as possible, we have made use of the authors' abstracts together with an over-all commentary by Dr. Berl. Several of these papers may be subsequently abstracted.

ROBERT M. FRISTROM, *Editor*

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FIRE PROTECTION SERVICES IN THE U.S.S.R.

D. I. LAWSON

Joint Fire Research Organization, Boreham Wood, England

[This is substantially a reprint of F.R. Note No. 574 of the Joint Fire Research Organization, Boreham Wood, England. FRAR appreciates permission to use this material. Editor]

During May 1964, the State Committee for the Co-ordination of Scientific Research in the U.S.S.R. agreed to receive a delegation from the Department of Scientific and Industrial Research to exchange information on fire research. So that the exchange should cover as wide a field as possible, Her Majesty's Chief Inspector of Fire Services and the Director of the Fire Protection Association were invited to join the party from the Fire Research Station, the final representation being:

D. I. Lawson, Director, Joint Fire Research Organization
H. M. Smith, H.M. Chief Inspector of Fire Services
N. C. Strother Smith, Director, Fire Protection Association
K. N. Palmer, Joint Fire Research Organization
G. J. Langdon-Thomas, Joint Fire Research Organization

The visit was to last a fortnight and, after indicating the topics we would like to discuss, the itinerary was left to the host country and was as follows:

	Moscow
September 7	Meeting with officials of Directorate of Fire Protection, Russian Federative Republic Ministry of the Maintenance of Public Order (equivalent to the Home Department in Great Britain) and of All-Russian Voluntary Fire Protection Association. Visit to Moscow State University.
September 8	Meeting with officials of Moscow Fire Protection Directorate and Moscow Voluntary Fire Protection Association. (See Appendix A.) Visits to Ordzhonikidze factory and to view fire-fighting equipment and appliances.
September 9	Meeting at Faculty of Engineering of Fire Protection. Viewing films on fire protection.
September 11	Visit to Central Scientific Research Institute for Fire Protection.
	Leningrad
September 12	Meeting with officials of Leningrad Fire Protection Board and Voluntary Fire Protection Association. Visits to Leningrad Fire Testing Station and Fire Technical Exhibition. Viewing films on fire protection.
September 14	Meeting at Leningrad Fire Technical School. Visit to Junior Voluntary Fire Brigade.
	Volgograd
September 16	Visit to Volzhskaya hydro-electric power station. Visit to Volgograd Central Fire Station (H.M. Chief Inspector of Fire Services).

September 17 Meeting with officials of Ministry of the Maintenance of Public Order and Volgograd Fire Protection Board.

Moscow

September 18 Meeting with officials of Ministry of the Maintenance of Public Order, All-Russian Voluntary Fire Protection Association, Moscow Fire Protection Directorate, Moscow Voluntary Fire Protection Association, Central Scientific Research Institute for Fire Protection. Meeting with Assistant Minister, Ministry of the Maintenance of Public Order, and Assistant Minister of Foreign Affairs, Russian Federative Republic.

PROFESSIONAL FIRE BRIGADES

Russian Federative Republic

The Russian Federative Republic is one of fifteen which together constitute the U.S.S.R. It is the republic with the largest population, 121 million (about two-thirds that of the U.S.S.R.) and covers 17 million square kilometres, extending from Leningrad in the west to Vladivostock in the east, and from the northern coast to the Caucasus in the south. Its greatest width is 10,000 kilometres and it is divided into 72 administrative regions.

Each region has a Council controlling the Fire Protection Department and the fire brigades are administered by these departments. The regions are further subdivided into districts each having an Inspectorate of Fire Protection.

The fire brigades have two functions: fire prevention and fire extinction. The fire prevention function includes inspection and the compiling of standards or Fire Codes in which the results of research are taken into account.

Building work is governed by the State Construction Committee, on which the Inspectorate of Fire Protection is represented, and the designs for new buildings must be approved by the Committee, the tendency being towards standardized designs. Buildings are inspected during construction to ensure that they are being built to specification, and if the standards are ignored, fines can be imposed up to £2 per worker and even more important, the work may be stopped.

Moscow Fire Brigade

The Brigade is responsible for an area of 886 square kilometres containing a population of 6.4 million. Altogether there are 86 million square metres of living space, and this area is increasing annually by 5 million square metres. The public buildings with which the Brigade is concerned include 900 schools, 91 cinemas, 23 theatres, and 53 museums.

The city is divided into 17 administrative districts, with two fire stations per district. There are about 3000 professional firemen in the Brigade (i.e., about 4.5 firemen per 10,000 population). They are on duty for 24 hours followed by 48 hours off duty and facilities for resting between 11 p.m. and 6 a.m. are provided. The telephone is used for calling the Brigade either by using a special button in public kiosks or by dialling 01. The number of false calls are so low that no records are kept. Each station has at least two appliances: a water tender and a self-propelled pump. Low pressure sprays are used but high pressure fog is not, although it was thought that a combined appliance might be useful.

Fire hydrants are usually spaced 80 to 100 metres apart, and their positions are indicated on nearby walls. The distance between hydrants and buildings is governed by regulations.

Leningrad Fire Brigade

The city has a population of 3.6 million and is divided into 19 administrative districts having one or two fire stations in each. There are 24 stations altogether, and they are manned by 1200 professional firemen, i.e., 3.3 per 10,000 population. They also work a 24-hour shift, followed by 48 hours off. It was estimated that 80 per cent of their time is spent on fire prevention, and the remainder on fire extinction and matters pertaining to this.

One interesting piece of apparatus which we saw in Leningrad was an oxygen-breathing apparatus weighing about 30 lb. The oxygen was compressed to 200 atmospheres in a cylinder having a capacity of 2 litres. Oxygen was delivered at a rate of 1.1 to 1.3 1/min; this is considerably lower than that of British sets. The equipment was stated to have a duration of 4 to 6 hours but it was thought to be rather heavy and work was in hand to lighten and simplify it. The latest apparatus in general use (KIP7) had a duration of 1 to 2 hours.

Volgograd Fire Brigade

Volgograd, formerly Stalingrad, is being entirely rebuilt and at present has a population of 600,000. The Fire Brigade has six stations and a strength of 352 professional firemen, about 6 per 10,000 population.

ALL-RUSSIAN VOLUNTARY FIRE PROTECTION ASSOCIATION

In addition to the professional fire service, there are also the Voluntary Fire Brigades within the All-Russian Voluntary Fire Protection Association; these have no counterpart in the United Kingdom.

The aims of the Association are to prevent fire, to extinguish fires where there is no professional brigade as on farms, to form industrial fire brigades, and to assist with fire propaganda, such as posters, films, and press notices. It has 4 million members (including 92,000 young firemen aged between 12 and 18 years) in 80,000 primary voluntary organizations which are run by Councils elected locally. The membership fee is 10 kopecks (about 10d) per annum and additional income is obtained from the State and from the earnings of 22,000 full-time civilian employees. The total income is about 50 million roubles (£20 million) per annum.

The full-time employees earn income by various activities, such as cleaning chimneys, recharging fire extinguishers, impregnating clothes and fabrics with fire-retardant materials, installing lightning conductors and spark arresters and repairing fire equipment. There are strong social pressures to join the Voluntary Fire Protection Association. It was explained that with State ownership it was only good citizenship to want to protect communal property.

MOSCOW VOLUNTARY FIRE PROTECTION ASSOCIATION

There are now 227,000 members in 6600 primary organizations within the Association, which was founded in 1857. There are 4000 separate voluntary brigades, which actively participate in fire fighting, attached to specific organizations such as factories, hotels, and hospitals. A further 400 junior brigades contain 11,000 members.

The main purpose of the primary organizations, which are spread throughout the city, is publicizing the causes of fire.

Members of the voluntary brigades are given certain privileges which include 6 days more leave per annum from their places of employment, a special uniform for those participating in fire fighting, and the opportunity to attend courses of instruction.

Leningrad Voluntary Fire Protection Association

The membership is 235,000 and is divided into 50 fire commands. The activities of the Association are similar to those of the Russian Federative Republic. One difference is that each school in Leningrad has its own voluntary brigade, and the teachers also instruct the children aged between 7 and 12. In addition, posters and films are regularly shown in the schools. We were impressed by the enthusiasm of the Junior Voluntary Fire Brigade in Leningrad. It has its own fire appliance and fire station equipped with fire detectors, sprinklers, and a telephone. The Brigade demonstrated its ability to extinguish a fire in a shed with great efficiency.

TRAINING ESTABLISHMENTS

Faculty of Engineers of Fire Protection

The Faculty was founded in Leningrad in 1933 but was subsequently transferred to Moscow. It received its present status in 1957, and is responsible to the Ministry of Higher Education.

The students must have a high school education and must also have worked for three years in the fire service before entry. The full-time courses last for four years or alternatively, it is possible to take a five-year correspondence course. (The correspondence courses attracted about 50 entrants when they were started, but recently members have risen.) There is no age limit for entry but an examination has to be passed before a course can be taken. About 45 qualified men are produced each year. Altogether, the internal students are given 4000 hours of instruction of which half is devoted to practical work. The syllabus is made up of social sciences, 9 per cent; general technical subjects, 32 per cent; building construction, 20 per cent; and fire prevention and safety technique, 39 per cent.

A number of the textbooks are written by teachers of the Faculty. The standard of the laboratories is high, with facilities for advanced experiments in physics and chemistry. There is good use made of models to demonstrate different methods of construction in building, the operation of industrial plant, and for the display of different fire situations. The wall space is extensively used for charts, photographs of visits by personalities, fire-applied sports, or notable fires. The charts are very good and are well illustrated, each one either describing equipment or giving information on fire protection. Institutes have boards of honour on which are displayed photographs of contemporary students and staff who are considered to be meritorious. This seems to be general practice even in factories.

The Faculty is divided into six departments:

(1) General technical sciences: higher mathematics, physics, theoretical mechanics, engineering construction.
(2) Fire prevention in construction: safety techniques, codes, fire prevention in heating and ventilation systems, fundamentals of heat transmission.
(3) Fire prevention in technological processes: oil and chemical industries, aspects of automation.
(4) Fire prevention in electrical equipment and installations.
(5) General and special chemistry: combustion.
(6) Fire technique: hydraulics, fire tactics, roof venting.

Leningrad Fire Technical School

The school was started in 1906 but up to the Revolution in 1917 only 117 students in all had been accepted. The present annual rate of graduation is about 150 and the school receives students from all over the Russian Federative Republic. Students enter from school, at the age of 17 to 18, and study full time for three years or they can take correspondence courses. The latter students come into Leningrad twice yearly for examinations at State expense. There are about 500 correspondence students at present. As in Moscow, the internal student gets a total of 4000 hours' tuition, half of which is practical training. On satisfactory completion of the course a Diploma of Middle Technical Education is awarded. The students, when qualified, are attached to brigades as officers in charge of watches or as fire prevention inspectors.

The syllabus is as follows:

(1) higher mathematics, (2) fire prevention—technological processes, construction, electrical, (3) applied hydraulics, (4) fire tactics, (5) organization of fire brigades, (6) fire-applied sports, and (7) physical training.

The school is proud of its library, which contains 100,000 volumes. Besides technical books there are substantial collections of works on literature, sociology, and politics. Two thousand books are by British authors popular in Russia and these include Shakespeare, Dickens, Galsworthy, and Jerome K. Jerome.

The school also provides courses for Junior Fire Inspectors to train eventually as Commanders. The entrants are generally from fire brigades, but school-leavers can also be taken. The courses run for 9 months.

OTHER VISITS

Ordzhonikidze Plant

This plant manufactures machine tools. It is well equipped with modern automatic machinery and the work turned out seems to be of a very high quality. The layout is different from British factories in that the density of plant is higher in relation to the floor space. Great use is made of safety posters, particularly those relating to fire precautions and the standard of housekeeping would compare well with most British factories. Smoking is permitted. There is no evidence of sprinklers or fire detectors, but extinguishers are provided and these carry maintenance tags.

We were invited to sound the alarm at a central point and within a minute, a fire engine turned out with a crew of four dressed for fire fighting; these workers would normally be engaged on production. No serious fire had ever occurred in the factory and the fire engine had not been used apart from practice drills.

Volzhskaya Hydro-Electric Power Station

The Volzhskaya Power Station lies a few miles from Volgograd and is one of a number of stations in the Volga scheme. The head of water is small (some 70 ft) and the generators have therefore to be capable of working with a large through-put at this small head. The turbines producing a total output of 2600 MW, rotate at about 1 revolution per second, generating current at 13 kV, which is subsequently stepped up to 500 kV for transmission to Moscow. Direct current transmission is not yet used on this line but pilot experiments are to begin shortly on one of the 22 generators. The turbine blades are of variable pitch, each blade weighing about 18 tons. The rotor has a diameter of about 45 ft. The oil temperature in the rotor hydraulic system, the rotor and its field are continuously monitored so that an alarm can be given long before any dangerous build-up of temperature occurs. Any incipient plant failure is displayed on a huge illuminated board in the hall showing the number of the faulty generator. The 22 generators are below the general level of the generator hall and can be physically isolated from each other by fire-stop doors. Fire-fighting hydrant connections are provided for each generator. The whole of the plant runs almost automatically and only 14 shift engineers look after this mammoth concern, the main hall of which is nearly half-a-mile long.

Moscow University

Moscow University, completed in 1953, now has 25,000 students; 6000 live in rooms in the University itself and another 4000 in rooms nearby. The University has its own fire brigade and a pumping system designed by the students provides water for fire fighting throughout. The spire is nearly 800 ft high and the main facade nearly 1500 ft long.

FIRE STATISTICS

Russian Federative Republic

The annual total number of fires in the Republic was stated to be about 19,500. This total excludes fires in chimneys, forests, ships at sea, and trains in motion. It corresponds to 0.16 fires per 1000 population per annum. For comparison, the United Kingdom total in 1962 was 167,000 fires, or 3.1 fires per 1000 population.

The direct fire loss in 1963 was given as 17 million roubles, i.e., £6.8 million which is equivalent to £56 per 1000 population. The United Kingdom fire loss in 1962 was estimated as £56 million, or £1040 per 1000 population.

The annual rate of fatalities in fire is about 150, i.e., about 1.2 persons per million population. In the United Kingdom in 1962 the total fatalities were 667, corresponding to a rate of 12.6 persons per million population.

It was estimated that 35 per cent of fires caused no significant damage or loss.

TABLE I

Distribution of causes

Cause of fire	Number of fires
Careless adults	306
Careless children	171
Heating installations and irons	138
Lightning	3
Others	212

Moscow

The total number of fires in 1961 was 1015, which corresponds to a rate of 0.16 fires per 1000 population which is the same as for the Russian Federative Republic. For comparison, the London figure for 1962 was 4.2 fires per 1000 population.

The majority of the fires in Moscow, 69.4 per cent, are small and are called "ignitions." The proportion of the total is about twice that for the Russian Federative Republic. The Voluntary Brigade extinguishes 17.4 per cent of the fires before the arrival of the professional brigade.

The causes of fires are summarized in Table I.

Leningrad

In 1963 the total number of fires was 338, which is a rate of 0.094 fires per 1000 population. This rate is substantially less than in Moscow and the Russian Federative Republic. In addition, the number of fires in Leningrad are diminishing annually in spite of the growth of industry. The annual direct fire loss is given as 48,000 roubles (£19,200), which is a rate of £5.3 per 1000 population. This rate is only about one-tenth of the stated loss for the Russian Federative Republic as a whole.

It was estimated that 50 per cent of the fires were extinguished by the Voluntary Brigade, or by the general public, and only 8 per cent of fires were serious which would mean that only one or two serious fires per annum were attended from any one fire station.

TABLE II

Causes of fires in Leningrad

Cause of fire	Percentage of total fires
Carelessness, general	45
Lightning	19
Domestic electricity	13
Chimneys and stoves	12
Careless children	7
Welding, electric or gas	4

TABLE III

Location of fires in Leningrad

Location of fire	Percentage of total fires
Inside domestic buildings	46
Inside industrial buildings	13
Rural areas, farms	5.4
Offices	20.1
Construction sites, temporary buildings	7
Cinemas, theatres, hospitals	5
Shops, warehouses	3.4

About 80 per cent of fires occur in buildings. A summary of causes of fires is given in Table II and their location in Table III. Fires due to the carelessness of adults and children represent about half the total; a similar figure was given in Moscow.

In both 1963 and 1964 (to date) there had been only one fire in an ocean-going ship in Leningrad and it was estimated that about 25 to 30 ships could be tied up at any given time.

FIRE RESEARCH

The Central Scientific Research Institute for Fire Protection, Moscow, is the centre of fire research in the U.S.S.R., and was founded in 1937. Its main lines of activity are (1) fire prevention, (2) new methods of fire extinguishing, (3) applied hydraulics, (4) automatic equipment for fires, (5) fire detection, and (6) fireproof properties of materials.

The Institute is responsible to the Ministry of the Maintenance of Public Order and is governed by a Scientific Technical Council of 30 members who represent the Ministry and other interested organizations. Its income is 150 to 200 thousand roubles (£60 to 80,000), half of which is provided by the State budget and the remainder by organizations interested in specific items of work. The staff number about 130.

The types of work undertaken are scientific research, consultation, standardization, and testing for industrial organizations (on a fee-paying basis if of specific interest only). In addition liaison is maintained with the 20 Fire Testing Stations distributed throughout the U.S.S.R. Two topics in particular were mentioned in this context: extinction of large-scale timber fires and the extinction of ship fires by high expansion foam. The results of work are published in information bulletins, the magazine "Fire Service," technical journals, newspapers, and on radio and television. Textbooks are written, which are used in the training of firemen. No annual report is issued.

The Institute has six main sections—

1) Chemical: properties of combustible materials, dusts, flash points
2) Fire technique: causes, electrical apparatus
3) Fire prevention in buildings: fire-resistant constructions
4) Fire detection

5) Fire extinguishing and applied hydraulics
6) Drawing office and information.

Recent work carried out at the Institute includes—

High pressure water sprays
Automatic high expension foam installations
Fire detectors
The development of a theoretical approach to the prediction of fire-resistance using thermal diffusion. No account was taken of the effect of end restraint
Extinction of flammable liquid fires
Prevention of electrical fires.

The Institute is also interested in fire-retardant paints, the problem of smoke in fires, and extinguishing fires with a jet engine inert gas generator.

During the visit a series of demonstrations and exhibits was provided as follows:

1. *Extinction of oil fire by water spray*. The fire was in a circular tray 8.5 metres in diameter and was extinguished by a water spray produced by a nozzle at a pressure of 8 atmospheres. All drops were said to be smaller than 150 microns.

2. *Extinction of diesel oil fire by the base injection of air*. The fire was in a tank of about 1 metre diameter.

3. *Use of ethyl bromide as a vaporizing liquid extinguishing agent*. Because of its toxic properties methyl bromide was not used.

4. *Dust explosibility classification tests*. A weighed amount of the dust under test was blown into a vessel 10 cm in diameter and 30 cm high containing a small hot coil. The dusts were classified according to the minimum concentration at which explosion occurred.

Class I	<15 g/m^3
Class II	16–65 g/m^3
Class III	66–250 g/m^3
Class IV	>250 g/m^3

5. *Flash point of oils*. The oil was heated in a small enclosure and the temperatures were measured at which the vapour could just be ignited by a flame or could still be ignited by a hot coil. These determinations gave lower and upper flash points.

6. *Combustibility of plastics*. A small specimen was heated electrically in air inside a water jacket; the rise in temperature of the water was measured. An estimate could then be made of the heat evolution due to the combustion of the plastic. If the plastic evolved less than one-half of the input heat at all temperatures, it was deemed to be noncombustible.

7. *Ignition of solids in an oven*. Specimens of a combustible solid were suspended in an oven and the times required for ignition (t) at various values of temperature (T) were measured. Log t was then plotted against $1/T$. The relation between T and the linear dimension of the specimen (x) was found to be of the form $\log T = A - n \log x$, where A and n are constants.

8. *Fire detectors*. Three types were demonstrated, one actuated by heat, another by ultraviolet light, the head containing a two-transistor amplifier, and an ionization detector operated by smoke. The detector actuated by ultraviolet light could be triggered by a match held 10 metres away.

9. *Hydraulics*. A double outlet standpipe was shown, which could be used either as a hydrant or for normal water supplies in rural areas. A trigger-operated spray gun working at a pressure of 60 psi and delivering about 0.5 gal/sec was also seen and a fixed foam head delivering 0.75 gal/sec of detergent foam demonstrated.

10. *Fire-resistance tests*. All furnaces were oil-fired. Beams and floors were tested in a horizontal furnace, about 10 ft x 20 ft and a load of up to 10 tons was applied by filling tanks with water; these were connected to the specimen by a lever. The temperature and the deflection of the specimen were measured. Panels were tested in a vertical furnace, about 6.5 ft x 6.5 ft and were not loaded. Walls were tested in a vertical furnace, about 8 ft x 4 ft, under load. For columns, two three-sided wall furnaces were placed back-to-back to form an enclosure. Spread-of-flame tests as known in the United Kingdom were not used. Any tests with fire-retardant paints were carried out in small buildings, although the impression gained was that fire-retardant paints were not widely used.

FIRE TESTING STATIONS

There are 20 Fire Testing Stations distributed throughout the U.S.S.R. and they are independent of the Central Scientific Research Institute for Fire Protection, although they work in liaison with it. They also work closely with the chief of the local fire brigade.

The functions of the Stations are to attend fires and to study their behaviour and to carry out research on problems of local interest (e.g., crops, forest, ships, etc.) but there is no participation in fire fighting. In addition, the Stations make films on aspects of fire fighting.

We were shown a film of a fire test carried out in a timber storage area. Tracked vehicles made from obsolescent tanks were being used as mobile monitors carrying 2500 gal of water. These enabled the fire fighters to get up to the burning area and discharge water at a rate of about 7 gal/sec.

The Leningrad Fire Testing Station has three main laboratories—temperature measurement, chemical, and photographic—and the staff consists of 6 engineers, 1 design engineer, 3 photographers, 3 drivers, and 1 secretary.

Work on the production of inert gas by a jet engine is being undertaken at the Novosibirsk Testing Station. The issuing gas was stated to have an oxygen content of 6 to 7 per cent. The equipment had also been used to produce foam having an expansion of 200 to 300.

BUILDING CONSTRUCTION AND LIFE SAFETY

Construction

Building construction for fire purposes is divided into a series of grades, I–V, Grade I having elements of construction with a fire-resistance from 1 to 5 hours depending upon its function and Grade V having a nil fire-resistance being combustible with the exception of the separating wall which is required to have a fire-resistance of 5 hours. The principles laid down in the Fire Regulations have, it would appear, been considerably influenced by the Ministry of Works Post-War Building Studies Report No. 20.

Although the time to see constructional works was very limited, it was evident that the majority of buildings were constructed in load-bearing brickwork with sand, cement rendering and colour wash finishes. It was, therefore, difficult to identify concrete slab construction from the more conventional types of structure.

From observations of buildings under construction and a visit to a new multistoried block of flats constructed in reinforced concrete with storey-height panels, it would appear that by virtue of the heavy sections employed, little difficulty is experienced in attaining the standards of fire-resistance required by the regulations. A reconsideration of the fire-resistance requirements may be necessary when lighter forms of construction become generally available.

Space above buildings to reduce potential fire spread is a requirement of building control, the distances between buildings being related to the type of construction of the adjacent occupancies. It is interesting to note in this connection that building regulations in Scotland and the proposed regulations for England and Wales make a similar, if somewhat more scientific, approach to this problem.

Means of Escape

Escape requirements are related to occupancy, the broad occupancy grouping being residential, public, and industrial, the requirements for escape purposes being related within each occupancy group to the type of construction and the height of the building above ground level.

In any of the buildings which were visited either domestic or public, staircases were without enclosures. We were informed that in domestic buildings over three storeys in height, a special fire-fighting staircase is required. In public buildings open staircases are permitted to the full height of the building provided that the construction is noncombustible and the general fire resistance is not less than 3 hours. In domestic buildings above 5 storeys, alternative means of escape are required and a variety of methods may be adopted. Escape upwards to the roof and re-entry into the building to a secondary means of escape is generally acceptable. Rescue by fire brigade ladders is also considered normal practice and external escapes are permitted for certain classes of building, where the fire resistance of the structure is high.

Internal linings would, from an inspection of a number of buildings visited, appear to be predominantly noncombustible, but there is evidence of plastic finish in rooms in the more recent domestic buildings, the intermediate grade "difficult to ignite" being used between the noncombustible and combustible materials. The general impression gained from visits to a number of different types of occupancy was that structurally they would, in most cases, retain their integrity in a burnout. There was little evidence of compartmentation to reduce structural loss and consequently if a fire occurred, evacuation of many of the buildings would be necessary.

PROPAGANDA

Russian propaganda for fire prevention is very thorough. It starts in school with children being given fire prevention instruction by teachers and schools often have their own fire brigade. Use is made of films of which it was stated about five were produced each year throughout the U.S.S.R. Two examples of these were shown, built around the following themes—

1. Teacher objects to children using candles and flammable trimmings on Christmas tree—teacher unpopular—one boy leads opposition to teacher—it is discovered teacher once displayed great heroism in saving child's life in fire—boy ashamed—teacher popular again.
2. Mother leaves children in flat to go to shop—is delayed by neighbour—children play with stove—fire starts—youths brave fire to rescue children, one child still unaccounted for—fire brigade arrives, finds child and brings her to safety—distraught mother learns her lesson.

Children are also encouraged to joint a junior voluntary fire brigade outside school. They are provided with helmets, uniforms, belts, and badges and also a fire engine and hose, the engine being driven by an adult. The "headquarters" is equipped with a field telephone and sprinklers.

The general public is expected to join voluntary fire brigades, usually at their place of employment, for which they get privileges (already mentioned) and this appears to engender a stricter attitude to fire prevention than in the United Kingdom. Smoking is prohibited in the auditorium of theatres, in stores, and in places of public assembly and discarded cigarette ends are not generally seen in public places.

Fire propaganda is used on bookmarkers distributed through shops. Leaflets are also put through letterboxes with newspapers and the post. Matchboxes carry general propaganda and these are naturally a vehicle for fire information. One main road intersection in Moscow carries a large illuminated sign about the dangers of discarding lighted matches. This stands out clearly because there is less illuminated advertising used than in the United Kingdom. The fire posters are striking, make bold use of colour and carry a minimum of wording. These are prepared by the Ministry of the Maintenance of Public Order and are displayed in works, schools, etc.

In addition to the above, it was stated that great use is made of the press, radio and television to carry fire propaganda.

No systematic attempt had been made to measure the impact of all the propaganda, but it was stated that fires attributed to children are fewer in Leningrad (5 per cent of all fires) than in the rest of the U.S.S.R. (18 per cent) and this was thought to be due to the greater attention given to these age groups in Leningrad.

GENERAL CONCLUSIONS AND SUMMARY

The most striking difference between the U.S.S.R. and the United Kingdom is the greatly reduced incidence of fire. In Moscow the fire incidence was stated to be 0.16 fires per 1000 population per annum which is typical of the figure for the Russian Federative Republic as a whole. This rate may be compared with 3.1 per 1000 population per annum in the United Kingdom. It is all the more remarkable because, in spite of an impressive rebuilding programme, there still remains a not inconsiderable proportion of substandard building, predominantly of timber construction. In Leningrad and Volgograd the fire incidence was stated to be 0.09 and 0.12 per 1000 population per annum, respectively. The discrepancy between these and the United Kingdom figures is so large that some time was spent trying to explain the difference. The figures were stated to include the attendances of voluntary brigades and even trivial fires. Perhaps the difference is partly attributable to a difference in reporting (statistical analyses comparable with those of the United Kingdom are not made) and partly due to different building traditions but possibly the biggest factor is the greater awareness of the public to fire danger through the All-Russian Voluntary Fire Protection Association. Certainly during the fortnight we spent in the U.S.S.R. we did not see or hear a fire engine on its way to a fire, so that it would be safe to assume that their fire attendance figures are considerably lower than ours, whatever differences there may be in reporting.

The fire losses are minute by our standards. Direct losses were given as follows—

	Annual direct loss	*Annual loss per head of population*
Russian Federative Republic	£6.8m	£0.057
Leningrad	£20,000	£0.005
Volgograd	£20,000	£0.028

These figures may be contrasted with the direct fire losses in the United Kingdom which, according to the latest figures of the British Insurance Association, are about £1.2 per head (most European countries have a per capita direct loss varying between £0.5 and £2). Perhaps some of the difference is due to buildings being State owned and the loss may therefore not be recorded; apart from this, there may be other differences in reporting. In spite of these very low figures for fire losses, the Russian insurance rates on contents of houses are comparatively high; 10/– per £100, the comparative rate in the United Kingdom being only 5/–. The premium income for Volgograd amounts to £56,000, a premium density of 1/8d per annum per head of population. The balance between premium income and claims was stated to be absorbed by fire protection work.

The training of fire engineers is very thorough and lasts for three to four years, about 4000 hours of teaching. The scientific and engineering standards are high. Models are extensively used for fire situations and to illustrate building construction. Technical posters are well illustrated; they convey the basic message together with graphs and any formulae needed for understanding the problem. The teachers in the fire technical institutes write textbooks covering various branches of fire protection. The laboratories in which practical work is carried out are very well equipped with modern apparatus. One laboratory is devoted to automation control systems.

Great emphasis is placed on physical training and fire sports are standardized, competitions being held through the U.S.S.R. Some of the competitors in a demonstration gave very fine performances over obstacle courses which included high fences, catwalks, and involved running over the roofs of huts before extinguishing a standard fire. Another race included hook-ladder drill up a four-storied tower.

The Central Scientific Research Institute for Fire Protection is about 130 strong and this number is to be increased in the future. It is backed by 20 Fire Testing Station, the members of which attend fires and carry out fire investigations. Each testing station specializes in a particular subject appropriate to its geographical region. The stations design fire-fighting equipment, e.g., spray heads, foam generators, foam sprinkler heads, etc. The furnace equipment at the Central Scientific

Research Institute is small and rather limited and no doubt it will be replaced before long. The Institute is considering the prediction of the fire performance of structures by studying thermal diffusion. When asked about the problems of providing restraint for structures during test, it was stated that a full-scale fire would be carried out on any type of building the State was about to construct.

The Research Institute expressed interest in our work on the problems of smoke on escape routes, the toxid and smoke hazards of plastics, and the production of foam from the jet engine. A film showing the buildings and activities of the Joint Fire Research Organization was shown several times in Moscow.

The Central Scientific Research Institute for Fire Protection had not received any reports from the Joint Fire Research Organization, possibly because in the past these had been sent to the Ministry of Construction. One publication, however, "Fire and the Atomic Bomb," had been translated into Russian for Civil Defence training. About one-hundred research publications were left in Moscow together with Home Office Training Manuals and Fire Protection Association publications and in return our hosts presented us with books. It was agreed that the Institute and the Joint Fire Research Organization should interchange publications.

We were naturally interested in the fire precautions in the buildings we visited which included hotels, department stores, theatres, offices, and museums. Fire extinguishers were always in evidence and these usually carried a paper tag showing the date of the last inspection. The hotels and an apartment house we saw did not have enclosed staircases nor did we see alternative staircases for escape. None of the buildings we visited had a sprinkler system although, of course, as the total number of buildings seen was small, it would be unwise to draw any general inference.

Any report would be incomplete without reference to the generous way in which we were received. The hospitality of our hosts was so prodigious that it is doubtful if we would have survived another week. No matter what time we departed from one place and arrived at another, a delegation of senior officials was there to see us off and to meet us. Our hosts were very keen to show us examples of their engineering achievements and their culture whenever we were not dealing with fire matters. The outstanding impression we were left with was of a genuine desire for friendship and co-operation and without doubt the visit will bring about a more ready interchange of information between the two countries. A report based on such a short visit must of necessity be incomplete but at least it will show the lines along which future co-operation can move.

Acknowledgment

This paper has been prepared by the Joint Fire Research Organization of the Department of Scientific and Industrial Research and Fire Offices' Committee; it is published by permission of the Director of Fire Research.

Subject Headings: *Building codes; Dust, explosions; Education, curricula; Ethyl bromide; Fire, detection; Fire, oil; Fire protection; Fire protection, chemical; Fire protection, in U.S.S.R.; Fire protection, voluntary organization of; Fire research; Fire resistance; Flash point; Ignition; Plastics, ignition of.*

APPENDIX A

People Interviewed

I. M. Zemskii (Major General) Chairman,
Directorate of Fire Protection,
Russian Federative Republic Ministry of the Maintenance of Public Order

A. K. Mikeev (Engineer Lieutenant Colonel)
Assistant to Chairman

N. A. Viktorov, Head
Technical Department of Fire Protection,
Ministry of the Maintenance of Public Order

P. M. Bogdanov, Chairman
All-Russian Voluntary Fire Protection Association

R. A. Perelyet
United Kingdom desk, Foreign Relations Department,
U.S.S.R. State Committee for Co-ordination of Scientific Research

I. N. Troitskii, Chief
Moscow Fire Protection Directorate

K. S. Krichiverov, President
Moscow Voluntary Fire Protection Association

V. F. Obukhov, Deputy Director
Higher Educational Establishment of Fire Protection Engineers

A. N. Smurov, Director
Central Scientific Research Institute for Fire Protection

I. V. Ryabov, Deputy Director

B. I. Konchaev, Chief
Leningrad Fire Protection Board

V. M. Sokolov, Assistant Chief

M. E. Yurko, Chairman
Leningrad Voluntary Fire Protection Association

B. W. Megorcky, Head
Leningrad Fire Testing Station

M. P. Zacharov, Head
Leningrad Fire Technical School

I. A. Glebov, Chief
Volgograd region, Ministry of the Maintenance of Public Order

Mr. Fomin, Chief
Volgograd Fire Protection Board

A. V. Kuzeev, Assistant Minister
Ministry of the Maintenance of Public Order

U. I. Volsky, Assistant Minister
Foreign Affairs, Russian Federative Republic

APPENDIX B

Extracts of books presented by the Ministry of the Maintenance of Public Order to the delegation are given below. The originals are in Russian and are in the Library of the Joint Fire Research Organization from which they may be obtained on loan. Acknowledgement is made to the National Lending Library for Science and Technology for its help in getting the subject headings translated.

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CONTENTS

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Chapter II. Methods for examining plans 25

2. Romanenko, P. N. and Roitman, M. Ya. *Fire prevention in heating and ventilating systems.* (Pozharnaya profilaktika otopitel'noventilyatsionnykh sistem). Izdatel'stvo literatury po stroitel'stvu "Stroiizdat". Moscow, 1964.

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Chapter X. Aeration of buildings 136
Chapter XI. Removing dust from air 145
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Chapter XIII. Air intake equipment for mechanical ventilation 170
Chapter XIV. Exhaust equipment for mechanical ventilation 178
Chapter XV. Fans 199
Chapter XVI. Fire prevention in ventilation systems 210

3. CHERKASOV, V. N. AND UL'YASHCHENKO, V. E. *Fire prevention in electrical equipment.* (Pozharnaya profilaktika elektroustanovok). Izdatel'stvo ministerstva kommunal'nogo khozyaistva RSFR. Moscow, 1963.

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Chapter IV. Electric machines and control apparatus 114
Chapter V. Electric lighting 136
Chapter VI. Domestic heating equipment 160
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4. BUSHEV, V. P. *et al. Fire-resistance of buildings.* (Ognestoikost'zdanii). Izdatel'stvo ministerstva kommunal'nogo khozyaistva RSFSR. Moscow, 1963.

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Chapter I. Duration and temperature conditions of fires 3
Chapter II. Methods of testing the fire-resistance of constructional designs 26
Chapter III. Fire-resistance of reinforced concrete structures 36
Chapter IV. Fire-resistance of steel structures 95
Chapter V. Fire-resistance of elements of large-panel buildings 115
Chapter VI. Protection of openings in fireproof barriers 136

5. KUZNETSOVA, A. E. *Water supply for firefighting.* (Protivopozharnoe vodosnabzhenie). Izdatel'stvo ministerstva kommunal'nogo khozyaistva RSFSR. Moscow, 1963.

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Chapter V. Pumping stations for lift II 83
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Chapter XI. General remarks on methods of examining plans for water supply systems to objectives and populated localities 230

Chapter XII. General remarks on methods for fire-technical investigation of water supply systems 232
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6. Information Bulletin. Issue, 1. *Fire prevention and extinguishing.* (Pozharnaya profilaktika i pozharotushenie). Stroiizdat. Moscow, 1964.

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Blinov, V. I. *et al.*—Relationship between the rate of combustion of a liquid and its surface temperature 3
Baratov, A. N. and Kucher, V. M.—Instrument for determining the explosiveness of vapour-gas–air mixtures 14
Baratov, A. N. *et al.*—Investigation of the range of explosiveness of the system ethylene oxide–methyl bromide–air 18
Milinskii, A. I.—Principles for standardizing the evacuation of people from large buildings 21
Pchelintsev, V. A. and Fedorenko, V. S.—Investigation of fires in underground buildings 35
Megorskii, B. V.—Classification of causes of fires connected with furnace heating 40
Ivanov, E. N.—Calculation of sprinkling intensity 52
Monakhov, V. T.—Investigation of the combustion processes of solid substances 60
Monakhov, V. T.—Methods for fire development analysis 71

7. Information Bulletin. Issue 4. *Fire Technology.* (Pozharnaya teknika). Stroiizdat, Moscow, 1964.

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Isaev, M. N. and Rode, A. A.—Types of fire engines 3
Kurbatskii, O. M.—Calculation of foam generators 11
Ivanov, E. N.—Cavitation processes in hydrants 17
Bogdanov, P. P.—Influence of cross sections of vacuum systems on the water intake time 28
Ivanov, E. N.—Hydraulic shock in fire hoses 46
Kudryashov, A. V.—Fire-hose jets 59
Ozherel'ev, I. I.—Experimental investigations of the stresses, deformations and vibrations in the benda of the ASM–30 automatic ladder . . . 63
Gunbin, Yu. I. *et al.*—Using wetting agents for extinguishing fires 81
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A REVIEW OF FIRE WEATHER INVESTIGATIONS IN AUSTRALIA*

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INTRODUCTION

The tremendous holocaust of January 1939 in southeastern Australia caused an acute public awareness of Australia's growing bushfire problem. The word growing is used advisedly; with the opening up of much former forest land for grazing, the opportunity for fire in the forests is increased enormously, and softwood plantations in particular are extremely vulnerable to fires originating in the grasslands outside.

The Bureau of Meteorology commenced its attack on fire weather problems in 1947 with the publication of Bulletin 38, *A Study of Meteorological Conditions associated with Bush and Grass Fires and Fire Protection Strategy in Australia.* Prior to this date most investigations were the work of forestry personnel in the various states and largely consisted of tests of various overseas fire danger tables and their local modifications, the use of hazard sticks as a method of predicting fire danger, and, particularly in Queensland, the selection of suitable days for burning felled rain forest.

Conferences of Forestry and Rural Fire Authority personnel made representations for the appointment of Fire Weather Meteorologists, which were implemented in certain states in 1955 and detailed investigations were commenced into various fire weather problems and aspects of fire behavior.

GENERAL

The History of Major Fires of the Past

The important work of collecting synoptic material pertaining to major bushfires was begun in 1947 with the publication by the Bureau of Meteorology of its Bulletin No. 3 (Foley [1947]). Fire occurrences from 1851 on were listed. This necessary work is now continued in the form of case histories of major fires, some of which have been published, e.g., Robin (1957) and Larkins (1958).

The Estimation of the Time of Curing of Annual Grasses

Fire danger rating systems of North American origin and local modifications thereof have been examined and used in the different states with varying degrees

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* Presented at the Tenth Pacific Science Congress of the Pacific Science Association, held at the University of Hawaii, Honolulu, Hawaii, U.S.A. 21 August to 6 September, 1961, and sponsored by the National Academy of Sciences, Bernice Pauahi Bishop Museum, and the University of Hawaii. Published in Australian Meteorological Magazine, December 1961. The author has made available to Fire Research Abstracts and Reviews a sequel covering the period 1961–1964 (see Appendix).

of success. In all cases some idea of the fuel state, particularly the degree of curing of the grass, is required at fairly frequent intervals. Robin (1957) demonstrated it to be theoretically possible to estimate approximately the time of curing of annual grasses in inland New South Wales using cumulative soil-moisture calculations. However, the idea has not been followed up, it being found more practicable to extend the fuel state reporting network.

Synoptic Patterns and Fire Occurrence

The study of synoptic weather patterns associated with and leading up to major fire outbreaks was commenced by Foley (1947). Robin and Wilson (1958) developed an objective method for forecasting major fire occurrences in the Riverina district of New South Wales, using as parameters the maximum temperature, 3 p.m. dew point, amount of last rainfall, number of days since last rainfall, and 3 p.m. wind speed. The analysis was made using the probability ratio method.

The Relation Between Fuel Moisture Content and Meteorological Parameters

This subject has received attention over a considerable period particularly from the forestry departments in the various states and the Commonwealth Forestry and Timber Bureau. Wilson (1958) has discussed some of the problems connected with moisture content estimations. McArthur (1958) summarizes the results of his work on the rate of spread of fire in three classes of fuel—eucalypt litter, radiata pine litter, and grass, made over a wide range of meteorological conditions. Measurements were made of rate of spread; and fire intensity, flame height, spotting potential, fire instability, suppression difficulty, and fire damage were assessed. All such observations were related to field measurements of air and fuel temperatures, relative humidity, wind velocity (in forest and in open), cloud cover, rainfall, and fuel moisture content. Tables are presented giving the surface fuel moisture content of eucalypt litter as a function of air temperature and relative humidity, and the relation between wind velocity in the forest and wind velocity in the open.

Measurements of temperature, relative humidity, and wind profiles have been made over a period of years in pine forests at Canberra and Mt. Burr (S. Aust.). Instrument towers were used and measurements made from canopy to ground level. However, the data have not yet been statistically treated.

The Effect of Meteorological Factors on Fire Behaviour

Rainbird (1958) has discussed the various ways in which wind affects fire behaviour. He mentions the importance of forecasting new cyclonic developments in existing troughs and points out that whereas conditions favourable for development over a broad zone can frequently be recognized, the exact location of development, critical for a successful wind forecast, is a much more difficult matter. An interesting suggestion for coping with the problem of forecasting local wind variations due to topography is that the local fire fighter should himself observe and study local wind behaviour in quiet seasons and compare his observations with broad-scale flow data subsequently obtained from the meteorologist.

The seabreeze is a most important wind mechanism during the fire season in Australian coastal areas and can have far-reaching effects on fire behaviour on account of (a) the changes in fire danger brought about by decreased temperature, increased relative humidity, and increased wind speed, and (b) the change in wind direction which may turn a flank into a fire-front and predisposes conditions towards the formation of fire whirlwinds. Accordingly the seabreeze has received considerable attention by Clarke (1955, 1958) in southern Australia and by Whittingham (1958) in southeast Queensland.

The closely allied subject of the cool changes of southeastern Australia has been analyzed by Berson *et al.* (1959). These cool changes are often double (and occasionally multiple) and can cause the establishment of new fire-fronts on large previously southward-moving bushfires. The prefrontal change is often dry.

The effect of temperature lapse rate on fire behaviour was first mentioned by Hounam in a section of the Bushfire Bulletin (Foley [1947]). The sparsity of the radiosonde network has limited the number of opportunities to examine the matter but Whittingham (1958) has shown it to be important in reforestation burns in heavy fuel in southeast Queensland. This paper also examines the effects of cloud amount, rainfall, and evaporation, gradient wind, and vertical wind shear on the success of the burns.

PHENOMENA

Fire whirlwinds have received some attention in the Australian literature. Whittingham (1955) collected many observations of their occurrence in various parts of Australia and attempted to correlate them with meteorological and other parameters. An interesting case of fire whirlwind occurrence in southeast Queensland was examined in detail by Whittingham (1959).

Cases have been described by Whittingham (unpublished) of unusual fire behaviour which seems to have been the result of sudden overturning of the lower 10,000 feet of the troposphere with resulting downward transport of momentum.

Some data on lightning as a fire-causing agent have been accumulated but not published. Fire storms have not been closely examined.

McArthur (unpublished) has concluded that crown fires can best be prevented by prescribed burning to reduce fuel concentration.

FIRE DANGER RATINGS

Various systems of rating fire danger or fire hazard exist in the different Australian States. However, throughout eastern Australia the index developed by Luke (1953) is widely used. This weights the following factors—temperature, relative humidity, wind speed, and fuel state. The Canadian grass fire tables described by Foley (1947) have had some application inland. Modifications were made to the Luke index by Whittingham (1960) to adapt it to dew point instead of humidity for greater operational efficiency when using synoptic data. Dissatisfaction with the Luke system as applied to Tasmania was voiced by Hickman (1958) mainly on the grounds of the subjectivity involved in estimating the fuel state, particularly the state of curing of the grass. The Chipman index, involving the use of hazard sticks, is preferred. Hazard stick readings are also preferred in South and West Australia, but are not in general use in the other states, although some observations are being made with standardized materials supplied by the Forestry and Timber Bureau, Canberra.

McArthur (1958, 1960) has produced fire danger tables for low quality eucalypt and for annual grasslands applicable to southeastern Australia. Based on the contention that the equilibrium fuel moisture content is a function of the meteorological variables, he bases his grasslands tables on the following calculations: basic fuel moisture content obtained from maximum temperature and minimum relative humidity, a correction of the basic f.m.c. according to the state of curing of the grass, a correction for recent rainfall, and finally a fire danger rating obtained from the adjusted fuel moisture content and wind velocity with a correction for fuel quantity.

Forecast Evaluation

The forecast accuracy requirements of forestry have been described by Douglas and McArthur (unpublished). McArthur (1958) has stated that blow-up conditions "are apparently virtually impossible for the Bureau of Meteorology to forecast, although such days probably account for 90 per cent of our total fire damage. The accurate forecasting of such weather would be an immense advance in preventing the appalling damage which occurs on such relatively isolated days." Wilson (1958) found that "a disturbingly high proportion of forecasts fail to predict accurately maximum temperatures of 90°F or more, and a high percentage of forecasts fail to predict low dew points and humidities accurately." He states that errors in prognosis are the root cause, particularly incorrect predictions of cyclogenesis. Whittingham (1958) examined temperature and dew-point forecasts for Queensland and Mizon (1958) investigated results in South Australia. The latter writer pointed out that lack of information concerning the early morning hydrolapse as a result of the unsatisfactory time of radiosonde release precludes the development of an objective method of forecasting the diurnal variation of dew point. Maine (1958) has developed an objective forecasting technique for maximum temperature prediction in South Australia.

CONCLUSIONS

Many aspects of the interrelations between fire and weather have been examined to some extent in Australia. It is evident that the most serious deficiencies are to be found in connection with the *forecasting* of the fire-important meteorological parameters, particularly wind, temperature, and relative humidity. Very often high winds, high temperatures, and extremely low humidities occur simultaneously and with exceptional suddenness; this leads to the widely held belief that such explosive fire conditions are incapable of being forecast. On examining the synoptic situations it almost invariably appears that sudden cyclogenesis has occurred over a relatively small localized area, usually in a broad pre-existing trough of low pressure overlain by a pattern of upper air divergence. The basic need is for better prognostic procedures to cover such occurrences. Momentum transfer is another factor which could receive more attention from forecasters particularly since it affects absolute humidity at the surface as well as wind velocity. A feature which has received no attention is the problem of 3- to 5-day forecasting. There is a pressing need for this type of forecast from a fire control point of view.

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APPENDIX

SEQUEL—PERIOD 1961–1964

In the period 1961–1964 fire weather research in Australia has been concerned mainly with a close examination of certain major fires in various states, with improvements in the fire danger rating system and with basic research into the response of organic forest materials to humidity changes. Temperature profiles under a eucalypt canopy have been studied. Several instructional works on fire weather have been published for training purposes.

Case Studies of Major Fires

The holocaust of 24 January 1961 at Dwellingup, West Australia, was the subject of a Royal Commission of enquiry and the report published (1961) contains a detailed account of the associated weather conditions. This fire (of 360,000 acres) has become an Australian classic. A less severe fire in the Dandenong Ranges, Victoria, in January 1962 was studied in detail by Whittingham (1964). The fire was close to Melbourne, where full surface and upper air meteorological observations are available. Alternate advances and retreats of the summertime coastal front of southern Australia hampered the fire fighting effort with its frequent changes of wind and air mass.

Fuel Moisture and Meteorological Parameters

King and Linton [1963(a) and (b)] studied moisture variation in forest fuels using an advanced experimental climate tunnel. Study was made of the equilibrium moisture content relationships of different woods and botanical materials under fluctuating temperature and relative humidity conditions with particular attention to hysteresis effects and the application to hazard sticks as fuel moisture indicators.

Temperature Profiles in Eucalypt Forests

Roberts (1964) has studied temperature profiles in the lowest 5 ft over eucalypt litter. He reports midday temperature lapses of up to 37°F in the first three inches above the litter and up to 42°F in the first 4 ft. He considers that such lapse rates are related to the intensity of convective column formation over a fire which in turn relates to the intensity of the spotting process. A temperature inversion between the 3 in. and 4 ft levels during the evening was noted on hot nights and is held to be responsible for damping down convection and therefore fire intensity. Heat storage in the soil with consequent high litter temperatures is regarded as primarily responsible for observed high rates of fire spread following a cold frontal passage late in the afternoon or evening.

Fire Behaviour

Douglas (1964) has examined the characteristics of fire behaviour during major fires in coniferous plantations in South Australia. He states that "wherever plantations have been established in the Mediterranean environment in the Southern Hemisphere the number of really successful suppression actions in conditions of bad fire weather has been remarkably small." He stresses the importance of the character and quantity of the ground fuels in relation to the nature and vertical continuity of the aerial fuels. He provides a useful table of fire behaviour in very high and extreme weather conditions for the five categories of plantation: (a) juvenile plantations, (b) from canopy formation to age of first thinning, (c) middle-aged stands, (d) old well-thinned stands and (e) slash after clear-felling. He discusses spotting, crown fires, and fire storms. Spotting distances of upwards of a mile from crown fires in Radiata pine have been authenticated. Breaks in the canopy of the order of an acre or more allow stronger winds from aloft to drop into the gap. Doubts are raised regarding the value of firebreaks 2 to 3 chains wide. Edge trees should be left unpruned to reduce wind speed in the stand.

Phenomena

King (1964) gives an account of a fire-induced tornado with estimates of the core velocity made from motion film pictures.

Controlled Burning

McArthur (1964) discusses the effect of fire upon stream flow in forested catchments. The magnitude of fire-induced changes are in direct relation to the fire intensity. The judicious use of carefully planned low intensity controlled fires is considered to be one of the most efficient means of reducing the damage resulting from wildfire.

McArthur (1961) had previously discussed the problem of excessive fuel accumulation and its relation to crown fire development. After ten years or so in the absence of fire, litter accumulation reaches such a level that any fire then starting is extremely difficult to control, and causes excessive damage to timber, soil, and watershed. Massive soil erosion, increased flood peaks, and deteriorated water quality result. Mount (1964) discusses the interdependence of the eucalypts and forest fires in southern Australia. The eucalypts are not only fire-resistant but they also produce a great deal of fuel. All species regenerate more abundantly after fire and some cannot regenerate without it. Some species suffer and die from prolonged absence of fire. Mount concludes that the wide distribution of fire in the past may have been maintained by the eucalypts. It is interesting to note that certain eucalypts such as the ribbon-barked and stringy-barked types are designed so as to accelerate the spread of fire. The ground fire is enabled to travel up the tree and burn fiercely in the wind. Burning bark and other aerial fuels then carry spot fires well ahead of the ground fire. Under hot, strong wind conditions (and especially with crown fires) there are probably millions of live sparks landing ahead of the ground fire. Mount considers the spot fire mechanism has not been given sufficient prominence in the literature.

Fire Danger Assessment

McArthur (1962) made a further revision of his Forest Fire Danger Rating Tables and in late 1963 converted them to a convenient slide rule form. The provisional Grassland Tables were revised in 1962 and a slide rule produced, which was converted for dew point rather than humidity as parameter in 1964.

Instructional and Educational Material

Luke (1961) brought out a small but useful book on fire control designed for popular consumption. The chapters relating to fire weather form a suitable introduction to the subject. The World Meteorological Organization has brought out a Technical Note on forecasting for forest fire services, the authors being Turner, Lillywhite, and Pieslak (1961). The Bureau of Meteorology (1963) has recognized the need for fire weather training of meteorologists by incorporating four chapters on fire weather in its Manual of Meteorology. McArthur (1962) has provided a very useful guide to control burning in eucalypt forests and another (unpublished) report relates to brigalow country.

Subject Headings: ***Controlled burning; Fire, danger rating, Australia; Fire, grass; Fire weather, Australia; Weather, forecasting; Weather, synoptic patterns; Whirlwind.***

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McArthur, A. G.: *Streamflow Characteristics of Forested Catchments;* Aust. For. *28*, No. 2 (1964).

McArthur, A. G.: *Fire Behaviour in the Brigalow Lands of the Fitzroy basin* (unpublished).

Mount, A. B.: *The Interdependence of the Eucalypts and Forest Fires in Southern Australia*, Aust. For. *28*, No. 3 (1964).

Roberts, W. B.: *Temperature Profiles under a Eucalypt Forest Canopy*, Aust. For. Res. *1*, No. 1 (1964).

Royal Commission: *Report on the West Australian Fires*, Govt. Printer, Perth, 1961.

Turner, J. A., Lillywhite, J. W., and Pieslak, Z.: *Forecasting for Forest Fire Services*, Tech. Note No. 42, W.M.O., 1961.

Whittingham, H. E.: *Some Cases of Vertical Transfer of Momentum Illustrating Its Application to Fire Weather Forecasting*, Working Paper 55/297, Bur. of Met., Jan. 1959; Manual of Meteorology, Chapters 31–34, Fire Weather, Bur. of Met., Dec. 1963.

Directory of Fire Research in The United States*

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL

Reviewed by R. M. Fristrom

The Directory is arranged in five sections: Government Agencies, Private and Industrial Laboratories, State Universities, Private Universities, and Associations. Projects are described under the laboratory where the work is performed. In general, the associations sponsor rather than perform research. Their interests are described.

An alphabetical list of sponsors, showing the projects sponsored by them, is appended. Another list described "in-house" research paid for by the laboratory that performs the research.

The index is compiled by titles of projects according to areas of scientific interest.

This is a survey of the research connected with fire which is currently underway in the United States. It is a comprehensive rather than a selective compilation since it was assembled by contacting those laboratories that were known or thought to be doing fire research, asking them to list the fire research that they had done or were doing. This represents the best available census of fire research in this country, although it is possible or perhaps likely that some projects have been missed.† For the convenience of the readers of FRAR we are copying the list of titles of research projects along with the names of the laboratory at which the work is carried out, the sponsor, and the director of the research. For more detailed information on the subject and status of the projects the reader is referred to the Directory.

As the list indicates, there are some two hundred applied and basic fire research projects of varying size underway at present. This work is taking place at some ninety different laboratories under the sponsorship of some sixty different agencies. This represents a great diversity of government, association, foundation, and industrial laboratories. Three-quarters of the work is directly supported by government agencies and the remaining support is about equally divided between non-profit organizations (associations, foundations, etc.) and private industry.

A few remarks would appear in order which represent the personal opinions of the reviewer. This is a census of laboratories who feel that they do fire research. Obviously, definitions vary widely and not all of the research reported would be considered fire research under a restricted definition. Despite this, the reported work represents a substantial research effort. Almost half of the projects are classified as basic research by the groups doing the work. A perusal of the content indicates that the reviewers' definitions of basic research differs markedly from that indicated in the Directory. (He would have designated less than 10 per cent of the projects "basic.") This is, of course, largely a question of semantics, but it points out a serious communication problem in the fire field. This diversity in

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* NAS—NRC Publication 1189, 214 pages, 1964. Library of Congress Catalog Number 64–60039.

† Mr. D. W. Thornhill, Executive Secretary of the Committee on Fire Research, who compiled the Directory, would appreciate any information on projects not listed, so that they can be included in future compilations. Address: Committee on Fire Research, National Academy of Sciences, 2102 Constitution Avenue, N.W., Washington, D.C. 20418.

interpretation of what is basic research is not confined to Fire Research; it represents a widespread disagreement between Management and Scientists. Scientists feel that basic research is that research which will add to the fundamental knowledge in a field while management usually defines basic research as any research without concrete immediate objectives. This results in considerable confusion on the status of basic research in Fire Research and almost every other field of scientific endeavor. There is no easy solution to this problem. What is required is mutual tolerance and understanding.

The weakest area in Fire Research in the United States is the study of fundamentals and a tendency to limit the scope of investigations rather than making broad interdisciplinary formulation of fire problems. The status is even weaker than the pessimistic figure of 10 per cent basic fire research would indicate, because there is a general tendency to issue a final report and drop problems rather than to publish in the open literature. This is to be deplored, since many of these reports are inaccessible to students who might want to enter the field and need the information most. The information communicated to the scientific public by a final report is at least an order of magnitude less effective than even the shortest publication in the journal literature. Many of the research workers are well aware of the problem and are making efforts to remedy the situation.

A positive virtue of the fire research picture is the diversity of interests supporting fire research. This is a healthy sign and can be a source of great strength to the field. It is particularly gratifying to note that there exists cooperation between industry and government in projects of mutual interest and that multiply supported research is not uncommon. This fosters a much needed mutual understanding between the groups involved.

Subject Headings: ***Directory, fire research; Fire research, directory of; Fire research, sponsors of; Fire research, workers in; Laboratories, fire research; Projects, fire research.***

FIRE RESEARCH PROJECTS IN THE UNITED STATES OF AMERICA

(Taken from Directory of Fire Research in the United States, Nat. Academy of Sciences, Pub. No. 1189, Washington, D. C., 1964)

Page	Laboratory and Research Director	Research projects, status, and Sponsor*
3	Argonne National Laboratory Chemical Engineering Div. 9700 South Cass Avenue Argonne, Illinois Dr. S. Lawroski, Division Director	Isothermal Oxidation Kinetics of Reactor Metals (completion in 1964), 1 Ignition of Reactor Metals (completion in 1964), 1

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FIRE RESEARCH PROJECTS IN THE UNITED STATES OF AMERICA

Page	Laboratory and Research Director	Research projects, status, and Sponsor*
6	Central States Forest Experiment Station 111 Old Federal Building Columbus 15, Ohio Richard D. Lane Director	Hardwood Fire Control (cont.), 2
7	Intermountain Forest and Range Experiment Station Forest Service Building 25th Street and Adams Avenue Ogden Utah, Joseph F. Pechanec, Director	Skyfire (cont.), 2 Fire Control Systems (cont.), 5 Fire Physics (cont.), 11 Fire Behavior (cont.)
9	Lake States Forest Experiment Station St. Paul Campus University of Minnesota St. Paul 1, Minnesota M. B. Dickerman, Director	Fire Control Systems (cont.), 2 Fire Control Planning (cont.), 2
10	Northern Forest Experiment Station P. O. Box 740 Juneau, Alaska Richard M. Hurd, Director	Fire Control Systems (cont.), 2
10	Pacific Northwest Forest and Range Experiment Station P. O. Box 3141 Portland 8, Oregon Philip A. Briegleb, Director	Fire Control and Use (cont.), 2 Fire Weather (cont.), 2
11	Pacific Southwest Forest and Range Experiment Station P. O. Box 245 Berkeley 1, California R. K. Arnold, Director	Conflagration Control (cont.), 2 Fire Control Systems (cont.), 2 Fire Chemistry (cont.), 2 Fuel Break (cont.), 3, 4 Fire Prevention (cont.), 3 Improvement of Fire Control Methods (cont.), 3 Fire Behavior (cont.), 5
14	Rocky Mountain Forest and Range Experiment Station Colorado State University Fort Collins, Colorado Raymond Price, Director	Fire Control (cont.), 2 Fire Use (cont.), 2

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FIRE RESEARCH PROJECTS IN THE UNITED STATES OF AMERICA

Page	Laboratory and Research Director	Research projects, status, and Sponsor*
15	Southeastern Forest Experiment Station P. O. Box 2570 Asheville, North Carolina Thomas F. McLintock, Director	Fire Use (cont.), 2, 6 Fire Control (cont.), 2, 6 Fire Potential (cont.), 2 Fire Environment (cont.), 2, 6 Fire Models (cont.), 2, 6, 7
18	Southern Forest Experiment Station 10210 Federal Building 701 Loyola Avenue New Orleans 12, Louisiana Walter M. Zillgitt, Director	Fuels and Fire Control (cont.), 2 Fire Prevention (cont.), 2
19	Division of Forest Protection Research Washington 25, D. C. Keith Arnold, Director	National Fire Danger Rating (cont.), 2
19	Forest Products Laboratory North Walnut Street Madison 5, Wisconsin Dr. Edward G. Locke, Director	Fire-Retardant Chemical Treatment for Wood, 2 Composition of the Products of the Fast Pyrolysis of Untreated and Chemically Treated Wood (completion 1965), 2 Charring Rate of Wood as Influenced by Species, Density, Ring Orientation, and Moisture Content (completion 1965), 2, 8 Heat of Reaction in the Pyrolysis of Untreated and Treated Wood (completion 1964), 2 Heat of Reaction in the Combustion of Untreated and Treated Wood (completion 1964), 2 Kinetics of the Fast Pyrolysis of Wood, with and without Inorganic Chemical Treatments (completion 1964), 2
26	National Bureau of Standards Washington 25, D. C. Dr. Allen V. Astin, Director	Fire Models (active), 7 Fire Hazard Studies (active), 7 Thermal Reactions (active), 7 Mechanism of Fire Extinguishment (active), 9 Fire Research (active), 5, 10, 11 Properties of Concrete at High Temperatures (active) 12 Heat Transfer Measurements (active), 7 Thermal Conductivity of Materials at Temperatures to 2000°C (active), 7 Heat Measurements (active), 7 Thermal Emittance Standards (active), 13 Mass Spectrometric Studies of High Temperature Degradation of Polymers (active), 13, 10 Fluorocarbon Chemistry (active), 7 Basic Combustion Research, 7

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FIRE RESEARCH PROJECTS IN THE UNITED STATES OF AMERICA

Page	Laboratory and Research Director	Research projects, status, and Sponsor*
		High Temperature Thermocouples (active), 7 Chemiluminescence in Gases (active), 7 Research in High Temperature Chemical Physics (active), 1
36	Weather Bureau Portland, Oregon Howard S. Ayer	Dry East Winds Structure of Winds Over Ridges Cascades Fire Weather Project
36	Weather Bureau Riverside, California Mark J. Schroeder	Cooperation with the U. S. Forest Service's Forest Fire Laboratory covering field studies and critical fire weather patterns
36	Air Force Systems Command Air Force Aero Propulsion Lab. Wright-Patterson Air Force Base, Ohio Col. E. A. Hawkens, Chief	Materials Fire and Explosion Hazard Characterization (active), 14, 15 Evaluation of Polyfluorinated Organic Esters of Inorganic Acids as Extinguishing Agents for Magnesium Fires (completion Jan. 1964), 14, 15 Hazardous Vapor Detection (cont.), 14, 15
38	Chemical Research and Development Laboratories Edgewood Arsenal, Maryland Col. James A. Hebbler, Commanding Officer	Storage and Handling of Liquid Rocket Propellants for Rockets and Guided Missiles (completion 1964), 14, 16
39	Army Engineering Research and Development Labs. Fort Belvoir, Virginia Col. J. H. Kerkering, Director	Flame Inhibition Mechanism studies (active), 17
39	Naval Applied Science Laboratory Naval Base Brooklyn 1, New York Capt. I. F. Fike, Director	Storage Deterioration of Foam-Liquids (cont.), 9 Fire Fighting Systems and Equipment (cont.), 9 Fire Protection and Fire Fighting of Missile Fuel-Oxidizers and Solid Propellants (cont.), 9
41	Naval Boiler & Turbine Lab. Philadelphia Naval Shipyard Naval Base Philadelphia 12, Pennsylvania Capt. W. W. Braley, Director	Mechanism of Ignition and Extinguishment, 9
42	Civil Engineering Laboratory Port Hueneme, California Cdr. W. J. Christensen, Com. Ofc. & Dir.	Near Infrared Attenuating Fluids, 18 Research on Properties of Materials Exposed to Intense Thermal Radiation (beginning), 18
43	Naval Radiological Def. Lab. San Francisco 24, Calif. E. P. Cooper, Sci. Dir.	Ignition and Fire Propagation by Thermal Radiation, 19

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44	Naval Research Laboratory Washington, D. C. Capt. A. E. Krapt, Director	Design Development of Foam Generating Equipment (cont.), 20 Studies in Free Radical Quenching Mechanisms and Properties of Dry Chemical Extinguishment (cont.), 20 12 Fuel Vapor Reduction Mechanism (cont.), 20 Foam-Forming Concentrate Investigations (cont.), 9, 12 Portable Fire Pump Development (completion 1964), 9 Study of the Damage Control Characteristics of New Liquid Propellants (completion 1964), 9, 20
47	Explosives Research Laboratory 4800 Forbes Avenue Pittsburgh 13, Pennsylvania Robert W. Van Dolah, Chief	Hybrid Flames (cont.), 21 Review of Fire and Explosion Hazards of Flight Vehicle Combustibles (completion 1964), 14, 21 Combustion of Dusts (inactive), 21 Formation and Flammability of Stratified Methane-Air Mixtures (cont.), 21 Investigation on Ignition Characteristics of Fuels and Lubricants (completion 1965), 14, 21 Ignitibility of Fuel-Tank Atmospheres (completion 1964), 21, 22
53	Health and Safety Research and Testing Center 4800 Forbes Avenue Pittsburgh 13, Pennsylvania Donald S. Kingery, Director	Control of Fires in Inactive Coal Deposits (cont.), 21 Control of Fires in Inactive Mines (cont.), 21 Factors Affecting Ignition and Suppression of Dust Explosions (cont.), 21
55	National Aviation Facilities Experimental Center Atlantic City, New Jersey C. M. Middlesworth, Chief, Aircraft Branch	Criteria for Fire Resistant Requirements, Project 311-2X, Phase I (completion 1964), 23 Thermal Criteria for Interior Materials, Project 311-3X, Phase I (completion 1964), 23 Crash Fire Ignition Suppression Systems for Large Aircraft, Project 311-6X (compl. 1965), 23 Power Plant Fire Tests, Full-Scale Turbo-Fan Engine Fire Tests, Project 321-5X, Phase I (completion 1965), 23 Power Plant Fire Tests—Model Fire Tests, Project 321-5X, Phase II (completion 1964), 23 Power Plant Fire Tests of Full-Scale Small Engine Installation, Project 321-15X, Phase III (completion 1964), 23 Design and Evaluation of Aircraft Engine Fire Extinguisher Systems, Project 321-12X (completion 1964), 23 Cargo Compartment Fire Protection, Project 331-5X (completion 1964), 23 Helicopter Fire-Fighting Techniques, Project 415-4X (completion 1964), 23

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64	Lewis Research Center 21000 Brookpark Road Cleveland 35, Ohio A. Silverstein, Director	Calculation of High Temperature Gas Transport Properties (active), 16 Diffusion and Heat Conduction in Polar Gases (completion 1964), 16 Direct Measurement of Prandtl Number (cont.), 16
69	AeroChem Research Labs., Inc. P. O. Box 12 Princeton, New Jersey H. F. Calcote, Director of Research	Mass Spectrometric Study of Combustion Plasma (cont.), 24 Ionization in Solid Propellant Rocket Flames (cont.), 20 Theory of Interfacial Reactions in Flow Systems (exp. completion Dec. 1965), 25 Kinetic and Aerodynamic Aspects of the Oxidation of Refractory Metals in Partially Dissociated Oxygen (exp. compl. Dec. 1964), 25
72	Arthur D. Little, Inc. Acorn Park Cambridge 40, Massachusetts James M. Gavin, President	Launch Vehicle Fire and Explosion Hazards (1963, cont.), 16
74	American Oil Company Research & Development Dept. Whiting Laboratories P. O. Box 431 Whiting, Indiana P. C. White General Manager	Industrial Explosions and Detonations (cont.), 26 Mechanism of Static Electricity Generation and Discharge in Petroleum Products (cont.), 26 Combustion Properties of Petroleum and Petrochemical Mixtures (cont.), 26 Process Industry Fire and Explosion Hazards (cont.), 26
76	Ansul Chemical Company Marinette, Wisconsin Dr. K. W. Vaughn, Chairman of Executive Committee	Development of Crash Fire Fighting Vehicle (in progress), 28 Evaluate Extinguishing Effectiveness of Dry Chemicals on Flammable Liquid Fires (in progress), 27 Evaluation of Factors Influencing the Application of Dry Chemical on Fires (in progress), 27 Dry Chemical Fixed Nozzle Protection for Restaurant Kitchen Hoods and Ducts (in progress), 27
79	Armstrong Cork Company Research & Development Center 2500 Columbia Avenue Lancaster, Pennsylvania F. B. Menger, Director of Research	Wood Fiber Board and Tile (cont.), 29 Mineral Fiber Board and Tile (cont.), 29 Prediction of Fire Resistance of Systems (cont.), 29 Fire Test Methods (cont.), 29
79	Atlantic Research Corp. Nuclear Engineering Div. Alexandria, Virginia Dr. Michael Markels, Jr., Director	Investigation of the Flashing of Aerosols (active), 30

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82	"Automatic" Sprinkler Corp. of America Youngstown, Ohio Dr. John A. Coakley, Jr., President	Ultra-high-speed fire detection and protection
83	Battelle Memorial Institute 505 King Avenue Columbus 1, Ohio B. D. Thomas, President	Thermochemical Reactions Influencing Corrosion and Deposits from Combustion Gases in Boilers and Gas Turbines (exp. completion April 1965), 31 Determination of a Practical Scheme for Vaporization of No. 2 Fuel Oil (cont.), 22 Coordination of an Industry-Wide Oil-Burner Research Program (1961 to present), 22 Abstracting of Combustion Literature (cont.), 22
87	Bio-Dynamics, Inc. 1 Main Street Cambridge, Massachusetts R. E. O'Brien, President	Practical Preparation of a Small Community's Fire-Fighting Resources against Major Fire Disasters (exp. completion August 31, 1964), 5
87	Browning Engineering Corp. P. O. Box 863 Hanover, New Hampshire James A. Browning, President	Investigation of Fire Suppression by Large Quantities of Fine Fog (inactive), 32
88	Douglas Aircraft Co., Inc. 3000 Ocean Park Boulevard Santa Monica, California D. W. Douglas, Jr., President	Improved Fire Detection and Containment of Engine Section Fires (cont.), 33 Thermal Radiation Resistant Materials (exp. completion 1964), 33
89	Dow Chemical Company Texas Division Texas Basic Research Freeport, Texas J. H. Brown, Jr., Director	Fire Control Research (cont.), 34
91	ESSO Research and Eng. Co. Linden, New Jersey Dr. C. F. Jones, President	Antistatic Additives for Hydrocarbon Fuels (inactive), 35
93	Fenwal Incorporated Ashland, Massachusetts G. J. Grabowski, Manager, Protection Systems	Control of Grain Elevator Dust Explosions (active), 36 Suppression of Hydrogen-Air Explosions (active), 36 Determination of the Explosive Limits of Binary and Ternary Flammable Mixtures at Elevated Temperatures and Pressures (active), 37

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		Evaluation of Lightweight Fire Extinguishing Systems (active), 20
95	General Dynamics/Astronautics Space Science Laboratory P. O. Box 166 San Diego, California 92112 Dr. H. Hoshihara, Manager	Theory of Ignition and Auto-Ignition (cont.), 38
97	IIT Research Institute Technology Center 10 W. 35th Street Chicago 16, Illinois Dr. J. T. Rettaliata, President	Prediction of Fire Damage to Urban Areas, 19 Fire Spread from Kindling Fuels, 19 Flame Height and Burning Rates of Well-ventilated Fires, 19 Calescence of Convective Columns from Free Burning Fires, 19 Fire Spread Within Structures, 19 Fire Storm Analysis, 5 Prevention and Control of Mass Fires, 5
101	Monsanto Chemical Company 800 North Lindbergh Blvd. St. Louis 66, Missouri R. K. Flitcraft, Director F. C. Meyer, Manager, Organic & Biochem. Res. R. C. Tallman, Dir. of Res.	Inorganic Research Department: Fire Retardants (PHOS–CHEK) for Forest Fire Control (active), 39 Research and Engineering Division Research Dept. Flame Proofing of Polymeric Products (active), 39 Hydrocarbon Division: Fire Retardant Bituminous Compositions (active), 39
108	National Foam System, Inc. West Chester, Penna. D. N. Meldrum, Chem. Director	Fundamental studies of fire-extinguishment of various liquid fuels (active) Basic development of fire-fighting foam agents and water surface tension reducing compounds (active) Field test evaluation of foam fire-fighting techniques (active) Engineering development of foam-protection devices and systems (active)
109	Phoenix Chemical Lab., Inc. 3953 West Shakespeare Avenue Chicago 47, Illinois J. Krawetz, President	Differential Thermal Analysis of Organic Fluids and Solids (exp. completion 1965), 13 Spontaneous Ignition of Hydraulic Fluids (exp. completion 1965), 13 Specific Heat and Thermal Conductivity of Fuels and Lubricants (active), 13 Instrument for Determination of the Thermal Conductivities of Fluids and Greases (active), 40

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110	Portland Cement Association Fire Research Laboratory 5420 Old Orchard Road Skokie, Illinois Hubert Woods, Director of Research	Fundamental Studies of the Physical Properties of Portland Cement Concrete and of Collateral Materials at High Temperature (cont.), 41 Behavior of Structural Elements and Building Systems of Concrete at High Temperature (cont.), 41
112	Serendipity Associates 14827 Ventura Boulevard Sherman Oaks, California	Human Engineering Survey of Fire Fighting Equipment (exp. completion Feb. 1964), 5
112	Southwest Research Inst. 8500 Culebra Road San Antonio 6, Texas Martin Goland, President	Mathematical Study of the Mechanism of Wood Burning (cont.), 7, 10 Evaluation of Surface Burning Characteristics of Building Materials (cont.), various Development of a Flame Spread Test Method for Warm Air Heating and Air Conditioning Ducts (exp. completion 1964), 42 Investigation of the Ability of Radioactive Waste Containers to Maintain Their Integrity in an Accident Environment (exp. compl. 1964), 1
116	Stanford Research Institute Div. of Chemical Physics Chemical Dynamics Dept. Menlo Park, California Dr. Henry Wise, Department Chairman	Chemical Kinetics of Solid Propellants (cont.), 24
117	Textile Research Institute Princeton, New Jersey Dr. John H. Dillon, President	A Study of the Properties and Reactions of Textile Materials by Dynamic Thermoanalytical Methods (cont.), ten industrial organizations
118	Thiokol Chemical Corp. Reaction Motors Division Denville, New Jersey Dr. H. G. Wolfhard, Manager, Phys. & Adv. Sysm. Dept.	Afterburning of Rocket Exhausts (exp. completion 1964), 20
119	Underwriters' Laboratories, Inc. 207 East Ohio Street Chicago 11, Illinois Merwin Brandon, President	Relation of Smoke-Density Rations to Impairment of Visibility in a Closed Room, 43 Survey of Available Information on the Toxicity of the Combustion and Thermal Decomposition Products of Certain Building Materials under Fire Conditions, 43

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		Research on Characteristics of Nonproprietary Flammable Liquids (cont.), 44
129	Operations Research Center Richmond Field Station 1301 South 46th Street Richmond, California Dr. George B. Dantzig, Chairman	Systems Analysis of Fire Control Systems (cont.), 2
130	University of California Department of Engineering Los Angeles, California L. M. K. Boelter, Dean	Forest Fire Research—Relating to Civil Defense (cont.), 2
131	Georgia Inst. of Technology Engineering Experiment Station Atlanta 13, Georgia W. C. Whitley, Director	Heat Transfer to a Gas Containing a Cloud of Particles, 16 Visual Radiation Detector, 45 Particulate Size Analyzer Using Ion Counter Principle, 46 Photophoresis as Related to Meteorological Phenomena, 11 Fused Silica Nuclear Applications, 1 Properties and Structure of Polymers Resulting from Post-Effect Irradiation, 1 Effect of High Intensity Radiation on Colloidal Systems and Suspensions, 1 Ceramic Systems for Missile Structural Application, 20
133	University of Kentucky Department of Mining and Metallurgical Engineering Lexington, Kentucky R. S. Mateu, Head	Carbonization of Kentucky Coals (active), 47
134	University of Maryland College of Engineering College Park, Maryland John L. Bryan, Head	Fire Protection Curriculum: Study of the Ingberg Flame Spread Tunnel (cont.), 48 Study of Water Flow from Two Inch Automatic Sprinkler System Drains (cont.), 48
136	University of Massachusetts School of Engineering Amherst, Massachusetts E. E. Lindsey, Acting Dean	Mathematical Model of Fire-Fighting Problems, Flame Propagation in Buildings (proposed)

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Page	Laboratory and Research Director	Research projects, status, and Sponsor*
136	University of Michigan Ann Arbor, Michigan J. A. Nicholls, Director	Aircraft Propulsion Laboratory: Interaction Process Between Gaseous Detonation Waves and Inert Boundary and its Analog to the Influence of Solid Walls on Condensed Explosives (exp. completion May 30, 1965), 49 Automotive Laboratory: Relation of Combustion to the Emission of Atmospheric Contaminants (1962 cont.), 50 Institute of Science and Technology Infrared Laboratory: Remote Sensing of Environment (cont.), 24
138	University of Minnesota Combustion Laboratory Mechanical Engineering Dept. Minneapolis 14, Minnesota Edward A. Fletcher, Director	Studies of Flame Propagation and Quenching of Fluorocarbon Compounds (cont.) Studies Related to Quenching and Reignition of Solid Propellant Rocket Engines (exp. completion 1965), 16 Measurement of Physiochemically Controlled Ablation Rates of Cellulosic Materials (cont.), 7
140	University of Missouri School of Mines and Metallurgy Dept. of Mining Engineering Rolla, Missouri E. M. Spokes, Chairman	Explosibility of Ammonium Nitrate Fuel Mixtures (active), 39
141	Montana State University School of Forestry Montana Forest & Conservation Experiment Station Missoula, Montana Arnold W. Bolle, Director	Climatological Data for the Lubricht Experimental Forest (cont.), 51 Use of Thermisters for Determining the Temperature of Forest Fuels Exposed to Direct Sunlight, 51 Effect of Prescribed Burning on Regeneration in the Larch-Douglas Fir Type in Montana (exp. completion 1964), 51 Development of Lightweight Equipment for Throwing Dirt on Forest Fires (exp. completion Fall 1965), 51 Role of Forest Fires in the Bob Marshall Wilderness Area of Montana (exp. completion 1964), 51
145	New York State College of Agriculture Cornell University Ithaca, New York E. W. Foss, Rural Safety Specialist	Fire Records (cont.), 52
145	North Carolina State College Mechanical Engineering Dept. Raleigh, North Carolina R. W. Truitt, Head	More Comprehensive Study on Natural Convection Plume above a Diffusion Fire and the Interaction between such Plumes, 11

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149	University of Oklahoma Research Institute Norman, Oklahoma Ralph C. Martin, Technical Editor	Effect of Wind on Uncontrolled Buoyant Diffusion Flames of Burning Liquids (cont.), 57 Selective Oxidation of Methane at High Pressures (exp. completion August 1964), 11
151	University of Pennsylvania Towne School of Civil and Mechanical Engineering Philadelphia 4, Pennsylvania Dr. Hsuan Yeh, Director	Experimental Investigation of the Universal Small-Scale Characteristics of Mixing in Turbulent Flow and the Development of Hot Wire Techniques for the Measurement of Concentration Fluctuation (proposal)
151	Pennsylvania State University College of Mineral Industries Department of Fuel Technology University Park, Pennsylvania Dr. Howard B. Palmer, Head of Dept.	Kinetics of Volatile Matter Release and Combustion in Flames of Pulverized Bituminous Coal (exp. completion 1964), 58 True Ignition Energies of Dust Clouds (cont.), 58 Theoretical Requirements for Initiation and Suppression of Spontaneous Ignition of Refuse Piles from Mixing Operations (cont.), 59
153	University of Wisconsin College of Engineering 1513 University Avenue Madison 5, Wisconsin Kurt F. Wendt, Dean	Drop Size Measurements in Sprays (cont.), 11 Concentration and Temperature Gradients in the Air-Vapor Film Surrounding a Vaporizing Drop, 11 Pre-reactions in End Gas (cont.), 60
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158	The Johns Hopkins Univ. Applied Physics Laboratory 8621 Georgia Avenue Silver Spring, Maryland Dr. R. E. Gibson, Director	Combustion Inhibition Research (cont.), 61
160	Massachusetts Inst. of Tech. Dept. of Chemical Engineering Cambridge 39, Massachusetts Professors H. C. Hottel & G. C. Williams	The Modeling of Fire Spread, 11
161	Northwestern University Gas Dynamics Laboratory The Technological Institute Evanston, Illinois Ali Bulent Cambel, Director	Detonation Wave Structure (cont.), 62 Effect of Radiation on Upper Limits of Inflammability (exp. completion 1965), 62
162	Syracuse University Research Institute Syracuse 10, New York W. C. Wheadon, Director	Mechanism of Flame Inhibition in Combustion Processes (cont.)
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165	Yale University School of Forestry 205 Prospect Street New Haven 11, Conn. George A. Garratt, Dean	Energy Budget of a Forest (exp. completion 1964), 11, 64

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172	Flight Safety Foundation, Inc. Aviation Safety Engineering and Research 2871 Sky Harbor Boulevard Phoenix, Arizona Victor Rothe, Manager	Operational Test of a Fire Inerting System for Helicopters-Reciprocating Engine, 65 Environmental Studies of Aircraft Occupiable Areas Subjected to Postcrash Fire Conditions (exp. comtion Summer 1964), 65

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COMMENTARY ON THE TENTH INTERNATIONAL SYMPOSIUM ON COMBUSTION CAMBRIDGE, ENGLAND—AUGUST 17–21, 1964

WALTER G. BERL

Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

The Committee on Fire Research of the National Academy of Sciences–National Research Council, firmly believing that the advancement of the technology of fire prevention and extinguishment must be supported by a concurrent clarification of underlying causes and relationships, joined with the Combustion Institute in arranging for the presentation of suitable papers in Fire Science at the Tenth International Symposium on Combustion, August 17–21, 1964, at Cambridge, England.

The Authors' summaries of the pertinent papers are presented in this issue of *Fire Research Abstracts and Reviews*. They were, in part contributed to a Discussion on Aerodynamics in Combustion (arranged by Mr. S. L. Bragg and Professor H. W. Emmons) and, in part, to sessions dealing with Fire Research and with Flame Chemistry. The full texts of the papers and a considerable body of comments are to be published in the Proceedings of the Symposium (Spring 1965).

It is gratifying to note that the contents of the papers point toward a growing sophistication in the understanding of principles, both chemical and fluid dynamic. Wilson's paper applies the powerful techniques of flame structure analysis to the clarification of why inhibitors are effective in particular flame systems. It is one of the first studies in which detailed, quantitative information is reported and mechanism specified from which a plausible picture of flame inhibition can be constructed. The vast body of empirical know-how requires consolidation of this sort in order to make it understandable and to permit rational exploitation and extrapolation.

The fluid-dynamically oriented papers deal with the nature of the convection column under various flow conditions and source arrangements. Here, too, one is encouraged in the belief that the many qualitative experiences of fire fighters (including those of "blow-up" fires and fire storms) will become amenable to understanding.

Particular attention should be given to the brief discussion of the Gas Dynamics Project at Harvard University (Prof. H. W. Emmons) where the flow phenomena in fire whirls are scrutinized in detail and where intriguing models of fire spread in idealized forests and across firebreaks are analyzed. The papers by Nielson and Tao, by Morton, and by Tarifa *et al.* show that the entrainment problem into strongly buoyant plumes offer many intriguing challenges to fluid dynamicists in addition to improving one's understanding of the "firebrand" problem.

The experimental fire modeling papers of Thomas *et al.*, Anderson and Rothermel, Putnam, Gross and Robertson, and Akita and Yumoto continue the relatively recent investigations of characterizing free-burning fires for a variety of fuel arrangements and external influences. The unsuccessful attempt by Hottel *et al.* to formulate a successful model that predicts fire spread rates shows the difficulties yet to be overcome.

In addition, work on ignition (including high energy flux rates), heat transfer, and mechanisms of thermal degradation has progressed quite satisfactorily.

This encouragement of fundamental fire research and its exposure to the comments and criticism of technically qualified professionals in the field of combustion is bound to have salutory consequences. The problems requiring solution are far from simple. As insights into the underlying basic processes mature it becomes profitable to expend the needed effort to attack the more complex situations. It will take persistence and patience to harvest the practical benefits from this investment.

ABSTRACTS

Emmons, H. W. (Harvard University, Cambridge, Massachusetts) "Fundamental Problems of the Free Burning Fire."

The growth of knowledge about the free-burning fire is observed to be of the slow evolutionary type of cut and try, as man has had to attack the unwanted fire through the centuries. Since such fires are the result of intimate interaction of geometry, chemistry, thermodynamics, fluid mechanics, and heat transfer, each at an advanced level, it has not been possible prior to the present century—almost the present decade—to use accumulated scientific know-how; there simply was too small an accumulation. This condition is changing and changing rapidly. In this paper some of the problems of the free-burning fire are described, an indication of the present state of understanding is given, and some suggestions are made for those avenues of approach that appear hopeful of successful attack in the near future.

Specifically, fire spread over building materials, through buildings, and through forests, is described in sufficient detail to indicate where we are today, where we should be going, and what it might get us if we go. The innumerable detail problems which must be individually solved and combined to produce solutions to the larger problems are little more than hinted at in the discussion. But it is clear that many man-years of research, worth many millions of dollars, will be required to solve these problems, but with the cost of fire to society of many billions of dollars every year the indicated research is more than urgent.

Subject Headings: *Firebreak; Fire jump; Fire research, building fires; Fire spread; Fire storm; Fire whirl; Forest fire; Plumes, fire; Pyrolysis; Theory, fire.*

Author's Abstract

Weatherford, W. D., Jr. and Sheppard, D. M. (Southwest Research Institute, San Antonio, Texas) "Basic Studies of the Mechanism of Ignition of Cellulosic Materials."

Mathematical and experimental studies are being conducted on the thermal processes involved in the ignition of slabs of wood-like substances. The results of extensive finite-difference machine computations suggest that the specified fuel-generation-rate criterion for sustained ignition, proposed by Bamford, Crank, and Malan, is incorrect. These results, however, also suggest that the experimental data of Bamford, Crank, and Malan reflect a thermal criterion of sustained ignition which has not been recognized previously.

In order to adequately describe this critical thermal condition for symmetrical, two-sided heating of plane infinite-width slabs, a concept of a "thermal feedback wave" being propagated from the surface of symmetry to the heated surface is introduced, and the time required for this wave to reach the heated surface has been derived. Expressed in terms of dimensionless time (Fourier number), this critical heating time appears to be constant for inert slabs of constant thermal properties. Also, it is approximately constant for noninert slabs of variable thermal properties, and it may decrease somewhat with increasing slab thickness when significant heat-generation effects are present.

Subject Headings: *Cellulose; Heat transfer, convective; Ignition, thermal, of slabs.*

Authors' Abstract

Martin, S. (U. S. Naval Radiological Defense Laboratory, San Francisco, California) "Diffusion-Controlled Ignition of Cellulosic Materials by Intense Radiant Energy".

The objective of this work is to provide information about the details of the transient-temperature profiles in radiantly-heated cellulose, and the evolution rates and chemical composition of the resulting pyrolysis products, and to consider the implications of the results to ignition processes.

The measured preignition, nonsteady-state-temperature profile is a function of parameters derivable from a simple, hypothetical heat-flow model. In detail, however, the actual profile is quite different from the theoretical and shows significant perturbation by heat of reaction and phase change. Extrapolation of the profile to the irradiated surface indicates a surface temperature, at the instant of ignition, which is independent of irradiance level and in excess of 600°C. Direct optical measurement of the "ignition temperature" confirm both its magnitude and constancy.

Measurements (in an inert atmosphere) of the volatile pyrolysis products show a maximum in the rate of evolution at a time close to the instant of ignition (in air). Levoglucosan, the main volatile-fuel component, increases in yield from about 25 per cent of the theoretical upper limit early in the exposure, to about 75 per cent at the ignition time. However, no evidence was found of an ignition criterion based on a threshold rate (or amount) of volatile-fuel evolution.

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

Chemical analyses were made of the volatile pyrolysis products of nearly identical exposures of thick and thin specimens. The results indicate that the persistence of flaming depends only upon achieving a temperature profile during exposure, whose relaxed value is sufficient to maintain the flow of flammable volatiles, and not on any unique composition of them.

Subject Headings: *Cellulose; Evolution, volatile components; Heat transfer, radiant; Ignition, temperature; Ignition, thermal, diffusion controlled; Photolysis, flammable flash; Pyrolysis, products, composition of; Temperature, profile.*

Author's Abstract

Blackshear, P. L., Jr. and Murty, K. A. (University of Minnesota, Minneapolis, Minnesota) "Heat and Mass Transfer to, from, and within Cellulosic Solids Burning in Air".

In this paper, the problem of cellulosic material burning in air is explored in the following three ways:

1. The free-convection heat-and-mass-transfer coefficients for fuel-soaked wicks burning in air are determined for a number of wick geometries and orientations. In brief, orientation, shape, and size have little effect on the coefficients for turbulent flames.
2. Gross characteristics of cellulose cylinders burning in air are examined. X-ray photographs show similarities between the burning process and drying of porous materials. The burning rate is found to depend on time and on the initial diameter of the specimen. Examination of the data suggests that the burning rate depends on the rate at which an isotherm propagates into the solid.
3. Detailed studies of temperature-time histories of pyrolyzing cylinders are employed to determine local heat source and sink strengths. These are in turn compared with Differential Thermal Analysis (DTA) data for cellulose. The decomposition appears to take place endothermically at 300° to 400°C; exothermically, above 500°C. The temperature-time history is strongly influenced by the movement of vapor in two distinct ways. Moisture resulting from the thermal decomposition diffuses, condenses, and re-evaporates to yield a thermostatic effect in the neighborhood of 100°C. Vapors produced by the endothermic pyrolysis of the solid in the interior of the specimen undergo exothermic pyrolysis in the hot char near the surface.

Subject Headings: *Burning, ventilation limited; Cellulose; Flame, alcohol; Heat transfer, coefficients; Laminar-turbulent transition; Mass transfer, coefficients; Pyrolysis, of cellulose; plane and cylindrical.*

Authors' Abstract

Akita, K. and Yumoto, T. (Fire Research Institute of Japan, Tokyo, Japan) "Heat Transfer in Small Pools and Rates of Burning of Liquid Methanol".

The rates of diffusive burning of liquid methanol, chosen as a fuel which produces a nonluminous flame, were measured in the special concentric vessels having three compartments as well as in the usual single laboratory vessels. The experimental results obtained include the interesting observation that the burning rate is much greater at the vessel rim next to the flame base than near the vessel center, and that the burning rate in the outer compartment of a concentric vessel is equal to that in a single vessel of the same size. These data are discussed in the light of burning rate theories presented independently by Spalding and by Hottel, and an attempt has been made to extend the latter's theory by introducing empirical local heat transfer coefficients. The equation proposed by the authors explains successfully all the results of the present study. Thus, it appears that Hottel's theory can be applied not only to the turbulent luminous combustion of liquid fuels, but also to nonluminous combustion under conditions of laminar flow.

Subject Headings: *Alcohol, methanol; Burning rate, radial dependence; Flame, nonluminous and turbulent; Heat transfer, in pools.*

Authors' Abstract

Wilson, W. E., Jr. (Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland) "Structure, Kinetics, and Mechanism of a Methane–Oxygen Flame Inhibited with Methyl Bromide".

Experimental profiles of temperature and composition were obtained for a 0.05-atm, lean, methane–oxygen flame inhibited with methyl bromide. The net rates of reaction were calculated and a hydroxyl radical concentration derived from the measured methane rate and the known rate constant. The hydroxyl radical concentration is about equal to the thermal equilibrium value in contrast to the excess radical concentration usually found in hydrocarbon flames indicating a reduction of radical concentration in the presence of inhibitor.

The primary reaction of methyl bromide is probably

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

A reaction rate constant of $k \approx 1.5 \times 10^{13}$ cm^3/mole/sec is calculated for the temperature range 1800°–2000°K.

The calculated rates of hydrogen bromide, methyl bromide, and methane show that the reaction of methane does not begin until most of the hydrogen bromide and part of the methyl bromide have reacted. A comparison of methane rates indicates that the primary reaction zone in the inhibited flame is shifted to a higher temperature, is narrower, and has a greater absolute value than in an uninhibited flame. These observations are used to support a flame-inhibition mechanism in which a major effect of the inhibitor is to prolong the preignition zone and shift the primary reaction to a higher temperature. The inhibition reactions have a lower activation energy so that radicals which diffuse into the preignition zone react preferentially with the inhibitor. These reactions do not initiate chains so that the rate of radical build-up is decreased and ignition is prolonged until a higher temperature is reached.

Subject Headings: *Flame, inhibition, by methyl bromide; Flame, structure analysis; Free radicals; Inhibition, theory of; Kinetics, of methane-oxygen.*

Author's Abstract

Hottel, H. C., and Williams, G. C., (Massachusetts Institute of Technology, Cambridge, Massachusetts) **and Steward, F. R.** (University of New Brunswick, Fredericton, New Brunswick, Canada) "The Modeling of Firespread Through a Fuel Bed".

Data are presented on the effects of artificial irradiation and of humidity on the propagation of a line fire through beds of torn newsprint and computer-card punchings. Intensities of irradiation simulating the flame radiation, which is substantially absent in small model fires, produced up to 200% increases in the velocity of fire-front propagation.

Four mathematical models were set up, primarily for the purpose of indicating how to allow, with some rigor, for surface heat losses during the irradiation process. Model I postulated the existence of a thin slab losing heat from its top face at a rate proportional to its temperature excess over the surroundings. Flame convection as a part of the propagating process was formulated in terms of eddy diffusivity and mixing scale. A quantity identified as a heat retention efficiency was formulated for each mechanism of heat transfer to the bed being heated.

Model II substituted a rate of surface heat loss proportional to the 1.6 power of the temperature difference, bed surface to air. A heat retention efficiency was formulated for a slab receiving heat from a line source.

Models III and IV were based on the assumption that surface temperature, rather than ignition energy per unit bed area, was significant, and that the fuel bed was a semi-infinite solid. These models lead to integral equations, approximate solutions of which indicated the magnitude of temperature rise expected compared to that of a no-loss slab. The surface loss in Model III was linear in temperature, in Model IV nonlinear.

None of the models predicted the experimentally observed decreasing effect of additional increments of artificial irradiation on the propagation velocity. Explanations were suggested.

Subject Headings: *Fire spread, rate of; Geometry, linear; Model fires, paper; Radiation, theory of.*

Authors' Abstract

Anderson, H. E. and Rothermel, R. C. (U. S. Forest Service, Northern Forest Fire Laboratory, Missoula, Montana) "Influence of Moisture and Wind Upon the Characteristics of Free-Burning Fires".

A study of free-burning fires in mat-type beds of two light forest fuels (needles of ponderosa and western white pine) showed measurable effects of certain environmental conditions on the characteristics of fire. Measurements of these characteristics of nearly 200 fires burned under controlled humidity, air velocity, and fuel moisture, provided data for developing equations that enable prediction of rate of fire spread in individual fuel types when moisture content and air velocity are varied. As fuel moisture content increases, rate of spread decreases linearly with no wind. Increasing wind causes rate of spread to increase exponentially or by a power function. The importance and usefulness of a unit combustion area measurement are demonstrated; such measurements make it possible to characterize all fires by use of unit combustion rate and rate of spread. A general equation that predicts rate of spread in any wood fuel may be developed by incorporating fuel particle size and fuel bed compactness with fuel moisture content and air velocity.

Subject Headings: *Fire, free-burning; Flame spread, effect of moisture; Flame spread, effect of wind; Flame spread, rate of.*

Authors' Abstract

Tarifa, C. S., del Notario, P. P., and Moreno, F. G. (Instituto Nacional de Técnica Aerospacial "Esteban Terradas", Madrid, Spain) "On the Flight Paths and Lifetimes of Burning Particles of Wood".

Results of a research program on the burning properties, flight paths and lifetimes of burning particles of wood are given in the paper. This study is related to fire spread produced by fire brands, which is the dominating propagation mechanism in major forest fires.

The laws of variation of the aerodynamic drag and weight of firebrands as functions of both time and relative wind speed are obtained experimentally in a wind tunnel. From these data the flight paths and corresponding lifetimes of the firebrands are calculated for giving horizontal wind conditions and for a certain model of the convection column above a fire.

The conclusion was drawn that it is an excellent approximation to assume that the firebrands always fly at their final or terminal velocity of fall. This assumption considerably reduces the experimental work as well as the theoretical studies.

The results obtained permit the valuation of the dangerous areas of possible fire propagation. Comparative results of the potential danger of firebrands according to size, shape, kind of wood, moisture content, and wind conditions are shown.

A preliminary study of the general laws governing combustion of wood with forced convection is also included.

Subject Headings: *Aerodynamics; Convection, forced; Convection, thermal; Firebrands, lifetime of; Firebrands, trajectories in wind; Moisture, effect of; Velocity, terminal; Wood, particles.*

Authors' Abstract

Putnam, A. A. (Battelle Memorial Institute, Columbus, Ohio) "A Model Study of Wind-Blown Free-Burning Fires".

In a study of free-burning fire modeling, both point- and area-source flames and line fires were exposed to cross winds. With point- and area-source flames, the flame height was found to decrease slowly with the initial exposure to the cross wind and then to decrease more rapidly as the velocity of the cross wind was increased. Specifically, the dimensionless flame height varied with the negative $\frac{1}{4}$-power of the Froude number based on cross-wind velocity and undisturbed flame height, above a Froude number of 0.2. The horizontal extension of the flame, on the other hand, increased rapidly with increasing cross wind at first, and then less rapidly with the $\frac{1}{6}$-power of the Froude number.

When line fires composed of point sources were exposed to cross winds, the height of the flame varied with the inverse square root of the Froude number plus a constant, the value of which depends on the fuel. The tangent of the flame angle varied directly with the square root of the Froude number. These observations agree generally with those reported in the literature relative to two-dimensional fires from wood cribs, up to a value of the Froude number at which buoyancy effects on the flame seem to vanish.

Subject Headings: *Arrays, lengths; Fire, free-burning, experimental correlations; Flame, buoyancy-controlled; Flame, laminar; Flame, turbulent; Geometry, hexagonal; Wind, cross velocity.*

Author's Abstract

Tinney, E. R. (Washington State University, Seattle, Washington) "The Combustion of Wooden Dowels in Heated Air".

A mathematical model is presented for the combustion of small wooden dowels heated externally. The heat transfer is described by the Fourier conduction equation, including a heat-source term, with both convection and radiation at the surface. The decomposition is assumed to follow a first-order Arrhenius equation. Both equations are solved simultaneously, for successive shells of the dowel. After one-half or more of a particular shell is consumed, the energy of activation, velocity constant, and heat of decomposition for that shell are all increased. These increases match a presumed change in the degradation process from a rapid evolution of gaseous products to a slower degradation of the remaining charcoal-like substance.

Experimental results are presented showing center-temperature, weight-loss, and internal-pressure histories for $\frac{3}{8}$ in. dowels, which were inserted into a preheated air furnace whose temperature was held constant in the range of 300° to 650°C. The center temperatures are fairly well predicted except for peak values of the exothermic contribution. The experimental and theoretical weight-loss histories agree quite well for all furnace temperatures. The pressure at the center rises to several psia and then drops suddenly to zero before the center temperature reaches the furnace temperature. While the pressure is dropping, serious structural failures, such as longitudinal channeling and surface cracking, occur.

Subject Headings: *Burning rate; Combustion, of wooden dowels, in heated air; Fire, model; Fire, spread, in heated air.*

Author's Abstract

Gross, D. and Robertson, A. F. (National Bureau of Standards, Washington, D. C.) "Experimental Fires in Enclosures".

Results are presented of experimental measurements of the mass rates of burning, temperatures, and gas compositions in model enclosures of three sizes. Interest was confined to the fully-developed period of burning, in which the burning rate of a combustible-fiberboard crib was limited by the size and shape of the ventilation opening. The burning rate was found to be generally proportional to $A(h^{\frac{1}{2}})$ (A = area, h = height of window opening), but a characteristic transition region was found for each enclosure, which resulted in a pronounced shift in the data line. Burning-rate data were correlated in terms of the ventilation parameter normalized by the square of the linear-scale ratio.

The over-all process involved in enclosure fires appears to be a combined gravity-controlled fluid dynamic regime and a radiation-controlled thermal regime. The dimensionless Froude group is the criterion for similarity in a gravity- (buoyancy-) controlled regime and, from the limited agreement found among the data for the two larger enclosures, this group appears to include the essential parameters in the scaling of burning rates of fires in geometrically similar enclosures.

Experimental measurements of piloted-ignition thresholds have been conducted in an apparatus designed to simulate convective-source symmetrical heating of plane slabs. These experimental results and published data of prior investigators have been analyzed in terms of various ignition criteria. For such purposes, a generalized correlating concept is described which relegates each of the various ignition criteria to its proper position of relative importance for a particular set of conditions. As an aid for this generalized correlation technique, improved transient-heat-conduction data have been machine-computed with the analytical solution for inert slabs, and the results are presented in graphical form.

Subject Headings: *Buoyancy, effects of; Burning rate, mass; Cellulose; Fire, crib; Fire, experimental, in enclosures; Fire, fully developed; Fluid dynamics, of fire; Gases, composition (CO, CO_2, O_2), heat content; Temperature, distribution, in enclosures; Ventilation, in enclosures*

Authors' Abstract

Morton, B. R. (University of Manchester, Manchester, England) "Modeling Fire Plumes".

Theoretical treatments for turbulent diffusion flames and for the strongly heated regions of fire plumes in a still environment may be based on those developed for weakly buoyant plumes, but appropriate modifications must be made to allow for the high temperatures and the large variations in density involved. A discussion is given of some of the modifications that are needed, and the effects of large variations in density on the plume dynamics and aspects of heat transfer by radiation are presented separately.

The entrainment into strongly buoyant plumes depends on the local ratio ρ/ρ_0 of mean plume to ambient densities as well as on the mean plume velocity u, and

dimensional arguments can do no more than define a local entrainment function $(\rho/\rho_0)^n E_0$, where n is undetermined and E_0 is the well-established entrainment constant for weakly buoyant plumes. The value $n=\frac{1}{2}$ is suggested by the dependence of lateral diffusion on the Reynolds stresses, and the form

$$E=(\rho/\rho_0)^{\frac{1}{2}}E_0$$

is adopted here; comparable assumptions have been made previously.

Equations for the conservation of mean mass flux, mean momentum flux, and mean heat flux along the turbulent diffusion column of the plume are obtained making full allowance for the dynamic effects of large variations in density. Provided that the level of intensity of the plume turbulence is not too high, these equations can be reduced approximately to a form directly related to the set of equations used previously in the study of weakly buoyant forced plumes. These sets of equations are related by the transformation

$$\rho^{\frac{1}{2}}a=\rho_0^{\frac{1}{2}}b,$$

where a and b are local length scales (essentially plume radii) for the strongly buoyant and weakly buoyant plumes, respectively. Hence the behavior of strongly buoyant plumes can be described in terms of existing solutions for weakly buoyant plumes, and in general it can be seen that strong plumes spread less rapidly than weak ones at first, although they are soon reduced to weakly buoyant behavior unless the large temperature differences are maintained as by combustion.

Fire plumes are often rich in smoke and soot from imperfect combustion, and in such cases when the mean free path for radiation is small in relation to the plume diameter the opaque radiation approximation may be adopted. In this case, the heat transfer by radiation can be divided into a vertical flux along the column of a diffusive character, and the outwards radiation from the edges of the plume through transparent air to the distant environment. It is shown that in many practical cases the vertical flux by radiation is small in relation to vertical convcetion and to edge radiation, and may be neglected for small values of the parameter $8\pi E_0^2/3kb_s$, where k is the absorption coefficient within the plume and b, the source radius. Indeed, when flow velocities are high, even the cooling effect of radiation from the plume edges may be small relative to cooling by turbulent entrainment of cold ambient air. A solution of this type is presented.

The purpose of this paper is to discuss questions involved in the formulation of fire plume theories; therefore, few solutions are given in detail and no attempt is made to link the dynamical effects with those due to radiation. A wider range of solutions will be published elsewhere.

Subject Headings: *Aerodynamics; Buoyancy, of fire plumes, strong-weak; Conservation, energy; Conservation, momentum; Diffusion, lateral; Plumes, buoyancy of; Plumes, composition of; Plumes, distribution of; Plumes, radiation lost by; Plumes, temperature of; Plumes, velocity of; Radiation; Turbulence, entrainment, by fire plumes.*

Author's Abstract

Nielsen, H. J. and Tao, L. N. (Illinois Institute of Technology, Chicago, Illinois) "The Fire Plume Above a Large Free-Burning Fire".

A model which describes the variation with altitude of the composition, temperature, and velocity of the gases within a plume above a large free-burning fire is presented. This model is an extension of previous analysis of buoyant plumes which includes the effects of combustion, composition variation, and radiation losses from the hot gases.

Combustible substances on the ground are assumed to undergo pyrolysis and liberate combustible gases. A set of differential equations based on the conservation laws of mass, momentum, and energy is derived for the upward flow of these gases and their products of combustion. The rate at which combustion proceeds is assumed to be controlled by the entrainment of oxygen from the surrounding air.

Subject Headings: *Fire, free-burning; Fluxes, energy; Fluxes, mass; Fluxes, momentum; Plumes, aerodynamics of; Plumes, combustion in; Plumes, radii of; Radiation, loss.*

Authors' Abstract

Thomas, P. H., Baldwin, R., and Heselden, A. J. M. (Joint Fire Research Organization, Boreham Wood, England) "Buoyant Diffusion Flames: Some Measurements of Air Entrainment, Heat Transfer, and Flame Merging".

Thistledown has been used as a tracer to measure the flow of air toward ethyl alcohol and wood fires 91 cm in diameter, and a small town-gas fire. The total quantity of air below the mean flame height is approximately one order times the stoichiometric requirements, a substantial part of the air flowing upwards around the flame. The total flow also exceeds that estimated from entrainment theory and measurements of flame tip velocity. The mean concentration of oxygen on the flame axis and the heat transfer back towards the fuel surface have also been measured. The convection transfer at 1–2 cm above the fuel surface was found to be about $\frac{1}{5}$ of the total heat transfer at the center increasing to about $\frac{1}{2}$ at the edge. The measured mean axial temperature rise at the mean flame height was about 300°–350°C for wood and alcohol and 500°C for town gas. The average period of the eddies outside the flame and the corresponding length were about 0.7 sec and 15 cm, respectively. No variation was found with height above the base.

Elementary considerations of entrainment and the motion of flames have been applied to the merging of the flames from two nearby rectilinear fuel beds and there is reasonable agreement between theory and experiment.

Subject Headings: *Alcohol, ethyl; Buoyancy, of flames; Composition, oxygen; Flame, diffusion; Flame, height; Flame, merging; Flame, tips; Gas, town; Geometry, rectilinear; Heat transfer, in flames; Wood, fuel beds.*

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Volume 7 Number 2

Fire Research Abstracts and Reviews

Committee on Fire Research
Division of Engineering and Industrial Research
National Academy of Sciences—National Research Council

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
Washington, D. C.
1965

FIRE RESEARCH ABSTRACTS AND REVIEWS is published three times a year by the Committee on Fire Research 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 of the Department of the Army, the U. S. Department of Agriculture through the Forest Service, the National Science Foundation, and the National Bureau of Standards. The opinions expressed by contributors are their own and are not necessarily those of the Committee on Fire Research.

Library of Congress Catalog Card Number 58–60075 rev

Available without charge from the
Office of the Committee on Fire Research
National Academy of Sciences—National Research Council
Washington, D. C. 20418

FOREWORD

In addition to abstracts, this issue contains reports of two meetings of interest to fire research workers: the Symposium on Forest Fire Research held in conjunction with the Tenth Pacific Science Congress; and the annual meeting of the National Fire Protection Association (NFPA). It is heartening that the Symposium on Forest Fire Research included workers from Australia, the U.S.S.R., and the United States. International cooperation is certain to speed the flow of information in our field. As is fitting, the agenda of the NFPA meeting covered material from practical fire fighting through the most advanced fire research. Meetings of this kind offer an excellent center for contact between the practical fire fighter and the specialist research worker.

A review of recent work on the structure of flames is given in this issue. These specialized techniques have provided major tools for the understanding of detailed flame processes and reaction mechanisms of simple flame systems. They are now being successfully applied to problems of flame inhibition chemistry by the groups at the General Electric Co. and the Applied Physics Laboratory, so that one has some hope that this small section of the fire problem will ultimately be understood quantitatively.

We note with pleasure the appearance of three new journals in the field: *Fire Journal*, the bimonthly successor of the *NFPA Quarterly*; *Fire Technology*, a bimonthly publication of the NFPA with scope of great interest to fire research workers; and finally the forthcoming Russian journal, *Combustion and Explosion Problems*. This sudden surge of publication media argues well for the field.

The editor would like to have laboratories in the fire research field submit reviews of their work at periodic intervals (from two to five years), since one of the aims of FRAR is to present fire research programs so that our readers can become familiar with other workers in the field.

ROBERT M. FRISTROM, *Editor*

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REVIEWS

FLAME STRUCTURE AND FLAME PROCESSES*

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The chemistry of flame combustion is a complex subject. The flames involved in fires show many variations. Throughout all of this complexity, however, certain fundamentals are preserved. The basic physical and chemical processes are identical for all flames although strong interactions between the processes may obscure much of this basic similarity.

During the past decade considerable progress has been made in the basic understanding of fundamental flame processes in detail. At the present time, the important physical and chemical processes in flames have been identified, and are individually well understood. There is a quantitative theory of flames[5] which is applicable to simple laboratory flames[1] and experimental techniques have been developed which allow quantitative studies to be made of simple laboratory bunsen flames. Studies have been made of the detailed structure of flames and it has been possible to identify a number of elementary reactions and study them quantitatively in these flames. As a result, the reaction mechanisms of a number of the simpler flames have been established and reliable quantitative rate data is now available for many important flame reactions. These techniques are now being applied to investigation of how inhibitors affect flames.

This is, of course, only a beginning for the fire research scientists who must consider not only the chemistry of the flame problem but also that of extinguishment and their relation to the over-all problem of fire control. The article by Wilson on page 69 provides a summary of the present status of the understanding of flames and flame inhibition processes as deduced from detailed flame structure studies.

Flames are exothermic reactions which possess the ability to propagate through space. They usually occur in the gas phase and are attainable under a wide variety of conditions. Fuel oxidizer reactions drive most common systems, but they can also be obtained from such diverse reactions as those of frozen nitrogen atoms and that of decomposing nitric oxide. Flames have been burned from a thousandth of an atmosphere to several hundred atmospheres. Reaction half lives cover the range from seconds to millimicro-seconds. Though they are normally and correctly considered as sources of high temperatures, flame-like reactions also occur at temperatures as low as 4°K, as for example in frozen films of atoms and free radicals.

A flame can be considered as a reaction occurring in a flow system coupled strongly with thermal conduction and molecular diffusion. These processes are well understood individually and it is possible to write a set of relations based on the constraints of conservation of energy, matter and momentum and incorporating the processes of thermal conduction, molecular diffusion, and chemical kinetics, which rigorously describes flames. These equations (the flame equations) can be solved in simple cases, but the chemistry is usually so unrealistically circumscribed

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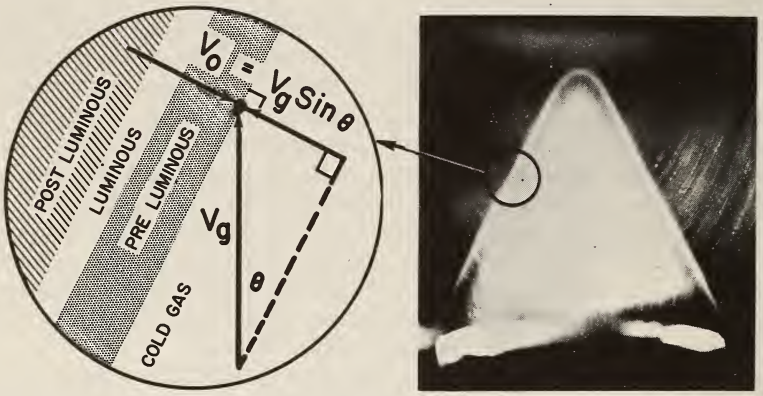
* Reprinted from *Birmingham University Chemical Engineer* (B. U. Ch. E.) *16*, 42 (1965), by permission of the editor.

that the results are satisfying only to the mathematician and physicist. The chemist and chemical engineer must still consider flames from the experimental point of view. The flame equations, however, furnish the necessary framework for the quantitative interpretation of combustion systems. In one-dimensional flames the solution of the equations is an eigenvalue which can be identified with an experimental parameter, burning velocity, which is commonly used to characterize flames (Fig. 1).

Premixed laminar flames are discussed in this paper, but the fundamental processes are common to all flame systems. Thus, in spite of the complications of practical combustion systems, they can usually be related to the simple systems which will be discussed.



BURNING VELOCITY

FIG. 1. Bunsen flame. Insert: Vector diagram of velocities in flame front showing relation between burning velocity and normal component of inlet gas velocity.

ONE-DIMENSIONAL FLAME STRUCTURE

All physically realizable flames are three-dimensional, but it is possible to attain systems in the laboratory which are one-dimensional in the practical sense. This abstraction offers an enormous simplification in the visualization and analysis of combustion processes. These flames have been almost exclusively used for the study of structure in the laboratory.

An ideal one-dimensional flame can be considered as a chemical reaction in a flow system. It is completely described by specifying the concentration (in absolute units) of each of the number N of chemical species at every point along the coordinate of propagation z, together with a parameter related to the burning velocity which specifies the mass flow per unit area. In an actual case a profile giving the geometry of the flow pattern is also necessary. This description is best visualized as a family of "profiles," giving the intensive variables as a function of distance through the flame front; this is shown in Fig. 2a.

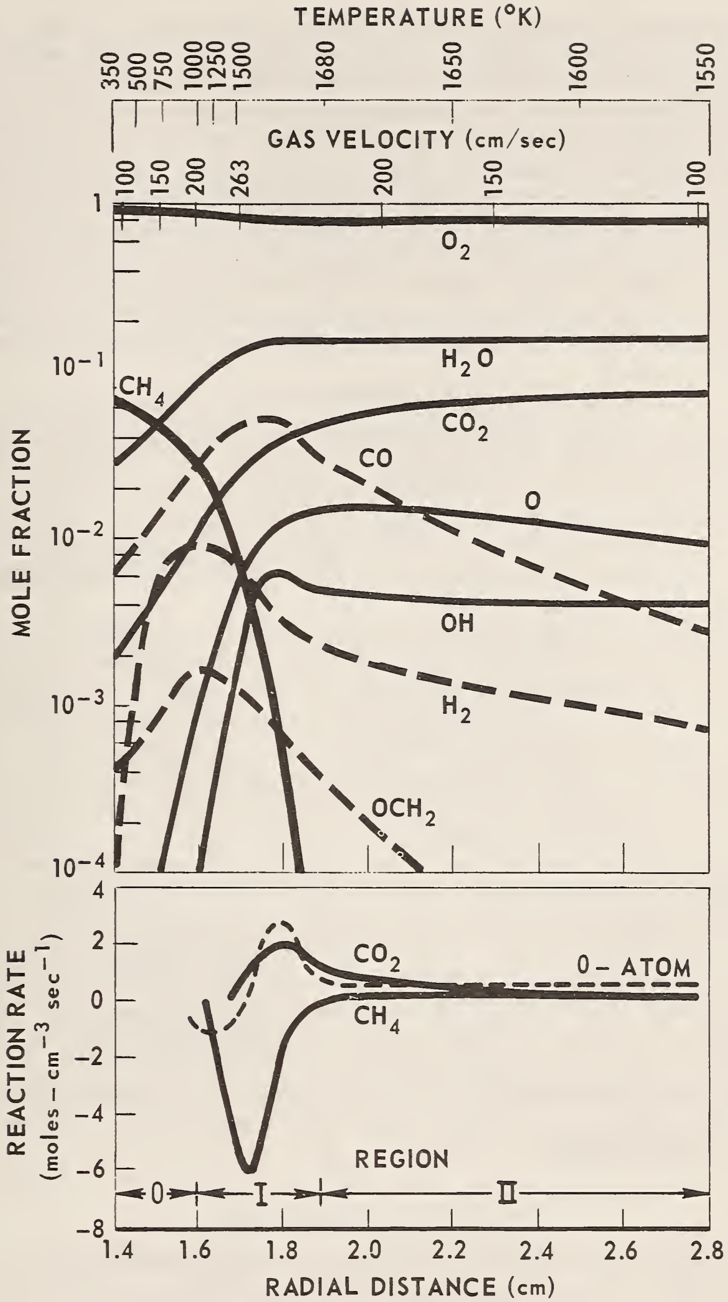


FIG. 2. Characteristic profiles of spherical flame front (CH_4 0.078; O_2 0.92; $P = 0.1$ atm). (a) Composition as a function of radial distance (also temperature and gas velocity). H atoms and CH_3 radicals are also present in Zone I in concentrations of the order of 10^{-3} and 10^{-4} M.F., respectively. (b) Reaction rates. Note that the flame can be roughly divided into three regions: 0, where no reactions occur; I, where the primary attack of CH_4 occurs; and II, where the radicals slowly recombine.

Distance is usually chosen as the independent variable since it is the common experimental one, but it is possible to use any single-valued variable such as time, density, temperature, or one of the compositions. The important point is that a necessary and sufficient set of variables is given by specifying $N+1$ of them as functions of a common independent variable. This is analogous to the phase rule used in closed systems. It has been possible to demonstrate that the one-dimensional concept provides a quantitatively adequate model for describing this system.[1]

Several experimental techniques are now available for making flame structure studies, and they have been applied to a number of systems. A typical example is the premixed methane–oxygen flame.[2,3,4] The characteristic profiles of intensive properties which describe this system are as illustrated. From these experimental data it is possible to derive the fluxes of species and energy and net rates of reactions for the various species.

This flame can be conveniently separated into three spatially distinct regions which are characterized by distinct processes, as illustrated in Fig. 2b. In the first region no reaction occurs although large temperature and composition changes occur because of diffusion and thermal conduction. In the second region the initial attack of methane occurs, finally forming carbon monoxide. In the third region the carbon monoxide is oxidized to carbon dioxide. This spatial separation is a convenient accident due to the relative rates of the processes involved; however, it can be expected to be a common case.

The energy flux in the flame front is dominated by the transport processes, but the flux due to thermal conduction is almost balanced by that due to diffusion. In such systems, where conductive and diffusive flux are balanced, the dimensionless Lewis number, $\rho C_p D/\lambda$, is approximately unity, ρ is gas density, C_p is heat capacity at constant pressure, D is diffusion coefficient, and λ is thermal conductivity. An interesting consequence of this is that there is a linear relation between temperature rise and "fuel" disappearance. ("Fuel" is defined as a species whose disappearance is directly connected with heat release.)

Many flames can be burned over a wide range of pressures with only a small change in the propagation velocity. This indicates that a flame reaction requires a fixed number of collisions, so that as the mean free path is increased, distance will be scaled to preserve the collision number. For the case of bimolecular reactions, it can be shown that distances in a flame should scale inversely with pressure.[5] Detailed studies have shown that this is a reasonable approximation in some flames.[1,6]

The processes occurring in flame fronts are well understood, and the theory of flames has been formulated in general. The application to specific flames is primarily an experimental problem since the parameters required are not usually available. However, flame theory provides the model for the quantitative interpretation of experimental flame studies.

PHYSICAL PROCESSES

Aerodynamics and transport phenomena are the quantitatively important physical processes in flames, the former is a continuum property of the system while the latter is best considered from the molecular standpoint.[1] Three-dimensional flame aerodynamics is a complex subject although the principles are straightforward. Flow is governed primarily by considerations of conservation of mass and energy and—for high-velocity flames—of momentum. Flow geometry is usually described in terms of an area parameter, and if this is assumed to be known, the flow is completely specified by the mass continuity equation and a density or temperature profile. The gross flame geometry is controlled by aerodynamics. The flame adjusts itself so that there is a balance between the burning velocity and the component of flow velocity normal to the flame front at any point (Fig. 1). Flames normally have velocities low compared with the speed of sound and, as a result, the pressure-drops across them are minute, and normally neglected. The accelerations of flame gases by contrast are large because of the narrowness of the region in which the gas is heated and expanded. In the acetylene torch, for example, the peak gas acceleration exceeds 8000 g.

The other physical processes are considered under the general heading of mole-

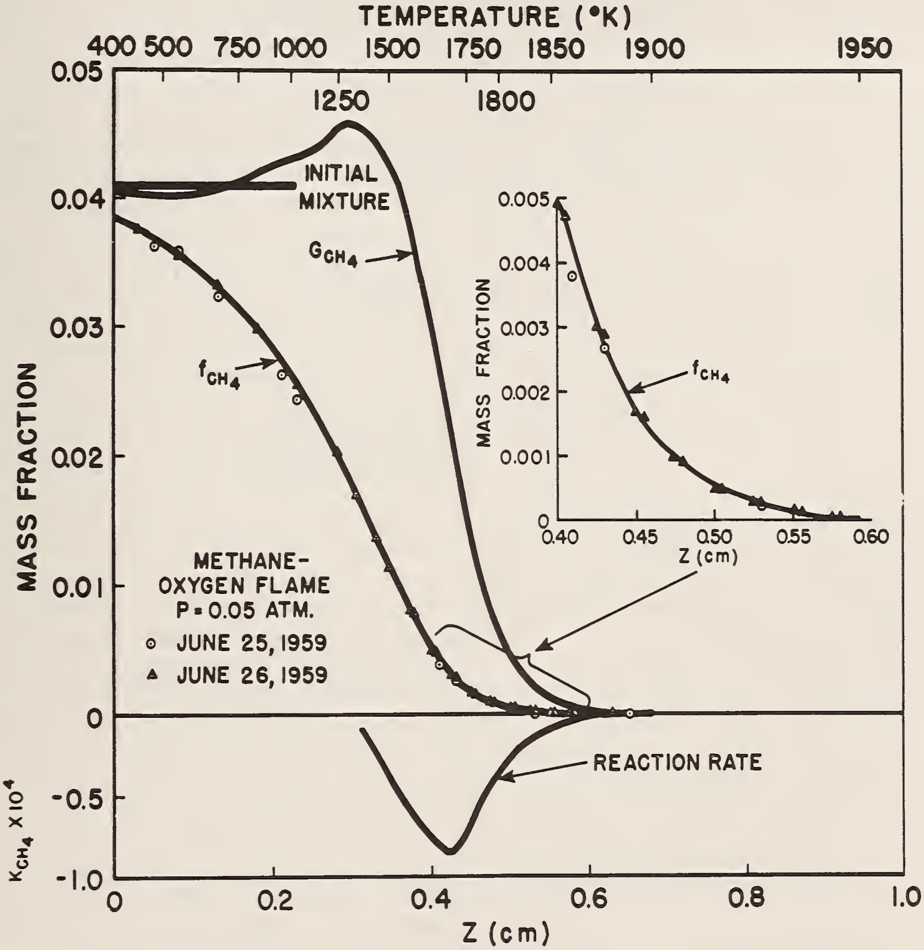


FIG. 3. Flux, concentration, and rate of methane in a methane–oxygen flame (0.1 atm, 7.8% CH_4).

cular transport. Of the five known transport processes, only two are important in flames (Chapt. III, Ref. 1): diffusion, which is the transport of matter in a concentration gradient; and thermal conduction, which is the transport of energy in a temperature gradient.

Diffusion has a profound effect upon flame reactions since it provides a mechanism for transporting reactive species such as atoms and free radicals into regions where they are out of thermal equilibrium. Because of the effects of diffusion it is necessary to distinguish carefully between the two composition variables used to describe a flow system. These are concentration (mass per unit volume) and flux (mass passing through a unit area in a unit time). In an ordinary flow system where diffusion is negligible, these variables are numerically identical when expressed in dimensionless units (mole fraction and fractional molar flux, for example). In flames, by contrast, the gradients are steep and the species flow has an appreciable diffusion velocity added to the mass velocity of the system. The diffusional velocity

$$V_i = (D/X)(dX/dz)$$

where V_i = diffusion velocity of species i; D = diffusion coefficient (cm²/in.); X = mole fraction; and z = distance, can be either in the direction of mass flow or opposed to it. If it is in the flow direction the flux is greater than concentration (Fig. 3). If it is opposed to the mass flow, flux is less than concentration and in an extreme case can be negative. This latter case means that the species (usually a radical) reacts at a point in a flame earlier than it is formed. This property is unique to flames as reaction systems and is responsible for many of their peculiarities. It should be noted that diffusion cannot affect the over-all mass flow because the sum

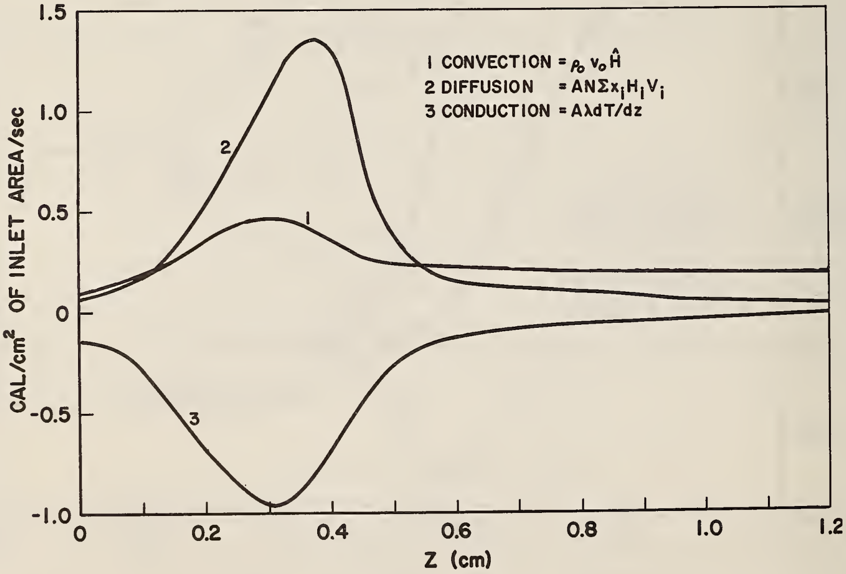


Fig. 4. Energy flux in a methane–oxygen flame front. Curve 1—flux carried by convection. Curve 2—flux carried by diffusion. Curve 3—flux carried by thermal conduction.

of diffusive fluxes must be identically zero, i.e., every positive diffusive flux is balanced by a negative flux.

Since reaction rate in a flow system is the spatial derivative of the flux rather than concentration (Fig. 3), it can be seen why it is necessary to consider the effects of diffusion quantitatively before positive conclusions can be made.

Diffusion coefficients depend on the species involved and upon the temperature. They have been measured for a number of pairs of molecules of interest in flames over a sufficiently wide temperature range to be useful for quantitative use (Chapt. XII, Ref. 1). Most of these measurements were made on binary systems, whereas flames generally have many components. However, binary coefficients can be used for many flame analyses because one species is present in excess while the others can be considered as traces in this carrier. In some systems this is not a good approximation. In this case, the true multicomponent diffusion coefficients can be derived from the binary diffusion coefficients of the system.[5] This is a very laborious computation, however.

The energy flux due to thermal conduction in flames (Fig. 4), is large, but it is characteristic of flames that this is almost counterbalanced by the energy flux carried by diffusion. Thermal conductivity is a well-defined parameter at each point in the flame although it has a very complex dependence on composition and temperature.

CHEMICAL PROCESSES

The important process in a flame for chemists and chemical engineers is chemical reaction. It is the source of energy and the driving force of the system. However, since the equilibrium properties of the burned gases are also often important, mention will first be made of methods for calculating adiabatic flame temperatures, compositions, and heat releases.

Many flames are adiabatic systems; where in principle, it is possible to calculate the final composition and temperatures of fully reacted gases. Such calculations are not applicable to those flame systems which are not adiabatic, which do not go to completion or for which reliable thermodynamic functions are not available. Fuel-rich flames and those containing solids are particularly difficult; the information required consists of enthalpies, heat capacities, equilibrium constants, and phase equilibria. There are excellent compilations of thermodynamic functions for most of the species of interest in common flame systems, and these data are among the most precise of physiochemical information. They are based on equilibrium measurements, calorimetric data, and spectroscopic information.

In the process of chemical reaction the principal differences between flames and homogeneous reaction systems are diffusion effects and the substitution of distance for time as a variable. The diffusion effects are twofold; the concentrations of reactants differ drastically from those of the incoming gas; and reactive species can be transported from later, higher temperature stages of the reaction into the low-temperature initial stage.

Any reaction which liberates heat and has a positive temperature coefficient of reaction rate could, in principle, form a flame system. In practice, however, the rate required to form a reaction zone of convenient laboratory size limits flames to initial reactions of high intrinsic rate. These are primarily bimolecular, usually molecule-radical (or atom) reactions of low-activation energy. In secondary regions, e.g., see Fig. 3, slower reactions can and do occur, particularly three-body recombination reactions involving radicals.

Because of the extreme rapidity and high temperatures of flame reactions, less pertinent, kinetic information has been available than would be desired. Many of the systems of interest have been studied at low temperatures and have shown such low activation energies that their extrapolation to flame temperatures is difficult and often meaningless. In recent years a number of investigators have undertaken the direct study of flame reactions, and much new information is becoming available.[1]

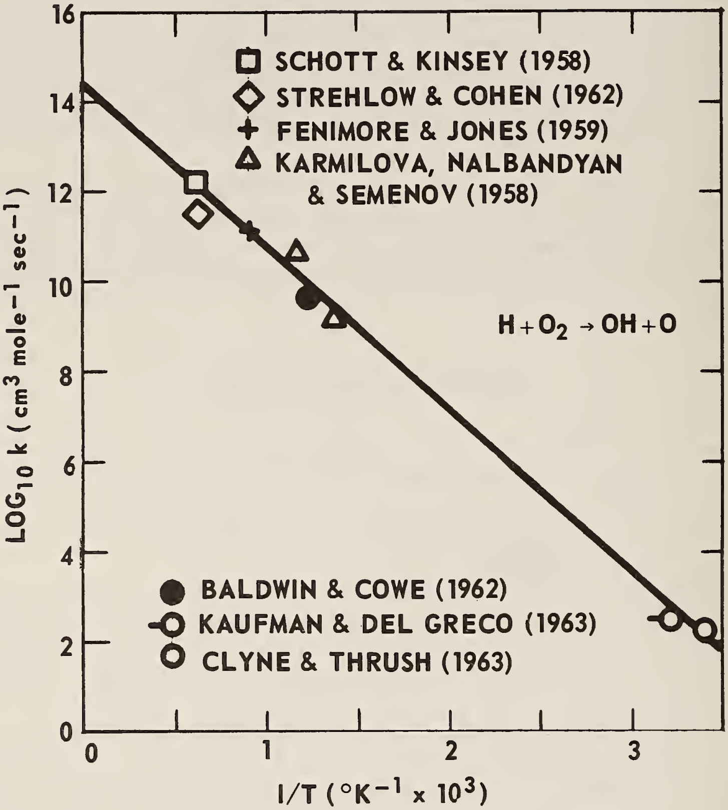


FIG. 5.—Arrhenius plot of the reaction $H+O_2 \rightarrow OH+O$. This has been studied over the widest range of rates of any reaction. High temperature data were furnished by flame studies and shock tube techniques.

Since even the simplest flames are multicomponent systems involving several reactions, the flame kineticist must immediately face the problem of multiple reactions, both in series and in parallel. Though all conceivable reactions occur to some extent, the problem is to choose the minimum number of reactions which provide a quantitatively satisfactory description of the flame system.

Since the fraction of species disappearing through a particular reaction is proportional to the rate of the reaction, the fastest reaction will dominate. There should be relatively few cases of parallel reactions of comparable importance since this would require that their rates be roughly equal—an unlikely coincidence. Therefore, it can usually be assumed that a flame system can be adequately explained by a simple dominant reaction scheme consisting of a sequence of reactions connecting the initial and final products. In such a sequence, subsequent reactions may be either faster or slower than the previous reaction. If the rate of the following step is rapid compared with the previous reaction, then the intermediate species will be present only as a trace (e.g., formaldehyde in the CH_4 flame) and an adequate representation can be made by considering the over-all reaction, neglecting the fast steps, as is commonly done in reaction kinetics. The second case, that of a subsequent step slow compared with the initial step, results in a physical separation of the flame. An example of this is the separation of the CO reaction region in the common hydrocarbon flame.

Flame reaction schemes are often considerably simpler than those associated with ignition or cool-flame phenomena and can be used to derive chemical kinetic information (Fig. 5).

In this section we will discuss the chemistry of flames of oxygen with hydrogen, carbon monoxide or hydrocarbons. This limitation is required because of space and because these are the major systems which have been studied quantitatively. The interested reader is referred to the original literature—the survey of Fristrom and Westenberg (Chapt. XIV of Ref. 1) and the discussions of Lewis and von Elbe,[7] Minkoff and Tipper,[8] and Fenimore.[9]

The flames of H_2, CO, and hydrocarbons with oxygen form a heirarchy. The hydrogen flame has the simplest chemistry, followed by the carbon monoxide flame which includes all of the reactions of the hydrogen system. Hydrocarbon flames are more complex; in addition to their own chemistry, they also involve both the CO and hydrogen systems. The chemistry of lean flames involves that of the fuel and its lower homologs. The flame chemistry of rich hydrocarbons is much more complex.

The Hydrogen–Oxygen Flame

O_3, H_2O_2, and HO_2 are usually excluded from consideration in flames because of their absence in flame fronts, as would be expected considering the high temperatures and the low thermal stability of these species. With these limitations the complete reaction scheme can be written down by inspection (Table I). The driving step is that of hydroxyl radical with molecular hydrogen. Hydrogen-rich flames often involve high excess radical concentrations (in extreme cases as much as 5000-fold over final thermal equilibrium) and as a result usually possess an extended recombination region following the primary reaction zone.

Flame structure techniques have been used to study several of these reactions and flame theory calculations have been applied with the major conclusion that thermal diffusion must be included for both H and H_2 if this flame is to be studied quantitatively.

TABLE I

Hydrogen–Oxygen Flame Reactions[a]

Reaction	Forward		Reverse	
	log A [b]	$E \times 10^{-3}$ [c]	log A	$E \times 10^{-3}$
1. $H+H+M \rightleftarrows H_2+M$	$k(300) = 10^{-14}$ [d] $k(2000) = 10^{-15}$		—	(104)
2. $O+O+M \rightleftarrows O_2+M$	$k(300) = 1 \times 10^{15}$ $k(3000) \approx 1 \times 10^{15}$		—	117
3. $H+O_2 \rightleftarrows OH+O$	14.34	16.5	13.2	0
4. $H+H_2O \rightleftarrows H_2+OH$	13.7	20	13.0	14.8
5. $O+H_2 \rightleftarrows OH+H$	13.05	9.4	12.7	7.5
6. $H+O+M \rightleftarrows OH+M^*$	—	≈0	—	102[e]
7. $H+OH+M \rightleftarrows H_2O+M^*$	—	≈0	—	≈100[e]
8. $O+H_2O \rightleftarrows 2\ OH$	13.6	18.1	12.6	1

[a] Kinetic constants taken from the survey of Fristrom and Westenberg (Ref. 4), unless otherwise noted. Bimolecular rates are fitted to form $k = A\exp(-E/RT)$.

[b] Units of A and k are cm^3 moles^{-1} sec^{-1}; log A is taken base 10.

[c] Units of E are calories per mole.

[d] Termolecular rate units are cm^6 moles^{-2} sec^{-2}.

[e] Dissociation energy (1).

The Carbon Monoxide–Oxygen Flame

A key peculiarity of this flame is the difficulty of burning dry, hydrogen-free carbon monoxide-oxygen mixtures. The burning velocity appears to be a monotonic function of the added hydrogen concentration whether it comes from added H_2 or H_2O. The most reasonable interpretation of this fact is that the attack of CO must involve either H, OH, or both; and that the reactions $CO+O_2 \rightarrow CO_2+O$ and $CO+O \rightarrow CO_2^*$ must be slow relative to the reaction responsible for CO disappearance. As a result the chemistry of the carbon monoxide flame must include at least some and probably all of the reactions of the hydrogen-oxygen flame. The principal reaction involved in carbon monoxide flames is $OH+CO \rightarrow CO_2+H$ and the oxygen is consumed by the reaction $H+O_2 \rightarrow OH+O$. Thus, the scheme for the carbon monoxide flame consists of the hydrogen–oxygen reactions with the addition of a single reversible reaction (Table II). This reaction has been studied in carbon monoxide flames and in the postluminous reaction zone of a number of hydrocarbon flames as well as by other techniques so that the kinetic constants are well defined (Ref. 1, Chapter XIV). In hydrocarbon flame systems the fact that this reaction is well understood has been used to estimate OH concentrations from the observed rates of CO_2 formation.

TABLE II

Carbon Monoxide–Oxygen Flame Reactions[a]

Reactions[d]	Forward		Reverse	
	log A [b]	$E\times10^{-3}$ [c]	log A	$E\times10^{-3}$
1. $OH+CO\rightleftarrows H+CO_2$[e]	12.5	4	14.1	19
2. $H+CO+M\rightleftarrows HCO+M^*$	—	—	—	≈16
3. $(H, O, OH)+HCO\rightarrow CO+(H_2, HO, H_2O)$	Probably rapid		—	—

[a] See Table I.
[b] See Table I.
[c] See Table I.
[d] Also includes reactions of Table I.
[e] H. Gg. Wagner, private communication.

Hydrocarbon Flames

Hydrocarbon flame chemistry is complicated and far from completely solved, but the general behavior is clear and several of the simpler systems are understood quantitatively. That this chemistry is complex is not surprising. A complete understanding requires consideration of fuel-rich flames and fuel-lean flames; the effect of changing molecular weight in a homologous series and the effect of unsaturated bonds on the chemistry.

In the hydrogen–carbon–oxygen flame system the principal attack of oxygen and the main radical branching step is the reaction $H+O_2\rightarrow OH+O$. It has a relatively high activation energy for a flame reaction (16 kcal/mole) and is hence only rapid at relatively high temperatures (>1000°K). This is probably related to the observation that the lowest flame temperature found in this flame system is of the order of 1000°K.

This is probably an indispensible reaction (since it is the chain branching step) and it is common to all of these flames. In the case of the hydrogen and carbon monoxide flames it is the only important mode of oxygen attack. In hydrocarbon flames it is a major mode although attack of oxygen by hydrocarbon radical fragments probably also can be important under some conditions.

The simplest and most completely studied hydrocarbon flame chemistry is that of fuel-lean saturated hydrocarbons. Methane, ethane, and propane, the lowest members of this series, have been studied extensively by flame structure techniques and a general pattern for the series is suggested by these studies. The general conclusions given here are, of course, subject to modification as direct studies of the higher members become available.

In these lean flames the hydrocarbon undergoes initial attack by hydroxyl radical with the formation of a radical C_nH_{2n+1}. Since hydrocarbon radicals higher than ethane are thermally unstable, methyl radical is usually split off forming the next lower molecular weight olefin. Complex radicals may fission into an intermediate weight radical and an olefin. It seems probable, however, that the thermal destruction of the complex hydrocarbon radicals is sufficiently rapid so that the major oxidizing step is always connected with methyl radical. The principal evidence in favor of this viewpoint is the absence of oxygenated hydrocarbons (alcohols, aldehydes, ketones, peroxy compounds, and acids) with the single exception of formaldehyde. Since formaldehyde is probably the most reactive of these compounds (except the peroxy compounds) it cannot be argued that the absence of the higher compounds is due to their reactivity.

The methane flame is the most widely studied system and is typical of the general hydrocarbons. The flame front itself can be divided spatially into three (or four) general regions (Fig. 2b): (a) An initial transport region where major temperature and composition changes occur, but little or no reaction or heat release takes place; (b) The primary reaction zone where the methane is attacked with the intermediate formation of formaldehyde and ultimate formation of carbon monoxide; (c) The secondary reaction zone where most of the carbon monoxide is oxidized to carbon dioxide and where the excess radical species recombine, approaching thermal equilibrium concentrations. These zones are, of course, arbitrary, though they are reasonably well delineated. For some purposes it is convenient to consider the carbon monoxide reaction zone separately from the radical recombination region. This can be reasonably done in the case illustrated; but this is partially a question of the pressure range being studied. As pressure is raised, these two regions will merge.

Fenimore has pointed out that such flames can be considered as a hydrocarbon reaction zone which acts as a source of a high temperature carbon monoxide–hydrogen flame. We have already discussed the carbon monoxide and hydrogen chemistry and the radical recombination chemistry will be considered at the end of this section, since it is common to all types of flames. For this reason the additional reactions required to describe the methane flame quantitatively are only those associated with methane.

The methane attack is confined to the primary reaction zone which can be roughly identified with the region of strong flame luminosity. There are two questions involved: (a) What reaction is responsible for the initial attack of methane in these flames, and (b) What is the reaction path followed by the fragments produced by the initial attack? The answer to the first question is quite definite. The initial attack of the methane is by OH radical. Contributions from other reactions such as those with oxygen, oxygen atoms, HO_2, and hydrogen atoms are negligible. It should be noted in anticipation of the discussion of the chemistry of the fuel rich flames that, as the relative fuel concentration is increased, attack by H atoms becomes increasingly important and finally becomes dominant in rich flames. The crossover point where the two rates are of about equal importance is in the region of the stoichiometric point in the methane-air system. The kinetic constants of the reaction are reasonably well determined (Table III), although they are subject to some revision as more low temperature information becomes available.

The second question of the fate of the methyl radical is a subject of debate. The facts are that formaldehyde is formed either as a side product or more likely as a second step and that ultimately carbon monoxide is formed. Fenimore feels that under all conditions oxygen atoms attack the methyl radical in an unspecified reaction with the formation of formaldehyde. Fristrom and Westenberg favor the more conventional view that if molecular oxygen concentration is high throughout the flame that the methyl radical is attacked by molecular oxygen with transient peroxide and subsequent formaldehyde formation. The attack of the formaldehyde could be by oxygen atoms or even possible by hydrogen atoms to form HCO; but the best present evidence indicates that the reaction is with OH radical to form HCO and water. The HCO radical rapidly forms carbon monoxide either by thermal decomposition or by reaction with one of the other radicals.

Fuel-rich hydrocarbon flames have more complex chemistry than the fuel-lean flames described above. There is a continuous gradation from the predominantly lean mechanisms (initial attack by OH radical) through the predominantly rich mechanism (initial attack by H atoms) into the very rich flames which are characterized by carbon formation.

The moderately rich flames are similar in mechanism to the lean flames except that the initial attack of the hydrocarbon is predominantly by H atom reaction and the attack of methyl radical is almost certainly by oxygen atoms. In the primary reaction zone of these flames there is usually neither radical recombination nor reaction of radicals with oxygen or oxygen atoms to form oxygenated intermediates. The best evidence for this is that in the study of the propane flame no evidence was found for the formation of hydrocarbons higher than the initial one (C_3H_8), although all of the possible lower hydrocarbons were detected and no oxygenated compounds were detected although the presence of small amounts of formaldehyde could not have been excluded.

TABLE III

A. The (Lean) Methane Oxygen Flame Reactions[a]

	Forward	
Reactions[d]	log A [b]	$E\times10^{-3}$ [c]
1. $OH+CH_4\rightleftarrows H_2O+CH_3$	14.7	9.9
2. $CH_3+\begin{cases}O\rightarrow OCH_2+H\\ O_2\rightarrow OCH_2+OH\end{cases}$	$k(O, 1500)=3\times10^{13}$(?) $k(O_2, 1500)=3\times10^{11}$(?)	
3. $OCH_2+OH\rightarrow H_2O+HCO$	15.7	13 (?)

[a] See Table I.
[b] See Table I.
[c] See Table I.
[d] Also includes reactions of Table II.

B. Self-consistent Reaction Scheme for the CH_4–O_2 Flame

$2\,O_2+2\,H\rightarrow 2\,OH+2\,O$
$CH_4+OH\rightarrow H_2O+CH_3$
$O_2+CH_3\rightarrow OCH_2+OH$
$OCH_2+O\rightarrow HCO+OH$
$HCO\rightarrow H+CO$
$CO+OH\rightarrow CO_2+H$
$2\,OH\rightarrow H_2O+O$
$2\,O+M\rightarrow O_2+M^*$

$CH_4+2\,O_2\rightarrow 2\,H_2O+CO_2$

Rich unsaturated hydrocarbon flames have been studied but as yet there is no definitive interpretation of the reaction kinetics. The dominant radical would probably be hydrogen atoms. In addition to stripping reactions of the type discussed above, one will probably have to consider addition reactions forming more saturated radicals, e.g., $H+C_2H_4 \rightarrow C_2H_5$. Under the reducing conditions occurring in these flames the recombination of radicals may be important, and it is likely many such processes will be in partial equilibrium as suggested by Fenimore, e.g., $2CH_3 \rightleftarrows C_2H_6$.

A spatially extended radical recombination region is a characteristic of most flames. This occurs because in the primary reaction zone excess radicals are generated and the three body reactions required to establish true thermal equilibrium are slow compared with the fast bimolecular primary reaction. In hydrogen and lean hydrocarbon flames the radicals of interest are H, O, and OH. The reactions involved are those of the hydrogen-oxygen flame (Table I). In addition to the four recombination steps there is also a group of fast bimolecular steps which tend to keep the three radicals in a partial equilibrium with one another. Thus, if one radical is in excess they all will be in excess, but their relative concentrations will be determined by a partial equilibrium. Because of this the decay of total radical concentration in this region is determined by the sum of all possible recombination processes and will generally be dominated by one fast recombination process.

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INHIBITED FLAMES

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Certain compounds when added to flames in very small quantities cause drastic reductions in flame speed. As shown in Table I these reductions are much greater than could be accounted for by dilution.[1] It has, therefore, been assumed that the inhibitor interferred in some way with normal flame kinetics. Because of the importance of free radicals to flame propagation, it has been suspected that chemical inhibitors cause a decrease in the concentrations of active particles such as hydrogen and oxygen atoms and hydroxyl radicals. This has recently been demonstrated in several systems.[2,3,4]

TABLE I

Volume of Additive Required to Reduce the Flame Speed of a Stoichiometric *n*-hexane–air Mixture by 30% (Ref. 1).

Substance	Volume %
N_2	8.0
CO_2	6.8
n-C_6H_{14}	1.05
Br_2	0.7
CCl_4	1.38
PCl_3	0.15
PBr_3	0.15
$(CH_3)_3PO_4$	0.26
$Fe(CO)_5$	0.017
$Pb(CH_3)_4$	0.015
CrO_2Cl_2	<0.024

The most complete description of the action of a chemical inhibitor has been for methyl bromide.[4] Figure 1 shows part of the composition profile of a methane-oxygen flame inhibited with methyl bromide. The most striking feature is the appearance of hydrogen bromide early in the flame and its disappearance prior to the luminous zone. In Fig. 2 the rate profiles for this flame show that the reaction of methyl bromide and hydrogen bromide begin before that of methane. A comparison with the rate curve from an uninhibited methane–oxygen flame shows that the methane reaction in the inhibited flame is delayed until later in the flame where the temperature is higher. All these observations suggest that the radicals which diffuse from the primary reaction region of the flame into the transport or preignition region react preferentially with the inhibitor (Fig. 3).

Consider the fate of a hydrogen atom which diffuses into the preignition or transport region of a lean flame. In an uninhibited flame it will react with oxygen in the chain-branching reaction, $H+O_2 \rightarrow OH+O$, forming an oxygen atom and a hydroxyl radical for a net generation of two free valences. If, however, it reacts with methyl bromide the following series of reactions can occur: $H+CH_3Br \rightarrow CH_3+HBr$, $CH_3+O \rightarrow H_2CO+H$, $H+HBr \rightarrow H_2+Br$, resulting in a net destruction of three free valences. All of these reactions are fast but the inhibition reactions have very low activation energies so that they are much faster in the cooler part of the flame. Thus, in an inhibited flame the primary reaction zone cannot begin until the

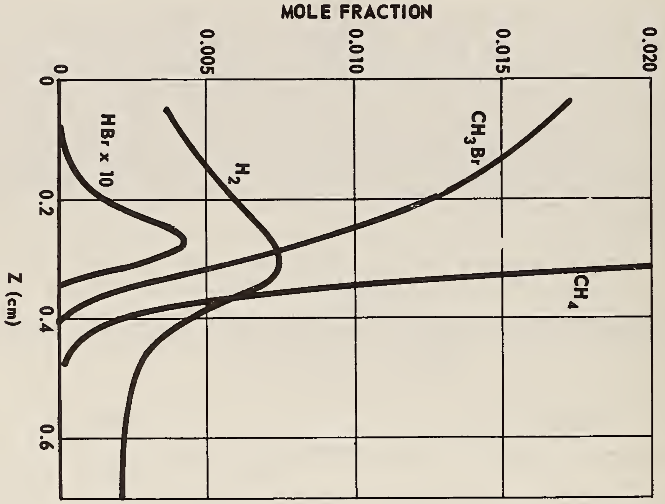

Fig. 1. Composition profile of a methane–oxygen flame inhibited with methyl bromide.

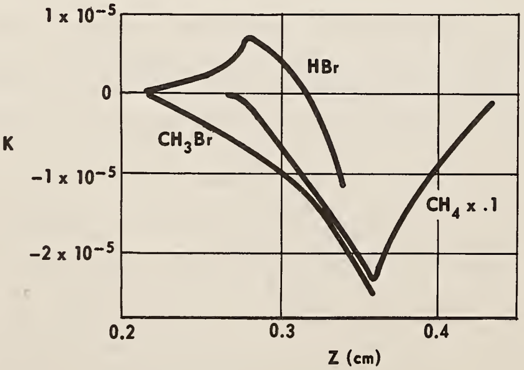

Fig. 2. Some rate profiles from a methane–oxygen flame inhibited with methyl bromide.

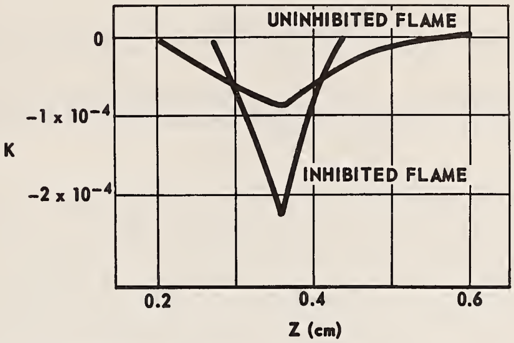

FIG. 3. Comparison of net reaction rate for methane (K_{CH_4} mol sec cm^3) in an inhibited and in an uninhibited flame.

temperature is high enough so that generation of radicals by $H+O_2 \rightarrow OH+O$ overcomes their loss by inhibition reactions, or until the inhibiting species has been used up.

SUMMARY

[This summary prepared by Dr. Wilson covers the work described in Dr. Fristrom's paper, which precedes Dr. Wilson's paper, and the work in Dr. Wilson's paper.—Editor.]

The present status of flame studies is as follows. The fundamental processes have been identified and are well understood individually. These are convection, thermal conduction, molecular diffusion, and chemical reaction. In flames they are strongly coupled and the interactions are responsible for the peculiarities of combustion reaction systems. A set of equations can be written combining the constraints of conservation of energy, conservation of atomic species and the differential equations of thermal conduction, molecular diffusion and chemical reaction. These equations (the flame equations) describe flames quantitatively and in their one-dimensional form they can be solved using high speed computers providing the chemistry is simple (e.g., the H_2–Br_2 flame). In most flame systems, however, the required parameters are not sufficiently well defined and the chemistry is too complex for this approach. As a result, the flame problem for the chemist and chemical engineer is an experimental one. Experimental techniques have been developed which allow quantitative study of the temperature and compositional history of the gas passing through the flame front. From the interpretation of these data, it has been possible to verify the applicability of the flame equations to laboratory flames, deduce the reaction schemes of a number of the simpler flame systems (notably in the hydrocarbon–oxygen systems), and provide quantitative high temperature rate data on a number of elementary reactions. The flame data extends the temperature range of kinetic studies for these reactions significantly and as a result they cover the widest range of rate and temperature in the literature and represent some of the most reliable determinations of kinetics constants in the literature.

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Subject Headings: ***Elementary reactions; Flame, structure of; Flame, inhibition; Flame, chemistry; Flame, hydrocarbon.***

SYMPOSIUM ON FOREST FIRE RESEARCH at Tenth Pacific Science Congress—University of Hawaii, August 31, 1961

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A symposium on forest fire research, participated in by researchers from Australia, the U.S.S.R. and the United States, was held in conjunction with the Tenth Pacific Science Congress, on 31 August 1961, on the campus of the University of Hawaii. It was attended by about forty foresters and scientists from the Pacific area.

Edward I. Kotok, the first Director of the California Forest and Range Experiment Station when it was established in 1926, discussed "A Half Century of Fire Research in California." The basis for modern forest-fire research can be credited to Coert DuBois, a professional forester working in the California Region of the U. S. Forest Service. His 1915 work, "Systematic Fire Protection," recognized fire as a field requiring organized research. His proposal for more adequate and complete individual fire reports was adopted, and these provided the factual base for the research that followed in the next two decades.

Shortly after, a Federal forester (S. B. Show) was given the specific assignment of fire research, and charged with studying rates of spread, the practice of "light burning", and fire damage. At that time, the U. S. Weather Bureau also initiated studies on fire-weather forecasting. In 1921, a Forest Service conference recommended a broad research attack on the fire problem; and the current research program stems directly from this conference.

Valentin G. Nesterov, Head Forestry Chair at the Timiryasev Agricultural Academy in Moscow, prepared a paper entitled "Forest Fire Research and Methods of Fire Control." The paper discussed the system currently used in Russia to integrate the various factors involved in the burning and control of forest fires. A mathematical expression describing the interaction between various factors can be derived. The factors include: flammability and burning ability of the forest; changes of weather; characteristics of fire sources; hazard; fire-brigade service's activities; and localization and suppression of fires.

To describe the buning index, the following equation is used;

$$\begin{aligned} T &= K_1K_2\int f(u)\,du \\ &= K_1K_2\sum(u), \end{aligned}$$

where T is the burning index; u is a meteorological index for a day ($=td$, where t is the temperature and d the vapor pressure deficit); K_1 is a coefficient representing last rainfall; and K_2 is a coefficient representing wind.

Maps showing the daily distribution of this index are published by the Central Institute of Weather Forecasting.

*Wallace L. Fons**, Physicist at the Southern Fire Laboratory of the U. S. Forest Service, described the "Use of Models to Study Forest Fire Behavior." He outlined

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* Deceased

the objectives of the study, which included examination of the effect on fire behavior of such variables as species of wood, density of wood, moisture content, size of fuel particle, spacing, dimensions of fuel bed, wind, and slope.

Tests on carefully made cribs were made using five species of wood with varying densities. Results showed that rate of spread decreases with increasing density; and for a given wood, density is practically independent of the species tested. Another series of tests was made using white fir wood at several densities to determine the effect of fuel moisture content on rate of spread. The results showed that the effect of moisture content on rate of spread was greater with decreasing density of wood.

The temperature distribution measured in the convection zone of test fires was expressed as a functional relationship between two dimensionless groups, one pertaining to atmospheric conditions and convected heat and the other to the height and diameter of the convection column.

H. E. Whittingham, Meteorologist with the Australian Bureau of Meteorology, prepared "A Review of Fire Weather Investigations in Australia." His paper was read by a colleague, Neil McRae. An updated version of the paper is published in the last issue of Fire Research Abstracts and Reviews (7—1).

"The Present Status in the U.S.A. of Fire-Weather Research and Plans for an Improved Fire-Weather Service" was the subject of a paper prepared by *DeVer Colson* and *Lynn Means* of the U.S. Weather Bureau, and presented by Mr. Means. The Weather Bureau, in cooperation with the Forest Service and other interested groups, developed plans for strengthening the fire-weather service. The plan proposed (1) adding meteorologists who are full-time specialists in fire-weather problems to existing and newly established offices where such forecasts and services are required; (2) adding mobile units for use in making weather observations and issuing warnings at the sites of fires; and (3) providing prompt and adequate communication of weather information to fire control agencies.

Specific needs for fire-weather forecasting research were detailed. Some of the needs include: (1) development of procedures for predicting important weather conditions that have a severe impact on fire danger; (2) development of procedures for fine-scale measurement and analysis of weather elements in mountainous terrain; (3) development of methods and techniques for interpreting long-range forecasts in terms of fire-weather conditions; and (4) development of techniques for use at area forecast centers in the preparation of essential guidance material for smaller fire-weather forecast offices that are unable to adequately prepare for themselves.

The convener of the Symposium, *William E. Reifsnyder*, Associate Professor of Forest Meteorology at the Yale School of Forestry, summarized the talks and presented his own comments on "New Horizons in Forest-Fire Research."

Although many lines of fire research are being actively pursued, as witnessed by the papers in this Symposium, there are several areas that should be pursued even more vigorously by virtue of their importance, comparative neglect, or potential for significant advance. These include prevention, effects of fire, and efficiency of suppression effort.

Fire prevention has much in common with accident prevention. It is not enough to say "prevent fires" or "stop accidents," for the causes of fires and accidents are often subtle and deeply buried in the psychology of the individual. Prevention of man-caused fires must first, then, be based on understanding of the motivations, often subconscious, of potential fire starters. In our fire research to date, we have barely scratched the surface in discovering who starts fires and why, and how they can be prevented from doing so.

Deep-rooted psychological attitudes toward fire have also distorted man's approach to the use of fire in wild-land management. Traditions for or against use of fire have often prevented rational research on effects and use of fire. Of particular importance in the Pacific area is the role of fire in agricultural practices in the tropics and subtropics. There is perhaps no other subject in fire so circumscribed with emotional bias as the use of fire in shifting agriculture. Much more objective research is needed in this important area.

Finally, although much effort has been directed toward organizing for fire control over the years, our organizations usually work much better on paper than they do on a fire. We need to know more about the response of individuals to the stressful situation of working on a fire, whether in a supervisory capacity or as a line-worker. Faced with a fire situation, we need to know quickly and continuously the optimum distribution of men and matériel. Modern techniques of mathematical analysis may have important application to this problem. Also needed is a rational system of describing fire behavior and the suppression effort applied to a particular fire. With a complete analytical and quantitative description of the "fire situation," analog or digital computing techniques could be used to optimize control efforts. Data fed to a central dispatcher could then be processed by high-speed computer to produce optimum assignments of men and matériel and a preferred strategy of fire control.

Subject Headings: *Fire fighting, techniques; Fire fighting, equipment; Fire, danger rating, in U.S.S.R.; Fire research, new horizons in; Forest fire, models; Forest fire, new horizons in research; Fire weather, forecasts; Fire weather, research in U.S.; Model, of forest fires; Fire prevention, psychological attitudes, accident prevention; Operations research, fire control.*

69TH ANNUAL MEETING OF THE NATIONAL FIRE PROTECTION ASSOCIATION

HORATIO BOND

Chief Engineer, National Fire Protection Association

A group of registrants numbering 2050 came together in Washington, D. C., at the Mayflower Hotel, May 17 to 21, 1965, for discussion of fire matters. The occasion was the 69th annual meeting of the National Fire Protection Association, and a number of related gatherings. The NFPA is generally recognized as the international clearinghouse for fire matters. By membership in NFPA, no one is pledged to any course of action and people from all walks of life may and do join. Insurance people who started the Association in 1896 have been successful in getting others to join with them; they are now outnumbered in NFPA, both by representatives of industry and by public fire departments. Membership includes 23,000 persons professionally concerned with fire matters in industry and commerce and in government agencies, Federal, state, and local, in addition to fire departments.

Features of the meeting included an Aviation Seminar, devoted to fire problems of aircraft and airports, a Petroleum and Chemical Industry Workshop, and a session on Fire Prevention Education. The international character of the Association was reflected in the opening session, a part of which was devoted to a symposium at which members from Australia, New Zealand, Switzerland, and the United Kingdom reported. Dennis I. Lawson, Director of the Joint Fire Research Organization, Boreham Wood, England, reported on Russia at a luncheon meeting. A representative of the United Kingdom Ministry of Aviation spoke at the Aviation Seminar and a representative of the British Industrial Fire Protection Association was the featured speaker at the closing session.

In sessions ancilliary to those of the NFPA, four organizations which operate as sections of the NFPA held their annual meetings. These are: Electrical Section, Railroad Section, Fire Marshals' Association of North America, and Society of Fire Protection Engineers. Another group of NFPA members, the industrial fire chiefs, met and petitioned the Association for authority to form a section. The NFPA sections require their members to be members of NFPA but each section sets its own membership requirements.

The week devoted to NFPA meetings also prompts convocations of groups concerned with fire matters but not directly associated with NFPA. For example, the managers and engineers of the fire insurance rating boards and bureaus held a meeting of their Advisory Engineering Council. The Office of Civil Defense held a meeting of its contractors engaged in fire research assignments. About twenty technical committees of the NFPA took advantage of their members being in Washington and held meetings during the week.

Warren J. Baker, Chief Engineer of the Insurance Company of North America in Philadelphia was re-elected president and Paul C. Lamb, Safety Administrator of Lever Brothers Company, New York, was re-elected vice-president. A new second vice-president was elected, Elmer F. Reske, Manager of the Illinois Inspection and Rating Bureau, Chicago. Co-chairmen of the local committee for the NFPA meeting were Robert C. Byrus, Director, Fire Service Extension, University of Maryland and William L. Hanbury, Director of the Federal Fire Council, Washington, D. C.

ACTION ON STANDARDS

The chief business of the NFPA annual meeting was action on proposed standards, which will affect fire laws and regulations, as well as practices in commerce and industry. At the 1965 meeting, 27 committees recommended action on 51 standards. The NFPA will formally compile a record of action on Technical Committee reports in Proceedings to be issued later in the year. In addition, it will make available copies of papers presented. Also, many papers will be processed for reproduction appropriately in the NFPA periodicals, particularly the six-times-a-year *Fire Journal* and the quarterly magazine *Fire Technology*.

ELECTRICAL SECTION

The meeting of the Electrical Section was of special significance since this marked the three-year interval at which time action is due on a 1965 edition of the National Electrical Code. This is the largest of Association standards as measured in printed pages and in extent of use. The National Electrical Code is almost universally used in the United States and is regularly adopted by most of the states and cities regulating electrical wiring. The associations of electrical contractors, installers, manufacturers, electrical inspectors, and others maintain machinery for processing, within their respective associations, recommendations or changes or new provisions for the National Electrical Code and hold many meetings during the three-year interval between editions of the Code. Resulting recommendations are fed into a group of seventeen code-making panels which are sponsored by the Electrical Section of NFPA. Each of these panels meets as often as necessary to consider recommendations in the subject area to which it is assigned. This requires numerous meetings for each panel each year between editions of the Code. Approval of the panels' recommendations is handled by the Electrical Section and by an Electrical Correlating Committee of nine which is assisted by a secretary who is the NFPA Electrical Field Engineer. At the meeting of the NFPA Electrical Section, anyone who felt he had not been heard through the normal committee channels was given opportunity to comment and criticize the proposed 1965 National Electrical Code, which had been printed in advance by the NFPA to permit review.

CHEMICAL AND PETROLEUM WORKSHOP

This workshop session occupied a full day. For the fourth year, it proved an attractive item to people in the chemical and petroleum industry and provided a forum at which questions could be raised to help identify problems that are often not fully resolved by the safety recommendations in NFPA standards.

AVIATION SEMINAR

The Aviation Seminar heard a report evaluating fire-fighting operations in a series of seven major fires on surplus C-97 airplanes, conducted last year by the Federal Aviation Agency at the National Aviation Facilities Experimental Center. The purpose of the tests was to determine ways to extend survival time of airplane occupants until evacuation or rescue can be made.

The tests showed that the rotor downblast of a helicopter with its "cooling" effect can, in certain instances, be helpful in beating back flames and can aid in clearing rescue evacuation paths. However, this is not without disadvantages. The Aviation Seminar also considered the latest developments in extinguishing media, techniques, and equipment and devoted some time to discussions of fuel safety and systems which are provided in aircraft to detect fires.

FIRE MARSHALS' ASSOCIATION OF NORTH AMERICA

The Fire Marshals' Association of North America, organized in 1906, is made up of state, provincial, county, and municipal fire marshals. These men are charged with investigation of fires in their respective jurisdictions and in administration of laws relating to hazardous chemicals and explosives, and safety measures to prevent loss of life due to fire. Since 1927, it has operated as a section of the NFPA.

Resolutions adopted by the Fire Marshals reflect the discussions of the meeting. One resolution was directed against the common practice of assuming that fire-resistive construction and fire-detection systems are adequate for nursing homes.

Another resolution recommended adoption of the provisions of the NFPA Model State Fireworks Law by the 23 states and the District of Columbia which, at present, have no legislation, or inadequate legislation to protect people, particularly children from injuries from fireworks.

It was recommended that increased protection be provided for aboveground tanks of gasoline and other flammable liquids.

The interest of the group in arson is reflected in the endorsement of a Federal law directed at racketeering enterprises.

SOCIETY OF FIRE PROTECTION ENGINEERS

The Society of Fire Protection Engineers, with 1300 members, operates as a section of NFPA. It is a member of the Engineers Joint Council and sets membership standards that are comparable to those of the other engineering societies. Among papers presented was one on "Fire Development Theory—An Overview" by Professor Howard W. Emmons of Harvard University, who is a member of the Committee on Fire Research of the National Academy of Sciences-National Research Council. Three papers were devoted to the "Systems Approach to Fire Protection Problems"; and two to "Fire Protection Engineering Education and Professional Development"; three to "Fire in Buildings"; and three to "Forecast for the Future." On "Fire Protection Engineering Education," Professor Harry E. Hickey, University of Maryland, described the philosophy underlining the undergraduate course of fire protection at the University of Maryland. Under "Fire in Buildings," the "Impact of New Materials and Construction Systems on Fire Test Technology" was ably presented by Professor Richard W. Bletzacker, Ohio State University.

FIRE PREVENTION EDUCATION

The things that motivate the actions of people have been found to be relatively more important than technical details of fire protection. The NFPA originated, about 1913, the first of the "Weeks," *Fire Prevention Week*. It has been supplemented by *Spring Clean-Up Campaigns* and by sponsorship like *Sparky*, the fire dog.

At the meeting of the Fire Marshals' Association of North America, the D. C. Fire Marshal, Hugh A. Groves, reported a successful campaign entitled "Operation EDITH" (Exit Drills in the Home) which was carried on to coincide with a similar campaign in Maryland, Delaware, and parts of Virginia.

Percy Bugbee, General Manager of NFPA devoted part of his annual report to emphasizing the importance of such educational campaigns. He said, "Last year 6550 people were killed in dwelling fires in this country. A substantial majority of these lives could have been saved if people had some elementary understanding of common fire hazards and had planned what to do in case fire broke out. Just so much fire protection can be engineered into the home structure itself. The people who live in these homes, by cleaning up fire hazards and developing fire-safe habits, must do the rest. We should redouble our efforts to reach children. The youngsters now being taught fire safety are interested and responsive."

A special session heard reports of successful educational campaigns from Fire Chief William D. Wentzel, Upper Arlington, Ohio, speaking about a small city's campaign, and Fire Chief John J. Killen of Baltimore describing the fire prevention program for which he was given NFPA's top award in 1965. On the same program, the veteran fire officer who headed New York City's Fire Department until last December, Edward P. McAniff, spoke eloquently of what the public fire department can do to secure public cooperation in fire safety. He urged a much tougher attitude by fire departments. "A disastrous fire," he said, "provides the opportunity to gain better cooperation from your citizens, and politicians. Strike hard and fast to increase the tempo of your inspections and, where necessary, demand passage of essential fire protection laws." He pointed out that an effective fire prevention program is difficult but rewarding from the point of the fire official who can see public response and results when the motivations of individuals are challenged.

ABSTRACTS

I. Ignition Phenomena

Adler, J. (Imperial College, London, England) **and Enig, J. W.** (U. S. Naval Ordnance Laboratory, Silver Spring, Maryland)* "The Critical Conditions in Thermal Explosion Theory with Reactant Consumption," *Combustion and Flame* **8**, 97–103 (1964)

This paper presents a mathematical analysis of the conditions for thermal explosion of a symmetrically heated material which is reacting exothermally and for which the heat of reaction is small enough so that reactant consumption cannot be ignored.

From the energy conservation equation for a symmetrically heated body, with the approximations that a mean temperature of the body and an effective heat transfer coefficient are assumed, the following equation is derived.

$$d\theta/d\lambda = -B(1 - a\theta e^{-\theta}/\lambda^n), \tag{1}$$

where θ is a dimensionless temperature defined by

$$\theta = E(T - T_{in.})/RT_{in.}^2$$

E = activation energy
T = absolute temperature
$\lambda = w/w_{in.}$, i.e., a dimensionless concentration
w = mass concentration of reactant per unit volume
B = dimensionless adiabatic temperature rise defined by

$$B = EW_{in.}\mathcal{Q}/\rho cRT_{in.}^2$$

$\mathcal{Q}$ = heat of reaction per unit mass of reactant
ρ = density
c = specific heat
a = dimensionless heat transfer coefficient defined by $a = A/\delta$
A = an effective heat transfer coefficient
δ = a dimensionless reaction rate constant defined

$$\delta = (\mathcal{Q}Er^2/kRT_{in.}^2)fW_{in.}^n \exp(-E/RT_{in.})$$

n = order of reaction
r = half-width of slab, radius of cylinder or sphere.

At the start of the reaction

$$\lambda = 1 \quad \text{and} \quad \theta = O \tag{2}$$

(since $T = T_{in.}$ and $w = w_{in.}$). This establishes one boundary condition. The problem then becomes to determine the relationship between B and a at the critical conditions for explosion.

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* Research done academic year 1962–63 when Enig was visitor at Imperial College, London, England.

To solve this problem the authors define the critical conditions as those at which the θ–λ curve passes through an inflection point, i.e., the conditions at which the temperature-concentration curve passes through an inflection. The customary treatments define critical conditions as those at which the temperature-time curve passes through an inflection. A mathematical treatment is presented to show that the latter criterion implies the former one.

For a first order reaction, Eq. (1) becomes

$$d\theta/d\lambda = -B(1-a\theta e^{-\theta}/\lambda). \tag{3}$$

The locus of inflection points is then

$$\lambda = B^{-1}[\theta/(\theta-1)] + a\theta e^{-\theta}. \tag{4}$$

The next step is to set a constant and to vary B until the integral curve of Eq. (3) is tangent to the curve of the locus of inflection points, Eq. (4). This defines the critical condition. A significant result of this treatment is that by differentiating Eq. (4) setting the expression obtained for $d\lambda/d\theta$ equal to the inverse of Eq. (3) and substituting the value of λ from Eq. (4), the results

$$\theta_c = 2 \qquad \lambda_c = 2ae^{-2} + 2/B \tag{5}$$

(where subscript c refers to the critical conditions)
are obtained analytically. The value of $\theta c = 2$ has been assumed for some time[1] but has never been derived.

Equations (2) and (5) now represent points through which the critical integral curve of Eq. (3) must pass and the values of B and a for the curve that passes through these points are the critical value.

The extension of the treatment to higher order reactions is discussed and the result that $\theta = 1 + n^{\frac{1}{2}}$ is derived.

Reference

1. RICE, O. K., ALLEN, A. O., AND CAMPBELL, H. C., *J. Am. Chem. Soc.* 57, 2212 (1935).

Subject Headings: ***Ignition, spontaneous thermal, theory of; Explosion, thermal, theory of.***

J. B. Levy

Hodges, D. J. (Nottingham University, Nottingham, England) "Spontaneous Combustion: The Influence of Moisture in the Spontaneous Combustion of Coal," *Colliery Guardian* **207**, 678–682 (1963)

In the mining and storage of coals, spontaneous ignition is an ever present hazard. Although this is an old problem and many investigators have studied it, there still remain many unanswered questions. In particular, the effects of water on the rate of coal oxidation has recently received considerable attention. Although there are many theories concerning the influence of moisture on the oxidation of coal, the precise mechanism is still controversial. Moisture that influences the kinetics of oxidation is contained both in the coal and in the surrounding atmosphere. Berkowitz and Schein[1] observed a temperature rise of 25° to 50°C when moist oxygen was passed over dry lignite and almost the same rise when moist nitrogen was used; smaller temperature rises were recorded with bituminous coals. In a differential thermal analysis experiment on coal, Stott and Baker[2] observed the presence of a small endothermal reaction at 100°C which they attributed to the loss of water vapor. This is an important reaction since for a coal to ignite spontaneously the exothermic heat of oxidation must exceed the endothermic heat of water loss. In addition, in a series of experiments using an isothermal microcalorimeter, Stott[3] measured the heat of oxidation of coal under controlled humidity conditions and also heats of desorption and adsorption of water vapor. In these experiments, sub-bituminous coals always showed a greater endothermic heat of water loss in a dry air stream than their exothermic heat of oxidation. In addition, it was shown that a 3 kg sample of bituminous coal crushed to less than 1/10 B.S. mesh and vacuum dried would ignite spontaneously in 30 min when water saturated oxygen was passed over the coal at a flow rate of 1 liter/min. Veselovskii[4] further showed that moisture absorbed on coal catalyzed the oxidation process. Smirmova and Shubmikov[5] demonstrated that the presence of moisture in coal considerably accelerates the oxidation of high volatile coals but has no appreciable effect on high rank coals. It has been observed by Wolowczyk[6] that the period of maximum humidity during midsummer coincides with the period when the greatest number of underground fires occur. He further says "the influence of air temperature is certainly greater than air pressure but according to investigation so far it is smaller than the influence of air humidity." Although there appears to be ample evidence that water significantly influences the oxidation rate of coal, the exact mechanism of the reaction is not clearly understood. The author's experimental program was designed to investigate the importance of inherent moisture of the coal and the humidity of the surrounding air on spontaneous heating. The experimental procedure followed that developed by Stott in New Zealand. A series of four experiments using the various combinations of moist oxygen, dry oxygen, dried coal, and as received coal were conducted on 5 different coal seam samples. The coal was dried and handled carefully to avoid any contact with the atmosphere prior to passing the oxygen stream over it. The same coal particle size (−72 B.S. mesh), total sample weight (2 kg) and oxygen flow rate (1 liter/min) were used in each of the experiments. Special attention was given to the collection, preparation, and storage of the coal samples; rapid oxidation takes place in the first few hours after coal has been mixed and it was important that the coal be as fresh as possible. Three of the five coals tested under the condition of dry coal-moist oxygen fired spontaneously from an initial temperature of 30°C, while the remaining coals reached maximum temperatures of 50° to 70°C before cooling. It has been suggested that drying the coal might alter the oxidation rate or the colloidal state of the coal. However, oxygen absorption studies conducted by the authors have shown that the drying of coal slightly reduced the rate of oxidation. In two of the experiments that resulted in fire, the characteristic smell of "firestink" was detected. In this series of experiments only the dry coal-moist oxygen combination resulted in spontaneous ignition of any of the coals. It is interesting to observe that none of the coal samples fired with dry oxygen. Therefore, the author concludes that these experiments demonstrate that the moisture in the air plays an important role in spontaneous ignition of coal. It is the mutually supplementing effects of (1) moisture in coal and (2) moisture in atmosphere, that ultimately leads to the development of spontaneous ignition of a coal sample.

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Subject Headings: ***Combustion, spontaneous, in coal; Coal, spontaneous combustion of; Moisture, effect on spontaneous combustion, in coal; Ignition, spontaneous, of coal; Oxidation, low temperature, of coal***

H. E. Perlee

Mutch, R. W. (Intermountain Forest and Range Experiment Station, U. S. Forest Service, Missoula, Montana) "Ignition Delay of Ponderosa Pine Needles and Sphagnum Moss," *Journal of Applied Chemistry* **14**, 271–274 (1964)

Prediction of fire ignition and spread in wildlands demands knowledge of the combustion properties of natural fuels. Sphagnum moss from the interior of Alaska and recently cast, dead ponderosa pine needles collected near Missoula, Montana, were chosen for study because of their dissimilarity. They were ground in a Wiley mill and conditioned in desiccating cabinets over silica gel and anhydrous calcium chloride. Tested (10 to 20 replications) were: (1) entire ground samples, (2) screened samples (0.208 to 0.295 mm), (3) entire ground samples previously extracted with ether to remove highly volatile constituents. Tests were made for (a) spontaneous ignition and (b) pilot ignition.

A Jentzsch ignition tester adapted by von Deichmann[1] was used. Four ignition chambers (15 mm wide, 40 mm deep) containing fuel were located in the center of an electric furnace. Oxygen (33 cc/min) was supplied through a tube to three chambers and a thermometer was inserted in the fourth. Ignition was observed through a mirror above the ignition chambers. Ignition delay (time from insertion of sample in furnace to first appearance of glow or flame) was measured at 320°.

Particle-size distribution of the ground samples was evaluated with U.S. Standard sieves and a laboratory shaker. Density was computed by measuring volumes with a Beckman air pycnometer. Moisture was determined by xylene distillation and vacuum-oven drying. Heat of combustion of entire samples and ether extractives was measured in an oxygen bomb calorimeter. Moss and needles were analyzed chemically for ash, ether extractives, crude fiber, protein, lignin, and moisture.

Moss always ignited sooner than needles. The differences were consistent and statistically significant. Although the needles contained more than four times as much ether extractives as moss, the needles ignited less rapidly by either spontaneous or by pilot ignition. Nevertheless, for pilot ignition only, removal of extractives retarded ignition of either moss or of needles. Heat of combustion of needles and moss was 8925 and 7494, of their extractives 15,593 and 16,407 Btu/lb, respectively. Particle size distribution differences did not contribute materially to the observed differences in ignition delay. Whether the lower density of moss contributed to its faster ignition must await determination by more extensive tests. Moisture was not a factor because the moss, which ignited faster, contained more moisture.

Reference

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Subject Headings: ***Ignition, of pine needles; Ignition, of sphagnum moss; Moss, sphagnum, ignition of; Pine needles, ignition of.***

F. L. Browne

II. Thermal Decomposition

Tang, W. K. (Forest Products Laboratory, U. S. Forest Service, Madison, Wisconsin) **and Neill, W. K.** (University of Wisconsin, Madison, Wisconsin) "Effect of Flame Retardants on Pyrolysis and Combustion of α-Cellulose," *Journal of Polymer Sciences*: *Part C* 6, 65–81 (1964)

The authors have used the techniques of thermogravimetric (TGA) and differential thermal analysis (DTA) to prove the effects of certain flame retardants on the pyrolysis and combustion of α-cellulose, the fraction of wood that contributes most to its flaming combusion. They investigated monobasic ammonium phosphate, aluminum chloride hydrate, sodium tetraborate decahydrate, and potassium bicarbonate at a low concentration (generally 2 per cent) to minimize complications from excess salts.

By dynamic TGA technique, the threshold decomposition temperature, kinetic data and char yield were obtained. DTA technique was used to find the temperatures for endothermic pyrolysis reaction and exothermic combustion reaction and their intensity. The heats of pyrolysis and combustion were also estimated through DTA thermograms using the calibration factors of known heats of fusion and vaporization.

Numerous investigators have found that the principal product in the early depolymerization of α-cellulose is levoglucosan which reacts further to form chars, tars, volatiles, and water. In this study, thermogravimetric analysis showed that flame retardants lower the threshold temperature of pyrolysis for α-cellulose and raise the char yield in the products. Differential thermal analysis in oxygen demonstrated that flame retardants reduce flaming but may extend glowing. Effectively, the retardants actually redistribute the heat of combusion of α-cellulose to a wider temperature range with a lower maximum intensity. Both the heat of pyrolysis and the maximum intensity of the heat of pyrolysis was reduced for many of the treated α-celluloses.

Analysis of the kinetic data indicated that pyrolysis occurs in two stages. The initial stage is controlled by pseudo-zero-order kinetics and the final stage is pseudo-first-order-controlled. The potassium bicarbonate changed pyrolysis kinetics in both stages while the monobasic ammonium phosphate decreased the activation energy mostly in the initial stage. Indications are that at a higher concentration the latter might have a further effect. Sodium tetraborate and aluminum chloride caused little reduction in activation energies.

Subject Headings: *Thermal decomposition, of cellulose; Pyrolysis, two-stage kinetics in cellulose; Flame retardants, on cellulose; Analysis, differential thermal; Analysis, thermogravametric techniques; Combustion, of cellulose; Cellulose, combustion of; Cellulose, pyrolysis of; Combustion products, of cellulose.*

G. S. Cuff

III. Heat and Material Transfer

Giere, A. C. and Franklin, M. E. (U. S. Naval Weapons Evaluation Facility, Albuquerque, New Mexico) "Analysis of Heat Transfer in a Two-Layer Slab: Constant Flux on One Surface and Zero Flux on Other Surface," *NAVWEPS Report 8005* (31 December 1964)

The problem which is solved in this report is that of one-dimensional time-dependent heat transfer in two slabs with perfect thermal contact between the slabs. One slab is exposed to a constant heat flux whereas the outer surface of the other slab is insulated. Values of thermal conductivity and diffusivity independent of temperature are assumed. A uniform initial temperature is assumed.

This model is a good approximation for situations occurring with physical systems. For example, a large fire provides a constant heat flux. Walls are frequently constructed of two materials in good thermal contact with the cool side insulated.

Solution of the problem is obtained by straightforward application of Laplace transform of the time variable. The transform is inverted by use of the method of residues. Residues of an infinite sequence of poles give an infinite series representation for the solution. Roots of the equation for the poles are tabulated; these roots are necessary for evaluating the infinite series. The solution was checked to show that it satisfied the differential equation and boundary and initial conditions.

Explicit formulas are given for temperature in either slab as a function of x and t with thermal conductivity, heat flux, etc., as parameters. The infinite series involves a term exp[−(constant)(root)(time)]. For long time the exponential term makes the series negligible. For short time the series is slowly convergent. A solution using the technique of Chapter 13 of Carslow and Jaeger's "Operational Methods in Applied Mathematics" would be desirable. For long time the temperature has a linear dependence on time and a parabolic dependence on distance.

Subject Headings: *Heat transfer, in two-layer slabs; Slabs, heat transfer in.*

A. E. Fuhs

IV. Diffusion Flames

Pipkin, O. A. and Sliepcevich, C. M. (University of Oklahoma, Norman, Oklahoma) "Effect of Wind on Buoyant Diffusion Flames," *Fundamentals* **3**, 147–154 (1964)

Although the work described in this paper was directed primarily to obtaining a better understanding of the effect of wind on the behavior of flames over burning pools of liquid fuel and the spread of fire beyond such pools, investigations of this type have much significance for fire spread in general. Almost all forest and wildland fires are influenced by wind. On many such fires wind is the dominant factor in their spread and behavior. This is also true of many urban fires.

The work of Pipkin and Sliepcevich is the first part of a more comprehensive study of buoyant diffusion flames over free-burning pool fires in wind. In the present paper they are concerned mainly with the effect of wind on angle of flame tilt. They also consider the effect of angle of flame tilt on the intensity of radiation received on the downwind side of the fire.

It is assumed that radiation heating ahead of the tilted flames is one of the important factors in fire spread. Theoretical calculations of radiation intensity are made from a configuration factor defined as

$$F_{dA,\rightarrow A_f}=\pi^{-1}\int^{A_f}[(\cos\phi,\ \cos\phi_f)/r^2]\,dA_f, \tag{1}$$

where r is the absolute value of the radius vector from an element of area dA_f on the flame surface to the receiving surface dA_1, of a vertical differential test object located downwind from the fire, ϕ_1 and ϕ_f are angles between the radius vector and normals to the surface elements dA_1 and dA_f, respectively. Solutions of Eq. (1) are represented graphically with the configuration factor $F_{dA_1\rightarrow F_f}$ shown as a function of D/x, the ratio of flame diameter to the horizontal distance of the differential object from the flame base. The dimensionless distance y/D of the differential test object above the horizontal surface was given values of 0, 0.25, and 0.5, each of which represents a separate family of curves.

Radiation intensities can be calculated by means of the configuration factor curves. If it is assumed that emissivities for the flame, receiving surface, and surroundings are all unity, the configuration factor can be expressed as

$$F_{dA_1\rightarrow A_f}=\frac{\sigma(T_w{}^4-T_o{}^4)+h(T_w-T_o)}{\sigma(T_f{}^4-T_o{}^4)} \tag{2}$$

where σ is the Stefan-Boltzmann constant and T_f, T_o, and T_w are the absolute temperatures of the flame, the surroundings, and the vertical surface of a differential wood test object. The convective rate of heat loss from the differential object receiving radiation is given by the term $h(T_w-T_o)$, where h is the convection heat transfer coefficient. If T_f is taken as 1975°R (the assumed temperatures of burning gasoline), T_w as 1435°R (the approximate ignition temperature of wood and cellulose), and h as 3.0 Btu/hr ft^2 °R, then the value of $F_{dA_1\rightarrow A_f}$ is 0.375. For $y/D=0.25$, ignition of the wood test object would occur. For a tank dike 40 feet wide containing burning gasoline, ignition of a differential test object 10 feet above the surface would occur at a distance of 20 feet or less if the angle of flame tilt was zero. If the flame was tilted 60° from the vertical, ignition would occur at a distance of 52 feet or less. This calculation thus indicates that the increase in radiation resulting from the tilting of the flames by wind should play an important part in fire spread.

In the experimental work, buoyant diffusion flames of natural gas were observed in a small wind tunnel to determine the effect of wind and flame buoyancy on the angle of flame tilt. The nozzle velocity of the natural gas was held constant at 0.5 ft/sec for all tests and the flame buoyancy was varied by changing the diameter of the nozzles over a range between 0.375 and 1.610 in. Wind speeds ranged from 0.45 to 3.58 ft/sec. Experimental results for 20 tests were tabulated.

Theoretical calculations of the effect of wind speed and flame buoyancy on the angle of flame tilt (measured from the vertical) were based on a simple cylindrical steady-state flame model. It was assumed that the initial direction of movement of the flame gases was parallel to the vertical axis. By applying a momentum balance to the buoyant flame "cylinder" in the direction perpendicular to the cylinder axis (positive upward), equations were derived which gave the angle of tilt θ in terms of the wind speed, flame diameter D, and the flame buoyancy. Buoyancy was represented by the term $1-\rho_f/\rho_a$, in which ρ_f is the density of the flame gases and ρ_a the density of the environmental air. After neglecting the initial momentum of the gas fuel and introducing a shape factor f, the general equation for θ becomes

$$\theta=\tan^{-1}\left\{\frac{C_f u^2}{2f(1-\rho_f/\rho_a)Dg}\right\}, \tag{3}$$

where u is the wind speed, g the acceleration due to gravity, and C_f the drag coefficient for the flame model. For the cylindrical model the shape factor f is $\pi/4$. For flames having the shapes of a cone, pyramid and parallelepiped, the values of f are $\pi/6$, $\frac{2}{3}$, and 1, respectively.

To correlate it with the experimental results, Eq. (3) was expressed in terms of the drag coefficient C_f which for $f=\pi/4$ gives

$$C_f=(\pi/2u^2)(1-\rho_f/\rho_a)Dg \tan \theta. \tag{4}$$

It was found that C_f dropped rapidly with increasing values of the Reynolds number Re which was taken as Du/ν_a where ν_a is the kinematic viscosity of the surrounding air. C_f also showed a marked dependence on the flame diameter D and a significant dependence on the angle of flame tilt θ. A good correlation of C_f with the experimental data was obtained with an empirical expression for a flame roughness factor which was a function of D.

The buoyancy term in Eq. (1) was determined from the equation

$$\rho_f/\rho_a=KT_a(L/D)^{\frac{1}{4}}(1-e^{-\alpha D})^{\frac{1}{4}} \tag{5}$$

in which K is a dimensionless constant, T_a the temperature of the surrounding air, and α the radiation absorption coefficient in the flame zone.

Since the work described in this paper is in a relatively new field and since the authors' over-all study is not yet complete, there are several questions which arise from the present investigations. One question concerns the flow of hot gas and air in and near the flame zone just above the floor of the wind tunnel. This surface boundary should have a pronounced effect on the flow in the lower part of the flame zone. The authors do not discuss this point but one of their photographs indicates that the elevation of the gas fuel source above the floor of the wind tunnel is an appreciable fraction of the flame length. If so, then the structure of the lower part of the flame zone might be considerably different than for a source in the surface plane—especially if the velocity of the gas fuel is low.

If the shape factor f is placed equal to $\frac{2}{3}$, Eq. (3) gives the angle that the tethering line (thin and weightless) of a tethered spherical balloon would make with the vertical. In this case, however, the drag coefficient C_f should be nearly constant throughout a wide range of values of the Reynolds number. Thus the resistance to wind flow for a volume enclosed by an impermeable surface may be quite different than for a buoyant gas plume. The dependence of C_f on Re and D when Eqs. (3) or (4) are applied to a buoyant flame indicates that the relationship between θ and the dependent variables may be more involved than Eq. (3) indicates. Some of the variation in C_f could possibly come from the buoyancy term $1-\rho_f/\rho_a$. Perhaps this term could be expressed more effectively in terms of the rate of convective heat output than the variables of Eq. (5).

Subject Headings: ***Wind, effect on flame; Flame, diffusion, wind effect on; Fire, pool, effect of wind on; Radiation heating, fire spread by; Radiation heating, by tilted flame; Fire spread, by radiant heating, model of; Wind, effect, on diffusion flame; Wind tunnel, for flame spread studies; Experimental techniques, wind tunnel for flame studies; Convection, of diffusion flame.***

G. M. Byram

V. Combustion Principles

à Donau Szpindler, G. (Division of Coal Research, C.S.I.R.O., Chatswood, Australia) "An Investigation of the Mechanism of Combustion of Solid Fuels in Thin Beds by the Sectioning Method," *Miscellaneous Report 248 of the Division of Coal Research, C.S.I.R.O.* (February 1964)

This report describes studies of the behavior of coal in the bed of an underfeed pot furnace made up of 10 to 12 cast-iron rings 1 in. thick by 12 in. internal diameter, fitting tightly into each other so as to form a cylinder of the required height. Four fuels were selected so as to cover a wide range of volatile-matter content: high-temperature coke, low-volatile coal, high-volatile coal, and brown coal. Each fuel was tested at three different rates of primary air flow and the air rate was kept constant throughout a test except for the period of initial (surface) ignition.

The air-dried fuel was charged into the pot to form a bed approximately 6 in. depth. After an ignition period and at a predetermined time the air supply was cut off, the top ring lifted slightly with a long pair of tongs, and a wide tray inserted underneath and pushed carefully through the fuel bed, thus separating a layer of the bed. Between 2 and 4 min. were required to section the whole fuel bed, the fuel in each layer being transferred to a cooled, sealed container. Each section was weighed and examined visually, attention being paid to incipient sintering or clinkering. Chemical analyses of the sections were then carried out by standard methods.

Test results are presented in 17 figures. It is concluded that for any given fuel, at a specified air-flow rate, the rate of evolution of volatile matter from the fuel bed is constant. In the time taken by the ignition plane to transverse a 1 in. layer of the bed, 85 to 100 per cent of the volatile matter in this layer is evolved.

At air flow rates of less than 220–250 lb/sq ft/hr the presence of volatile matter has the effect of reducing the rate of consumption of fixed carbon during the ignition state. At higher air rates in both combustion stages, fixed carbon burns at a fairly constant rate which is independent of volatile matter yield.

With the exception of brown coal, at low air rates the fuel bed at the end of the ignition stage was of uniform composition throughout its entire depth.

Ash begins to fuse in those parts of the bed where temperatures exceed the ash-fusion points as determined by standard laboratory methods. Incipient fusion occurs long before the carbon in the fuel particles has burnt out.

Subject Headings: ***Coal, combustion, in thin beds; Combustion, of coal, in thin beds.***

R. Long

Kaesche-Krischer, B. (Bundesanstalt für Materialprüfung, Berlin-Dahlem, Germany) "The Rate of Flame Propagation and the Composition of Mechanism of Chlorinated Hydrocarbons," *Chemie-Ingenieur Technik* 35, 856–860 (1963)

A detailed study of the combustibilities of mono-, di-, and tri- chloromethanes was initiated after an explosion had occurred in an oxygen line subsequent to its cleaning with trichloroethylene. The principal purpose of the investigation was to determine the effect of hydrogen substitution in the chloromethanes upon the differences in rates of combustion and range of flame stabilities.

The $O_2/N_2/CH_xCl_y$ mixtures were made up in a flowing mixing chamber. Gas flow was measured by calibrated flowmeters. The O_2/N_2 mixture was passed over a thermostatically-controlled saturator containing the fuel. The values of the relative gas flows and fuel vapor pressures facilitated the final calculation of the fuel concentration for each mixture. A secondary check was made upon this value by freezing out the halomethanes and measuring the effluent gas flow.

The apparatus consisted of a combustion tube 1 meter long and 1 inch in diameter, with an exchangeable quartz tip at one end. The diameter of the latter varied from 4 to 20 mm. The flame was ignited in a collimating tube situated between two quartz windows. The measurement of the flame speed can be obtained by knowing the ratio between volume gas flow and flame surface area. The schlieren photos were retained using a high-pressure mercury arc light source placed between two horizontal schlieren screens and two spherical mirrors oriented in the z-plane. The normal photos of the flames were obtained without any interfering optics. Evaluation of the schlieren photos gave the limiting area of the exterior surface of the flame kernel. The conical surface area was determined by graphical integration.

$CH_3Cl/O_2/N_2$ flame fronts appear quite unlike that of $CH_4/O_2/N_2$ flames. Lean mixtures are bluish in color, rich mixtures are green. Marked distortions occur in the flame front. This seems to indicate that the stabilization of the undulatory burning surface of the kernel may be effected by the selective diffusion of all of the species present. CH_3Cl itself has a diffusion coefficient greatly lower than CH_4.

A graph of flame speed vs fuel/O_2+N_2 ratio indicates that the maximum flame speed occurs near the stoichiometric fuel/O_2+N_2 ratio. As the $O_2/(O_2+N_2)$ ratio is increased from 21 per cent to 100 per cent the maximum V shifts to leaner fuel/O_2+N_2 ratios. At 21 per cent O_2(normal air) the maximum is at 1.1 fuel/O_2+N_2; at 100 per cent O_2 it is at 0.9 fuel/O_2+N_2. A small effect in the shifting of the maximum flame speed also occurs with CH_4 as the O_2 content is varied. The absolute flame speeds of CH_4 are higher than those for CH_3Cl.

The CH_2Cl_2 flame burns in two reaction zones; one diffuse, the other sharp. The diffuse front was rounded while the sharp zone indicated two sharp peaks. The exhaust gases from the first front appear to cause the pale green coloration in the second kernel. The appearance of the second flame front does not depend upon the unburnt gas content but upon the flow conditions. Stability of the second burning zone is apparently a function of tube diameter also. The flame speeds of the $CH_2Cl_2/O_2/N_2$ flames are only valid when reference is made to the combustion occurring in the first flame front. The maximum flame speeds occur at fuel/O_2+N_2 of 1.5. The existence of much more Cl_2 than HCl was observed downstream of the reaction zone. The over-all combustion mechanism is broken up as follows:

Flame 1. $CH_2Cl_2+O_2 \rightarrow CO_2+Cl_2+H$

Flame 2. $CO_2+Cl_2+H_2 \rightarrow CO_2+2\,HCl$

The relatively higher temperature of the first (Flame 2) zone indicates this is where the Cl_2 dissociates. Visual inspection of the flame shows that the exhaust gases from Flame 1 have the pale green color of Cl_2.

$CHCl_3$ will burn only in pure O_2. The flames fluctuate and are hard to stabilize. The flame front is relatively thick and has the appearance of two closely coupled fronts. The second zone is thin and very diffuse and it is not at all certain whether the second front is truly independent of the first. Good photographs are not obtained due to the fluctuating nature of the flame; consequently, the flame speed is only estimated (5–10 cm sec).

CCl_4 does not exhibit any stable flames at atmospheric pressure. Other workers have ignited a flame at higher pressures.

The plot of flame speed (V) vs inert gas concentration shows the influence of successive halogen substitution in CH_4. Replacement of one H with Cl in CH_4 results in a drop of the maximum flame speed to about $\frac{1}{3}$ of the CH_4 value. The slope of the linear portion of the curve also drops markedly. The maximum V in the linear portion of the curve for CH_4 is 6.8 cm/sec. For $CHCl_3$ V_{max} is 2.7 cm/sec, for CH_3Cl V_{max} is 0.8 cm/sec. The latter is for pure O_2 mixtures. The combustion enthalpy drops with addition of Cl to the molecule. The result is a decrease in flame temperatures with consequent lowering of flame speeds. A comparison of the flame speeds was made of mixtures of $CH_4/2\,O_2/7.56\,N_2$ and $CH_3Cl/1.5\,O_2/5.66\,N_2$. The flame temperatures are calculated as 1950° and 1980°C, respectively, although the relative enthalpies are quite different, —192 kcal (CH_4 mixture) and —154 kcal (CH_3Cl mixture). The flame speeds are 40 cm/sec (CH_4) and 11 cm/sec (CH_3Cl). Thus an explanation for these large differences in flame speed must be sought elsewhere. Addition of a trace of Cl_2 to CH_4–air flames does not lower the enthalpy of the mixture very much while the flame speed is reduced considerably. One can attribute this to the inhibitory effect the Cl atom has in the propagation of the radical chain reaction. It is not possible to evaluate quantitatively the connection between all the kinetic parameters and the vast variations in flame speed. The N_2 content of the mixtures does, however, greatly influence the value of the maximum flame temperature. The calculation of the flame temperature for $CH_xH_y/O_2/N_2$ mixtures in general is difficult on account of the large number of equilibria present in the downstream side of the luminous reaction zones.

The high halogen-containing mixtures such as $CH_2Cl_2/O_2/N_2$ have a tendency to form two flame zones, as noted earlier. This can be explained by the fact that the over-all combustion reaction must pass through an intermediate product such that, after a definite induction period, the initial reaction results in a separation of burning fronts at certain gas velocities.

The build-up of intermediate products between the reaction zones is accomplished in a finite time (several milliseconds). The residence time at certain gas velocities is long enough to effect this result. At higher gas velocities the residence time is not long enough to permit this build-up of intermediates. The intermediate reacts in an exothermic reaction supported by the second burning front. It is frequently observed that the reaction products at the upstream edge of the luminous or reaction zone are not in thermodynamic equilibrium. The intermediate products react in the burnt gases until a parallel equilibrium state is established. This is not clearly the case in flames with two flame fronts since they must interact with each other so that the downstream reactions of the intermediates must be exothermic and the flame speeds of both partial reactions must not be too different, since they are dependent upon each other. Once the intermediate products have been identified it is possible to say something of the reaction mechanism. In the case of trichloroethylene (C_2HCl_3) it was suspected that the intermediate was Cl_2O. The characteristic brownish color was seen to occur on the upstream edge of the lower flame zone but not within the second front. Thus it is believed that a breakdown product of Cl_2O is actually the active species within the second flame zone. A postulated mechanism would be:

Flame 1. $C_2HCl_3+O_2 \rightarrow CO_2+HCl+CO+Cl_2O$

Flame 2. $(CO+Cl_2O)^* \rightarrow CO_2+Cl_2$

Similarly, the same type of reaction should occur in $CH_2 \cdot Cl_2$ flames. The only corollary is the burning of an explosive mixture of Cl_2 and H_2 within the second flame front of the CH_2Cl_2 flame. The active complex present downstream of the front flame is then possibly one made up of Cl_2 and H_2.

On the surface the CH_3Cl flame does not materially appear different from that of CH_4 except for a 67 per cent reduction in observed flame speed. The influence of H atoms and intermediate species acting as radical scavengers is again demonstrated. $CHCl_3$ can burn only in pure O_2 since the inhibitory effect is so dominant in reducing the flame speed. CCl_4 is not combustible with pure O_2 even at normal conditions.

Subject Headings: *Hydrocarbons, chlorinated, flame propagation rates of; Hydrocarbons, chlorinated, mechanism of; Combustion products, of chlorinated hydrocarbon flames with oxygen; Flame speed, of chlorinated hydrocarbons with oxygen.*

P. Breisacher

Miyama, H. and Takeyama, T. "Kinetics of Methane Oxidation in Shock Waves," *Bulletin of the Chemical Society of Japan* **38,** 37–43 (1965)

The mechanism of methane oxidation in reflected shock waves was studied over the temperature range 870° to 2100°K by using spectrometric method and single pulse technique.

In the case of a methane-rich mixture with the ratio $[CH_4]/[O_2]=6$, the gas chromatographic analysis of reaction products revealed that methane is consumed by a second-order reaction with activation energy of 50.9 ± 5.3 kcal/mol. The reaction, $CH_4+O_2=CH_3+HO_2$, was considered to be responsible for this.

For a methane-lean mixture with the ratio $[CH_4]/[O_2]=\frac{3}{7}$, the induction period for the appearance of OH was measured by the spectroscopic observation of ultraviolet absorption at 3067 Å, together with pressure measurement by a quartz pressure transducer. Both the induction period τ for OH absorption and the pressure increase were found to be dependent upon the concentration of oxygen: the plots of $\log \tau[O_2]$ vs $(1/T)$ gave fairly straight lines with activation energies of 21.5 and 33.8 kcal/mol, respectively. From this, the authors proposed that the rate-determining step for OH formation is $CH_3+O_2=CH_2O+OH$, while that for the over-all reaction is $CH_2O+O_2=HCO+HO_2$.

For an intermediate mixture with the ratio $[CH_4]/[O_2]=1.5$, it was found that the induction period for OH appearance was almost identical with that for pressure increase, that it was dependent on the product of both concentration of oxygen and methane and that the activation energy required was 49.5 ± 2.3 kcal/mol. The reaction $CH_4+O_2=CH_3+HO_2$ was considered to be the rate-determining step for the formation of OH and over-all reaction.

Experiments were also carried out for mixtures of methane and oxygen without diluting with excess argon, and it was found that both the methane-rich mixtures and methane-lean mixtures were not suitable for investigation, for several reasons. The authors discuss this in some detail.

Subject Headings: ***Combustion mechanism, of methane; Methane, combustion mechanism for; Shock tube, studies of methane combustion.***

T. Kinbara

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de Socte, G. (French Institute of Petroleum, Paris, France) "Application of Vibrating Flames to the Study of Turbulent Flames," *Revue de Instut du Petrole et Annales du Liquids Combustibles* **19,** 766–785 (1964)

This paper presents a careful study of vibrating flames with the objective of increased understanding of turbulent flames. The vibrating flames are studied experimentally in two ways:

1. The flow of air-propane mixture is modulated by a loud speaker placed at the bottom of a burner;
2. The flow rate of the mixture is perfectly steady, but the flame is vibrated by a flame holder which is made of one or two wires. In both cases, the author uses the technique of stroboscopic photography for taking pictures of flame shapes and particle tracks, and a hot wire probe for determining velocity.

By assuming that the density of the medium is constant and the sinusoidal fluctuation is true everywhere, the local mean velocity of flow has been deduced for both cases. It is found that, for the first case, the amplitude of perturbation decreases rapidly as the flow leaves the burner, and the phase difference between the local velocity and the velocity at the outlet of the burner is a function of space; for the second case, the diagram of constant velocity lines shows that the flow is no longer sensitive to the flame holder, whether it is vibrating or not, as soon as its normal distance from the vibrating plane of the flame holder is greater than 5 mm.

The local and the mean normal rate of propagation of the flame front relative to the cold gas are calculated by using the vector sum of the flow velocity and the instantaneous velocity of the flame front. The parameters in the equations are determined experimentally. The results show that the normal rate of propagation is a function of space and time for both cases.

It is interesting to notice that the shape of the flame for the first case is usually conical with a surface wave propagating from the bottom toward the tip of flame, but if the frequency of the vibration is sufficiently high (>1000 cps), the shape of flame changes entirely. It forms a spherical cap with the concave side downward and the surface wave disappears. According to the author's estimation, this checks with Kovaznay's criteria.[1]

From the study of the vibrating flames, the author concludes that: (1) The normal rate of propagation is fluctuated by the flow velocity fluctuations. The local normal rate of propagation of the turbulent flame may be very high due to the fluctuation of the local flow velocity. (2) The normal rate of propagation of the turbulent flame is higher than that of the laminar flow because the fluctuation of velocity takes time to diminish; the remaining vibration is added to the current vibration at every instant. Thus, the normal rate of propagation increases.

Reference

1. Kovaznay, L., *Jet Propulsion 26*, 485 (1956).

Subject Headings: ***Flame, vibrating, application to turbulent flame; Flame, turbulent.***

S. J. Ying

VII. Suppression of Combustion

Fenimore, C. P. and Jones, G. W. (General Electric Research Laboratory, Schenectady, New York) "Phosphorus in the Burnt Gas from Fuel-Rich Hydrogen-Oxygen Flames," *Combustion and Flame* **8**, 133–137 (1964)

This report, while primarily concerned with flame radiation, has some interesting observations on the pressure dependence of chemical flame inhibition by a phosphorous compound. Trimethyl phosphate, used in these experiments, is a good flame inhibitor, 0.26 per cent being equivalent to 0.70 per cent bromine. (These amounts reduce the flame speed of a stoichiometric *n*-hexane-air flame by 30 per cent.[1]) Although Fenimore and Jones did not measure flame speeds, the usual indicator of flame inhibition, they could infer inhibition efficiency from the more subtle influence of the inhibitor on flame structure and kinetics. Previous studies have shown that the effect of chemical inhibitors on flames is a reduction in the concentration of radicals and an increase in the reaction temperature required for combustion at the same flow rate. For a H_2–O_2–Ar flame burning at atmospheric pressure, the addition of 0.00, 0.11, and 0.40 per cent trimethyl phosphate gave 0.22, 0.15, and 0.09 per cent hydrogen atoms, as measured by the D_2O technique. The final flame temperatures were 1362°, 1500°, and 1530°K, respectively. This decrease in hydrogen atom concentration and increase in flame temperature indicates that chemical inhibition is taking place.

However, flames burnt at low pressures were not inhibited by 0.1 per cent of trimethyl phosphate. Low pressure flames have much higher radical concentrations, for example the burnt gas from a 5 cm Hg flame (0.066 atm) contained 7 per cent hydrogen atoms. The authors suggest that inhibition may occur only when the inhibitor concentration is of the same order of magnitude or larger than the hydrogen atom concentration. In the case of the atmospheric pressure flames both inhibitor and hydrogen atom concentration were at the level of a few tenths of a per cent. In the reduced pressure flames the inhibitor concentration was only a few per cent of the hydrogen atom concentration. In support of their hypothesis the authors found that atmospheric flames were not inhibited by trimethyl phosphate when the concentration of the additive was appreciably less than the hydrogen atom concentration.

The intensity of the green bands observed from rich H_2–O_2 flames containing phosphorous were shown to be proportional to

$$[P]^{0.4\pm0.1}\{[H]^2[H_2O]^{0.5\pm0.5}/[H_2]^{1.0\pm0.5}\}\ \exp\{-(5\pm5)\ \mathrm{kcal}/RT\}.$$

The authors suggest that the emitter is HPO, with intensity proportional to [H][PO] or [H][P], and that most of the phosphorous is in the form of P_2.

Reference

1. Lask, G. and Wagner, H. Gg., *Eighth Symposium (International) on Combustion*, The Williams and Wilkins Co., Baltimore, 1962, pp. 432–438.

Subject Headings: *Inhibition, pressure effect, by trimethyl phosphate; Flame, inhibition pressure effect, by trimethyl phosphate; Phosphorous compounds, inhibition, by trimethyl phosphate.*

W. E. Wilson

Fenimore, C. P. and Jones, G. W. (General Electric Research Laboratory, Schenectady, New York) "Decomposition of Sulfur Hexafluoride in Flames by Reaction with Hydrogen Atoms," *Combustion and Flame* **8**, 231–234 (1964)

This is another in a series of kinetic studies of the reaction of flame inhibiting chemicals with radicals important in flame propagation. A low pressure flame was used to provide a known concentration of radicals at a high temperature. In this study small amounts of sulfur hexafluoride (SF_6) were added to low pressure flames of H_2–O_2–Ar, C_2H_2–O_2–Ar, and H_2–N_2–O–Ar. The rate of reaction of SF_6 was measured by the now standard techniques used to determine flame structure. Samples are taken through a quartz probe, the reaction quenched by the rapid decrease in pressure and temperature, and the composition determined by mass spectroscopy. Temperature is measured by quartz-coated thermocouples. After making corrections for diffusion, the net reaction rates of the stable species may be calculated. The hydrogen atom concentration is estimated by combining the known rate constants of reactions involving hydrogen atoms with the reaction rates measured in the flame. In this study three reaction rates were used. (1) D_2O was added, the rate of formation of HD measured and used with the rate constant for $H+D_2O \rightarrow HD+OH$. (2) The heat release rate was measured and used with a rate constant, measured in H_2–O_2 flames of $R=1.1\times10^{22}[H][O_2][H_2O]$ cal cm^{-3} sec^{-1}. (3) The rate of disappearance of N_2O was measured and used with the rate constant for $N_2O+H \rightarrow N_2+OH$. Although more accurate measurements of hydrogen atoms are needed (Fenimore and Jones suggest relative errors of ±30% and assume a constant concentration throughout the flame), these estimates are the best available at this time and furnish useful kinetic constants.

The rate of disappearance of SF_6 was consistent with a decomposition controlled by the process $H+SF_6 \rightarrow HF+SF_5$, with a rate constant of $k=2\times10^{15}\exp(-30\pm5)$ kcal/RT cm^3 $mole^{-1}$ sec^{-1}. The subsequent reactions are unknown. The pre-exponential factor is large but not impossible; it equals the collision frequency at 1500°K.

Sulfur hexafluoride is of interest both because it is an inhibitor of rich hydrogen flames and because electrical equipment is sometimes filled with SF_6 to prevent arcing. Although thermodynamically a good oxidizer ($SF_6+4\ H_2 \rightarrow 6\ HF+H_2O$, $\Delta H=-128$ kcal/mole, theoretical flame temperature >2000°K) attempts to establish flames of H_2–SF_6 and C_2H_2–SF_6 were unsuccessful. The reaction rate of H with SF_6 is only 1/30 of that of H with O_2 and N_2O at $\approx$ 1300°K. However, it increases to 1/6 at 1900°K. Although this indicates a higher activation energy for the reaction of H with SF_6 than with O_2 or N_2O, the difference in reactivity does not seem a sufficient reason for the nonflammability of H_2–SF_6. Arguments are advanced to explain both the inability of SF_6 to act as an oxidizer and support a flame and its ability to inhibit a flame in terms of the lack of regeneration of H atoms. Consider the following reactions: $H+O_2 \rightarrow OH+O$, a chain branching reaction with an increase in radicals; $H+N_2O \rightarrow N_2+OH$, a chain reaction in which radicals are conserved; $H+SF_6 \rightarrow HF+SF_5$, if SF_5 is considered relatively inert this reaction removes radicals. Therefore, SF_6 can act as a flame inhibitor by reducing the concentration of free radicals and will not support a flame since flames generally require chain or chain branching reactions.

Subject Headings: *Inhibition, by sulfur hexafluoride, kinetics of; Flame, lack of, with sulfur hexafluoride, as oxidizer; Flame, inhibition, by sulfur hexafluoride, kinetics of.*

W. E. Wilson

Fish, A. (Imperial College, London, England) "Inhibition of Combustion by Bromine-Containing Additives," *Combustion and Flame* **8**, 84–85 (1964) Letters to the Editors.

The addition of HBr to hydrocarbon–air flame systems is known to inhibit or retard the flame temperatures, flame speeds, and flammability limits of such burning mixtures. Some controversy has existed as to the exact nature of the chief chain arrestor present in the hydrocarbon-air-inhibitor mixture.

Specifically, the addition of hydrogen bromide to a methane–air mixture shows the HBr is responsible for the level of the OH radical concentration which in turn regulates the extent of the important chain branching reaction.

$$\cdot OH + CH_2O \rightarrow \cdot CHO + H_2O \qquad (1)$$

Hydrogen bromide reacts with OH radicals according to

$$\cdot OH + HBr \rightarrow H_2O + Br\cdot, \qquad (2)$$

while the Br radical produced reacts with CH_4

$$\cdot Br + CH_4 \rightarrow HBr + \cdot CH_3. \qquad (3)$$

The normal course of hydroxyl radical annihilation is

$$\cdot OH + CH_4 \rightarrow CH_3\cdot + H_2O. \qquad (4)$$

By comparing the relative rates of reactions (1) and (4) with and without HBr addition we find that the addition of HBr to the reaction mixture actually reduces the percentage of the OH radicals taking part in the chain branching reaction (1) by 20 per cent. The comparison is made at 783°K. The effect of reactions (2) and (3) is to increase the rate of linear chain producing CH_3 radicals while reducing the chain branching effect due to reaction (1).

To be noted is the fact that reaction (4) is really identical in net effect to that of reaction (3) followed by reaction (2). Despite this fact the author has attempted to show that the percentage of OH radicals present in the gas mixture which actually take part in reaction (1) determine the over-all inhibitory effects due to HBr or any other halogenated material added to a hydrocarbon-oxygen flame system.

Subject Headings: *Bromine compounds, influence on combustion; Flame, inhibition, by bromine compounds; Inhibition, of flame, by bromine compounds.*

P. Breisacher

VIII. Model Studies and Scaling Laws

Eggleston, L. A., Ambrose, J. E., Bradshaw, W. W., and Yuill, C. H. (Southwest Research Institute, San Antonio, Texas) "The Development of Models for Use in the Investigation of Fire Spread," *Final Report SwRI Project No. 03–1212—DASA 1561 NWER Subtask 12.024* (November 2, 1964)

There are obvious advantages to the establishment of significant coherent factors relating fire behavior in unit structures to mass fire spread. One of the techniques employed and developed by the authors is the use of small-scale combustible models in controlled tests to ascertain the ignition and burning characteristics of various building types. In addition, these researchers designed and built a nondestructible (electronic) fire simulator. Calibrated by combustion data, this electronic device holds great promise as a convenient and rapid tool for fire research.

Regarding the combustible models, the investigators found excellent scaling correlations, for still air conditions, between their 3 to 12 inch cube hardboard models and actual buildings (based on weight loss and flame height). A lower model size limit (on the order of a one inch cube or less) and the effects of environment and geography among other things still have to be determined.

A miniature (less than 0.2 cubic inch) economical and rugged electronic simulator model resulted from this project; more than half the report describes this development. Through programmed input, trigger and outputs circuits, the simulator responds to radiant and convective heat transfer input data derived from combustion tests and in a manner controlled by the initial module arrangement permits visual tracing of mass fire progress. Enough data are currently available to generate a "rough program" for fire spread studies.

This effort undoubtedly represents a milestone in miniature modeling of so complex a process as mass conflagrations. However, a great deal more research is needed (and for less idealized situations than tackled by this reported project) to reveal whether the full potential of this concept can ever be realized. The authors readily acknowledge this point by recommending an extensive program of future work.

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

K. M. Foreman

Grinberg, I. M. and Putnam, A. A. (Battelle Memorial Institute, Columbus, Ohio) "A Model Study of the Interaction Effects of Mass Fires," *Summary Report No. 3 for OCD Project Order OCD-OS-62-89 through NBS Contract CST-1104* (September 28, 1964)

This is a report of the third phase of a continuing study in which the behavior of mass fires is being modeled by gaseous diffusion flames in which the fuel burning rate is controlled by the experimenter rather than by heat flux from the flame back to the fuel, as in the case with liquid and solid fuels. Previously reported phases of this work[1,2] considered arrays of sources, effect of cross winds and influence of source spacing and other fuel parameters on flame configuration. The present report reverts back to a study of single source, turbulent diffusion, buoyancy-controlled flames. The general objective was to develop a technique whereby the laboratory observations of flames of one fuel could be applied to large fire masses in which other fuels are consumed. The experimental program was designed so that effects of adiabatic flame temperature, stoichiometric air–fuel ratio, and fuel density could be varied independently to determine their effects on flame characteristics.

Theoretical analyses of flame behavior were based on two different approaches. First consideration was given to the classical theory of buoyant turbulent plumes, as derived by Spalding, based on the assumption that the gases in the plume differ little in density from the ambient atmosphere. Because this assumption of small densities is critical, resulting in possible poor correlation at high temperatures, a second modeling-type approach based on similarity principles was also followed. This similarity solution assumes that the ratio of buoyancy force to turbulent shear force is constant.

During the experiment it was necessary for the flames to be both buoyancy-controlled and turbulent. This required that the operating range of gas flow velocity as a function of nozzle diameter be controlled between definite limits. The lower limit of flow velocity was determined by the Reynolds number, which was large enough to ensure turbulence, while the upper limit was controlled on the basis of the Froude number, which was adjusted so that the flame was buoyancy-controlled. The limitations of the Froude number and Reynolds number criteria are discussed, but it is concluded that they are adequate for the purpose of this study.

Experimentally, flame characteristics as depicted by temperature profiles were determined as a function of fuel density, air-fuel ratio, adiabatic flame temperature, and fuel flow rate. Considerable ingenuity was demonstrated in the successful attempts to maintain three of these parameters substantially constant while the fourth was being varied. The technique involved appropriate dilution of the fuel with air, oxygen, or nitrogen as necessary. A factorial design, which was not attempted, would probably have supplied information on the interaction effects of the parameters with a concomitant simplification of the experimental procedures.

It was found that fuel density had no appreciable effect on the temperature profile when the other parameters were held constant. This confirms the theoretical results predicted by both the similarity theory and the theory based on small density differences. Similarity theory, however, seems to be confirmed by the slope of the decreasing temperature portion of the curve in a more satisfactory manner than the other theory. The results obtained by varying the stoichiometric air-fuel ratio are displayed in a set of temperature profile curves which fall quite close together, indicating rather negligible effects of this parameter as well. When adiabatic flame temperature was varied, the curves are together on the decreasing temperature side but the flame corresponding to the lower adiabatic flame temperture, produced by the addition of nitrogen, has a lower temperature profile and maximum temperature level than do the other fuel compositions.

Finally, curves are presented which show the correlation of the data with both similarity theory and the theory based on small density differences. The correlation predicts a more rapid decrease in temperature after combustion is complete than do previously developed theories and is more accurate at higher temperature levels than are previously used correlations. It is therefore concluded that the expression based on similarity theory can more accurately predict the temperature profile of a turbulent buoyant plume.

The discussion of results is followed by a number of recommendations for further research. These indicate that, despite the start that has been made here, the state of the art of modeling fire masses, or even the combustion region of a turbulent diffusion buoyancy-controlled flame is far from satisfactory.

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Subject Headings: ***Model, turbulent diffusion, buoyancy-controlled flame.***

A. Strasser

Thomas, P. H., Hinkley, P. L., Theobald, C. R., and Simms, D. L. (Joint Fire Research Organization, Boreham Wood, England) "Investigations into the Flow of Hot Gases in Roof Venting," *Joint Fire Research Organization Fire Research Technical Paper No. 7* (1963)

This report presents the results of a comprehensive analysis, including both theoretical and experimental results, of the use of roof vents to exhaust the smoke and hot gases resulting from fires in large single-story buildings. This approach provides very useful results since suitably designed vents can eliminate the commonly encountered difficulties in locating and extinguishing fires in such structures. An imaginative hydrodynamic analog has been employed to illustrate the flow patterns by using colored water (hot gases) flowing through a brine solution (normal atmosphere), the density difference between the two fluids producing the equivalent of the thermal convection. Model experiments using a gas burner to provide the appropriate heat input gave results in good agreement with the theoretical predictions. A series of equations and monograms are presented for use in designing practical roof vents.

The consequences of scale changes between the model and actual fire are considered and it is shown that the energy input must vary as $L^{\frac{5}{2}}$ if the temperature is to be the same on all scales. Similar arguments lead to the conclusion that events happen more quickly in the models and the time scales as $L^{\frac{1}{2}}$. In order to verify these predictions experiments were conducted on a 9 cubic foot model of a flat roofed factory bay. The results showed that the model was large enough and sufficiently well insulated so that conduction and radiation effects were negligible and the scaling laws did apply.

Using 21 fan-tail burners as the heat source the primary experimental data on velocity and temperature distributions was obtained for a variety of screen depths and vent sizes for a heat input of 2.1 Btu/sec. Thus, the mass rate of an input to the model, the mass rate of discharge of hot gases beneath the screen, the mass rate of discharge of heat beneath the screen and through the vent were calculated.

Based upon the experimental results a theoretical model is postulated. It is based upon the assumption that a distric layer of hot gases with a uniform temperature exists beneath the ceiling and there is no mixing between this layer and the cool air beneath it. Heat losses to the ceiling and walls are neglected. The depth and temperature of this layer of hot gases thus depends only on the various mass flow rates. The depth of the hot gas layer d_b, can be obtained from the relation

$$C_vA_vd_b^{\frac{1}{2}}+0.67C_nW_s(d_b-d_s)^{\frac{3}{2}}=0.043(r_g+h_c-d_b)^{\frac{5}{2}},$$

where A_v is the vent area, W_s and d_s are the perimeter and depth of the roof screen, h_c is the building height, and C_v and C_n are the discharge coefficients for the vent and inlet. The model presumes that the fire is roughly circular and the plume rising from it behaves as if it originated at an effective point source a distance r_g below the floor. The temperature in the hot gas layer is given by

$$\theta_c/(\theta_c+T_0)^{\frac{2}{3}}=\frac{6.5\mathcal{Q}_f^{\frac{2}{3}}}{(\rho_0C)^{\frac{2}{3}}(gT_0)^{\frac{1}{3}}(r_g+h_c-d_b)^{\frac{5}{3}}}$$

where $\mathcal{Q}_f$ is the convective heat ouput of the source, C is the specific heat. T_0 and ρ_0 are the absolute ambient temperature and density, and θ_c is the temperature above the ambient temperature. Since these equations are difficult to use in practice, nomograms have been made up to facilitate their use. Good agreement with the experimental data was found. It is anticipated that the assumptions used in the theory would apply to any shape model provided that (1) the fire is roughly square or circular, the dimensions are small compared to the height of the building, and the flame does not extend into the layer of hot gases; (2) the relative velocities of the hot and cold layers are small enough to neglect mixing; and (3) the loss of heat to the walls is small enough so that the temperature in the hot layer is at least 200°F above the ambient temperature.

For a large fire the assumption of an equivalent point source is not warranted. An additional set of experiments were run using a compartment enclosed on three sides and a variable depth roof screen. For a fixed vent position and area the roof screen was lowered until the flames were confined within the compartment. The results show that vents near the roof screen are slightly more efficient. If shallow screens are used the vent area is strongly dependent upon the severity of the fire.

The equations and nomograms included in this report provide a quantitative procedure for designing roof venting systems if the anticipated fire size can be estimated. Alternatively, for a given design, the size a fire must attain before the hot gases spill over to adjacent compartments can be calculated. If the rate of fire growth can be determined this second computation will give the time during which the most effective fire fighting action can be initiated.

Subject Headings: ***Model, flow of hot gases in roof venting; Roofs, use of venting.***

T. P. Anderson

IX. Atomization of Liquids

Csanady, G. T. (University of Windsor, Windsor, Ontario, Canada) "Turbulent Diffusion of Heavy Particles in the Atmosphere," *Journal of Atmospheric Sciences* **20**, 201–208 (1963)

This theoretical paper estimates the effect of free fall velocity on the rate of growth of a diffusing cloud of heavy particles. The principal conclusion is that the effective lateral diffusivity may be reduced by as high as a factor of four as compared to the diffusion of a gaseous cloud. This is a consequence of the fact that heavy particles fall out prematurely from larger eddies that would disperse them over larger distances.

The discussion centers about three effects that may play a part in diffusion of heavy particles and their individual contributions to the total phenomenon. These are the inertia effect, the crossing trajectory effect, and the continuity effect.

The inertia effect, due to the fact that the greater inertia of the heavy particle causes it to respond to accelerations more slowly than the fluid particle, is shown to be negligible. That is, the rms velocity difference between a heavy particle and its fluid neighborhood is shown to be negligibly small for particles smaller than about 500 microns provided that the vertical diameter of a typical atmospheric eddy is at least 30 feet.

The crossing trajectory effect, so-called by Yudine,[1] is a consequence of the velocity history of the particle. In this case, the velocity is such that it will fall out from the eddy where it was at an earlier instant and will lose its velocity correlation more rapidly than a fluid particle.

It is shown that the vertical velocity correlation, R_{33}, is approximately an exponential decay curve. By using this exponential form of R_{33} and Taylor's theorem[2] the variance of the dispersion in the vertical is written down and it is shown that at large free-falling speeds both the diffusivity and the variance of vertical dispersion are inversely proportional to the free-falling speed.

The continuity effect arises from a discussion of the dispersion in the lateral and longitudinal directions, where the correlation coefficients are shown to have negative loops. From this it is shown that the asymptotic diffusivity, which is proportional to the integral of the correlation coefficient, is further reduced.

The theoretical results are summarized in a figure which indicates the reduction in asymptotic diffusivity of heavy particles owing to the effect of crossing trajectories and the continuity effect. The author recognizes the necessity of confirming these theoretical results and in a subsequent paper[3] he reports on experiments performed in which the deposition patterns of 100 micron and 200 micron diameter glass particles were compared. The results indicated that in this size range a reduction in lateral spread takes place with increasing size, but the author emphasizes the need for more experimental work.

In these experiments, Csanady found that the maximum cross wind integrated deposition rate occurred at roughly half the calculated distance, where the center of the cloud reaches the ground. The discrepancy was explained by Hage[4] on geometric considerations.

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Subject Headings: *Diffusion, of heavy particles in the atmosphere; Fallout pattern, of heavy particles.*

A. Strasser

Marshall, W. F. and Palmer, H. B. (Pennsylvania State University, University Park, Pennsylvania) **and Seery, D. J.** (United Aircraft Corporation, East Hartford, Connecticut) "Particle Size Effects and Flame Propagation Rate Control in Laminar Coal Dust Flames," *Journal of the Institute of Fuel* **283**, 342–349 (1964)

The authors present the results of an experimental study of the combustion of coal dust in a mixture of N_2 and O_2. Flame stability necessitated the use of oxygen enriched air (28 per cent O_2), but studies of the effect of oxygen content on burning velocity allowed a corrected air-burning velocity to be computed.

The coal dust-gas mixture rose through a tube and was burnt at the top by means of a circular flame stabilizer located 1.5 cm above the tube end. The flame stabilizer was heated before ignition and evidently served as a thermal ignition source as well as a bluff body flame holder. An auxiliary stream of N_2, concentric to the main stream, served to maintain the cylindrical form of the main stream.

Measurements included dust concentration, mass median particle size, flame photographs, oxygen concentration, and coal analysis. The flame speed was determined from the photographs using a visible cone frustrum method.

It was found that above a given dust concentration, which depends on the particle size, the flame speed was very nearly independent of concentration, while for lower concentrations, a decrease in concentration caused a monotonic decrease in flame speed. An attempt was made to correlate the flame speed with particle size, with the authors concluding that the best fit resulted from setting the flame speed proportional to the reciprocal square root of the particle diameter.

Physical arguments were presented to support the contention that the first stage of combustion is the burning of volatile matter, and that the combustion rate in the inner cone of the flame is controlled by the rate of formation of volatile matter from the coal. A simple thermal model of the flame structure was then used to relate the flame speed to the various flow and chemical parameters. An analysis of this equation was made with regard to the dependence of the parameters on particle radius, and it was concluded that the average rate of release of volatiles per particle is approximately proportional to the square of the particle diameter.

Subject Headings: *Dust, flame propagation in; Coal dust, flames of; Flame, propagation, in coal dust, O_2–N_2 mixture.*

T. C. Adamson, Jr.

X. Meteorological Interactions

Ebert, C. H. V. (State University of New York, Buffalo, New York) "The Meteorological Factor in the Hamburg Fire Storm," *Weatherwise* **16,** 70–75 (1963)

As a result of the Allied air offensive against Hamburg during the night of 27–28 July 1943 a unique combination of factors led to a severe fire storm. Contributing to the cause was the high density of buildings, narrow streets, and high bomb saturation. However, the major factor was the unique meteorological conditions prevailing at the time.

The weather conditions included abnormally high temperatures at ground level partially due to a blanket of smoke from preceding bombing raids which absorbed excessive amounts of solar energy and reduced radiation loss at night. Ground temperatures were 86° to 102°F but of more significance was that the temperature dropped rapidly with altitude. One measurement made that afternoon showed a lapse rate of 4.8°F per 1000 ft up to 12,000 ft altitude. Since this lapse rate was considerably higher than the normal adiabatic rate the climatic condition was very unstable. The prevailing ground wind at the start of the raid was 0 to 8 miles per hour.

Because of these atmospheric conditions (which are described in the paper in considerable detail) a severe fire storm developed. The core of the fire was 4.5 square miles. A convectional system developed which produced fast-growing cumulonimbus clouds to 30,000 ft and a vortex ground wind or cyclone. Wind velocities of over 112 miles per hour were witnessed in the narrower streets. The high convective velocities caused intense burning because of the continuous supply of oxygen and caused complete burn-out of all combustible material in the core area.

It was concluded that the fire storm was generated by the unstable atmosphere in which the convective rise of hot gases from the fire led to a vertical flue effect. The vertical draft induced hurricane-like high ground winds with a counterclockwise vortex pattern. The resulting fire damage was extremely severe because of these factors.

Subject Heading: *Fire storm, Hamburg, meteorological aspects.*

R. W. Ziemer

Edinger, J. G., Helvey, R. A., and Baumhefner, D. (University of California, Los Angeles, California) "Surface Wind Patterns in the Los Angeles Basin during 'Santa Ana' Conditions," *Part I of Final Report on USFS Research Project No. 2606* (September 1964)

This study supplements an early report prepared for the Office of Civil Defense entitled "Synoptic Weather Types Associated with Critical Fire Weather." The report reviewed here is an example of studies which can be done locally to provide useful fire-weather information.

The purpose of the study is to provide descriptions of the local winds in the Los Angeles Basin during Santa Ana conditions that will be useful to those responsible for fire prevention and control. The study utilized a defense network of weather stations established by Los Angeles County for air pollution control investigations. There were two parts to the study: (1) a general statistical treatment of weather information associated with Santa Ana winds and (2) case studies of specific Santa Ana wind conditions to determine how they vary from the mean wind direction and velocity. As a result of this study (and use of previous knowledge) a rather detailed picture can be assembled showing the prevailing air movement in the Los Angeles Basin area.

The statistical study shows probable wind directions and mean wind speeds for all parts of the basin and for all times of the day. The data represent no real wind situations—only approximations to the real flow. Actual situations should be studied to determine how statistical data compare with specific cases—this is done in the second part of the report.

The report is illustrated with charts and overlays for a visual presentation of some rather complex interactions of wind, temperature, and topographic features. The wind speed and direction charts are superimposed on contour maps of the Los Angeles Basin and surrounding mountains so that the effects of topography are more easily evaluated.

The first series of charts with overlays show the nature of wind direction and wind speed variability about the most frequently observed conditions. These charts show for each station location the frequency of wind direction and velocity for the hours of 5:00 a.m. to 9:00 p.m. The charts show that on any particular Santa Ana day there is (1) a tendency for stronger winds during daylight hours, (2) reversal winds may be present at any given station in the wind shadow of the San Gabriel Mountains, and (3) boundaries of the wind shadow may be roughly determined from the charts.

The evidence of the reversal of wind direction mentioned appears on a map that shows the most frequently observed weather patterns in the protected area near the San Gabriel Mountains. The reversal conditions are due in part to the topographic condition and the thermal circulations from the valley.

The second portion of this study is concerned with detailed wind information for three separate Santa Ana conditions. Situations studied were February 1 and 2, 1956; November 21 and 22, 1957; and November 4, 5, 6, and 7, 1961. The last of these covers the famous Bel-Air fire that destroyed so many homes in the Santa Monica Mountains.

Flow maps were constructed for each hour of the eight days making up the three case studies. Only twelve of the 200 maps constructed are presented in the report but these adequately substantiate most of the more general findings from the statistical study. The sample maps show the familiar features of the mean pattern, the wind shadow effects, and the strong currents on the flanks of the wind shadow.

A deficiency in the study was pointed out by the authors as being the lack of surface wind information on the south-facing slopes of the San Gabriel Mountains. The missing data prevented a more detailed description of wind patterns in an area critical from fire standpoint.

Subject Heading: ***Wind, pattern of, during "Santa Ana" conditions.***

J. H. Dieterich

Saffman, P. G. (King's College, London, England) "The Effect of Wind Shear on Horizontal Spread from an Instantaneous Ground Source," *Royal Meteorological Quarterly Journal* **88**, 382–393 (1962)

Atmospheric turbulence is an extremely complex problem in the absence of a statistically steady state and a large range of scale in atmospheric turbulence. An idealization is possible by considering the spreading of an instantaneous line or point source in a turbulent wind parallel to the ground. The velocities and turbulent transport can be assumed to be functions of height only. Horizontal diffusion in the presence of wind shear suggests two possible configurations.

First, that atmosphere can be considered to have a finite effective height. This would be the case if the material were unable to diffuse above a given height because of an inversion. The solution to this problem is similar to that of lateral diffusion by turbulent transport in a pipe flow as determined by G. I. Taylor. It is found that the horizontal spread is inversely proportional to the vertical transport.

Alternatively, for an unbounded atmosphere, the problem is more complex but solutions can be obtained. The technique used is to investigate integrated forms of the diffusion equation, equations for the moments of the concentration. The main features are described by the first and second moments only. In this case the horizontal dispersion is directly proportional to the vertical transport. From an experimental viewpoint, however, this significant difference in behavior may not be apparent. This consequence is a result of the dependence of the vertical transport on the wind shear.

Subject Heading: *Wind, effect, on horizontal spread.*

T. P. Anderson

Schroeder, M. J., et al. (Pacific Southwest Forest and Range Experiment Station, Berkeley, California) "Synoptic Weather Types Associated with Fire Weather," *Report prepared by the Weather Bureau, U.S. Department of Commerce, and the Forest Service, U.S. Department of Agriculture for the Office of Civil Defense, Office of the Secretary of the Army, Contracts OCD-OS-62-143 and OCD-PS-64-24* (1964)

The purpose of this study was to determine what weather patterns lead to critical fire hazard conditions. The fire load index was used to determine the fire danger due to the weather; this index includes such factors as strong winds, low relative humidity, high temperatures, and lack of rainfall. While it might appear best to apply a standard critical value of the fire index to all parts of the country the result would be that the eastern United States never has a fire hazard while the western United States has a fire hazard virtually all the time. Therefore the level of the fire load index selected to represent high fire danger varied from 17 in the East to 50 in the Southwest.

Over a ten-year period the periods of fire danger were determined at 89 stations from weather records. Then the weather types associated with these critical periods were determined. It was found that most of the periods of high fire danger were related to a relatively few weather types. The critical weather patterns are discussed for fourteen regions of the country. Perhaps the most spectacular demonstration of the relation between fire hazard and the weather is along the California coast. In this region, periods of high fire danger are associated with offshore winds. The most severe of these is the Santa Ana wind in southern California. The San Francisco Fire of 1906, the Berkeley Fire of 1923, and the Bel-Air–Brentwood Fire of 1961 all occurred during this kind of weather. Other correlations between weather and fire hazard are less spectacular but just as important. The authors conclude that "... with the proper consideration given to season, antecedent weather, surface and fuel conditions, and effects of topography, the description of the patterns and types (of weather) provide fire-weather meterologists with a means of anticipating periods of critical fire weather in local areas."

Subject Headings: *Fire weather, patterns; Weather, relative to fire incidence; Wind, Santa Ana and fires; Fire hazards, relative to weather.*

D. L. Turcotte

Thorarinsson, S. (Museum of Natural History, Reykjavik, Iceland) **and Vonnegut, B.** (Arthur D. Little, Inc., Cambridge, Massachusetts) "Whirlwinds Produced by the Eruption of Surtsey Volcano," *Bulletin of the American Meteorological Society* **45**, 440–444 (1964)

This article describes whirlwinds occurring on a grand scale beneath a volcano convective column. Similar vortices have been observed beneath convection columns from large, intense fires, and on a smaller scale beneath convective columns from less intense fires and other sources. Five excellent surface and aerial photographs accompany the article.

The volcanic eruption producing the whirlwinds began 14 November 1963 and was continuing in April 1964. It produced a small new island named Surtsey 33 km off the south coast of Iceland in water 130 m deep. During the eruption, whirlwinds beneath the convection column were the rule rather than the exception, with several often present at once. These took on many forms—inverted cones extending only a short distance below the cloud, long sinuous horizontal vortices that sometimes appeared to curve back up into the cloud, and intense vortices that descended to the ocean surface where they caused vigorous disturbances.

Formation of the vortices depend on the intensity of the eruption, there being none when the volcano was quiet. They were observed to form as close as 100 meters from the crater and as far as a kilometer. No estimate is given of total vortex lengths, except that condensation in the funnel was observed to extend vertically at least 400 m. Wind appeared not to affect number of vortices, though no observations were made in a calm. Direction of rotation was variable, most vortices being cyclonic at one time and anticyclonic at another. The authors suggest direction of rotation may be related to position of the vortex in the cloud and to wind direction.

The authors suggest that before this type of whirlwind can form, the atmosphere must have sufficient angular momentum and an adequate supply of concentrated energy. The angular momentum may arise from mesoscale vorticity present in the area, from the interaction of ambient wind with volcanic cloud and island, and vorticity introduced directly by the eruption. Sources of energy are the falling of the particulate matter ejected, which was not of important density at Surtsey, the electrified volcanic cloud that on occasion produced lightning, and, most important, the thermal and kinetic energies of the intensely hot lava and gases. There appeared to be no appreciable heating of the sea surface where the whirlwinds usually formed. The lava, however, was incandescent and gases were emitted at speeds estimated well in excess of 100 m sec^{-1}. The volcano itself served as a large concentrated heat source that produced convective updrafts and whirlwinds in much the same way as forest fires (Graham),[1] oil fires (Hissong),[2] burning cities (Landsberg),[3] large bonfires (Glaser),[4] large gas jets (Dessens),[5] and the large burners of the thermal experiments of Dessens.[6]

Whirlwind activity appeared proportional to the amount of energy being released by the volcano. The article compares the rate of energy release by the Surtsey volcano with the energy rates of known whirlwind-producing fires. The authors estimate rate of energy release at not less than 2×10^{18} ergs sec^{-1} during the first 10 days when eruption was practically continuous and whirlwinds were most numerous. This rate compares with 5×10^{15} ergs sec^{-1} for a wild gas fire, 7×10^{15} ergs sec^{-1} for Dessens' oil-burning experiments, and 10^{15} ergs sec^{-1} by the Texas A&M University annual bonfires which have produced many small whirlwinds. They computed 4×10^{17} ergs sec^{-1} for the oil fire described by Hissong and estimated 4×10^{17} ergs sec^{-1} km^{-2} for burning forests and cities. These, they suggest, are comparable to the 10^{18} ergs sec^{-1} of thermal energy that Vonnegut[7] has estimated might be produced by lightning in the severe thunderstorms that sometimes produce tornadoes. Although Vonnegut has suggested that electrical energy may be important in the energy budget of some tornadoes and waterspouts, the authors agree this does not appear to be the case at Surtsey, where whirlwinds continued when no lightning had occurred for hours.

Judging by the disturbance at the ocean surface, windspeeds in the vortices were often quite high. Using Ferrel's[8] relationship as reported by Brooks,[9] the authors computed surface winds of 90 m sec^{-1} or higher. Ferrel's relationship suggests that the windspeed at the base of a vortex is equal to the free fall velocity of an object dropped in a vacuum from the height having the same pressure in the environment as that at the ground in the vortex. This requires an estimate of the central pressure in the vortex, or of the difference in pressure between the vortex and the ambient air, or of a height equivalent to this pressure difference. To make this estimate, the authors assume that the visible funnel represents a surface of constant pressure and constant dewpoint to which the air is cooled adiabatically. Hence, the length of the visible column indicates the pressure difference at the base of visible column between ambient air and the vortex center. In applying Ferrel's relationship, this visible column length is the height from which an object dropped in a vacuum would fall to reach a speed equal to windspeed in the vortex. The authors observed "some condensation in the center of the vortex . . . to be at least 400 m in vertical extent" and thereby calculated "wind speed in the vortex . . . of the order of 90 m sec^{-1} or higher." This reviewer cannot vouch for the correctness of Ferrel's relationship nor the assumptions made in applying it. Possibly, the vortex pressure could have been estimated by the cooling required to produce condensation if temperature and dewpoint were known. The pictures show intense disturbance of the sea surface by several of the vortices making the estimate seem reasonable.

The authors raise the question: Would the vortices occur on a calm day? This would mean a vertical convective column. Any whirls might be hidden within the column. But if vortices do occur in the column, this leads to the exciting question:

Do they ever intensify to the extent of involving the entire column as a single vortex? Such large vortices have occurred over fires.

The authors conclude that since the whirls occurred in all kinds of weather, the most important requirement for their formation is a large and intense heat source. Further, since the vortices usually descend into a region supplying no energy, they are mere appendages and not a source of energy for the system.

Though not mentioned in the article, vortex tubes are occasionally seen on a much smaller scale beneath convective columns from sawmill slab-pile fires and debris piles. Curved vortex tubes that re-enter the column may also be seen on the lower side of leaning hot convection columns issuing from large stacks. One must, therefore, assume that the smaller and weaker the convection column, the less intense and less numerous the dependent vortices. Possibly more important to vortex formation than rate of energy release is the ratio of kinetic and potential energy to friction. If so, an intensely erupting volcano surrounded by water provides the most favorable breeding ground for intense and frequent pendant vortices.

It may have been frustrating to the authors not to be able to make supporting observations of such factors as windflow patterns in the lower layers around the convective column, the temperature and actual speeds within the convective column, or even ambient temperature and dewpoint. But near an erupting volcano at 63° north latitude over the open Atlantic in late fall and winter, there was sufficient hazard involved by it's merely being there to make us indebted to the authors for their skilled observations, and to their sponsors.

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Subject Heading: ***Vortex, produced by Surtsey volcano.***

O. P. Cramer

XI. Operational Research Principles Applied to Fire Research

Moysey, E. B. (University of Saskatchewan, Saskatoon, Canada) "Prediction of Space Separation of Farm Buildings Necessary for Fire Control,"* *Paper No. 64-414 Presented at 1964 Annual Meeting of the American Society of Agricultural Engineers, Ft. Collins, Colorado* (June 21–24, 1964)

American and Canadian agencies concerned with fire prevention generally recommend that major farm buildings should be located 100 to 150 feet apart to

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* Also appears in *Fire Technology 1,* 62 (1965).

prevent the spread of fire. However, there is a lack of specific information regarding the spacing of farm buildings for effective fire prevention and spread.

The author ignores the spread of fire by flaming brands in order to simplify the problem and to use the following radiant heat transfer equation for estimates of the space separation required between farm buildings to prevent the spread of fire

$$\mathcal{Q}_1-\mathcal{Q}_2=0.173AFe(T_1^4-T_2^4),$$

in which $\mathcal{Q}$ is the heat transfer rate, A the area, F the shape factor, e the emissivity or absorptivity, and T the absolute temperature.

The author utilizes published literature to obtain reasonable values for use in the above equation. The temperature required for ignition of a material such as wood is not a constant value, but depends on such factors as presence of a pilot flame and the air velocity over the surface. The intensity of radiation necessary to cause ignition is complicated by factors such as the thermal capacity of the material, the convective transfer of volatiles within the solid, the chemical generation of heat by decomposition and the surface cooling. From published data the author concludes that pilot ignition of wood can occur if the radiation intensity exceeds 0.3 cal/cm^2/sec^2, but ignition without a pilot flame will require intensities of the order of 0.7 cal/cm^2/sec^2. The author notes that in only a few cases have temperatures in excess of 1850°F and the corresponding radiation intensity, 3.6 cal/cm^2/sec^2, been observed or measured in burning buildings.

Having established the radiation intensity at the source as 3.6 and the permissible radiation intensity at the receiver as 0.3, the author calculates the shape factor relating the two as 0.08. He uses an emissivity and absorptivity of 1 because a reflective surface exposed to intense heat will likely be darkened.

Table I shows the author's calculated distances of separation required between buildings to prevent ignition by radiation. The table is broken into sections A and B to allow for differences in the type of occupancy. Buildings in group A might

TABLE I

Recommended minimum distances between buildings to prevent the spread of fire due to radiation

Occupancy classification of burning building	Dimensions of burning building seen by adjacent building height of ridge (ft)×length (ft)	Recommended space separation for ordinary construction with windows (ft)
Group A	10×14	40
	10×50	70
	10×100	95
	12×20	50
	20×30	80
	20×50	100
	30×60	135
Group B	10×14	30
	10×50	55
	10×100	75
	12×20	45
	20×30	65
	20×50	80
	30×60	105

include fuel storage, hay and bedding storage, and tobacco curing, which, due to the nature of the occupancy, would tend to produce large fires. Buildings in group B might include fruit and vegetable storage, equipment and vehicle storage, storage for small grains, and similar occupancies where there is either less material to burn or where the combustible material burns with less intense heat. To allow for a margin of safety, the shape factors used in arriving at the two sets of values were 0.03 and 0.05, rather than the theoretical value of 0.08. The reduction in shape factor makes provision for the increased size of flaming area compared to the actual size of the building. The author cites published information which suggests that the intensity of radiation from flames is less than 3.6 unless the mass of flames is at least 6 ft thick. The actual increase in effective radiating area may therefore be less than one would expect.

Although the values given in Table I cannot be considered precise, they do represent a step forward. There is considerable room for refinement based on the fire resistance of the potential burning building and the fire resistance of the covering materials on adjacent buildings. The effect of wind on convective heat transfer from the exposed building might also be taken into consideration. The calculations in Table I assume that the exposed building will have some portion of it directly opposite of the center of the flaming mass. The author suggests that future calculations could be made for buildings located diagonally at various angles. Ignition by flaming brands has been ignored in arriving at Table I, since flaming brands can travel several hundred feet on a windy day.

The author concludes by stating that the difference between radiation intensity required for pilot ignition and spontaneous ignition raises interesting possibilities in the use of noncombustible claddings. If combustible materials were completely covered with noncombustible claddings so that the vapors given off would not be ignited by flaming brands, the values shown in the Table could undoubtedly be reduced considerably. In order for this to be possible, the exposed surfaces of the building would have to be completely covered with the noncombustible material, with no windows or wood trim exposed and with no openings through which sparks could enter. The author notes this would be an extreme, but not impossible, solution for some situations.

The author states that research on radiation intensities required to ignite a variety of wall and roof constructions suitable for farm structures is currently underway at the University of Saskatchewan.

Subject Headings: ***Buildings, farm, separation for fire control; Radiation, ignition, of farm buildings; Fire control, by separation of buildings, Fire spread, between buildings; Ignition, of buildings, by radiation; Model, of fire spread, between buildings.***

E. C. Woodward, Jr.

Parks, G. M. (University of Pennsylvania, Philadelphia, Pennsylvania) "Development and Application of a Model for Suppression of Forest Fires," *Management Science* **10,** 760–766 (1964)

Operations research techniques were applied to a simple fire-growth model to yield equations for minimizing the total costs of fire suppression plus fire damage.

The optimal situations derived from the model were then used to analyze the effectiveness of the initial attack upon a number of actual fires in the Plumas National Forest in California. The results indicate that the initial attack can be made more effective and total fire costs significantly reduced by considerably increasing the size of fire suppression organizations.

The model is based on a flame front propagating at a rate G_D (acres/hour) at the time of fire detection which accelerates at a constant value H (acres/hour) to a rate G_A at the time of initial fire attack. The following equations for the optimal suppression force and minimum total cost were derived:

Optimal suppression force, x^*, number of men,

$$x^* = G_A(C_B'/2C_S E)^{\frac{1}{2}}\ (1+2\epsilon_x)^{\frac{1}{2}} + H/E;$$

Minimum total cost, C^*, dollars,

$$C^* = C_0 + 2G_A(C_S C_B'/2E)^{\frac{1}{2}}\ (1+2\epsilon_x)^{\frac{1}{2}};$$

where

E = an effectiveness factor which depends on the area of the fire and the type of forces and equipment being used to fight it, area/unit of force — time^2,
C_B' = the cost of values burned plus emergency fire-fighting costs, dollars/unit area,
C_S = the cost of the suppression force, dollars/unit of suppression force,
$C_0 = C_F + C_S H/E + C_x G_A/E + C_B Y_A$,
C_F = the fixed costs of maintenance of the fire suppression organization, dollars,
C_x = variable costs of suppression, dollars/man-hour,
C_B = the cost of values burned, dollars/unit area $= C_B' - 2C_T/G_A$,
C_T = the cost of emergency services during the fire, dollars/time,
Y_A = area burned at the time of initial attack,
$\epsilon_x = C_x \chi_0/(C_B' G_A)$ variable costs of minimum suppression force. These costs are usually small relative to fire damage costs.
$\chi_0 = H/E$ = minimal suppression force to prevent fire from accelerating.

During the year 1959, 139 fires burned a total of 11,478 acres in the Plumas National Forest causing damage costs of $4,210,000 and suppression costs of $754,000. Data for approximately half these fires were complete enough to allow the estimation of values of G_A and H by fitting curves to the actual fire histories. Where the data were incomplete, values for G_A and H were obtained by statistical analysis of 14,000 actual woodland fires in California, selecting those that had similar causes and burned in the same fuel under comparable weather conditions. Values of E were obtained in a similar manner. Cost data were obtained from existing fire records and existing cost rates for manpower and equipment.

The analysis of the 139 fires indicated that for 85 of the fires the optimal number of men that should have been sent on the initial attack was 10 or less; for 32 of the fires, the optimal number of men was 11 to 50; for 15 of the fires, the optimal number of men was 51 to 200; for the remaining 7 fires, the optimal number of men was more than 200. In actual practice more than 10 men were sent on only 6 of the fires. Seventy-five per cent of the fires were undermanned and with three exceptions all fires covering more than 0.25 acre were undermanned.

From a practical viewpoint, having optimal manpower available to cover each of the 139 fires would require a costly stand-by reserve of suppression forces. In order to minimize total costs some fires would have to be fought with a nonoptimal number of men. Via iterative procedures, the optimal size of a fire force for a selected group of fires may be determined so as to obtain minimum costs for manpower, transportation and damage.

If the fire year is divided into three periods, with the number of permanent fire fighters held constant to each period, the optimal number of fire fighters determined by the above method would be 96, 180, and 162 for the respective periods. Using this number of fire fighters, total fire costs would be reduced from $4,964,000 to approximately $1,541,000, a theoretical saving of $3,423,000. Total acreage burned would be reduced from 11,478 to 281.

Although the model appears adequately to describe actual field conditions for fires that are relatively small in size, larger fires require more complex models to describe proper attack procedures.

This model is limited in that it does not treat situations in which a fire changes acceleration or "blows up." Furthermore, the application and field testing of the model is difficult because of problems in estimating the "effectiveness factor," *E*, when mobilizing for a specific fire situation. The analysis also assumes that the distribution of growth rates and ignitions are known prior to the start of the fire season, and this is not always the case.

In spite of the above deficiencies the model does point the fire-fighting program in the right direction in indicating the need for more permanent fire fighters and in giving an indication of the size of the fire-suppression force. More work needs to be done to further define and evaluate additional fire variables and to develop appropriate data so that refinements on this and related models can be tested.

Subject Headings: ***Operations research, application to forest fires; Forest fire, application of operations research to.***

A. L. Goldstein

Rogers, J. C. and Miller, T. (Stanford Research Institute, Menlo Park, California) "Survey of the Thermal Threat of Nuclear Weapons," *Office of Civil Defense Contract No. OCD-OS-62-135* (*iii*) (May 1964)

This paper presents a detailed survey of the thermal threat of nuclear weapons and includes information on the present state of knowledge on atmospheric transmissivity, ignition of target materials, and the nature of fire propagation. Factors involved in the analysis of the thermal threat are:

1. the attack assumptions;
2. the interaction of the atmosphere, clouds, and topography with thermal radiation;
3. the effects of weather and topography on fire spreading;
4. the thermal response of various materials to thermal radiation; and
5. vulnerability of humans.

Finally, the value of particular countermeasures are discussed and worthwhile suggestions made to minimize the catastrophe that would probably result from the thermal effects of nuclear weapons. This paper is an unclassified version of a classified report—the declassification being accomplished simply by deleting all classified paragraphs and figures. The resulting review, while still extremely useful and interesting, lacks in certain areas the coherence and completeness that must have been associated with the original work.

In his introduction the author emphasizes the damage characterized by incendiary bombings during World War II. In the European Theater incendiary bombs were, ton for ton, five times as effective as high explosive weapons. As a result over 99 per cent of the total bomb loads dropped on Japanese cities were incendiary with a resultant destruction greater than that experienced in European cities. With the advent of atomic bombs, interest in fire damage lagged, largely because the blast damage was as extensive as the damage due to flame. However, the very high yield thermonuclear weapons have again turned the attention of military planners to fire damage since with these weapons the area in which ignitions can occur can be much greater than the area of blast damage. The author has pointed out that World War II experience has shown not only the destructive power of incendiary bombing but, in cities such as Hamburg, has also demonstrated the probability of surviving resulting fire storms in adequately designed shelters.

In a detailed analysis of the thermal threat, consideration must be given to the tactics employed by the enemy. The possibility of being attacked by a salvo of missiles may lead to higher intensity thermal radiation due to an overlapping of thermal pulses from several weapons. In addition, fires created by several weapons might coalesce into conflagrations or fire storms. Follow-on weapons could increase the vulnerability of certain target elements—the first weapon causing charring and later weapons causing ignition with less intense radiation than was originally required. Information on the relationship between yield of weapons and the energy required for ignition, obviously related to the shape of the thermal pulse, and the effect of altitude of detonation on pulse shape is dealt with in some detail.

The timing of the attack can be of great significance in estimating the total damage expected. On a long term basis, the year when such an attack may occur will certainly determine the technology of attack. On the shorter term, the season will alter the susceptibility of particular target areas to ignitability. The hour chosen may influence cloud cover, wind speed and direction, atmospheric transmissivity, and the location of large segments of the population. A detailed review of these effects is covered in an appendix to the main article.

With respect to the interaction of thermal radiation with the atmosphere, clouds, and topography, the author points out that the amount of thermal radiation transmitted through the atmosphere may vary from almost zero to practically one-hundred per cent depending on the weather. In addition, reflections from snow and/or clouds may reinforce the radiation, causing greater intensity than expected on a clear day. Data is presented to demonstrate a fivefold variation in range for a given radiation intensity (10 cal/cm^2) for a clear or heavily clouded day.

Analyses of atmospheric transmission have been made on the effects of differences in visibility. The effects of complete cloud layers for detonations above and below the clouds have been handled quantitatively. Little usable data is available to account for the effects of layers of clouds, broken clouds, or actual rain storms. Nevertheless, the importance of this is graphically portrayed by data showing the ignition radius of dry pine needles as a function of visibility. For a weapon with a yield of the order of ten to thirty-five megatons detonated at thirty thousand feet this radius can vary from twenty miles with unlimited visibility to less than one mile in a dense fog.

The possibility of shielding of targets by topography for low altitude bursts is alluded to. However, no analytical studies have dealt with this quantitatively.

The interaction of the thermal pulse with various elements of the target is discussed. Tests made on the radiation intensity required to ignite a large number of plastics, metals, and light and heavy fuels is reported in an appendix. These are related to distances for particular weapons detonated at particular altitudes. Mention is made of the transmission characteristics of many "screening" materials such as glass, plastics, window screening, and cloth which might afford considerable protection from thermal radiation. These data, too, are reviewed in detail in an appendix.

The interaction of weather with the nuclear fire problem is quite important. The effect of cloud cover has been previously mentioned. Of at least equal importance is the moisture content of potential fuels. Correlations between temperature and humidity on the one hand, and moisture content of kindling and heavier fuels, on the other, are presented. While the moisture content in the kindling is relatively unimportant due to its very rapid evaporation, it is crucial in heavy wooden materials. Moisture content in excess of fifteen to sixteen per cent make the wood extremely difficult to ignite while wood with a moisture content below twelve per cent is easily burned. Statistics are available summarizing the moisture content of building materials as a function of time and geography.

Topography can have an extreme effect on fire spread as has been demonstrated in some of the brush fires in California. A slope causes spreading much like a wind, the steeper the slope the greater the rate of spreading. In addition, particular terrain may make the job of fighting the fire more difficult, thus, indirectly, helping the fire spread.

The target itself plays a vital part in fire spreading. The density of buildings has been shown in Japanese and German studies to be crucial in determining the possibility of fire storms and conflagrations. While the precise correlations are probably not valid for cities in the United States due to different building techniques, the general concept is quite useful.

Finally, with respect to the threat itself the vulnerability of humans is discussed briefly. Besides actually being burned the human is susceptible to oxygen depletion, carbon dioxide, carbon monoxide, and heat. Nevertheless, even in the fire storm in Hamburg in which 280,000 people were within the fire storm area—some 240,000 escaped with their lives. The majority of these, fully 60 per cent survived in basement shelters, or the like.

The question of survival leads directly to a discussion of countermeasures, a subject dealt with in the final appendix of the review. Strangely, this appendix appears to have been proportionately more deleted due to security classification than any section other than one dealing with the thermal pulse shape. Nonetheless, useful information is provided. For example, the use of artificial fog and smoke generation to minimize transmissivity is discussed. For a city the size of Los Angeles such a system would require an investment of $3,000,000 and would cost $25,000 per alert. With fifteen minutes warning such a system could be activated and would prove effective.

With such warning, flashburns, the source of 20 to 30 per cent of total casualties in Hiroshima and Nagasaki, could be eliminated. Under these conditions eye damage should be virtually nonexistent.

Among other steps that could minimize the hazard would be the elimination of kindling fuels. A general cleanup of an area would provide fewer sources with which the fires could be initiated due to thermal radiation. Special fabrics have been developed which are particularly resistant to ignition from high intensity radiation and others which are effective in shielding targets. Use of the latter as full window draperies and the former throughout the home would provide obvious advantages. Special paints to produce smoke and foam have been designed and provide a slight measure of protection. Improved paints are being developed which should be more satisfactory.

The author indicates that great gains in minimizing the fire hazard could be obtained with modified and strictly enforced building codes. Fire walls and low building densities which have been demonstrated consistently to inhibit fire spread should be required. On the other hand, attic vents and louvers which create drafts through which fires can be spread, and wood shingles, and shakes which are particularly deadly in spreading fires should be eliminated.

While the subject of the paper is so complicated that simple, straightforward, and quantitative answers are unlikely at this stage, the authors do provide a real service; first, by categorizing the problem areas, and then by summarizing the very useful countermeasures that are to be taken.

Subject Headings: *Buildings, density and fire; Human susceptibility, to fire; Fire, urban; Conflagration, induced, by nuclear weapons; Fire hazards, reduction, by clean up; Mass fire, induced, by nuclear explosion, Fire storm, induced, by nuclear explosion; Nuclear weapons, fire threat from; Radiation, thermal, from nuclear weapons; Weather, effect on fire; Topography, effect on fire spread.*

F. Falk

Swersey, R. J. (University of California, Berkeley, California) "Simultaneous Parametric Programs," *Operations Research* **12**, 781–783 (1964)

In the course of research into a forest fire control project, a nonlinear programming problem was encountered. This was convertible to a linear programming problem which was simultaneously parametric in the right-hand sides and in the objective function.

Using an all-purpose algorithm, excellent results were obtained in solving the problem and this approach may be useful for solving certain other nonlinear programming problems.

The original problem concerned the initial attack models in which the optimal number of men to be dispatched to a forest fire depended upon the rate of growth of the fire, cost of suppression, transportation costs, burned values, and on the effectiveness of the crew. In 1963, the author extended some of these models to the case where any of several types of forces could be dispatched.[1]

If the following parameters are first defined,

L_j = transportation cost per unit of the jth force (\$/man),
W_j = cost per unit hour of the jth force (\$/man hr),
C = cost of burn (\$/acre),
G_a = growth rate of fire at the time of attack (acres/hr),

H = acceleration of fire growth rate (acres/hr^2),
E_j = effectiveness of the jth force type (acres/man hr^2),
X_o = number of acres burned after attack,
X_j = number of units of the jth force type,

the problem then becomes one of minimizing the expression

$$CX_o+\sum_{j=1}^{j=n}(L_j+2W_jX_o/G_a)X_j.$$

Subject to the following conditions

$$\sum_{j=1}^{j=n}E_jX_j-H=G_a^2/2X_o$$

$$X_j\geqq 0, \qquad (j=1, 2, \cdots, n)$$

$$X_o>0,$$

the above model was then generalized to find a solution to

$$\sum_{j=1}^{j=n}a_{ij}X_j=b_i(i=1,2, \cdots, n), \tag{1}$$

$$\theta_o+\sum_{j=1}^{j=n}\theta_jX_j=R(X_o), \tag{2}$$

$$\sum_{j=1}^{j=n}\left\{\mu_j+\lambda_j[R(X_o)]^p\right\}X_j=\text{Minimum}, \tag{3}$$

where $-\infty<p<\infty$; $X_o, X_1, \cdots, X_n\geqq 0$; and θ, μ, and λ are constants.

The structure of this problem depends largely on p and on $R(X_o)$. Some special cases simplify the problem; these are

a. For $p=1$ and $R(X_o)$ = a constant, the system (1), (2), (3) reduces to an ordinary linear program.

b. For $p=-1$ and

$$R(X_o)=X_o+\sum_{j=1}^{j=n}\sigma_jX_j$$

(1), (2) and (3) becomes a fractional linear program.

But for a general form of $R(X_o)$ an all-purpose algorithm is needed.

For any particular value of $R(X_o)$, say R', (1), (2) and (3) then become

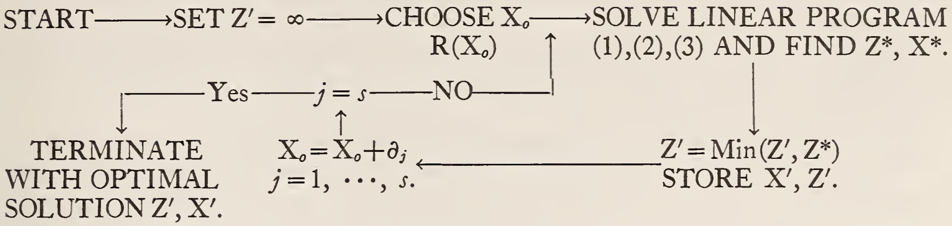
$$\sum_{j=1}^{j=n}a_{ij}X_j=b_i, \tag{1a}$$

$$\sum_{j=1}^{j=n}\theta_jX_j=R'-\theta=b', \tag{2a}$$

$$\sum_{j=1}^{j=n}\pi_jX_j=Z(\text{minimum}), \qquad \text{where } \pi_j=\mu_j+\lambda_jR', \tag{3a}$$

which is an ordinary linear program.

By iterating on R', there is a general algorithm for the solution of (1), (2), (3). The algorithm may be outlined as follows



There cannot be an optimal solution if such a solution has $X_o < X_o' < X_o + \partial_j$ for some j, where X_o' is the optimal value of X_o; however, it is possible to re-optimize in the neighbourhood of X_o' by a proper choice of the initial value of X_o and of ∂_j.

In the specific problem of forest fire control, the function $R(X_o)$ is restricted to a range of values so that the solution to (1), (2), (3) can be obtained.

A computer code using a linear programming subroutine can be written which, with suitable modification, makes it possible to use the previous optimal solution as a starting solution for each new value of R'.

Thus, by making use of a parametric algorithm in an iterative way it may be possible to solve some practical nonlinear programs until algorithms are devised to solve more general nonlinear models.

Reference

1. Swersey, R. J.: "Parametric and Dynamic Programming in Forest Fire Control Models," *RR 63-8, Operations Research Center, University of California, Berkeley, 15 May 1963.*

Subject Headings: *Forest fire, application of operations research; Operations research, application to forest fire.*

G. I. Isles

Special Projects Branch Computation Center, University of North Carolina. "FLAME I Fire Spread Simulation Model," *National Resource Evaluation Center Report No. 21 (January 1964) under Contract No. CDM-SR-61-3 with Office of Emergency Planning and Contract No. DA-18-020-ENG-1744 with the U.S. Army Corps of Engineers.*

The Flame I Report describes a mathematical model of fire spread phenomena with primary emphasis on wildland fuels. The Report is in three parts: Part I is designed for the general reader not interested in the mathematical model; Part II explains the details of the model; Part III describes the realization of the model on the Univac Computer (Scientific 1103A). For those interested, the Flame I Operating Instructions Users Manual, NREC Technical Manual No. 132, contains complete users instruction for the computer programs.

Flame I, using a fire spread simulation (model) attempts to predict the extent of fire spread following nuclear attack by estimating for each grid rectangle on a map the probability that it is burned. No attempt is made to predict fire intensity or fire damage. The original circle of ignition is approximated by grid rectangles, and the fire spreads outward from the center depending on natural barriers, fuel, weather, and a normal rate of decrease as fire moves from one rectangle to the next. As a final product, the area of total involvement is indicated, and an indication is given as to barrier effectiveness, per cent of rectangle burned, and relative degree of fuel flammability.

As stated in the preface of the report, "The Flame I programming research and development effort does not provide a deeper understanding of the mysteries of fire spread, but rather a more precise and systematic way of applying some comparatively simple techniques for estimating fire spread." Flame I is a damage assessment program designed for damage assessment use in the early days following a nuclear attack, and for hypothetical fire spread studies. The fire spread studies may be used to predict nationwide, which land areas would be affected by fire following a large-scale hypothetical attack; or to predict for a smaller area (only one fire) what the extent of fire spread would be.

The Flame I program considers three relevant factors in attempting to model fire spread. These are (1) weapons information, (2) geographical and fuel characteristics of the detonation area, and (3) prevailing weather conditions. The model is designed in such a way that when new and better information becomes available, it can be incorporated without extensive revisions. More detailed information on each of the three relevant factors follows:

1. *Weapons Information.*—Included here is information on location of ground zeros in terms of geographic position, weapon yield, height of burst, and month detonated. The month is required in order that the proper geographic and weather data can be used since this data is season-dependent. The height of burst and weapon yield determine the slant range and the probable area of original ignitions.
2. *Geographic Characteristics.*—A map is developed which describes the distribution of fuel and the incidence of fire barriers over the area of interest. The fuel data used were developed by the U. S. Forest Service in 1957 in a "Forest Damage Assessment" study and applies to rural areas only. Additional data are needed on fire spread in urban areas, and improved information on rural fuels would make the model more reliable. Fire barrier information is available from regular maps showing lakes, rivers, and other natural barriers.
3. *Weather Characteristics.*—Maps are developed which describe the weather conditions prevailing in the area of interest. Weather conditions, being season-dependent, were determined for each month. The weather data used assume average-bad weather conditions for the month all over the country—a condition which is extremely unlikely. Weather data were used primarily as a basis for determining direction of fire spread outward from the ignition point. Since Flame I is concerned with long-term fire spread, with the fire stopping because of natural causes, weather conditions were not considered instantaneous but rather those expected to prevail throughout the time of the fire spread.

Both geographic and weather data are given on a grid basis, with appropriate parameters for each grid rectangle. The model then attempts to predict the extent of fire spread resulting from the detonation of the nuclear weapon by estimating for each grid rectangle, the probability that the grid is covered by fire.

The Flame I program is designed to be incorporated with output of other programs in the Natural Resources Evaluation Center, Office of Emergency Planning, JUMBO III System. This means that the output may not be readily usable directly since it is designed for use by a specific over-all program of damage assessment.

Subject Headings: *Fire spread, mathematical model for; Fire spread, mathematical simulation; Conflagration, mathematical model for; Mass fire, mathematical model for; Model, fire spread; Weather, effect on fire model; Nuclear explosion, fire spread from; Operations research, applied to fire spread.*

J. H. Dieterich

Waterman, T. E., Labes, W. G., Salzberg, F., Tamney, J. E., and Vodvarka, F. J. (IIT Research Institute, Chicago, Illinois) "Prediction of Fire Damage to Installations and Built-Up Areas from Nuclear Weapons," *Final Report—Phase III (Experimental Studies—Appendices A—G) for National Military Command System Support Center Contract No. DCA-8* (November 1964)

The development of an accurate model for predicting fire damage to an urban area as a result of a nuclear burst depends primarily on a thorough understanding of the process governing the initiation and spread of fires and the reliability of the data employed to describe these processes. IIT Research Institute undertook a series of experiments designed to produce data needed to satisfy these two requirements. The experiments were not designed to treat, exhaustively, any one area of research on fire, but rather only to upgrade the "art" to a usable level. The information sought and the methods employed in obtaining it are discussed below. First, however, to indicate more specifically the need and the application of the data obtained, the salient features of the fire damage model are described.

In an urban area subjected to a nuclear burst, the development of fire can be identified by three main stages: ignition, fire spread within and between structures, and development of mass fire.

The part of the computer program which deals with the initiation of fire by the thermal pulse is referred to as the "ignition model." In constructing the ignition model, an assumption is made that only kindling fuels, such as fabrics, newspaper, etc., can be ignited by the thermal pulse. Since even sound wood was found not to sustain burning when ignited by the pulse, the initial fires from the nuclear burst can result only from kindling fuels located within or outside structures. In this connection, experiments which are described show that the ignition of exterior structural members requires large quantities of exterior kindling fuels, not usually found in urban areas. Hence, the ignition model assumes that fires from a thermal pulse will result primarily within structures.

Two conditions must be met for kindling materials situated within some enclosure to be ignited by a thermal pulse. First, the material must be exposed to the pulse, and second, the radiation intensity must be at least equal to the critical ignition energy of the exposed material. The locations of kindling materials such as upholstered furniture, couches, beds, etc., can be quite arbitrary within each room. Hence, to determine whether kindling materials will be ignited by the thermal pulse, an approach based on probability of ignition is used. This is accomplished by assuming that the probability of a kindling item being ignited is equal to the ratio of the room area irradiated with critical ignition energy to the room area within which the material can be located.

The computer program dealing with the ignition model calculates the probability of exposure and then assigns it as the probability of ignition of the kindling item.

If fires would not spread from their places of origin, the ignition probabilities would be indicative of the damage to the urban area. But fires do spread, first involving the whole room where the ignition takes place and then on the floor of the whole building if it is not of fire resistive construction. Depending on the distances and on the heat released by burning structures, fires spread to adjacent structures not initially ignited by the pulse. The computer program treats this by examining the fire spread within structures and their effects on adjacent structures. The corresponding parts of the program are referred to as "fire history model" and the "fire spread model."

Briefly, the fire history model determines spread of fire within the structure using fire resistance ratings of the structural components. It also provides, as a function of time, information on duration of the fire within various parts of the structure and on the flame area visible from the outside. The latter information is used by the fire spread model to determine the heating and possible ignitions of exposed structures.

The three models, ignition, fire history, and fire spread, are subprograms of the main computer program. The program is designed to treat each structure separately. However, the large number of parameters involved limits the application of the program to small areas such as blocks or tracts. By studying the fire behavior of these smaller areas, it is possible to predict the damage to the entire urban area.

To obtain data for the program, several experimental studies were performed:

1. *Flame Heights and Burning Rates of Well-Ventilated Fires*

The duration of fire and the flame areas of burning structures determine to a great extent whether an exposed structure will ignite. The flame area is used in the fire spread model to calculate the amount of heat impinging on the exposed structure. By this method, the fire spread between structures is predicted. Since the burning rates of structures determine the number of simultaneous fires, they also affect the heating of exposed structures and, consequently, the spread of fire.

The burning rate of the fuel depends greatly on the fuel surface area and the amount of the oxygen supplied. The fire may be ventilation-controlled (if the amount of available oxygen is less than required for a given amount of fuel), or it may be fuel-controlled (i.e., a well-ventilated fire with an excess supply of oxygen). There may also be some transition region where a fire may be partially ventilation- and partially fuel-controlled.

The burning rates of a ventilation-controlled fire have been considered by numerous investigators; and knowledge of them, within the accuracy of the fire damage model, was assumed as satisfactory. This is not the case for fuel-controlled fires. Only a few preliminary investigations were previously conducted which, in fact, resulted in contradictory opinions. This is unfortunate, because each fire, after penetration or collapse of the roof, becomes well-ventilated. A similar case exists in structures with large window areas.

As indicated above, the flame area from a burning structure is one of the most important parameters governing the spread of fire. It is also the least understood parameter.

Experiments were designed to provide the burning rates of well-ventilated fires and their flame heights. The experiments involved crib fires situated on scales for continuous monitoring of burning rates. The correlation obtained for flame heights and burning rates of fuel-controlled building fires improved considerably the accuracy of predicting the fire spread between structures.

2. *Fire Spread Within Structures*

The progress of fire within structures has a direct effect on the fire spread between structures as it determines the flame area and the duration of fire. Therefore, any error committed in describing the fire histories of structures has a direct bearing on the accuracy of the over-all fire damage model.

The existing information pertaining to this problem dealt primarily with the fire histories of single rooms. As a result, in the development of the model it was necessary to use standard fire-test data for describing fire development within structures. For situations where the mode of the fire resembles, at least approximately, the method employed in standard fire tests, this approach is reasonably good, although the time lag from ignition to flashover in subsequent compartments still needed to be evaluated. However, in numerous cases, the path of fire can create conditions entirely different from those existing during standard fire tests. In such cases, as in the fire spread through stairwells, through corridors, downward through floors, etc., only crude estimates could have been made.

For these reasons, the progress of fire within structures was studied, using half-scale rooms and full-size structures. Particular attention was paid to the relationship between the flame area and the fire spread within the structures.

Because the behavior of free-burning fires depends on their size, great care had to be exercised to insure that scaling laws based on model studies apply to full-scale cases. For this reason, in designing the laboratory experiments, an attempt was made to use the largest model sizes possible. Nevertheless, to gain confidence in the results obtained, they had to be verified by some full-scale fires. These experiments were conducted with fires in a number of actual buildings with contents typical of several selected occupancies. Since these experiments were to verify the results obtained with half-scale structures, the information sought was similar in both cases, i.e., the relationship between the flame area and the fire spread within the structure.

3. *Fire Spread from Internal and External Kindling Fuels*

Because a thermal pulse can only ignite kindling materials, the fire spread from these fuels has a profound effect on fire damage from nuclear explosions. Considerable effort was expended in the past to determine the levels of thermal pulse, i.e., critical energy, necessary for igniting kindling materials. Little or no attention was paid to the subsequent behavior of kindling fuel fires. The latter are, however, of primary concern since a kindling fuel fire not capable of spreading fire to other fuels is of little consequence. Experiments were performed to determine what is required for a kindling material fire to ignite other fuel.

For interior kindling fuels, experiments were performed in a full-size room (12×12×8 ft) using various items of upholstered furniture for ignition points. The amount of kindling fuel needed to flashover the room and the time between ignition and room flashover were investigated. For exterior kindling fuels, various wooden structures (siding, railings, etc.) were exposed to fires of kindling materials.

4. *Coalescence of Convective Columns from Free-Burning Fires*

In their final stages of development, fires initiated in an urban area by a nuclear burst can coalesce and form a mass fire. Since the coalescence can considerably increase the damage, it must be considered by the fire damage model. Unfortunately, the mechanism governing the formation and the subsequent behavior of mass fires is not known. To gain some understanding of those phenomena, experiments were conducted with liquid fuel and wooden crib fires. The objective was to study the flame coalescence and to develop criteria for the formation of mass fires. As far as the fire damage model is concerned, such information is sufficient for the case of a fire storm since within its periphery a total destruction takes place. However, for a conflagration the criteria of flame coalescence is only the first step in the analysis of the fire damage because subsequent spread of the conflagration must also be known.

As indicated earlier, no attempt was made to investigate extensively any particular aspect of free-burning fires, but rather to provide minimum data necessary for the development of the fire damage model. Some results are summarized below.

a) For crib fires burning in the open, the data show somewhat smaller flame height than that reported by other investigators. This difference can be attributed to the variation in wood spacing, which is not included in dimensionless correlations. For cribs burning in enclosures, the analysis of data indicated that when the fire is ventilation-controlled, the flame height L and the opening (window) height H are proportional. However, when the fire is mostly fuel-controlled, $L \sim H(d/H)^{\frac{2}{3}}$, where d is the crib height.

b) Preliminary experiments indicated the 1/3- and 1/4-scale models do not properly represent fire behavior in full-size rooms. Satisfactory results were obtained with half-scale models, which were subsequently used in the experimental series. The results show that a description of the insulating qualities, as well as the combustibility of the wall-covering materials of a room, are required to adequately describe the fire build-up in a room. Penetration times were about 40 min for roofs, 25 min for finished ceilings, and 5 min for plywood doors.

c) It was determined that the fire build-up in upholstered furniture differs from that of individual samples of fabric or padding materials. Generally, sustained burning took place in joints and seams only. Except for items padded with foam rubber, most of the build-up time involved the penetration of the fire to the interior spaces. The build-up time was apparently shorter for beds than for chairs and couches. The average flashover time was 18 min for a living room.

d) In general, exterior kindling fuels cannot readily ignite well-maintained combustible members of structures. An exception to this is the case of stairways which can be ignited by burning fuel containing thick and thin kindling materials. However, the compensating effect here is that the stairs offer more shielding from the weapon to such items than do the walls.

e) In general, the results from full-scale fires confirmed the conclusions reached in the model experiments. The calculations of radiation intensities using the assumed flame model, i.e., temperature, emissivity, and flame area, were in good agreement with measured values. This information is of vital importance to the prediction of fire spread between structures. It has also been determined that the volumetric spread of fire through a building divided into various interconnecting spaces can be described as a succession of predictable flashovers. The relationship between the cumulative building volume subjected to flashover and the time after the first flashover is best given by an equation of the form

$$V_T/V_o=\exp(T_f/m),$$

where T_f is the time after the first flashover, V_T the flashover building volume at T_f, V_o the flashover building volume at time $T_f=0$, and m the constant.

f) Burning rates provide a more suitable description of flame coalescence than do visual observations. As the distance between individual cribs increased, the total burning rate increased until the transition from a coalesced to non-coalesced fire occurred. This transition was accompanied by a sudden drop in burning rates. The peak burning rate, just prior to the transition, was determined as

$$R_{\text{peak}}=1.56(n)(R_s),$$

where n is the number of cribs and R_s the burning rate of an individual crib. The ratio of the distance between cribs to the dimension of the individual crib for peak burning of a coalesced fire was found to be:

$$(\text{distance between cribs/crib dimension})_{\text{peak}}=0.069(n\cdot R_s)^{0.4}.$$

The interaction of individual fires to form a mass fire is still one of the least understood phenomena of fire behavior; however, it is believed that the experiments described above have produced a step toward such understanding.

The final portion of the report describes the experimental development and testing of several special instruments needed in the study and not readily available commercially.

Subject Headings: *Fire, convection column; Conflagration, analysis of; Mass fire, analysis of; Fire storm; Flame, coalescence; Fire, prediction, of damage; Fire damage, model; Fire spread, model, urban areas; Model, of fire spread; Model, scaling laws for, Model, computer program for; Fire, analysis, for prediction damage, urban areas; Fire, propagation, urban areas; Ignition, by thermal pulse (nuclear), model for; Scaling laws, for fire spread; Mass fire, model for; Nuclear explosion, prediction, of fire spread from; Operations research, applied to urban mass fires; Buildings, fire spread in.*

E. C. Woodward

XII. Instrumentation

Monaghan, M. T. (University of Sheffield, Sheffield, England)* "A Technique for Studying the Combustion of Small Single Drops of Liquid Fuel," *Journal of Scientific Instruments* **41,** 206–209 (1964)

This article describes an apparatus constructed to measure the burning rates of liquid drops ranging in size from about 100 to 2000 μm. This particular apparatus

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* Present address: "Shell" Research Limited, Central Laboratories, Surrey, England.

utilizes fine (down to 5 μm diameter) silica fibers to support the liquid drops during the burning process. The liquid is ignited by means of an electric spark and the burning rate determined from photographic records. The entire apparatus is housed in a Perspex box to protect the system from drafts and permit the use of different atmospheres.

The silica fiber is held taut in a horizontal position by means of a mechanically adjustable arm which permits accurate positioning of the drops in the field of the camera. Each drop is prepared and placed on the silica fiber by means of a micropipette.

The spark-ignition system employed consists of a 12 volt car ignition circuit with the distributor points replaced by a Burgess microswitch. The lever arm of the microswitch was soldered to a release cable which operated an interlens shutter in front of the drum camera. This formed a simple and effective synchronization device.

The first lens in the optical system, which is arranged to give an approximately parallel beam of light from a Phillips 12 volt, 100 watt, filament projection lamp, formed half of a matched achronomatic doublet in which the objective lens was the other half. The liquid drop is located between these two lenses. A final lens is used to form an image of the drop on the film of a rotating drum camera. The magnification of the system could be varied over a wide range.

The drum camera used is a M731 universal oscilloscope recording camera manufactured by Southern Instrument Co., Ltd. The drum speed could be varied from 12 to 3600 rpm. In order to get a framing sequence of photographs of the burning drop, a disk image cutter is incorporated in the system. This consists of an 8 in. diameter blackened Perspex disk with a number of holes drilled around the periphery attached to the shaft of a high-speed motor. By varying the speed of the motor and the spacing of the holes, the framing rate and exposure time could be varied over a wide range; times down to 50 μsec and framing rates up to 1000 per sec have been obtained. Because of the low flame luminosity and high framing rates it was not possible to observe the flame envelope of the burning drop.

Subject Heading: ***Drops, apparatus to measure burning rate of.***

H. E. Perlee

Nelson, L. S. and Richardson, N. L. (Sandia Laboratory, Albuquerque, New Mexico) "The Use of Flash Heating to Study the Combustion of Liquid Metal Droplets," *The Journal of Physical Chemistry* **68,** 1268–1270 (1964) (Communications to the Editor)

An apparatus is described to produce and burn single droplets of molten metal as they fall freely in air. Samples of zirconium foil 0.2–2.0 mm square by 16 μ thick were dropped past a helical quartz flash lamp in air at reduced pressures, 50–629 Torr. A 4 kV, 3600 joule capacitor discharge to the lamp gave sufficient thermal radiation to melt the zirconium (1855°), and form brilliantly incandescent droplets 100–500 μ in diameter.

The oxidation process was followed by motion picture photography at 5,000 frames/sec, and by quenching and collecting the combustion residues at various heights in the apparatus.

The zirconium droplets falling freely in air, exploded or sparked 175–375 msec after they were formed. This effect was observed directly, and was inferred also from the presence of shattered hollow spheres after the combustion. The induction period, that is, the time between the start of the flash discharge and the onset of the explosion increased with increasing particle diameter, and with decreasing air pressure. Given the zirconium droplet diameter (202, 234, or 265 μ) and the air pressure (50–629 Torr), the time to explode (175–375 msec) was reproducible within ±2% average deviation.

The combustion residues varied from gray metal particles with transparent glassy coating, before explosion, to fragmented hollow spheres of white, vitreous material after explosion. (No physical or chemical analyses were reported.)

The cause of the explosions was not known, but it was considered likely that the driving force was the expansion of a gas at high pressure. A later, more complete, report was promised.

Subject Headings: *Flash heating, to study droplet combustion; Zirconium, combustion of droplets; Metals, droplet combustion, techniques; Droplets, metal, techniques for study of combustion; Radiation, ignition of metal droplets, by flash heating; Ignition, metal droplets, by flash heating.*

B. Greifer

Rohrbough, S. (**General Mills, Inc., St. Paul, Minnesota**) "A Study of High Altitude Water-Vapor Detectors," *Scientific and Final Report under Contract No. AF 19(628)-483 Air Force Cambridge Research Laboratories* (March 31, 1963)

A balloon flight was made in which the balloon rose to an altitude of 80,700 feet at an average rate of 624 ft/min, remained there for approximately 30 min, and then descended slowly. The instrument package included a Goldsmith Vapor Trap, a Dual Molecular Sieve unit, four hygrometers, and two refractometers. There were two separate data channels for each sensor.

The Goldsmith Vapor Trap was a duplicate of the original design by Goldsmith in the United Kingdom. Air is drawn through a stainless steel tube immersed in liquid nitrogen, thus freezing out both the water vapor and carbon dioxide. An alternative gravimetric water vapor unit, the Dual Molecular Sieve, was also included. In this instrument the air is drawn through an adsorbent bed that removes, and collects, both the water vapor and carbon dioxide. A flowmeter is used to meter the air flow as a cross check on the deduced flow from the carbon dioxide measurements.

There were three types of hygrometers. The first uses a Peltier-cooled surface through which alpha particles are passed and then detected. As a frost layer builds up the alpha particles are attenuated and, by comparing the signal with that from an identical uncooled cell, the cooling current is reduced until the layer vanishes. Then the cycle is repeated. The optical hygrometer is very similar except a light beam is reflected from a cooled mirror. When frost interrupts the light the cooling ceases and the film disappears thus recycling the system. The third instrument also uses an optical sensor but the mirror is cooled by a frozen ethyl alcohol bath and heated by a resistance heater. In all cases the temperature of the surface is continuously monitored by a thermistor.

The refractometers were of the microwave type and an air capaciter is an integral part of the circuit. Any change in the refractive index changes the capacitance and thus the basic frequency of the unit. A temperature correction can be made and the index of refraction calculated.

The experiment was partially successful. The alcohol-cooled hygrometer shorted out prior to launch and the resulting impact disabled the other optical hygrometer and one refractometer. A malfunction of a relay caused the absorbent in the water vapor detector to become contaminated, thus invalidating the data. The remaining refractometer data seemed good until a pressure of 480 mb is reached, at which point questionable results were obtained. However, upon comparison with the frost point profile the index of refraction data was found to be unacceptable. Frost point data from the hygrometers is good up to the float altitude, at which time contamination from the outgassing of solar-heated styrofoam probably introduced significant errors. The Goldsmith Vapor Trap gave an average mixing ratio of 0.09±0.01 gm/kg over a pressure range of 28 to 78 mb.

Subject Headings: *Meteorology, moisture profiles in the atmosphere, experimental techniques for; Water, detectors for; Humidity, detectors for.*

T. P. Anderson

Welker, J. R. and Sliepcevich, C. M. (University of Oklahoma Research Institute, Norman, Oklahoma) "A Low Speed Wind Tunnel for Measuring the Effect of Wind on Buoyant Diffusion Flames," *Technical Report No. 1 OCD Contract OCD-OS-62-89, NBS Contract CST 1142* (September 25, 1964)

This report considers the problem of transverse wind effects on the combustion characteristics of diffusion flames emanating from circular liquid pools. Although long acknowledged as a significant factor little effort has been expended on the study of the influence of flame angle on combustion.

A steady-state model is postulated in which the flame is represented by a tilted cylinder with a diameter equal to the burner diameter D (consequently the flame volume is directly proportional to the length L). It is further assumed that the flame bending is uniform, air is introduced uniformly around the flame, and the fuel burning rate is constant. Applying a momentum balance and restricting consideration to pans large enough (2 inches or more) so that the fuel momentum may be neglected, the equality of drag and buoyancy forces gives the angle of tilt, θ, as

$$\tan\theta/\cos\theta = \frac{2C_f u^2/\pi}{gD(1-\rho_f/\rho_a)},$$

where C_f is the drag coefficient based on the projected flame area in the direction of the wind velocity u, and ρ_f and ρ_a are the flame and air densities.

Dimensional analysis is employed to show that the drag coefficient is a function of the product of the Reynolds and Froude numbers. Based upon a limited amount of experimental data[1] the correlation is given by

$$C_f = 60(\mathrm{ReFr})^{-\frac{1}{2}}.$$

Although extrapolation of this data may be questionable it does provide a convenient estimate of scale effects.

Based on the above considerations and providing for a scale large enough to produce fully turbulent flames (burner diameters up to 2 feet) a design is presented for a versatile experimental facility to examine the problem. Essentially, this is a low-speed wind tunnel with a test section 8 feet square and 20 feet long. Air flows up to 100,000 cfm can provide velocities of 25 fps and resulting angles of tilt in excess of 75°. The corresponding Reynolds number is of the order of 250,000. Planned instrumentation includes temperature, radiation, humidity, velocity, and flow measurement. The flame itself will be examined primarily by using still and motion picture techniques. Specific designs for burners and associated equipment are included.

Reference

1. Pipkin, D. A. and Sliepcevich, C. M.: Effect of Wind on Buoyant Diffusion Flames, *I and E C Fundamentals* **3**, 147 (1964).

Subject Headings: ***Wind, effect, on buoyant diffusion flames; Diffusion flame, effect of wind on.***

T. P. Anderson

XIII. Fire-Fighting Techniques, Equipment

Factory Insurance Association "Recommended Good Practice for the Protection of High-Piled Stock," *Report of the Factory Insurance Association* (June 1963)*

Rising costs in warehousing, due to construction, maintenance, and labor, have brought about efforts to utilize the maximum volume of a warehouse structure for storage purposes, thus resulting in the piling of commodities higher and higher. This trend has been further expedited by the development of efficient stackers and lift trucks, as well as the use of semi- or fully-automatic mechanical handling systems for stacking commodities in very high racks.

This publication points out the following major fire control problems created by high piling of combustible stock:

1. *Obstructed Water Application.*—Where a pile exceeds 15 ft in height and/or where stock or packaging has the inherent characteristic of shedding water, bottom portions of a pile may not be adequately "wetted" to control fire spread.

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* This publication discusses the result of a fire test program reported by J. E. Troutman in the *Quarterly of the National Fire Protection Association 57*, 15–24 (1963). An abstract of this appears in *Fire Research Abstracts and Reviews 6*, 177 (1964).

2. *Effect of Slowly Developing Fires.*—When stock is piled in large closely-packed masses, fires (except for those which start along aisles) may be slow in developing because of dense piling and a deficiency of air.

3. *Effect on Rapidly Developing Fires.*—This type of fire can be expected when ignition occurs along the external portions of a large pile or a group of small piles where there is adequate air to support a rapidly increasing fire, spreading both vertically and horizontally.

4. *Effect on Accessibility.*—When a warehouse is filled with dense smoke and intensely hot gases, the problem of gaining access to the seat of a fire, as well as that of salvaging stock for the ultimate reduction of the loss, is intensified.

5. *Maintaining Structural Integrity.*—As pile heights increase, it becomes more difficult for sprinklers to control not only fires within the piles and between the piles, but to also maintain ceiling or roof temperatures sufficiently low to avoid structural collapse.

6. *Effect on Increased Values.*—The maximum utilization of warehouse volume by the stacking of stock in high piles covering large floor areas results in an exceedingly high concentration of insurable values. That this, in turn, represents an exceedingly high loss potential has been previously demonstrated by statistics wherein it has been found that where combustibles are stored in excess of 8 ft in height, the ratio of the average loss as compared to that in stock piled less than 8 ft in height was nearly nine to one.

These problems present a severe challenge to both the fire protection engineer and the insurance underwriter. It has been demonstrated in a number of severe fires in industry that this is a very real problem and will continue to intensify. The test program was conducted to determine what protection features would be necessary to maintain the integrity of the building structure and confine the fire to the pile of origin. The conclusions include the following:

1. If the contents of cartons burn in a manner similar to the paper cartons, variation in contents does not appear to change the initial fire characteristics, but does change the fire duration.
2. A stable pile resists control by automatic sprinklers to a much greater extent than an unstable pile. Pile collapse permits more water to reach the seat of the fire.
3. Ceiling temperatures can be controlled and serious structural collapse can be prevented by proper selection of the water spray application rate.
4. Fire in palletized cartons of stock 11 ft high can be controlled by a minimum application rate of 0.20 gpm/sq ft for ordinary hazard materials, with the opening of a large number of sprinklers. At this low density, the tendency for the fire to spread horizontally to the edges of the pile still exists.
5. Sprinkler discharge at any practical application rate cannot be expected to extinguish a fire that is well established in stock below the top two pallets of a pile.
6. When sprinklers are on a dry pipe system rather than a wet pipe system, a fire can be expected to establish itself deeper in the pile and open a large number of sprinklers.
7. Under conditions of slow fire development, combined with the generation of a large quantity of smoke and relatively slow sprinkler operation, a smoke de-

tection system resulting in the early application of small hose streams would be of considerable value.

8. Fire can be expected to communicate from one pile to another when the aisle space between piles is less than 30 per cent of the height of the highest adjacent piles and may communicate when such clearance is less than 50 per cent of the highest pile.
9. The vertical and horizontal rate of spread of fire increases as clearances between piles diminish. As thermal updraft increases, pressure develops between closely spaced stacks and flame is pushed out in all directions.

In addition to these conclusions the present article sets forth detailed recommendations for the use of Factory Insurance Association personnel in the handling of risks of this type. Detailed recommendations are made as to the relationships between the width of the aisles and the pile heights and, also, for maximum area of piles in relation to the hazard classification of their contents. The most important and useful feature of the publication, however, is the detailed recommendations made concerning emergency roof ventilation requirements and sprinkler discharge densities balanced against hazard classification, pile heights, and construction.

These recommendations will be of great assistance to architects and engineers in the design of new structures to be used for warehousing purposes.

Subject Headings: *Fire protection, in warehouses; Fire danger, in warehouses, reduction of;* Warehouses, fire danger in.

J. J. Ahern

Haswell, D. B., Williams, D. W., and Cummings, T. J. (Bio-Dynamics, Inc., Cambridge, Massachusetts) "Small Community Fire Fighting Resources for Major Fire Disasters," *Final Report Office of Civil Defense Contract No. OCD-PS-64-39* (15 April 1965)

Initial study efforts were devoted to assembling information pertaining to the small community (15,000 to 25,000 population) fire department, its modus operandi for various size fires and its use of and interaction with other municipal departments, including civil defense. From the standpoint of fighting major fires, there are several factors which presently limit the capability of the average fire department:

(a) Fire command personnel lack command and control experience in dealing with large numbers of men and equipment. The mutual aid planning arrangements for major operations are informal at best.

(b) Communications are sometimes overloaded for normal operations and are not adequate for coordination between and among all resources within the community.

(c) Towns of the size considered by this report usually have a municipal water supply, and little attention is given to the development of alternative water sources or to optimization of the use of the municipal supply.

(d) In the majority of the towns, the fire department has not been given the "education" and assistance necessary to undertake disaster planning.

The study recommends, among other things, that civil defense efforts be directed in support of municipal departments with the personnel from these departments forming the staff for a disaster organization.

Subject Headings: ***Disaster, fire-fighting resources, small communities; Fire fighting, small communities.***

H. Bond

Haswell, D. B., Williams, D. W., and Cummings, T. J. (Bio-Dynamics, Inc., Cambridge, Massachusetts) "A Disaster Planning Manual for Small Communities," *Report Office of Civil Defense Contract No. OCD-PS-64-39* (15 April 1965)

This is a "demonstration" manual, for the lack of a better description, which represents the contractor's interpretation of plans and methods used by municipal fire departments for building an expanded fire-disaster capability. It was prepared as a part of a study performed for the Office of Civil Defense entitled "Small Community Fire Fighting Resources for Major Fire Disasters."

In preparing the advice given in the manual, it is recognized that the largest portion of disaster-control capabilities must be built around services that exist in peacetime and, as such, will have the operational and organizational experience to respond to nuclear effects. The smaller communities of 15,000 to 25,000 population cannot afford to maintain the tremendous standing forces periodically demanded by a major fire situation, so they rely on mutual aid. There have been cases of large fires, industrial explosions, and forest fires where the effectiveness of mutual aid was hampered by the lack of good communications, fire-scene access, apparatus assignment, and centralized command. In these instances, the difficulties were not due solely to insufficient men and machines, but insufficient preplanning for large-scale exercises.

Although the basic purpose of the fire department is to protect life and property against loss by fire, the expansion of emergency activities has arisen because:

(1) The fire department is ready to respond 24 hours a day.
(2) It has specialized training and equipment.
(3) The fire department is usually the peacetime emergency force best prepared to respond instantly to any type of physical destruction.
(4) Its responsibilities and authority have long been established by law.

Operations in various disasters are discussed including tornados, earthquakes, aircraft crashes, hurricanes, floods, electrical storms, blizzards, and nuclear disasters. The existing nuclear threat is referred to as not so overwhelming as to preclude organized disaster operations. The organization of a community disaster staff organization is recommended. An explanation is offered that the chief of the local fire department is the most logical choice for the head of this staff, so far as municipal government is concerned. It is pointed out that the fire department has acquired a unique position over the years by its capability to perform emergency services in addition to fire and that invariably the town's people turn to the fire department when any unusual emergency occurs. Therefore, in terms of flexibility, experience in the control of physical damage and organizational achievements, it is logical that the fire department hold the central role in the municipal disaster staff organization.

The line functions for the municipal disaster-operating organization are assigned to the fire, police, department of public works, and medical resources of the community.

The police have a difficult, complex responsibility in time of disaster. They must maintain the order that is necessary for other disaster services to function without interference. Secondly, they must enforce some sort of law to prevent looting and to protect critical resources. Thirdly, they may be called upon for special disaster services among which intelligence, transport, and evacuation are listed.

The planning, staffing, and organizational aspects of disaster first aid, medical organization, public health, rehabilitation, personal sustenance, and welfare are stated in terms of general requirements. References to the department of public works include municipal groups associated with engineering construction and maintenance of municipal systems. It is pointed out that these groups possess sources in the community for the heavy equipment so necessary for drastic operations; secondly, they have trained personnel; and thirdly they are familiar with equipment and manpower available from contractors.

Special attention was given to the need for developing alternative water resources by assessment of the community for all water resources supplementary to a public water system. It was further suggested that the exact method of using water in fire fighting be worked out for important locations.

A most useful recommendation is the emphasis that was placed on integrated community response by individuals to be effective in preventing the spread of scattered fires to conflagration proportions. Under a nuclear attack, for example, many small fires would be expected of which most could be extinguished in their early stages with a broom or a bucket of water.

The report concludes that an effective disaster-control organization can be set up by a municipality, provided it is staffed by professionals with experience in civic management and operation. This method is one which was observed to be workable and, as a practical matter, is in existence.

Subject Headings: *Operations research; Nuclear attack; Disaster, small communities.*

H. Bond

Holliday, J. (Dounreay Experimental Reactor Establishment, United Kingdom Atomic Energy Authority, Warrington, England) "The Extinguishing of Uranium and Plutonium Fires," *TRG Report 86* (November 22, 1961)

A major problem in the handling of fission materials such as uranium and plutonium results from the tendency of these metals, when in powder or similar form, to ignite spontaneously in air at room temperature. In spite of elaborate safety precautions and careful handling in inert atmospheres of helium or argon, serious fires have developed involving extensive damage. The work of the United Kingdom's Atomic Energy Authority, Reactor Group, was directed toward the development of an effective extinguishant for these fires.

Common extinguishants, such as carbon dioxide, carbon tetrachloride, soda acid, and water were found unsuitable since in many cases, they added to the hazards or even actively supported the fire. Dry powder extinguishants such as sodium chloride, calcium fluoride, sand, graphite, and magnesium oxide were also unsatisfactory, although they contributed somewhat to the control of the fire, because their porous structure did not allow the formation of a continuous powder blanket.

The successful extinguishant had to be a dry powder, chemically stable with plutonium and uranium at elevated temperatures. The melting point had to be lower than that of uranium and plutonium, so that on application it would "frit" where it is in contact with the burning metal and completely exclude the surrounding air from the fire, while at the same time, the absorption of latent heat by fusion of the powder would exert a chilling effect on the metal.

For extinguishing fires involving massive or finely divided uranium, the ternary eutectic salt $NaCl/KCl/BaCl_2$ was found to satisfy the above requirements. The salt had the following composition by weight: NaCl, 20%; KCl, 29%; $BaCl_2$, 51%. The salt melted at 555°C to form an impervious coating over the uranium and produced rapid chilling.

The ternary chloride salt was also applied to plutonium and to cerium–Misch-metal alloys which were found to be an excellent substitute for plutonium. Although chloride salt was effective in containing the plutonium fire, it was not effective in extinguishing it.

Experiments continued with binary and ternary systems of fluoride salts. Initial indications are that the ternary system LiF/NaF/KF will be more suitable for the extinguishment of plutonium fires than the chloride salt.

Subject Headings: *Fire, extinguishment, of uranium fires; Fire, extinguishment, of plutonium fires; Extinguishment, of uranium fires, by dry powders; Extinguishment, of plutonium fires, by dry powders; Dry-chemical agents, for extinguishment, of uranium fires; Dry-chemical agents, for extinguishment, of plutonium fires.*

A. L. Goldstein

Jensen, R. H. (Underwriters' Laboratories, Inc., Chicago, Illinois) "The Compatibility Relationship between Mechanical Foam and Dry-Chemical Fire-Extinguishing Agents," *Underwriters' Laboratories, Inc. Bulletin of Research No. 54* (July 1963)

The incompatibility of ordinary (sodium bicarbonate base) dry chemical powders with mechanical foams when used in combination for the extinguishment of flammable liquid fires has been known for at least ten years. Through the combined efforts of the U. S. Naval Research Laboratory (NRL) and industry, compatible dry chemical powders were developed.

This Bulletin describes a series of indoor fire tests conducted to evaluate the breakdown effect of both compatible- and noncompatible-type dry chemical extinguishing agents on various types of mechanical foams. In all tests, the foam was applied through a foam nozzle supplied with a premix foam solution of currently

UL listed 3 per cent, 6 per cent, 3 per cent low-temperature, and 6 per cent low-temperature foam liquid concentrates. Except for control fire tests, run with foam alone, dry chemical, in predetermined application densities was applied to the burning fuel area, prior to foam application.

The first test series conducted on 50 sq ft pan indoor test fires, using a 2 in. depth of fuel floating on 4 in. of water, indicated that the degree of compatibility depends on the amount and type of sodium-base dry chemical, the type of protein foam, the foam application rate, and the method of application (plunging or gentle) used.

Further testing indicated that the most severe breakdown effect of dry chemical on foam was encountered on spill-type fires where considerable agitation of the fuel surface resulting in intimate contact of the foam, fuel, and dry chemical in the presence of heat occurred. Test fires ranged in size from 10 sq ft to 400 sq ft. Pans with 12 in. sides were used containing a layer of water equivalent to 0.40 gal/sq ft of fire test area. The fuel (stove and lighting naphtha) in the amount of 0.10 gal/sq ft of area was floated on top of the water base.

Where the fires test area was contaminated with ordinary (noncompatible) dry chemicals, it was found that excessively high foam solution application rates, in the order of 1.0 gpm/sq ft, were required to overcome the breakdown effect of small amounts of ordinary dry chemical. The author justifies this comparison by pointing out that when foam alone is used on this type of fire, it can be extinguished with a solution rate of 0.10 gpm/sq ft as specified in NBFU (NFPA) Pamphlet No. 11.

The UL rating given a dry chemical extinguisher is equivalent to an application density of 1 lb dry chemical per sq ft fire area. The results of the fire tests using foam-compatible dry chemical in the amounts of 1.2 to 3 lb/sq ft showed some foam breakdown, but all fires were extinguished when foam was applied at a minimum solution rate of 0.45 gpm/sq ft. Lower dry chemical application densities resulted in a lowering of foam application rates for fire extinguishment. The author recommends a minimum field application foam solution rate of 0.50 gmp/sq ft, which includes a safety factor for use in other than laboratory conditions.

The investigation includes an evaluation of the small-scale laboratory test for foam compatibility developed by the Naval Research Laboratory and comparisons of this test method with results obtained from the combined use of foam and dry chemical on the large-scale simulated spill fire tests. The NRL test method is based on a measure of the rate of breakdown of foam as affected by exposure to heat and dry chemical. Complete correlation of results from both of these test methods was not obtained. Once the basic compatibility relationship between dry chemical and foam had been established on spill fire tests, the NRL test method was judged useful in maintaining control of the degree of compatibility of these extinguishing agents.

A method of classifying dry chemical extinguishers containing foam-compatible dry chemical suitable for use with dry chemical, compatible, foam liquid concentrates is given in the Appendix.

Subject Headings: ***Dry-chemical agents, compatibility with foam; Foam, compatibility with dry-chemical agents.***

E. J. Jablonski

"Soviet Progress in Forest Fire Control." Edited by N. P. Kurbatskii. Original Russian text published for the Institute of Forestry and Wood by The Academy of Sciences Press in Moscow in 1963.*

This publication in Russian consists of nine papers two of which were written by N. P. Kurbatskii who edited the series for the Institute of Forestry and Wood, for publication by The Academy of Sciences Press in Moscow in 1963. All were translated by Consultants Bureau Enterprises of New York, but the first five, which were devoted to the development of localized forest fire danger scales for different geographic areas of Russia, were omitted in the translation reproduced under this title. These five will be discussed as a single subject followed by notes on each of the additional four papers.

Much of the material is in the nature of a review of present knowledge and an analysis of existing forest fire problems. The significance of these papers is enhanced by the editor's preface which explains that they represent the work of the new "Laboratory of Forest Pyrology" at the Forestry and Wood Institute organized in 1963 at Moscow. With a newly organized group there may well be further progress to report in the next few years.

FOREST FIRE DANGER AND ITS MEASUREMENT BASED ON LOCAL SCALES

This subject is discussed by N. P. Kurbatskii, E. N. Valendik, G. V. Snytkia, and V. V. Furyaev in five papers. These papers describe the effort to date to develop useful ratings of forest fire danger. The early work was much influenced by research in this field by American investigators, particularly Gisborne. Show, Jemison, Shank, and others are also quoted.

In the 1930–45 period relative humidity and air temperature, with corrections for rainfall were used as indicators of the combustibility of a forest area. In 1949 Nesterov introduced a more complex system for computing a flammability index in which the days since the last rain were taken into account, and other cumulative effects were given weight. This took the focus of $Dn=dt$, where Dn is the desired flammability index for a given day, and dt is the sum of the products of the moisture deficit d, times air temperature t, taken at 1:00 p.m. for all days since the last rain. Because corrections were introduced to distinguish between rainy situations the formula was restated as

$$Dn=K\times(Dn-1)+dt_{1300}.$$

The correction factor for precipitation "K", takes values from 0–1 depending on the amount of rain. $Dn-1$ is the index of the preceding day.

As will be observed these are empirical formulas which neglect several important factors. They do not take account of the vegetative stage of forest fuels nor of wind speed. The activity of fire-starting agencies is also neglected. In application the resulting ratings proved unsatisfactory.

In 1960 an effort was made to improve the flammability index but retain a single scale for all Russia. This involved a new formula with an arbitrary seasonal adjust-

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* Authorized translation from the Russian by Consultants Bureau Enterprises, Inc. Five of the papers in the original publication, concerned with fire-hazard scales for specific Soviet forest regions, have been omitted from this translation.

ment to take account of higher fire danger in the spring, and a change in the observation time to 7:00 a.m. Extensive tests of this system have also produced negative results. It was found that the probability of a day with fires was the same for all classes of fire danger. This failure of the system to discriminate, led to the decision to abandon the proposed unified fire danger scale for all Russia.

Local scales are accordingly being substituted. In developing them, answers to four questions are being sought. These are: (1) Are fires possible in a particular protected area during a specific time period? (2) If so, how many are likely to occur? (3) Specifically, where should they be expected in the protected area? (4) How fast are they likely to spread and how intensely will they burn?

The new local scales are based on statistical analysis of weather records and of fire occurrence. They are divided into four fire danger classes which are separately defined for each geographic area or major fuel type. Each is based on a given range of probability of fire occurrence. Further localization is attained by subdividing the fire season into periods which reflect changes in vegetative stage of local fuel types. To perfect such systems, the author concedes that much more research is needed.

COMPARATIVE FIRE RESISTANCE OF TREES IN THE TAIGA ZONE—

I. N. Balbyshev

This paper surveys the extensive ravages by fire throughout the forests of Russia during the last century and reports on the differences in degree of survival or recovery by species

According to data quoted, forest fires burned over 12.5 million hectares or over 30 million acres in 1915. In Siberia, Primorskii, and Khabarovsk Krais 483,000 acres burned in 1935. This was 22 per cent of the 2,195,820 acres burned that year. In 1938 fires in these areas accounted for 53 per cent of the 2,869,624 acres burned and in 1939 76 per cent of the 3,053,000 acres of forest land burned.

Data quoted for the Altai Krai show that losses in the 1940–44 period were less than half those suffered in 1906–1910 though the number of fires were decreased only slightly. These and other data indicate much improvement in the efficiency of fire control but also much depletion in existing forests from the repeated conflagrations of the past.

Lethal temperatures for living tree cambium are quoted at 50°–55°C. This is slightly lower than the 140°F found for living pine needles by research in the U. S. but is in good general agreement.

From the surveys made, the degree of resistance to fire by species is in the following descending order: larch, pine "cedar" (Pinus cembra), fir, and spruce for the conifers. Aspen is more fire-resistant than birch among the deciduous species in these northern areas.

The generalization is made that the thicker the bark, the deeper the root system, the higher the crown, the lower the resin content and the content of volatile oils, the less the danger of fire damage. This too corresponds closely with American experience.

EFFECT OF RELIEF ON FOREST FIRES IN WESTERN SAYAN—

M. A. Sofronov

This paper is in the nature of a survey of observed relationships between topography and forest fires, in Western Sayan. As such, though it does not add significantly to what is known about this subject, it does focus attention on interrelations between solar radiation, slope, and exposure. For the most part the author is content to examine the fixed factors of solar radiation at the latitude of interest, steepness of slope, and direction of exposure, since these are each observed to have significance. In Western Sayan he found that north slopes, then east slopes and ravines, hollows and valleys in all situations were least often visited by fire.

In a drought year, he observed that these areas became more susceptible to fire but apparently assumed that the same general relationship would persist. In parts of the U. S. fires on north slopes in a drought year may become more intense and more destructive than on other exposures. Such variable factors as wind and diurnal air flow in mountainous terrain with frequent formation of valley bottom inversions, which are recognized as highly important in the U. S., were not discussed.

PRINCIPLES AND PROSPECTS OF FINDING NEW CHEMICAL MEANS OF EXTINGUISHING FOREST FIRES—*G. A. Amosov*

The author criticises the fuel-oxygen-heat triangle concept as explained by K. P. Davis in "Forest Fire Control and Use." This concept is widely used in the U. S. to explain the process of burning and suppression in training forest fire fighters. Though very useful for this purpose, the author rightly points out that it is too superficial to be very helpful to the research scientist.

The author then examines the quenching of fire from the chemists' point of view. To reduce the complexity, he divides it into seven simpler processes that have so far been established, and examines each in turn.

His discussion is reviewed in the same order.

(1) *Cooling of the Seat of Burning*

The use of heat absorbents to absorb heat faster than it is being liberated is the principle in the use of water as an extinguisher. It is considered an almost "pure" example of the cooling process. An example is taken of a forest fire in lichen cover, where the fuel per sq m is 1.5 kg, the burning time of the lichen is 30 sec, and the calorific value per kg of dry lichen is 4300 kcal, reduced to 4240 by the assumed 10 per cent moisture content. The rate of application of water to reduce temperatures from 900° to 300°C is 45.8 g/sec. On this basis 16 m of fire edge could be extinguished per minute.

This is an interesting calculation but it neglects the high proportion of water that is always wasted in conventional methods of application.

Even so the discussion is clear and gives emphasis to the critical relationship between heat absorption and liberation capacities in the extinguishing of fire.

(2) *Isolation of Fuel from Oxygen by a Layer of Gases*

This process has most significance in treatment of wood to give it fire resistance.

According to references quoted, the burning of a gas ceases when an inert gas dilutes it to form 33 per cent of its volume. The author's calculations show that water vapor does not normally function in this way, though it may enter into the extinction of fire where the principal effect is cooling.

(3) *Isolation of Fuel from Oxygen by Creating a Solid or Liquid Film Around It*

Tests with potassium chloride and magnesium chloride which are widely used in forest fire control in Russia, showed that solutions of these chemicals did not form a film when the water was evaporated. So they do not operate in this way. The author thinks it is unlikely that this factor can play an important role in the chemical control of forest fires. Nevertheless, he is much interested in the use of viscous extinguishers in the U. S. which may operate in part in this way.

(4) *The Formation of Stable Chemical Compounds with the Fuel, Preventing Access of Oxygen to It*

This factor is significant for phosphoric acid which forms esters with cellulose groups on the surface when heated. This is evidently the factor that makes monammonium and diammonium phosphates effective in recent forest fire fighting practice in the U. S. The effect is nearly equal to that of cooling, according to experimental data presented. The ammonia escapes on heating so does not reduce the number of fire acid groups. Other basic phosphate salts such as sodium or potassium are more stable and so much less effective.

(5) *Inhibition of Reactions in the Gas Phase*

The hypothesis here is the formation of relatively inactive radicals which neutralize active radicals and thus break the chain.

The possible use of inhibitors in forest fire fighting was illustrated by experiments. The inhibitors consisted of carbon tetrachloride (30 per cent) and solutions of calcium chloride or magnesium chloride with addition of an emulsifier to produce a homogeneous emulsion. This mixture was over twice as effective as the same volume of water. Two-thirds of the effectiveness was ascribed to the inhibition effect, one-third to cooling effects.

There was no reference to the extensive recent research on inhibitors in the U. S.

(6) *Chemisorption of Various Substances on Coals, Preventing the Access of Oxygen To Them.*

The adherence of gas molecules to the surface of solids in such a way that a weak bond is formed is termed physical adsorption. In chemisorption the bond is stronger and can be detached only at high temperatures as illustrated by chemisorption of oxygen on carbon.

That such a process can play a part in extinguishment of forest fires in the future is illustrated by experiments of N. N. Krasavina of Russia in 1959. These were with chemisorption on coal at different temperatures of phosphorus oxychloride, dibromomethane, carbon tetrachloride, and dichlorethane. Dibromomethane showed the greatest chemisorption followed by phosphorus oxychloride, carbon tetrachloride, and last, dichlorethane. However phosphorus oxychloride had the greatest stability.

Experimental data is not quoted though it is said to illustrate that extinction of fire by this process is entirely possible. No field tests have yet been conducted.

(7) *Distribution of the Extinguishing Agent on the Surface or in the Volume of the Burning Fuel*

Though this discussion is directed toward matching the extinguisher to the fire, it is chiefly confined to the subject of wetting agents. It is pointed out that wetting agents function chiefly though reducing the waste of water or other liquid extinguisher. The advantage is considered best for low intensity fires.

Conclusion

The future prospects of application of each of these processes in forest fire fighting is analyzed. The author considers that the potential of cooling has already been fully developed. That isolation of the fuel by creating a layer of gases has little promise outdoors. He is much interested in the formation of a liquid or solid film by use of viscous solutions as being developed in U. S. practice, but feels that much research is still needed. Besides the use of salts of phosphoric acid to form stable compounds with the wood surface, the behavior of haloanhydrides of this acid and other active substances should be tested on burning wood. He believes that the high fire extinguishing properties of oxychloride may have a bearing on this process. He considers the inhibition of flame very promising and thinks attention should not be limited to the halogen derivatives but should also be directed to the amino compounds and phenols, and to the heteroorganic compounds, in particular organic phosphorus, organic silicon, etc.

He regards chemisorption as potentially the most attractive since it would stop generation of heat at its source, but the least is known about application of this process.

CALORIFIC VALUE OF CERTAIN VARIETIES OF FOREST FUELS—

N. G. Gorbatova

The author carried out tests of the calorific value of various forest fuels by means of a bomb calorimeter. These were in an "absolutely" dry state. Typical values obtained in calories per gram were:

Sphagnum moss	3770
Fern	4040
Dry grass	4100
Fir twigs	5250
Spruce twigs	4900
Pine twigs	5210

After extraction of resin from coniferous needles they then gave calorific values typical of grass and other nonresinous fuels, though this varied with the solvent used.

The resins extracted gave high calorific values ranging from 7500–8500 cal/g, with spruce resin somewhat lower than pine resin. Calorific variations in all coniferous fuels were closely associated with resin content.

Subject Headings: ***Fire, danger rating, in USSR; Fire resistance, of trees in Tiaga Zone, USSR; Forest fire, effect of topography and solar radiation on; Extinguishment, mechanisms in fires; Fuel, calorific values for forests.***

A. A. Brown

Mitchell, D. W., Nagy, J., and Murphy, E. M. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Rigid Foam for Mines," *Bureau of Mines Report of Investigations 6366* (1964)

This report describes the results of a Bureau of Mines study of the potential uses of urethane foam in mining operations. A mine operator, wishing to use this foam, can determine the correct chemicals, equipment, and procedures from the information and procedures presented.

Urethane foam, a tough cellular material, is produced when two liquid chemicals, a resin and an isocyanate, are mixed together in the presence of a foaming agent and a catalyst. During the chemical reaction, gas bubbles expand the mixture up to 30 times in volume. The foam cures within seconds, adheres to most mine surfaces, has low thermal conductivity, and is resistant to the transmission of air and water vapor.

In this study, the foam ingredients were mixed in a nozzle and sprayed as fine droplets onto a surface. The chemical reaction took place on the sprayed surface. Various types of spray equipment for applying foam are discussed near the end of the report.

Potential uses included sealing ribs and roof from mechanical and chemical decay; reduction of air leakage through stoppings, overcasts, doors, bulkheads, and fire seals; insulating the ventilating air from heat and moisture transmitted from the walls and roof; and controlling water efflux from mine surfaces.

The foam is easy to apply on unprepared surfaces, it expands to seal joints and cracks, and appears to have good stability. It also provides a quick safe method for constructing fire seals. The authors report that an effective seal was constructed in less than one man-hour by spraying foam on fiber glass or brattice cloth. By comparison, an equivalent seal constructed of concrete blocks and sealed with plaster would take from 15 to 20 man-hours to build.

The physical properties of urethane foam discussed in this report included cell structure, stability, adherence to surfaces, resistance to transmission of air and water vapor, thermal conductivity, and potential fire hazards.

Foam of a density from 2.5 to 3.5 lb/cu ft has a thermal conductivity of 0.16 Btu/in/sq ft/hr °F and is therefore a very good thermal insulator.

The fire hazards of foam which can result from improper formulation, inadequate mixing, and incorrect application are:

1. flame penetration through foam to underlaying combustibles;
2. flame spread across extensive foamed surfaces;
3. thermal deformation and noxious gas evolution;
4. spontaneous ignition.

Standardized testing procedures are presented for evaluating flame penetration and thermal deformation properties. Inclusion of flame inhibitors in the chemical formulation provide the best resistance to flame penetration and thermal deformation. Several inhibitors were examined and their effectiveness was evaluated.

Spontaneous ignition is preventable by proper mixing and by holding foam thickness to less than six inches.

Isocyanate vapor evolving from heated foam is irritating but its concentration is insufficient to be toxic. Burning of foam releases both isocyanate vapor and carbon monoxide; the concentration of carbon monoxide becomes toxic before that of the vapor.

Flame spread can be prevented on foams having an ASTM flame spread index of 140 or less by applying a protective coating of fire-retardant paint, sodium silicate, or water emulsion latex.

Subject Headings: *Fire hazards, from urethane foam; Mines, use of rigid foams in; Foam plugs, use in mines; Combustion products, hazards from urethane foam.*

A. W. McMasters

Phillips, C. B. (California Division of Forestry, Sacramento, California) "Testing CMC-Thickened Water as a Fire Retardant," *California Division of Forestry Fire Control Experiments Number 2* (February 1961)

One of the chemical additives for water in forest and grassland fire fighting is sodium carboxymethyl cellulose (CMC). This progress report concerns results of tests in 1960 on grass plots treated with CMC solutions, plain water, diammonium phosphate–CMC solutions and diammonium phosphate solutions.

CMC has several advantages. It is easy to handle and mix with water, is nontoxic to plant and animal life, and gives a high viscosity solution with relatively small amounts. The tests carried out showed that its viscosity decreased rapidly when the solution was stored in contact with galvanized surfaces and that at summer temperatures of 80° to 100°F bacterial action reduced the viscosity drastically in 5 to 6 days. Preservatives such as formaldehyde delayed the onset of decomposition, but could not prevent it. The obvious solution of mixing just prior to use is stated to be one of the aims of trials in 1961.

The grade of CMC used was du Pont S75 XH at 20 lb in 400 gal of water. This gave a solution of initial viscosity 250 to 300 centipoises. This solution can be readily pumped, but the high friction loss limits the hose length to 200 to 300 feet.

The tests were made on light grass plots at Cathay in Mariposa county. Each plot was approximately 20 ft wide by 15 ft long. A line 2 ft wide was treated at one end of each plot with 4 to 6 gal of the retardant. The solutions used were plain water, 6-day old CMC (viscosity$\approx$1/4 of fresh solution), fresh CMC, 12 per cent diammonium phosphate in each of the CMC mixes and 12 per cent diammonium phosphate in water. The air temperature during the test varied from 80° to 88°F and the relative humidity from 35 to 21 per cent. The plots were on a gentle slope and a light 3 mph wind upslope was blowing during tests. The treated plots were allowed to dry for 1, 2, and 3 h before burning.

The results showed that water and CMC thickened water were successful in preventing fire spread after 1 h of drying, but that after 2 h of drying neither was successful. The grass treated with the low viscosity CMC–diammonium phosphate solution would not support combustion even after 24 h drying, whereas the higher viscosity CMC–diammonium phosphate mixture only moderately retarded the fire after 1 h of drying. This may have been due to the method of mixing used in the latter case.

On the basis of these and other tests in Mariposa county in 1960, this grade of CMC appeared at least as good as plain water in suppressing fires, was much better than water in preventing rekindling in grass fires and provided good wet-lines from which back firing could be done with greater security.

Subject Headings: ***Fire retardants, test of sodium carboxymethyl cellulose (CMC); Fire retardants, test of diammonium phosphate.***

M. G. Perry

Pryce, J. N. (Canadian Underwriter's Association, Montreal, Canada) **and Cole, A. H.** (Reed, Shaw & McNaught, Montreal, Canada) "Wood-Chip Pile Burning Tests at the Restigouche Mill of Fraser Companies Limited," *Pulp and Paper Magazine of Canada* **64**, 389–399 (1963)

The pulp and paper industry lacks sufficient knowledge of fire hazard associated with piles of wood chips (the raw material of paper) stored in the open. The objective of these tests was: (1) to obtain data on fire potential and burning characteristics of chips piled in the open and accidentally ignited; (2) to test the efficiency of selected methods of fire control; (3) to determine the extent of contamination of the remaining chips after either a surface or a penetrating fire.

The tests were planned to demonstrate on one small pile and two full-scale large storage piles how fires from several possible causes might start, spread, and be suppressed. The chips ranged in size from those that pass a $\frac{1}{4}$ in. screen to those that pass a $1\frac{1}{4}$ in. screen. Tests were not replicated. On the two successive testing days, the chips on the surfaces of the piles, as well as those beneath, contained too much moisture to allow either ready ignition or moderate rate of spread. The two large piles were formed outdoors in early summer. The last rain occurred three days before the October 11 and 12 tests, but on the test days the relative humidity at 2 p.m. was more than 70 per cent, there was practically no sun and the temperature averaged about 45°F for the day.

Ignitions from an encroaching grass fire, from flying brands, and from an overturned bulldozer working on the pile were simulated respectively by a fire in a 1 foot layer of shavings adjoining the pile, burning charcoal briquettes, and 5 gallons of burning fuel oil spilled on the pile. None of these produced a fire that spread appreciably in the chips.

The authors concluded that a high moisture is normal for chips within a few inches of the surface in such piles and that a fire would spread very slowly through dry chips 1 to 2 inches deep. Such fires can be extinguished with a small quantity of water. They recommend low velocity fog applicators to avoid mixing the charred with the unscorched chips.

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

W. G. Morris

XIV. Miscellaneous

Joint Fire Research Organization (Boreham Wood, England) "Fire Research 1963," *London: Her Majesty's Stationery Office*

The Report of the Director of the Joint Fire Research Organization, Boreham Wood, England should be required reading for anyone interested in the following questions: (1) What are some of the important current scientific and engineering research topics in the fire field? (2) How should an Annual Report be organized and written so as to be of greatest usefulness to the reader? (3) How is it possible to do good work with a relatively small investment of people and funds? The answers to all three questions are to be found in "Fire Research 1963."

The Joint Fire Research Organization, at the end of 1962, was modestly staffed with 133 employees, counting Director and Temporary Storekeeper. A Professional Staff of half that number was grouped administratively in 5 divisions (Chemistry and Chemical Engineering, Extinguishing Materials and Equipment, Operational Research and Intelligence, Ignition and Growth of Fires, Building Materials and Structures). The Director's Report lists their accomplishments somewhat differently, i.e., Studies of Outbreaks of Fires; Ignition and Growth of Fires; Structural Aspects of Fires in Buildings; Detection, Extinction and Study of Explosions; Special Hazards; Special Investigations and Technical Inquiries.

Among the thirty projects under active investigations several deserve a more detailed discussion: Under the direction of P. H. Thomas the aerodynamics of buoyant flames is being investigated in detail, with particular attention to the flow of gases into the combustion zone, the entrainment of air into the convection column and the interaction of several fires, and the effects of a cross-wind on fire behavior. The correlations, together with the data of Putnam, of Fons, and estimates from large-scale fires give a reasonable estimate of flame height as a function of burning rate and size. Direct measurements of air inflow rates, velocities in the burning column, and of heat transmission within the flame are being undertaken in order to assess the factors that determine the burning rates of various fuels and fuel arrangements.

Quantitative results are presented for the effectiveness of sprinklers mounted in a variety of ways in compartments of differing areas and heights. By varying the heat input rate of crib fires sprinkler performance was evaluated in detail. If the sprinkler head is located directly over the fire, the heat output required for operating the device is proportional to $(\text{ceiling height})^{\frac{5}{2}}$. If the head is located off-axis a more complex relation is obtained for low ceiling heights. Such studies should be of considerable value for rational design of sprinkler location, spacing, and water flow requirements.

Development work has proceeded on the use of turbojet engine exhausts to generate large volumes of nearly inert gas and foam. Large-scale tests in compartments with open windows, when the inerting gas was introduced on the ground floor, showed the effectiveness of the technique in extinguishing fires in upper storeys. In conjunction with high-expansion foams a promising new fire-fighting tool is becoming available.

Model experiments are in progress on the most effective means for removing smoke-laden gases from enclosures. Adequate venting techniques can reduce the rate of fire spread and improve fire-fighting operations. The combination of large roof vents (by using plastic materials of low melting point) with water curtains may prove advantageous in large single-compartment buildings.

The excellence of the current state of fire research in Great Britain, unmatched anywhere, makes it mandatory to study the report with particular care. It would be wrong to say that all the rewarding fire research problems are under investigation at Boreham Wood. Yet, it is difficult to find many areas in which there is not some expertise in the Joint Fire Research Organization or in groups with which they are closely allied. One of the strengths of the program is that despite the unavoidable engagement in much ad hoc testing and evaluation of materials and of structures, an effort is made to find the underlying connections among the observables and to establish design rules based on sound scientific concepts and engineering correlations. There are many research problems in which the Boreham Wood work is at the forefront, to whit, the aerodynamics of buoyant flames, the movement of gases through structures or the development of sophisticated fire-fighting equipment.

The technical progress is clearly summarized so that no doubts exist about the status of projects, the intent behind their execution and the level of effort [a detailed summary can be found in D. I. Lawson's Review on "Research in Fire Protection," *Fire Research Abstracts and Reviews* 6, 193 (1964)]. In addition, a careful assembly of statistics on fire occurrences and losses, which includes a sufficient number of years to establish trends, completes this impressive volume. The staff publishes prolifically in technical journals (37 reports in journals, 26 Fire Research Notes). A valuable feature of publicizing the accomplishments of the organization are 25 lectures, given to a wide variety of audiences.

A distinguished group of scientists and assessors from various Government agencies, directed in 1963 by the late Professor F. H. Garner, examines the work of the Establishment at periodic intervals. This Fire Research Board convenes special committees, with joint membership from extramural establishments and the Fire Research Organization. Does not a Committee on the Modeling of Fires augur well when it includes among its members Professor M. W. Thring, Sir G. I. Taylor, Messrs. D. I. Lawson and P. H. Thomas? Other committees on Industrial Fires and Explosions and on Aircraft Fires are staffed equally well. Some research work, best suited to university laboratories, is carried out on contract. Thus, a lively flow of information in many directions has been established. The technical community and the public are kept informed of problems as well as solutions.

Almost the only question unanswered by the Report is how this remarkable organization came into being, its current funding and its plans for the future. As for its past, the reader is referred to the review in *Fire Research Abstracts and Reviews* 1, 149, 1959, on "Fire Research in the United Kingdom." A union between the venerable Fire Officers' Committee (an association of insurance companies founded in 1868) and the appropriate section of the Department of Scientific and Industrial Research occurred in 1946 to pursue the common aim of carrying out research and development in fire protection along modern lines. The Joint Fire Research Organization, partly supported by private funds and partly by public money, was the result.

Subject Heading: ***Fire research, in United Kingdom.***

W. G. Berl

Safety in Mines Research Establishment (Sheffield, England) "Safety in Mines Research, 1963," *London: Her Majesty's Stationery Office*

The Safety in Mines Research Establishment has continued its wide-ranging attack on the many safety hazards connected with coal-mining. In particular, the ignition of explosive mixtures by sparks (both electric and frictional) and by the hot combustion gases from explosives were investigated, as was the aerodynamics of wave propagation in the complex feed-back systems in which coal dust is dispersed into air by a pressure wave that is supported, in turn, by the coal dust-air combustion process.

In addition, means for dissipating methane "roof layers" have been studied in model and full-scale experiments. Interesting boundary layer flow and combustion problems have been uncovered concerning the mixing and flame propagation in unmixed methane-air layers. In particular, ventilation requirements have been assessed for a variety of roadway sizes, slopes, and roof roughnesses. A "layering index" has been defined as:

$$l=\sqrt[3]{U^2/500cA^{\frac{1}{2}}},$$

where U is the ventilating velocity in ft/min, c the average methane concentration, and A the width of the tunnel in ft². Values of the "layering index" below 2 gave the possibility of forming hazardous layers of methane. (A detailed discussion is available in *Research Report 222* "Experiments on methane roof layers: Single sources in rough and smooth tunnels with uphill and downhill ventilation, with an appendix on experimental techniques", by S. J. Leach and L. P. Barbero.)

Subject Heading: ***Mines, research on fire, in United Kingdom.***

W. G. Berl

Laderman, A. J., Urtiew, P. A., and Oppenheim, A. K. (University of California, Berkeley, California) "On the Generation of a Shock Wave by Flame in an Explosive Gas," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 265–274 (1963)

The evidence provided in this paper showed experimentally and analytically that a laminar flame could generate a shock front quite early in the course of its initial acceleration.

This series of experiments was a part of the program concerned with the generation of pressure waves at the flame front and the development of the flow field ahead of the flame. It was carried out with stoichiometric mixture of hydrogen and oxygen in a rectangular cross-section detonation tube. Ignition was effected by a hot-wire glow-plug, and the process was observed by means of streak schliren photography, interferrogram, and pressure measurements.

Photographs, in agreement with the space-profile transformed from the pressure records obtained simultaneously, displayed that a shock of strength corresponding to Mach number of 1.5 had been formed. The flame at this stage of the process was wrinkled laminar and propagates at a velocity only a few times larger than the normal burning speed.

A theory was then developed for the formation of the shock wave at this stage by referring to a schlieren record obtained earlier in the program, in which the ignition process was initiated by spark discharge and was tractable right from its inception. The basis of the theoretical model was originally suggested by Chu[1] where the flame was treated as an advancing plane heater. The compression wave and flame acceleration computed on this basis had been found to be in good agreement with the experimental results.

The analysis was extended to determine the position where the shock wave was formed in the simple wave ahead of the flame by first obtaining the equation of motion for a hemispherical flame front (the surface area of it was adjusted for the rectangular cross section of the tube), which led to the equations for the world-lines of the flame and the simple compression waves. The condition for a shock wave to occur was, then,

$$(\partial x/\partial u)_t = 0.$$

Three characteristics lines on the time–space diagram were of particular interest during this initial acceleration process. They represented respectively the sound waves generated at ignition, and at times when the flame front reached the two metal walls (1 inch apart), and later the two windows (1½ inches apart) of the detonation tube. The results of the analysis in the two regions bounded by these characteristics lines agreed well with the schlieren photograph and the pressure records, and led to the conclusion that shock was formed inside the simple waves generated by the flame front rather than at its leading edge.

Reference

1. Chu, Boa-Teh: *Fourth Symposium (International) on Combustion*, pp. 603–612, The Williams and Wilkins Co., Baltimore, 1953.

Subject Headings: ***Explosion, generation of shock waves, by flames; Flame, transition to detonation.***

A. C. S. Ma

Nagy, J. and Mitchell, D. W. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Experimental Coal-Dust and Gas Explosions," *Bureau of Mines Report of Investigations* 6344 (1963)

The purpose of this report is clearly stated in the Introduction: to present information on the behavior of coal dust and gas flames under controlled conditions that can then be used "to assist in the difficult task of interpreting observations made after an explosion in an operating coal mine when detailed evidence is collected to establish the cause and factors affecting ignition and propagation." To do this, the authors have collected and collated in this report the condensed essence of conclusions drawn from the half-century of continuous experimentation on mine explosions (and earlier).

The contents of the report are divided into two: the first part is on coal-dust explosions; the second part on gas explosions. Topics considered in the first section include: consideration of the circumstances and reasons for formation and deposition of coke; occurence of soot; indications of flame and its terminal point; incidence of fire (ignition of wood, oils, paper, clothing, etc.); movement of air; mechanism and transport of dust; examples of explosion damage illustrative of explosion violence; and factors limiting flame propagation.

In the second section, gas explosions, the topics include: a brief statement, with comments, of the energy and temperature required for ignition; the influence of the point of ignition on the severity of the explosion; the variation (with a graph) of the methane low limit plotted against coal-dust concentration in a mixture of the two (shown as being linear); the hazard of layered gas; a listing of the explosion pressures developed under various conditions of flame volume and gas concentration; the influence of gas volume on flame length, and on flame velocity; the difficulties of quenching a gas explosion; and, finally, some comments on the circumstances under which a coal-dust explosion will and will not be initiated by a gas explosion.

There are 26 figures, including 14 photographs that are well illustrative of the points made in the report. Figure 18, showing the effect of the "backwash" on contraction due to cooling behind the flame, with debris carried backwards to pile up against a blind face, is particularly striking.

Data in the sections listed are already too detailed and condensed to be usefully summarized further; readers interested in the further detail are referred to the report. However, since the report is primarily a summary of past conclusions, readers experienced in the subject will find few surprises. Its value will be chiefly as a useful listing of practical points as an *aide mémoire* to the experienced reader; and as a summary introduction to the subject for newcomers. The only criticism the reviewer has is the too general nature and paucity of references (totaling 20) for following up the origins and details of the work on which the conclusions are based.

Subject Headings: ***Explosion, gas; Explosion, coal dust; Coat dust, explosion of; Mines, explosion, coal dust; Mines, explosion, gas; Ignition, of gas; Ignition, of coal dust.***

R. H. Essenhigh

Roth, E. M. (Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico) "Space-Cabin Atmospheres. Part II-Fire and Blast Hazards," *National Aeronautics and Space Administration SP-48* (1964)

This report is primarily a literature review of data bearing on fire hazards in space cabins. Of the seven chapters, the first four are general reviews of combustion phenomena related to these design problems. The remaining three chapters deal specifically with particular problems of space cabins.

Flames, detonations, ignition and flame suppression are reviewed in the first chapter. The main emphasis in this section is on ignition. Environmental factors are then discussed. These include effects of temperature, pressure, gas velocities, gravitational fields and inert diluents in the space cabin atmosphere. The zero gravity conditions of a space cabin would perhaps result in a less severe fire, although extinguishment by a conventional technique such as a water spray might be ineffective.

Chapter 2 reviews data on the burning of fabrics, paper, fabrics treated with retardants, and plastic foams in atmospheres containing varying amounts of oxygen. Ignition temperatures, and flame speeds of gases and liquids (principally hydrocarbons) in various atmospheres are briefly reviewed in Chapter 3. The influence of pure oxygen atmospheres at various pressures on the breakdown of electrical wire insulation is the subject of Chapter 4. The toxicology of burning insulation (polyvinyl chloride, Teflon and silicone rubber) is discussed in some detail.

A brilliant oxidative flash is produced when a hypervelocity small particle penetrates the wall of a vessel containing oxygen. A rapidly rising pressure pulse of short duration accompanies this flash. In a space-cabin such a potential catastrophy might occur if a meteroid penetrated the wall of the cabin. Burns, eye damage and blast effects which could happen in the event of meteroid penetration are discussed in Chapter 5.

In Chapter 6, fire prevention and extinguishment are reviewed. Lists of potentially hazardous materials are given. In particular, properties of liquid rocket oxidizers and fuels are tabulated. Ignition sources, and especially hazardous equipment, are listed and discussed. Physical arrangements to minimize fire hazard are described in general terms. Fire detectors of various kinds are compared in a qualitative way. Various properties of chemical fire extinguishing agents (i.e., halomethanes, CO_2) are tabulated. A unique extinguishing technique is possible in a space cabin—the atmosphere can be dumped to the outside.

Two fires in 100 per cent oxygen atmospheres are described in some detail in Chapter 7. This experience and the preceding material are evaluated and the author concludes the safest cabin atmosphere is probably that corresponding to an 8000 ft air atmosphere.

Subject Headings: *Explosion hazards, in flight vehicles; Fire hazards, in flight vehicles; Hazards, in flight vehicles, explosion; Hazards, in flight vehicles, fire; Oxygen, influence on fire; Toxicology, of burning insulation; Fire prevention, in flight vehicles; Fire, extinguishment, in flight vehicles; Fabrics, burning; Gravity, zero, effect on fire.*

P. R. Ryason

Rothbaum, H. P. (Department of Scientific and Industrial Research, Wellington, New Zealand)* "Self-Heating of Esparto Grass," *Journal of Applied Chemistry* **14**, 436–439 (1964)

Rothbaum, studying hay, advanced the theory[1] that spontaneous ignition of moist biological materials permeable to air is most strongly favored over a narrow range of initial relative humidity between 95 and 97 per cent. Since esparto grass, like hay, is a cellulosic material that holds considerably less moisture than hay at the same R.H., study of self-heating of esparto grass affords a crucial test of the theory.

A 2-liter flask was filled (230 g dry matter) with humidified Moroccan esparto grass cut to 2 cm lengths. Samples were humidified at different relative humidities

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between 50 and more than 99 per cent. Adiabatic heating was effected by the methods previously described, using the apparatus of Walker and Harrison.[2] The rate of production of carbon dioxide was measured.

Esparto grass humidified at 89 per cent R.H. (initial moisture 20 per cent of dry weight) showed no self-heating, lost no moisture, and had peak microbial CO_2 output of 10^{-8} g/sec g of dry matter. Grass humidified at 93 per cent R.H. (initial moisture 23 per cent) attained an adiabatic temperature rise to about 60° after 7 days, evolved 4.9×10^{-8} g CO_2/sec g, and had maximum heating rate of 2.3×10^{-4}°/sec. Grass humidified at 96 per cent R.H. (initial moisture 26 per cent) attained about 65° within 4 days, evolved 8.8×10^{-8} g CO_2/sec g, and had maximum heating rate of 2.8×10^{-4}°/sec. Grass humidified at 99 percent R.H. (initial moisture 45 per cent) attained about 65° within 3 days, evolved 15.5 g CO_2/sec g, and had maximum heating rate of 5.1×10^{-4}°/sec. But grass humidified at the intervening 96 per cent R.H. reached 90° within 9 days, after which the air passing through external humidifiers held at 90° slowly dried the grass, temperature rose to 195° at which point the bath was put on thermostatic control and the central temperature in the flask rose to 220°. At the end of this test the grass was black, had lost 18 per cent of its dry weight, and had evolved about 11 per cent of its dry weight as carbon dioxide.

A separate test showed that there is no essential difference in the rate of chemical heating of microbially heated grass, and grass that has been artificially heated to 90°.

The mechanism of self-heating in esparto grass is essentially the same as in hay, and further chemical heating is most likely to occur at R.H. between 95 and 97 per cent, in conformity with Rothbaum's theory. In the critical region the moisture content was between 25 and 27 per cent, which is a narrower range than for hay. Microbial heat outputs from esparto grass examined in these tests are less than those of hay in equilibrium with the same relative humidity.

References

1. Rothbaum, H. P.: *J. Appl. Chem. 13*, 291 (1963).
2. Walker, I. K. and Harrison, W. J.: *N.Z.J. Agric. Res. 3*, 861 (1960).

Subject Headings: ***Hay, self-heating; Ignition, spontaneous, of hay.***

F. L. Browne

Varley, R. B. and Maatman, G. I. (IIT Research Institute, Chicago, Illinois) "Shelter Fire Vulnerability—Specific Fire Limiting Activities for Occupants," *Summary of Research Report for Office of Civil Defense Contract No. OCD-OS-62-210* (1964)

This report is concerned with the countermeasures to be undertaken by occupants of fallout shelters in the event of fires.

Fallout shelter occupants will be exposed to fire from several sources. Combustibles in buildings may be ignited by the nuclear weapon either directly by the thermal pulse, or indirectly as a result of broken gas equipment, shorted power devices, etc. During the fallout period, shelter buildings can be ignited through their proximity to adjacent burning structures. Accidental fires may occur within the shelter buildings themselves.

A previous study of existing shelter buildings indicated that fire-resistant construction predominates. It suggested further that a self-help level of extinguishment of incipient fires, using portable extinguishers, would be successful in most cases. However, most structures are located near or within the principal business districts and ignitions from nearby burning buildings were found possible in about one-half of the surveyed buildings.

Operational guidance criteria were developed for the selection and upgrading of fallout shelter buildings. In that connection, three levels of building-fire performance were established to be used to identify the relative fire vulnerability of shelter buildings. The three levels consisted of (1) fire-limiting, (2) suppression-dependent, and (3) untenable.

Fire-limiting buildings consisted of those in which fully developed fires, originating outside of shelter floors, will be confined to the floor of origin. The spread of smoke and toxic gases from fires to the shelter area in such buildings must be kept below critical limits. This could be done with the use of special materials and devices to control the spread of smoke and gases.

Suppression-dependent buildings represent the intermediate level in which the building structure cannot satisfactorily resist a spreading fire, but where it is reasonable to assume that all incipient fires can be located and extinguished before they present a danger to the shelter occupants.

Untenable buildings consist of those in which incipient ignitions could be expected to develop rapidly into fires of such magnitude that they could not be controlled and extinguished through the use of portable equipment by shelter building occupants. In addition, buildings containing combustibles located in concealed spaces or arranged in a manner making them relatively inaccessible are also included in this classification.

To direct fire control activities, the shelter organizational structure should include a shelter fire chief having appropriate authority. He should be selected from persons familiar with the shelter buildings. He should receive training in fire detection, prevention, and extinguishment. He should participate in pre-emergency planning for fire control and shelter building equipment. During the attack period, and the subsequent internment period, he should be charged with the manning, instructing, and supervising of fire-fighting and fire-watch teams.

For each shelter building, a shelter fire-control plan should be developed that provides for the preparations in the post-alert, pre-burst interval, and for the post-attack fire control operations. As a basis for developing the plan, a survey should be made of the building to determine (1) areas capable of withstanding unsuppressed burnout, (2) measures needed to prevent spread of smoke and gas into shelter areas, (3) fire exposure from surrounding buildings, (4) ignition preventative measures against the weapons' thermal pulse, (5) controls needed for existing utility and process systems, and (6) required fire-control equipment.

For fire suppression by self-help teams, five-gallon stirrup pumps and breathing masks are recommended.

One mask and extinguisher should be provided for each 1250 square feet of shelter area, but there should be at least four per shelter. In non-shelter areas, one mask and extinguisher should be provided for each 2500 square feet of suppression-dependent area. Areas capable of withstanding unsuppressed burn-out may have one mask and extinguisher for each 5000 square feet. Cover material should be provided for windows to prevent ignition from the thermal pulse or from adjacent burning buildings. Where necessary, materials to prevent spread of smoke and gas should be supplied.

All personnel engaged in fire fighting should be given training which includes actual suppression of interior fires with portable extinguishers and masks, as well as basic instruction in the use of fixed extinguishment systems which may be found in shelter buildings. As the manpower needs of fire-control programs of shelter buildings will be very large, an organized training effort on a national scale is needed. This should utilize the public fire service as far as possible.

A continuing program of fire surveillance throughout each shelter building will be necessary in the post-attack period, since all fires must be controlled in the incipient state. Manpower required for the fire watch depends on the number of separate tours and on the condition of personnel. The number of tours in turn depends upon the pace, duration, and frequency of travel required on each. Tour frequency should be based on the magnitude of the fire hazard within the building. A method has been developed for determining the frequency, duration, and manpower requirements of the fire-watch tour.

The recommendations for operational guidance are: (A) All presently stocked shelter buildings and any future selected locations should be surveyed from the standpoint of their potential fire vulnerability in accordance with previously mentioned criteria; (B) A plan for fire-control operations should be developed by the fire chief for each shelter building, which should include both pre-attack and post-attack activities; (C) Develop a nationwide program of fire instruction, including actual extinguishment work on simulated interior fires requiring the use of smoke masks.

Subject Headings: ***Fire protection, in shelters; Shelters, vulnerability of.***

L. A. Povinelli

Books, Pamphlets, and New Journals

Comments—ROBERT M. FRISTROM, *Editor*

NFPA Technical Reference Library. "Library Classification System for Fire Protection," May 18, 1964, National Fire Protection Association (International), 60 Batterymarch Street, Boston, Massachusetts 02110 33 pp. $1.75

This booklet outlines a classification schedule for publications in the field of fire protection engineering. The system was devised by and used in the NFPA reference library.

"The structure of the system is based on the assignment of a numbering and lettering arrangement corresponding fundamentally to the sections, chapters, and paragraphs in the *NFPA Fire Protection Handbook*, 12th edition, 1962. Provision is made for an expansion, further subdivision, or realignment of existing categories according to advances made in the state of the art." Twenty-four major section headings are used and these are sub-divided into two thousand subheadings.

This should be a useful classification for specialized collections of fire-related publications. It is not directly related to either of the two major library cataloging systems, and, therefore, integrating the classification into existing systems would require recataloging by the librarian. It could, however, be used directly by a library whose collection consists principally of fire-related material or it could be added as a subsidiary number to either Dewey Decimal or Library of Congress cataloging systems.

Fire Journal. National Fire Protection Association (International), 60 Batterymarch Street, Boston, Massachusetts 02110. Bimonthly. $8.00 per year (Successor to *Quarterly of the National Fire Protection Association*). First issue May 1965, labeled Vol. 59, No. 3.

This is the official organ of the National Fire Protection Association. It is the successor to the *Quarterly of the National Fire Protection Association*. The content is similar to that of the *Quarterly* but the new publication is bimonthly, with a new, larger format.

Fire Technology National Fire Protection Association (International), 60 Batterymarch Street, Boston, Massachusetts 02110. $10.00 per year. Quarterly, Vol. 1, No. 1, February 1965.

This new publication is intended to cover the engineering and practical aspects of fire problems. Although the emphasis is on the technology rather than the scientific aspects of the problems, it is a pleasure to report that the scientific content of the articles in the first issue is not at all negligible. The scope can be best judged by the table of contents of the first issue, which is given below.

The NFPA and the editor of *Fire Technology* are to be congratulated on the quality and the appearance of their first two issues. If, as is to be hoped and expected, the quality is maintained, this journal will be an important source of information on the technology and science of fire.

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Factors Influencing the Use of High-Temperature Sprinklers—Miles R. Suchomel
Detonation Characteristics of Prilled Ammonium Nitrate—C. H. Winning
Ignition or the Flame-Initiating Process—Robert W. VanDolah, Michael G. Zabetakis, David S. Burgess, and George S. Scott
Smoke Detection by Forward Light Scattering—Walter M. Haessler
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Soviet Journal on the Combustion and Explosion Problems. Quarterly by the Siberian Branch USSR Academy of Sciences. First issue scheduled for 1965. Five rubles per year.

The Siberian Branch of the Academy published the following announcement concerning its new Journal:

"Our Journal will publish original papers, reviews, and short remarks on different questions concerning the physics and chemistry of combustion, detonation, and shock wave propagation in various media. The problems to be discussed are the following:

1. The Combustion Gasdynamics. Solid and Liquid Propellant Decomposition and Combustion Fundamentals.
2. The Explosion Hydromechanics. The Shock Waves Propagations and Properties in Various Media. Fast Hydrodynamic Processes.
3. High Temperature Thermodynamic Properties of Gases and other Continuum Media. Nonequilibrium Shock Waves Phenomena. Shock Wave Front Structure.
4. Reaction Kinetics of Combustion. Combustion and Detonation Ionization Phenomena. The Shock Wave Technique in Reaction Kinetics.
5. Shock Waves and High-Speed Processes in Plasma. Explosion Problems in Cosmic Gasdynamics.
6. The Technique of Physical Experiment in Combustion and Gasdynamics.

The Journal is meant for scientists, engineers, post-graduates, and students interested in the above-mentioned problems. The Journal is supposed to publish papers by foreign authors as well as those of USSR authors. The Journal will be published quarterly by the Siberian Branch USSR Academy of Sciences beginning with 1965 (in Russian). There is no page charge for publication. Contributors may send their manuscripts in any language. Manuscripts should be addressed to: Editorial Staff of the *Soviet Journal on Combustion and Explosion Problems*, Novosibirsk-72, USSR."

Robert M. Fristrom, *Editor*

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Volume 7 Number 3

Fire Research Abstracts and Reviews

Committee on Fire Research
Division of Engineering and Industrial Research
National Academy of Sciences—National Research Council

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
Washington, D. C.
1965

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

Library of Congress Catalog Card Number 58-60075 rev

Available without charge from the
Office of the Committee on Fire Research
National Academy of Sciences—National Research Council
Washington, D. C. 20418

FOREWORD

As the alert reader already will have deduced from the inside cover of the last issue, *Fire Research Abstracts and Reviews* is under the auspices of a reconstituted Committee on Fire Research. The editor joins the fire research community as a whole in expressing thanks to the retiring Committee members who have labored so diligently over the past ten years and in welcoming the new Committee with high hopes for the future. The members of the original committee were: Professor H. C. Hottel of the Massachusetts Institute of Technology, Chairman; Dr. W. H. Avery of the Applied Physics Laboratory, The Johns Hopkins University; Mr. Horatio Bond, Chief Engineer of the National Fire Protection Association; Mr. A. A. Brown, former Director of Forest Fire Research of the U.S. Forest Service; Professor Howard W. Emmons of Harvard University; Mr. Joseph Grumer, Project Coordinator of the Explosives Research Laboratory, U.S. Bureau of Mines; Mr. J. B. Macauley, former Assistant to the Director of Defense Research and Engineering, Department of Defense; Dr. W. T. Olson, Assistant Director of NASA Lewis Research Center; and Dr. A. F. Robertson, Chief of the Fire Research Section, National Bureau of Standards.

Many problems remain to be solved and the new Committee is attacking them with vigor. A two-day meeting was held in Washington, D.C., at the National Academy of Sciences on September 24 and 25, 1965. The first day was devoted to briefings by various Government agencies interested in fire research while the second day was devoted to organizational matters and a discussion of the scope and objectives of the new Committee. One of the first concrete accomplishments of the new Committee was the selection of thermal decomposition as a topic for a technical meeting.

Members of the new Committee are: Professor H. C. Hottel of the Massachusetts Institute of Technology, Chairman; Dr. Walter G. Berl of the Applied Physics Laboratory, The Johns Hopkins University; Dr. Perry L. Blackshear of the University of Minnesota; Professor Howard W. Emmons of Harvard University; Dr. Walter T. Olson, Assistant Director of NASA Lewis Research Center; Mr. John Rhodes, Director of Engineering and Research, Factory Mutual Engineering Division; Mr. George M. Tryon, Technical Secretary of the National Fire Protection Association; Dr. Richard L. Tuve, Head of the Engineering Research Branch of the U.S. Naval Research Laboratory; and Dr. Edward E. Zukoski of the California Institute of Technology.

Two meetings of interest to fire research workers have been scheduled. These are the Eleventh Symposium (International) on Combustion to be held in Berkeley, California, August 14–20, 1966, with sessions on mass fires, and the Spring Meeting of the Western States Section of The Combustion Institute to be held in Denver, Colorado, April 25–26, 1966, with sessions on fire research.

Robert M. Fristrom, *Editor*

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REVIEWS

FIRE ASPECTS OF CIVIL DEFENSE*

W. E. STROPE AND J. F. CHRISTIAN

Office of Civil Defense, Department of The Army, Washington, D. C.

This evaluation report is intended for ultimate use by civil defense officials and other interested persons as a summary of the best available estimates of the incendiary effects of nuclear attack. For this purpose, an effort has been made to summarize the state of knowledge in simple and direct terms and to relate this knowledge to current operational problems. In doing so, there is necessarily some loss in technical precision and detail on the one hand, and some inclusion of material that is not strictly needed for operations on the other. The latter is considered desirable, however, so that the important reasons for the incendiary behavior of nuclear weapons and the consequent threat to life and property are generally understood.

SUMMARY

This report describes the general dimensions of the fire threat resulting from nuclear attack, particularly as a result of ignition of thin materials by the thermal (heat) flash.

A review of the best available information on the thermal ignition capabilities of air-burst nuclear weapons with yields from 1 to 100 megatons (MT) indicates that thermal ignitions may occur, under average to good visibility conditions, at ranges where the blast overpressure is between 1 and 3 pounds per square inch (psi) with perhaps 2 psi as a reasonable estimator of the region within which ignitions may occur.

The severity of resulting fires and the likelihood of fire spread depends on the amount and spacing of combustibles within the ignition area. Mass fires are likely only in built-up urban areas rather than in suburban or rural areas. Thus the potential ignition areas cannot be considered as a single fire area "engulfed in flame" since the controlling factors are the occurrence and size of the combustible areas rather than the ignition range of the weapon.

Experience with large fires of the past shows that only a small portion of the population at risk are killed as a result of the fire. The rate of development of large fires has been sufficiently slow to permit control or movement of people to areas of relative safety. The most serious complication introduced by modern weapons is the threat of fallout that could hamper fire fighting or remedial movement.

In planning a fire defense program against the threat of nuclear attack, the reduction of fire vulnerability by removing or covering ignitable materials and by reducing the concentration of combustibles in cities is equally important as the development of a capability to control and extinguish fires.

INTRODUCTION

The incendiary potential of nuclear weapons that might be used in a future war has received wide attention in the past few years, particularly in debates over the

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merits of the fallout shelter program. The possible extent of serious fires following nuclear attack was a major topic in the hearings on H. R. 8200, the shelter development bill, before the Hebert Subcommittee of the House Armed Services Committee in June 1963.[1]* The information provided the subcommittee at that time by the Office of Civil Defense was the best then available on a subject that is, and has always been, beset with considerable uncertainty.

The Hebert Subcommittee hearings brought into sharp focus the wide range of possible interpretations of existing knowledge on the ignition of combustible materials by the heat flash of a nuclear detonation. It also dealt with the subsequent growth and spread of fires, and on resultant hazards and possible fatalities. The interest aroused by the hearings encouraged an extensive review of the nuclear fire problem within the Department of Defense and by outside groups. One such group was the HARBOR study project on civil defense, convened by the National Academy of Sciences in August 1963.[2]

These reviews, together with new experimental data, have resulted in some modification of earlier conclusions and a wider consensus among experts not only about the general dimensions of the problem but also concerning the areas of uncertainty that still persist. It is the purpose of this paper to summarize the state of knowledge on fire effects at the beginning of 1964 for the information and guidance of officials responsible for civil defense and public safety.

This review will discuss several key factors affecting the fire-making potential of nuclear weapons and the threat to a population whether in fallout shelters or not. In addition, measures to reduce the fire hazard and to control the extent of fire damage will be cited, both those requiring further research, development, and planning, as well as those that can be undertaken immediately.

A range of nuclear weapon sizes from 1 to 100 MT is reviewed to show the comparable effects of variations in yield. For the present and the near future, weapons of yields up to about 20 MT are considered feasible as offensive weapons against this country. Weapons of 100 MT or greater are not considered a significant threat, not only from the standpoint of efficiency of use but also largely because of the problems of delivery to the target.

IGNITION THRESHOLDS

One of the major factors affecting the fire-making potential of nuclear weapons is the amount of heat (thermal radiation) from a nuclear weapon burst that is required to cause ignition of combustible materials. This critical ignition energy, or ignition threshold, will depend largely upon the thickness of the combustible materials. Of concern are thin combustible materials, such as newspaper and drapes, which act as kindling fuels for heavier combustible materials. Thick combustible materials, such as wood siding on homes, cannot effectively be ignited by the thermal radiation from a nuclear detonation.

The ignition threshold is also dependent upon the rate at which the thermal radiation is delivered. For example, during a hot day the sun delivers about 700 cal/cm^2 to exposed materials on the earth's surface but does not cause ignitions because of the low rate of delivery. When a nuclear weapon is detonated in the atmosphere thermal radiation is emitted over a longer period of time for large yields than

* Numbers refer to notes at the end of this report.

TABLE I

Approximate ignition thresholds for several common kindling fuels exposed to low air bursts of nuclear weapons

	Ignition thresholds (cal/cm²)		
Kindling Fuels	1 MT	10 MT	100 MT
Newspaper, dark picture area, crumpled or folded sheets	7	11	25
Kraft corrugated paper carton (18 oz/sq yd)	25	38	50
Heavy dark cotton drapes (9 oz/sq yd)	18	34	50
White typing paper	30	50	80
Dry rotted wood (punk) and dry thin decidous leaves	6	8	30

for small ones. As the yield of a nuclear detonation is increased the ignition threshold for a given kindling fuel is also increased. Additionally, the ignition threshold is affected by the nature of the kindling fuel involved, the moisture content of the kindling fuel, and the orientation of the kindling with respect to the location of detonation.

Knowledge of the critical ignition energies for commonly available kindling materials has been obtained almost entirely from laboratory experiments in which relatively small samples are exposed to heat sources that are designed to duplicate the characteristics of the pulse from nuclear detonations. Differing estimates of the ignition threshold can arise among experts through the various interpretations that might be placed on the experimental results. Table I presents for several weapon yields the current best estimates of the critical ignition energies necessary to ignite some common kindling fuels.[3]

It will be noted that the values of ignition threshold for newspaper which has been widely used as representative of available kindling materials, are about one-half those cited during the Hebert Subcommittee hearings and about twice those then listed in the publication, "Effects of Nuclear Weapons." The estimates in Table I resulted from intensive review following the Herbert Subcommittee hearings and were reflected in part in the subsequent printing of the "Effects of Nuclear Weapons."[4]

ATMOSPHERIC ATTENUATION

A second major factor—possibly the most critical factor in terms of the ignition radius —is the screening effect of the atmosphere through which the thermal radiation must pass to reach materials on the ground. Examples of this effect are the decreased solar radiation reaching the ground because of smog, haze and clouds over cities, and the low intensity of the sun near the horizon. Information about the relative transmission qualities of various atmospheres has been limited to short distances of about one visibility range (the usual visibility range is about 10 miles in typical cities but can exceed 50 miles for a very clear day). There are also uncertainties due to inaccuracies in estimating visibility. Recent theoretical and experimental studies, however, have provided a somewhat better basis for usable estimates of atmospheric transmissivities of greater distances.

Because of current uncertainties in atmospheric transmission, estimates of the amount of thermal radiation reaching locations 20 to 40 miles from a nuclear detonation, especially in metropolitan areas, can vary by about a factor of 10. The estimates in the "Effects of Nuclear Weapons" represent the most conservative transmission theories; that is, they predict the greatest amount of energy to reach the kindling fuel. There has not been a sufficient accord, however, on an alternative prediction to permit immediate modification of the atmospheric transmission data in the "Effects of Nuclear Weapons."

During the HARBOR study the available experimental and theoretical information on atmospheric transmission was carefully reviewed and recommendations made. Following the HARBOR study further work was undertaken to develop an adequate answer for atmospheric transmission for burst heights below 30 miles.[5] Using these new formulations for transmission in conjunction with the ignition thresholds of Table I for newspaper, the ignition ranges shown in Table II are obtained.

TABLE II

Comparison of newsprint ignition radii and low blast overpressure radii

Weapon yield	Ignition ground radius (miles)		Blast ground radius (miles)		Height of burst (miles)
	Medium hazy day (6 mile visibility)	Clear day (12 mile visibility)	3 psi	1 psi	
1 MT	7	9	6	13	2
10 MT	16	22	13	28	5
100 MT	32	46	28	60	11

These numbers are not exact values but are indicative of the most probable ground radii for the various yields. The visibilities in Table II associated with the medium hazy and clear days are those as commonly observed. These visibilities are equal to approximately one-half the standard meteorological range which is defined in terms of visual threshold contrast of two per cent.

It will be noted that the ignition radius for air burst will be between the 1- and the 3-psi ranges depending on atmospheric conditions. Ignition effects could be further reduced by conditions of very low visibility, although they might also be enhanced for low air and surface bursts by reflection from overlying cloud cover.

MAXIMUM IGNITION RADIUS

The fire potential of a nuclear weapon has usually been considered a secondary effect and one that is not readily predictable. This problem of predictability is discussed later under Climate and Weather. Maximizing the thermal radiation area is a matter of complex interplays between height of burst, weapon yield and effects of changes in the thermal radiation phenomena. As the burst altitude is increased, the atmosphere becomes less dense and the effect is a shortening of the duration of the thermal pulse. The faster the radiation is delivered the lower the radiative losses. As a consequence, the ignition threshold is reduced as the altitude of detonation is increased, resulting in an increase in the ignition radius. Another major factor tending to increase the ignition radius is that the thermal radiation from a higher altitude burst passes through less atmosphere and so is subjected to less attenuation throughout the greater part of its path to the ground than the radiation from a low altitude burst which travels largely horizontally to the target area.

On the other hand, there are concurrent changes in the fireball characteristics since the whole phenomena of thermal radiation depends on the heating up of an air mass to incandescence by an interaction with X rays produced by the detonation. As the upper air gets thinner, the size and other characteristics of the fireball change. Above about 60 miles, the fireball no longer coincides with the detonation point because there is too little air to be heated to incandescence. That part of the initial X rays that is effectively directed downward (less than one-quarter of the total) should produce a pancake-shaped fireball at about the 60-mile altitude where the air is sufficiently dense. Thus the incendiary efficiency of a large-yield nuclear weapon detonated above 60 miles is less than one detonated well below this altitude. There is some evidence to indicate that for large nuclear weapons, a burst height of about 30 miles may be optimum for creating only incendiary effects. It has been estimated than on a clear day the ignition ground radius for a 100 MT detonation at 30 miles altitude would be about 65 miles.[6]

For weapons which are likely to present the major threat now and for some years to come (up to 20 MT), their maximum ignition radius has been estimated at about 25 miles.

CLIMATE AND WEATHER

Other factors affecting the fire-making potential are climate and weather. The transmission of the thermal energy to the ground, particularly from high air bursts, is strongly affected by the presence or absence of clouds and their types and locations, by clearness of the air, by surface reflectivity and by other meteorological factors. A critical factor is the amount of cloud cover between the weapon and the target area. Cloud transmission of thermal radiation, assuming 100% for a clear day is about 30% for light cloud to about 3% for dense cloud, based on solar radiation data. As a result, it has been estimated that, for a 100 MT detonation at 30 mile altitude, the ground ignition radius would be reduced from 65 miles to 30 miles by a layer of high thin clouds and to 10 miles by a layer of lower dense clouds.[6]

Weather enters the problem in several other ways. Foremost is the ignitability of the materials in the target area. Thin easily-combustible materials may have their ignition threshold significantly raised by increased moisture. Also, the possibility of spread of fires after ignition is directly influenced by the weather conditions at the time of attack and during the weeks preceding attack.

A detailed weather study of American cities of 100,000 population or larger shows that the average city has but 125 clear days a year and less than 10% have as much as 200 clear days. The average American city has about 130 days of heavy cloud or dense fog and about 110 days a year it is raining. Thus for the average American city, the high-altitude incendiary weapon system would be effective one-third of the time, partially effective one-third of the time, and ineffective one-third of the time.[7]

Military planners would probably not be satisfied with a weapon system of such

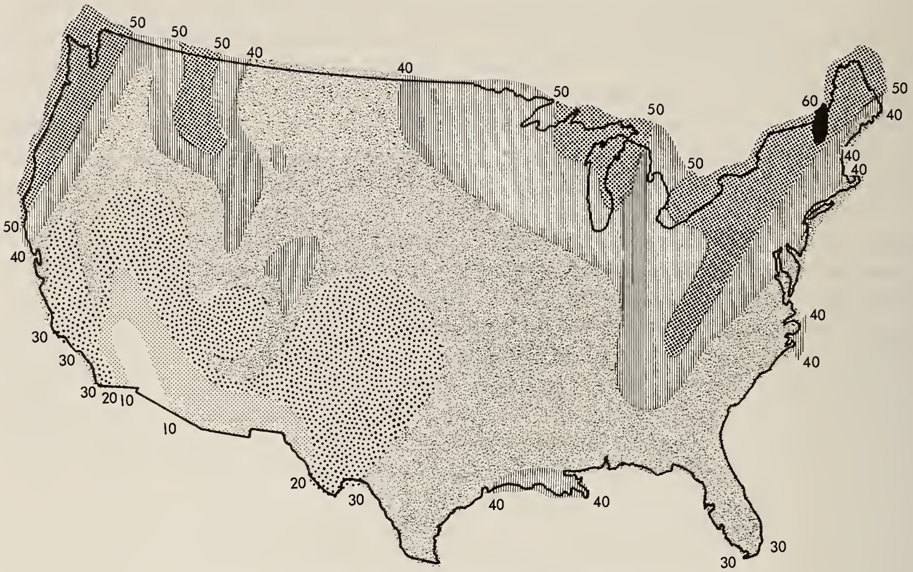

Fig. 1. Percentage of "opaque" cloudiness (annual).

low reliability. However, it might be considered that, even so, one might be able to choose a particularly advantageous day for the attack. But the occurrence of clear skies simultaneously over all or nearly all of our major cities is extremely infrequent and hard to predict. Most of the time some of our cities have clear skies and others have cloudy skies. So an enemy planner would have to settle for an uncertain chance of starting fires in some fraction of our cities as a result of attacks on all.

This difficulty facing the high-altitude incendiary attack is summarized in Figure 1 which shows the percentage of time that "opaque" cloudiness occurs in various parts of the country. It can be seen that most of our cities are located in regions where cloudy conditions are common.[8]

IGNITION POINTS AND FIRE GROWTH

Although it has been shown that sufficient thermal energy to ignite kindling fuels can be delivered over large areas, this irradiated area cannot be considered to become engulfed in fire. The effectiveness of the thermal radiation in actually creating a fire is dependent upon kindling fuels that are "visible" to the radiation and in order to maintain the fire, upon the availability of heavier combustible materials close to the ignited kindling. In contrast to rural areas, most kindling fuels in urban areas occur indoors. In order to be susceptible to possible ignition these indoor kindling fuels must be in that part of the room that is visible to the sky. Buildings, trees and hills can create shadows to shield kindling fuels both indoors and outside, especially from low altitude bursts or at the extreme ranges of high altitude bursts. Cities with active "clean up" programs would present few outdoor kindling fuels, but highly flammable vegetation close by buildings, as in the Los Angeles suburbs, would pose a serious fire hazard.

It has been estimated that there are many thousand potential "ignition points" or exposed kindling fuels per square mile in urban areas.[9] Some correlation of the number of ignition points with the type of neighborhood has been suggested but the significance of this in terms of the over-all fire hazard has not been established. From these ignition points fires can develop if there are heavier fuels close by which, in turn, can be ignited.

Fires following a nuclear attack can also be expected from blast-disrupted gas lines, heating plants, and electrical systems and from other causes of an indirect and accidental nature. Although fires from the latter causes are of a "peacetime" nature and not the result of weapons effects, they must be expected to continue to occur during a nuclear emergency, adding to the fire protection problem.

Some of these fires may be limited to the immediate area, such as the buildings in which they start and eventually burn out, while others may spread and form mass fires.

MASS FIRE DEVELOPMENT

Fires from whatever cause in a nuclear war will spread, in general, in the same manner as would peacetime fires in the absence of any fire fighting activity. In many circumstances, spreading fires will move in a downwind direction as a conflagration, such as the Bel Air–Brentwood fire of 1961 in Los Angeles and others which, in the past, have swept major cities and national forests. Under some not well-defined conditions a stationary mass fire called a fire storm might occur. The critical elements appear to be a large number of nearly simultaneous ignitions in a heavily built-up area (such as a slum), little or no ground winds and unstable atmospheric conditions. In a fire storm, the convection currents rising from the many small fires combine in a central vertical column and cause air from outside the fire area to be drawn in. This action eventually creates an intensely burning fire together with violent indrafts at its outskirts. The fire storm will burn out within 3 to 4 hours without spreading much beyond the initial fire area.[10] On the basis of our knowledge of fire storms in World War II and from forest fire studies, a fire storm could probably occur only in a relatively few congested areas of our larger cities and in the heavier forests. Since congested areas are also the most probable targets if cities are attacked, the major fire damage usually would be in areas of extensive blast damage.

In most urban areas, the critical factor in determining the extent of fire damage could be the likelihood of fire spread rather than the number of ignition points. Fire spread is largely dependent on the density of fuel, i.e., the height and congestion of combustible buildings or other buildings with combustible contents. Topography, vegetation and wind conditions may also be key factors in fire spread, depending upon the particular locality, season and time. Mass fires, in the form of conflagrations, will continue to move downwind as long as favorable conditions exist. Eventually, though, winds may reverse and drive the conflagration back into the burned area, or the conflagration may reach an area where there is no fuel or where the fuel is too widely separated. Parks, large bodies of water and rivers, rocky ridges, deserts, and wide rights-of-way for highways or railroads would serve as barriers to a conflagration. Dense areas of fuel where fire spread is likely are of limited extent. Within the area circumscribed by the ignition radius of a large weapon burst there could be several "fuel areas" each of which might support a mass fire. Scattered fires would likely occur in the remainder of the potential ignition area. Thus, the potential ignition area cannot be considered as a single fire area "engulfed in flame" since the controlling factors are the occurrence and size of a fuel area rather than the size of the weapon.

LIFE SAFETY IN FIRE AREAS

We can expect large numbers of survivors in fallout shelters, such as the shelters now being marked and stocked, in the fringe areas of blast. These shelters generally offer complete protection against flash burns from the initial thermal radiation. They also provide a small but significant degree of protection against blast. Therefore, we would expect many survivors from the initial weapons effects in the region of one to 10 psi blast overpressure. For a 10-MT surface detonation, this region extends from four miles to sixteen miles from ground zero and includes most of the damaged area.

It is in this peripheral region of survival that the secondary threat of developing fires from ignitions caused by both blast and thermal radiation will be encountered. There will be places within this general over-all fire area that will have no fires. These will be areas clear of any fuels, fire-resistive buildings without openings exposed to the surrounding fire, or buildings so located that they are not seriously exposed to the fire. Within these areas, survival is considered probable, expecially for people in fallout shelters within the less fire-vulnerable buildings and in separate shelters. Moreover, there are documented cases from World War II—the "bunkers" and other shelters in Hamburg and fire-resistive buildings in Hiroshima—where people survived within the fire storm area.

An official German report on the Hamburg fire storm noted that:

> "Many Air Protection bunkers and splinter-proof surface shelters were situated in the middle of extensive area fire and fire storm zones. The heat round these buildings was more than human beings could stand. Nevertheless in no instance either in bunkers or surface shelters did shelterees come to any harm from the heat, nor had they to leave the buildings prematurely. Shelterees remained in many of these structures till the morning after the raid and until the fires surrounding them had abated. In some cases a covering of water had to be supplied at the exit by the Fire and Decontamination Service in order to get the inmates out. This was the case especially in special buildings situated in narrow courtyards. Often the ventilating plan could not be operated on account of heat, smoke and fumes and had to be abandoned."
>
> "In spite of much overcrowding, air conditions even in buildings not provided with ventilating plants as well as in bunkers full of homeless persons remained bearable for days. The presence of openings for natural ventilation was found to be of advantage."[11]

At the time of these raids Hamburg had a estimated population of 1.5 million, of which an estimated 470,000 people were in the area subjected to attack and heavily damaged. Within this damaged area was the actual fire storm area of about five square miles, with an estimated 280,000 people. Of these, an estimated 40,000 (or 14%) who were in either poor basement shelter or outside, were killed by blast or fire. However, there were some 142,000 people who survived in basement shelters or escaped by their own initiative and 45,000 who were rescued in addition to an estimated 53,000 who survived in the bunkers.[12] The same German report concludes:

> "The raids on Hamburg have again proved the great importance of shelter construction as an Air Protection measure. That many people from ignorance of the situation, lost their lives in shelters in the fire storm area, does not alter the fact."

An outstanding example in Hiroshima was Building 24 on the records of the U.S. Strategic Bombing Survey, which was located only a quarter-mile from ground zero.[13] Here, a group of people remained in the building, snuffed out fires, and survived in the heart of the Hiroshima fire area. This incident, and others, show that fire guard actions in snuffing out small fires are feasible and effective. They also indicate that such action can be effective in a particular building despite fires in other buildings in the same area.

In both Hamburg and Hiroshima, a great many people also survived by fleeing from fire areas to places of relative safety, in addition to those people who survived by remaining in shelter. It is possible that areas of fire involvement in a thermonuclear attack would be larger than those at Hamburg and Hiroshima, thereby making rescue and escape more difficult. This possibility would depend primarily on the size of the conflagation areas of U.S. cities relative to those mentioned rather than on the range of incendiary action of megaton-yield weapons. Moreover, a study of past conflagrations has shown that their average speed has been less than 1 mile per hour, with surges up to 3 miles per hour under the influence of strong winds.[14] These data suggest that there would be time to conduct remedial movement of threatened shelter population to areas not exposed to the fire danger although such movement might involve exposing the people to the hazard of fallout.

Perhaps the most serious complication that has been injected into the problem of life safety in fire areas by modern weapons is the imminent threat of fallout that could hamper fire fighting or remedial movement. Although there would be a short period of time immediately following a detonation in which countermeasures could be undertaken, the downwind part of the area threatened by fire would shortly be threatened by fallout unless the attack had employed air bursts or high-altitude detonations. In practice, the preferred defensive actions would depend upon the relative severity of the threats of fire and fallout. Because of this difficulty, it would be desirable to provide a high degree of life safety from fire in fallout shelter areas through a careful selection of such areas as well as to prepare for intensive efforts to prevent or control the ignitions that might occur.

Prediction of life safety from fire in fallout shelter areas is difficult because of the effects of combustion gases upon people which is not well understood, and the complexities of construction and air circulation patterns within buildings.[15] Despite a lack of basic knowledge about this problem, a procedure based on empirical knowledge is now being developed for use by architects and engineers to indicate both "fire safe" fallout shelters and how other shelters can be upgraded to be "fire safe."

FIRE COUNTERMEASURES

Since the fire problem outlined above is not expected to introduce any heretofore unknown problems other than fallout, we can develop a fire defense program based upon our existing knowledge and experience. In this program, the reduction of fire vulnerability is equally important as planning for control and extinguishment. Many of the ways to reduce the fire hazard are essentially the same as those recommended for peacetime fire safety. Measures to make urban areas less combustible and to reduce fire losses not only result in greater safety and lower insurance rates in peacetime but would also reduce their vulnerability to wartime fire.

Countermeasures to reduce the vulnerability of an urban area fall into three categories: long-range planning, everyday actions, and emergency actions.

Long-range Planning

It is possible on a long-term basis to significantly reduce the fire hazard to life through changes in the structure and composition of an urban area. The concepts of good city planning, such as residential clusters instead of disorganized urban sprawl, with ready access to arterial highways and surrounding open areas of parks or farmland are all elements which are compatible with reducing the vulnerability to both peacetime and wartime fires. The design, construction, and location of buildings can reduce the incidence of primary fires.

The requirements for fire safety and, for that matter, shelter in buildings, need not go against current architectural trends. This has been strongly indicated by the results of recent OCD design competitions. Imaginative guidance appears as important as fire code restrictions in the design of new construction to minimize fire vulnerability. The placement of parks and playgrounds among these buildings provides ideal locations for shelters and reduces the possibility of fire spread. Wide highways located within a city can also serve as fire breaks and provide access routes into damaged areas. Coordinated urban transportation systems, whether highways, rapid transit, or some combination of the two, may be useful to permit population movement from threatened areas.

Everyday Actions

National fire prevention, clean-up, and family safety programs and local fire inspections by fire marshals and fire departments are important everyday actions that help reduce fire vulnerability. The adoption and enforcement of model building codes are essential in controlling undesirable construction. Support of these programs, especially those which are continued year-around, can assist in reducing vulnerability of a city to wartime fires.

Emergency Actions

There are many emergency countermeasures that can be taken to reduce the vulnerability of buildings to thermal ignitions and subsequent fires. Since thermal radiation, like the sun's radiation, can be stopped by an opaque material, simple measures such as closing venetian blinds or shutters, whitewashing windows, or blocking windows with plywood, sheet metal or aluminum foil can be very effective in preventing ignitions within buildings, Alternatively or in conjunction, kindling fuels such as drapes, curtains, rugs, newspapers, magazines, upholstered furniture, and bedspreads can be removed or placed where the sky is not visible through windows. Trash piles and other combustible rubbish outdoors can be removed or covered. In addition, secondary sources of fire can be largely minimized by shutting off electricity and heating plants.

For these emergency countermeasures to be effective where fire spread is possible, they must be widely practiced by the entire community. Failure to act on the part of a few people could endanger adjacent areas through fire spread from a limited number of ignition points.

The community fallout shelter program provides a basis upon which the community can organize to cope with many defense problems, among them fire. During the fallout shelter period, fire control efforts will, by necessity, be restricted to the immediate vicinity of the shelter or the building in which it is located. Within this area fire guards organized from the shelterees can cope with accidental fires as well as ignitions caused by the radiant heat from fires in nearby buildings. Should a community shelter become untenable because of fire or other reasons, the shelter management can organize an orderly movement of people to other shelters or areas of lower hazard.

NOTES

(1) The matter of incendiary use of nuclear weapons came up at these hearings through the testimony of various witnesses opposing the shelter development bill, notably Professor William F. Schreiber.

(2) Project HARBOR was a six-week study of civil defense problems by a group of over 60 scientists and engineers drawn from universities, private industry, and government organizations under the leadership of Dr. Eugene P. Wigner. Part of this study, Future Weapons and Weapons Effects, dealt specifically with the thermal and fire problem. The distinguished scientists who participated in and contributed to the evaluation of the fire threat included Dr. Harold Brode, the RAND Corporation; Dr. Abraham Broido, U.S. Forest Service; Dr. Mathew G. Gibbons, U.S. Naval Radiological Defense Laboratory; Dr. Robert J. Hansen, Massachusetts Institute of Technology; Dr. Arthur J. Hudgins, Lawrence Radiation Laboratory; Dr. Clarence R. Mehl, Sandia Corporation; and Mr. Luke J. Vortman, Sandia Corporation.

(3) The estimates in Table I for the 1 MT and 10 MT ignition thresholds for drapes, typing paper, and dry rotted wood and leaves are those recommended by the Defense Atomic Support Agency for inclusion in the new printing of the "Effects of Nuclear Weapons." The estimates for newspaper and Kraft corrugated paper carton and for the 100 MT yield are based on experimental work done by the U.S. Naval Radiological Defense Laboratory and the U.S. Naval Applied Science Laboratory and are believed by DASA to represent the best estimates at this time. Detailed characteristics of the kindling fuels given in Table I can be found in the ENW. Variations, such as color, weave, weight, density and moisture content can materially affect a kindling fuel's ignition threshold. For example, a dirty, crumpled and loosely folded newspaper exposed to a 100 MT detonation in the lower atmosphere would require only 25 cal/cm^2 (as given in Table I) for ignition, whereas a single sheet of finely printed text requires approximately 45 cal/cm^2. The reduction under similar circumstances for a 10 MT detonation is only from 12 to 11 cal/cm^2.

(4) The new printing of the "Effects of Nuclear Weapons" will have the date "February 1964" and is to be available in mid-June, 1964.

(5) The additional work was undertaken by Dr. M. G. Gibbons of the U.S. Naval Radiological Defense Laboratory, a key contributor at Project HARBOR and an active researcher in the field of atmospheric transmission. Dr. Gibbons has restricted his latest transmissivity formulations for a standard clear atmosphere and for nuclear weapon burst heights from 0.25 to 30 miles.

(6) These estimates are from "Transmission by the Earth's Atmosphere of Thermal Energy from Nuclear Detonations Above 50-km Altitude" by T. O. Passell of Stanford Research Institute.

(7) According to the Weather Bureau a "day" is listed as cloudy if during a 24-hour period the cloud cover persists 70% or more of the time. Although any partially effective or ineffective day could thus be effective up to 30% of the time we consider that this would be balanced by the occurrence of clouds during part of a "clear day."

(8) Figure 1 is adapted from the 1960 sheet, "Mean Percentage of Possible Sunshine, Annual," published by the U.S. Department of Commerce, Weather Bureau.

(9) Several surveys were made in the 1950's for the Armed Forces Special Weapon Project of potential ignition points by neighborhoods in various cities.

(10) Based on a definitive study of past mass fires by the U.S. Forest Service for OCD and reported in "A Study of Mass Fires and Conflagrations."

(11) Police President of Hamburg, "Report by the Police President of Hamburg and local Air Protection leader of Hamburg on the large scale raids on Hamburg in July and August '43. Experiences, Volume 1: Report," (translation), p. 88.

(12) These estimates are from "Deaths From Fire in Large Scale Air Attack—with special reference to the Hamburg Fire Storm," by Kathleen F. Earp of the British Home Office. April 1953.

(13) Reported in the U.S. Strategic Bombing Survey report, "The Effects of the Atomic Bomb on Hiroshima, Japan," Volume II, May 1947.

(14) This information in based on the U.S. Forest Service study mentioned previously in which the records of past conflagrations in forests and urban areas were critically analyzed.

(15) The problems associated with the effects of combustion gases upon people is reviewed in "An Investigation of the Hazards of Combustion Products in Building Fires" by Bieberdorf and Yuill under a U.S. Public Health Service contract.

Subject Headings: ***Civil defense, fire; Fire, civil defense.***

EFFECTS OF FIRE ON STRUCTURAL DEBRIS PRODUCED BY NUCLEAR BLAST*

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The objective of this phase of the program was to evaluate the effects of fire on the production of structural debris by nuclear weapons. Fire can decrease the total quantity of debris by consuming combustible portions of that produced by air blast, or it can increase the total amount by causing further structural failure.

APPROACH

To evaluate fire effects, records of past catastrophies involving major conflagations were studied. Events studied included the Chicago fire of 1871, the Baltimore fire of 1904, the Toronto fire of 1904, the San Francisco earthquake and fire of 1906, the Hamburg incendiary attack and fire of 1943, and the nuclear attacks on Japan in 1945. Most of the information pertinent to these events was in the form of annotated photographic coverage. Examination of hundreds of these photographs, along with discussions of fire effects with various fire departments through the country, and a knowledge of the behavior of structural members when subjected to fire provided the essential elements for correlation and prediction of fire effects on various types of structures.

GENERAL

As in the first phase of the study (whose purpose was to estimate air-blast-produced debris), it was found that fire damage, like blast damage, is a function of building and construction type. However, the effects of the controlling parameters are accentuated quite differently. Fire damage, being related primarily to degree of fire resistance and materials of construction, is relatively independent of the physical strength and structural response characteristics of the building. However, general massiveness is a definite controlling factor. Damage is found to vary with type of building (steel or concrete frame, concrete shear wall, etc.), since different types have quite different degrees of stability at elevated temperatures. For example, the stability of concrete shear-wall buildings is only mildly impaired, while unprotected steel frame buildings are made quite unstable by elevated temperatures. Fire-resistant structures, such as those of reinforced concrete or with a fireproofed steel frame, can also become vulnerable to fire when refractory materials protecting structural members are damaged by blast or structural deformation.

These effects are summarized graphically in Figs. 1 through 7. These figures show the percentage of debris as a function of overpressure for blast effects only and for blast and fire coupled. [Fire effects, of course, are basically related to range rather than overpressure; but to permit comparison between blast effects and "coupled" effects, ranges for fire effects have been converted to overpressure levels.] The vertical

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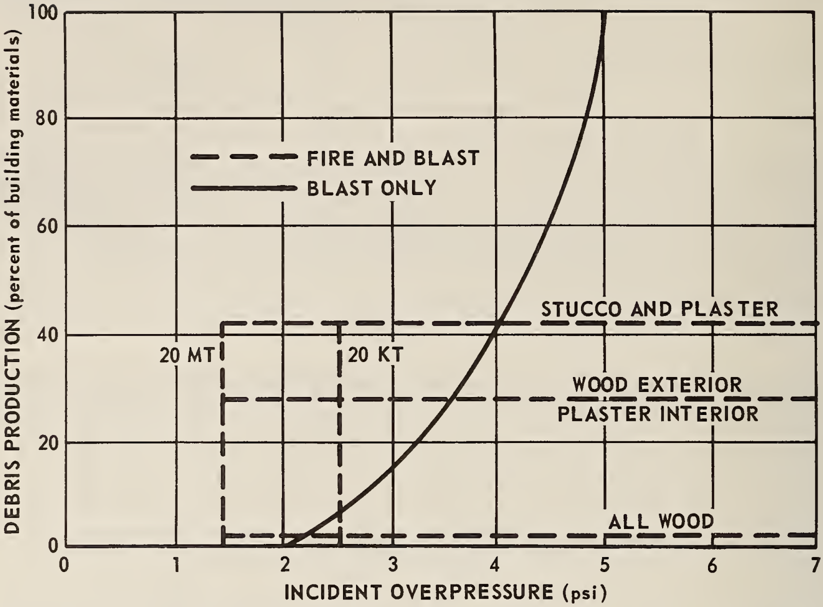

Fig. 1. Coupled fire and blast per cent debris vs overpressure—wood frame residential buildings.

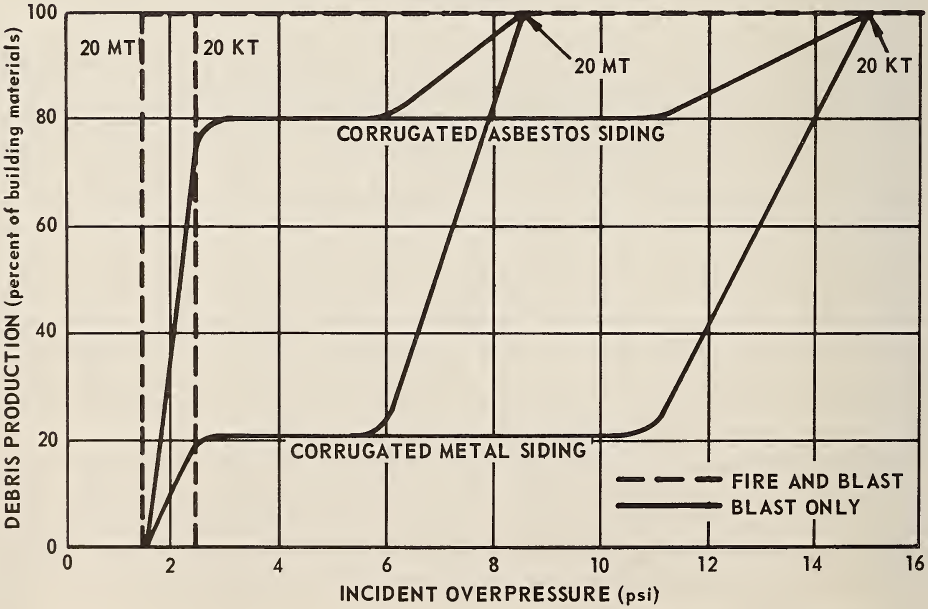

Fig. 2. Coupled fire and blast per cent debris vs overpressure—light steel frame industrial buildings.

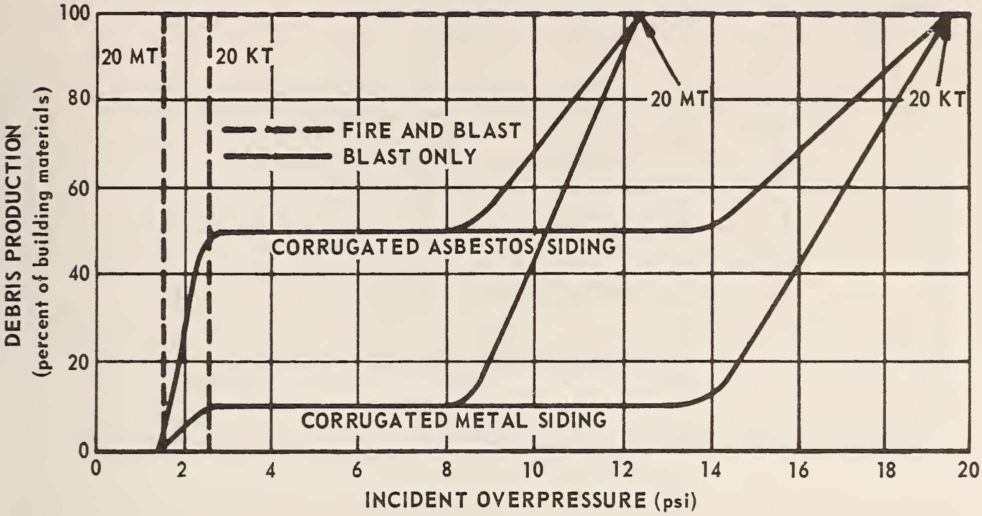

Fig. 3. Coupled fire and blast per cent debris vs overpressure—heavy steel frame industrial buildings.

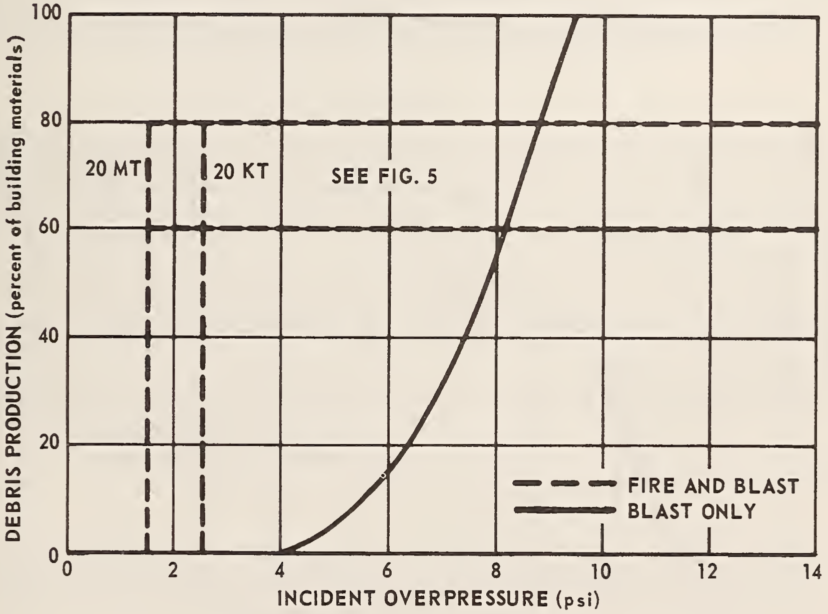

Fig. 4. Coupled fire and blast per cent debris vs overpressure—masonry load-bearing wall buildings.

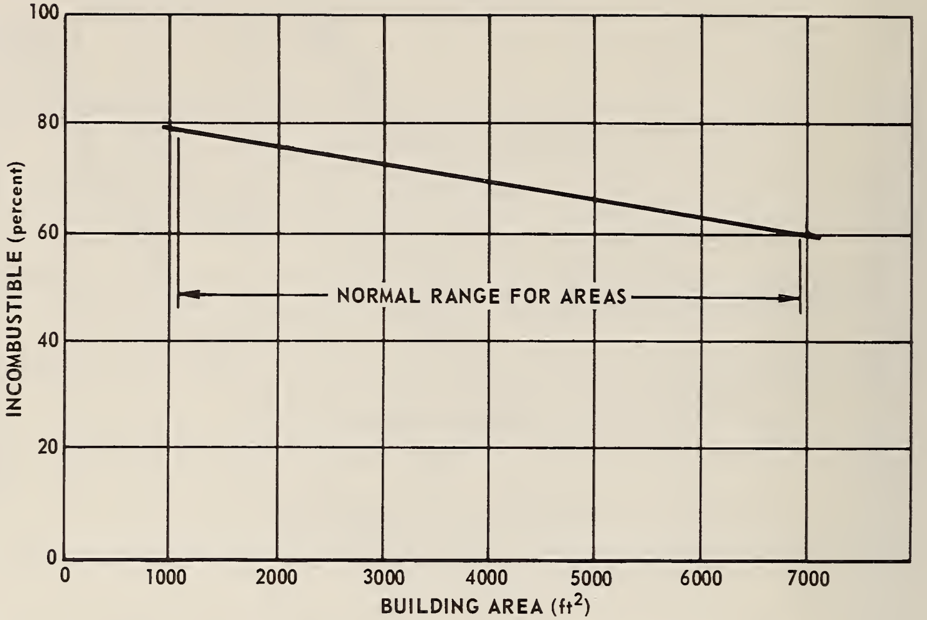

FIG. 5. Per cent incombustible vs plan area—load-bearing wall masonry buildings with all wood interior.

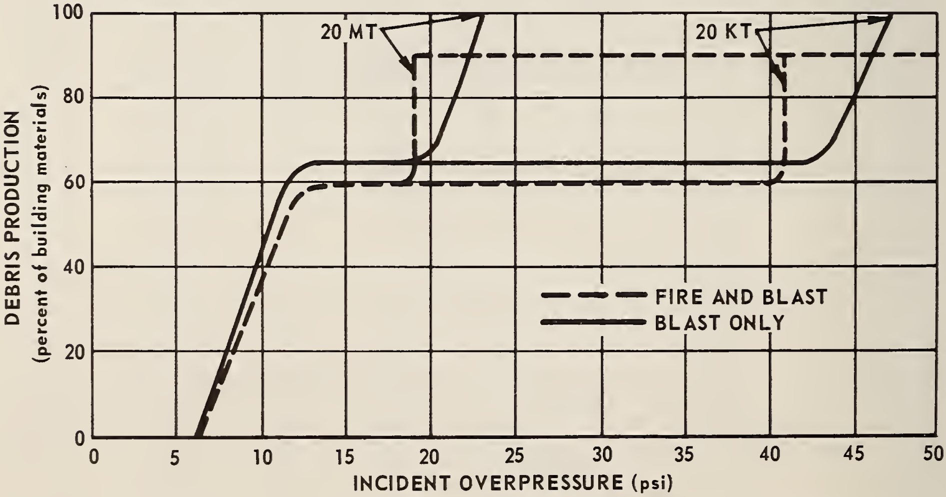

FIG. 6. Coupled fire and blast per cent debris vs overpressure—heavy reinforced concrete frame—type buildings with heavy interior partitions.

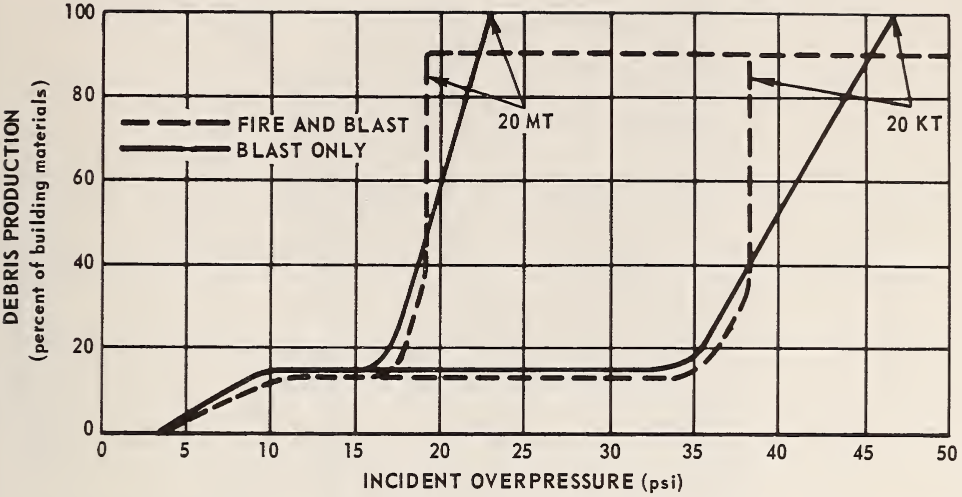

FIG. 7. Coupled fire and blast per cent debris vs overpressure—heavy reinforced concrete shear-wall buildings with light interior partitions.

portion of the "coupled" curves in Figs. 1 through 4 corresponds to the outer limits of the probable ignition range for fine kindling fuels, such as newspaper. The horizontal plateaus indicate the percentage of incombustible debris being produced.

EXAMPLE

The developed curves and techniques for debris evaluation were then used to predict debris depths along a particular route (see Fig. 8) through a city, San Francisco. The weapon was assumed to have a 1-MT yield and to be detonated at an altitude 5,000 ft above the City Hall. The results of this exercise are summarized in Fig. 9, in which debris depth and overpressure are plotted against distance along the route. The dashed lines indicate debris depth after the area has been subjected to fire. The consistent decrease in debris depth after fire is a characteristic of the predominant building types found in the city. If, however, brick masonry buildings had been encountered instead of wood frame buildings (especially in the outlying districts), this trend may well have been reversed.

CONCLUSIONS AND RECOMMENDATIONS

This investigation has revealed that fire is a major factor, and sometimes the primary factor, to be considered in evaluation of debris production from a nuclear attack. The area initially subjected to fire will compare to that for blast damage for small weapons but, in general, will be more extensive for larger weapons (megaton range). Fire spread would serve to further increase the area affected by fire.

To evaluate fire effects, additional information regarding ignition range and fire resistance of buildings is necessary. With these data and knowledge of the behavior of the type of building involved, its fate after being subjected to fire can be predicted.

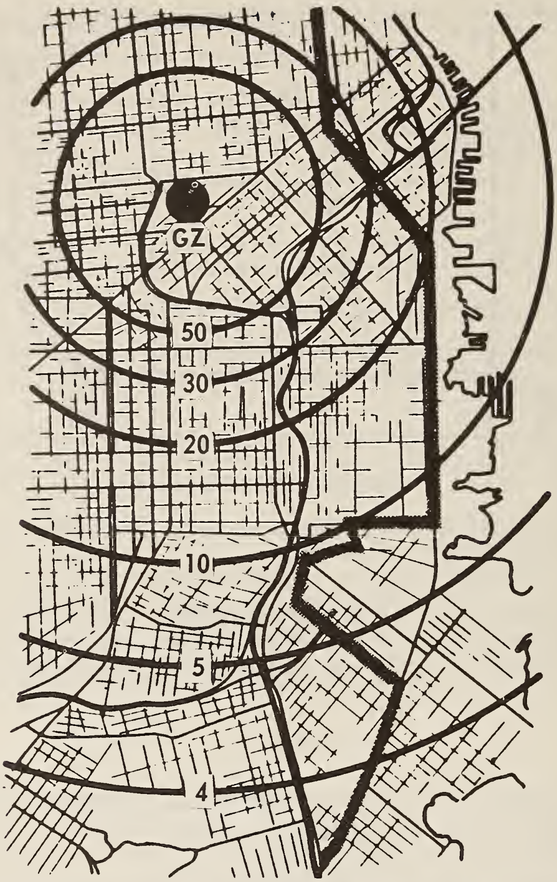

Fig. 8. Route through section of San Francisco (with pressure isobars superimposed).

Use of altered debris curves will enable prediction of the amount of debris that will be produced by the combined effects of blast and fire.

To increase the usability and extend the scope of the debris prediction techniques developed, this work should be continued in the following areas:

1. Development of debris prediction curves for structure types not previously considered.
2. Development of additional debris prediction curves to accommodate subgroups of major structural types.
3. Extention of prediction techniques to include debris produced from building contents.
4. Refinement of debris distribution procedures.
5. Determination of blast and structural deformation sensitivity of various common types of fire proofing.
6. Develop prediction curves for a more complete coverage of weapon sizes.

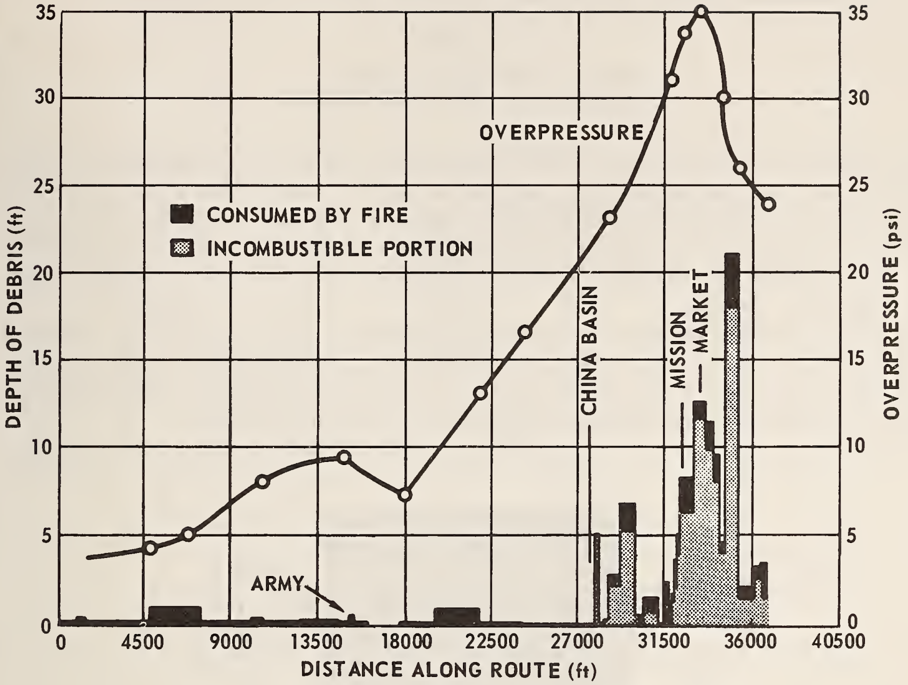

FIG. 9. Composite debris depth and overpressure vs distance.

7. Automate debris prediction procedures.
8. Gather and digest data for use in automated model.

Work in Areas 1 through 4 is presently in process.

Subject Headings: ***Debris, produced by nuclear explosion; Nuclear blast, debris from.***

SIMULATING FOREST FIRES FOR RESEARCH*

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The effects of a forest fire on a single tree can be simulated by burning an oil wick encircling the tree near groundline. Some of the advantages of this method over the setting of fires in natural fuel include ease of replication, standardization of amount of heat, a saving of labor, and low risk of fire escape. Trees are also conserved, for only those needed are burned, whereas natural-fuel burns usually damage many trees not used in a study.

The wick, braided from wire-reinforced asbestos and saturated with SAE-30 motor oil in kerosene (1:3), is wrapped around the trunk about 1 foot off the ground, and ignited after litter is removed (Fig. 1). Temperature regimes on and under the bark are recorded by thermocouples connected to a multiple recorder.

Wick flames, lasting about 7 minutes, give temperature histories on both wind-

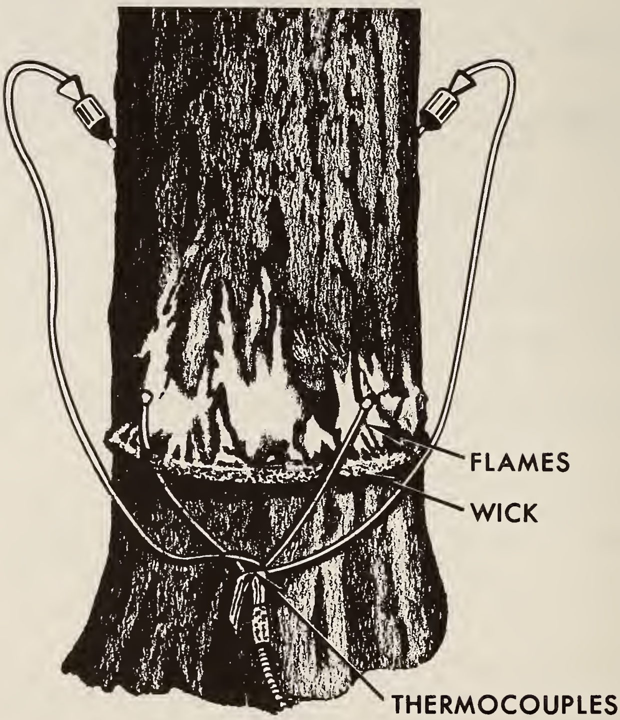

FIG. 1. Wick braided from wire-reinforced asbestos and saturated with SAE-30 motor oil in kerosene is wrapped around the trunk and ignited.

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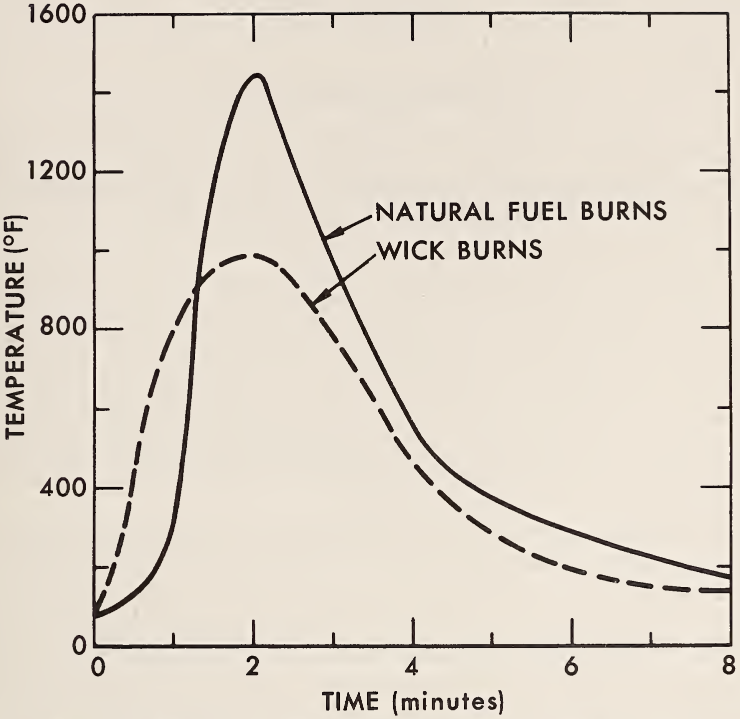

FIG. 2. Typical lee-side, bark-surface temperature curves 1 foot above the wick and in nautral-fuel burns.

ward and lee sides that are quite similar to those obtained in natural-fuel burns (Fig. 2). Maximum cambium temperatures in a number of tests varied from 85° to 520°F. in wick burns, and from 85° to 500° in pine-litter burns.

Although the wick fire cannot reproduce a moving front, it responds to wind much as natural fires do. Because of a cooling effect on the windward side and a convection column buildup on the lee side, maximum lee temperatures in both types of fires are at least twice as high as windward maxima, and the difference increases with height.

Subject Headings: *Forest fire, simulation of; Simulation, of forest fire; Trees, temperature during fire; Temperature, of burning trees.*

ABSTRACTS

I. Ignition Phenomena

Cutress, J. O., Peirce, T. J., and Tucker, A. C. N. (Central Generating Board, Research and Development Laboratories, Portishead, Near Bristol, England) "On the Ignition of Pulverized Anthracite," *Combustion and Flame* **8**, 289–298 (1964)

In this report the authors developed a one-dimensional mathematical model for the pulverized anthracite boiler at the Tir John Generator Station. In particular, they attempt to demonstrate the significance of including the hot recirculating gases in the model. A preliminary experimental study was made of the boiler's aerodynamics using a scaled-down water model. Although the processes occurring in the hot furnace are undoubtedly more complicated than indicated by this simple model, the general description was shown to be valid by observations of the ash patterns deposited on the refractory walls of the boiler.

The primary air-to-coal mass ratio at the burner was approximately 4:1 and the jet velocity calculated as an average over the burner nozzle area was of the order of 50 ft/sec, falling to 20 ft/sec before ignition occurred. The authors indicate that this flame speed of 20 ft/sec is not in accord with the measurements of de Grey[1] which would predict, for anthracite at this mass ratio, a value of about 5 ft/sec. In addition, anthracite loads of 140,000 lb/hour were used in conjunction with primary preheat air temperatures of about 370°C, giving a coal-air mixture temperature of about 260°C. Measurements of gas temperature, velocity, and solid content were made in the pre-ignition zone employing water-cooled probes similar to the design used by Peplow.[2] Temperature contours of the boiler were made with both a bare thermocouple and a suction pyrometer. These results indicate that the flame front is well-defined and extends down into the boiler approximately 75 inches. Velocity and solid content measurements were hampered by turbulent conditions that existed within the boiler. These studies showed that the coal–air jet consists of an outer mixing zone surrounding a cooler potential core. In the first region heat will reach a coal particle by radiation from the surrounding flame and refractory, by radiation and conduction from the flame front, and also by conduction from the entrained high-temperature fluid. In the second region the experimental measurements indicated that radiation has a negligible effect because of screening by particles in the jet periphery. The measured low temperature on the jet axis indicate that the particles lose rather than gain heat by conduction to the surrounding fluid.

In a previous study by Nusselt,[3] in which the effect of the hot recirculating gases was neglected, an expression was obtained that predicted a critical size of particle below which finer particles will take longer to ignite because they lose heat more rapidly by conduction to the surrounding fluid than the coarser particles. This is not in accordance with experience, since finer grinding has never been found to worsen ignition stability. In the present development the authors make a heat balance assuming the rate of thermal absorption by the particles to be equal to the sum of three terms: (1) heat gain by radiation from the flame front; an exponential decrease with distance from the flame front was assumed because of the screening effects of other particles; (2) heat gain by radiation from an external field; it was assumed that the energy loss by re-radiation from the particle is small in comparison with the radiation absorbed; (3) heat loss, or gain, by conduction to surrounding fluid; for simplicity, it was assumed that the fluid temperature around a particle is constant throughout its trajectory in the pre-ignition zone. Ignition delays of 26 to 40 msec were obtained by means of these expressions assuming a particle size of 76 μ, a mixing zone gas temperature of 750°C, a core temperature of 500°C, and two values for the screening constant. Although the actual ignition delay observed at the Tir John is an order of magnitude higher (200 msec) than calculated, these calculations indicate the importance of entrainment of recirculated gases on the heating of the coal particle in the pre-ignition zone.

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3. Nusselt, W.: Process of Combustion in Pulverized Coal Firing, *Z. Ver. dtsch. Ing. 68*, 124 (1934).

Subject Headings: *Anthracite; Coal, ignition of; Furnace design; Ignition, of coal particles.*

H. E. Perlee

Kuchta, J. M., Cato, R. J., and Zabetakis, M. G. (U. S. Bureau of Mines, Pittsburgh, Pennsylvania) "Comparison of Hot Surface and Hot Gas Ignition Temperatures," *Combustion and Flame* **8,** 348–350 (1964) (Letter to the Editor)

This note consists of a comparison of ignition temperatures of hydrocarbons and hydrogen with air, found by various methods. These methods consist of autoignition, wire ignition, and ignition caused by hot air jets flowing into stagnant combustible air mixtures. While ignition temperatures tend to vary widely depending on the method of measurement, the authors claim that when the heat source dimensions are equivalent, hot surface ignition temperatures do not show significant variations. A table, in which various ignition temperatures are compared, is presented to support this contention. Evidently it is valid at least for the hydrocarbon–air and hydrogen–air mixture considered. A brief discussion of the unknown factors encountered in measuring ignition temperatures is given, illustrating the fact that the concept of an ignition temperature is still a nebulous concept.

Subject Headings: *Autoignition; Ignition, gaseous; Ignition, by hot gas; Ignition, by hot surface; Ignition, temperature; Spontaneous ignition.*

T. C. Adamson, Jr.

Rae, D., Singh, B., and Danson, R. (Safety in Mines Research Establishment, Sheffield, England) "The Size and Temperature of a Hot Square in a Cold Plane Surface Necessary for the Ignition of Methane," *Safety in Mines Research Establishment Research Report No. 224* (1964)

This report describes part of a general study of the ignition of flammable gases by surfaces heated by friction and impact.

Frictional forces and impact forces can create very high surface temperatures on small areas of otherwise cool surface as well as producing hot ejected particles which are often called sparks. If these patches are large enough and hot enough, they will ignite certain flammable gas–air mixtures. This particular report supplies data that link two nearly completely independent phenomena in frictional ignition experiments: the formation of hot surfaces by mechanical energy and the ignition of a gas–air mixture by the transfer of energy from the hot surface to the gas. The conclusions from these data are expected to have general application.

The authors review the literature on minimum surface temperatures required to ignite methane–air mixtures where the igniting surfaces are in the form of wires, tubes, spheres, bars, and plates. They point out that catalytic effects and flameless combustion are especially important where very small hot areas are involved.

The apparatus used in the experiments consists of a small electrically heated square of alumina-coated platinum set flush with one of the walls, ceiling, or floor of an explosion box. The alumina is the hot surface which is used as the ignition surface, and the platinum support is used as an electrical resistance heater to heat the alumina surface. The squares of alumina were varied from 2.5 mm to 18 mm on a side, and the methane concentration in air was varied from 5.6 to 13.1 volume per cent methane. The methane–air mixture was introduced into the explosion chamber and allowed to equilibrate. A cover was removed rapidly from the hot alumina surface, ignition occurred, and the resulting explosion was observed by an amplified infrared photocell current displayed with a timing signal on a double beam oscillograph or by an ionization gap set as close to the surface as the removable cover would allow (about 1 inch). The surface temperature of the heated surface was measured with a disappearing filament optical pyrometer.

As a result of these experiments varying the size of the heated square for ignition and the concentration of methane, it was concluded that the size of the surface required for ignition increases rapidly with decreasing temperature below 1100°C. The temperature of the surface necessary for ignition increases rapidly as the size of the ignition surface decreases below a $2\frac{1}{2}$ mm square where it is about 1600°C. Increasing methane concentration causes an increase in ignition temperature of about 20°C for each per cent concentration increase from 8 to 12 per cent. The minimum ignition temperature is least for the hot surface in the floor, it is up to 50° higher for the roof position, and 50° still higher for the wall position. There was an aging effect, probably due to platinum, which caused a decrease in the minimum ignition energies of about 25°C as the experiments progressed on one platinum-supported alumina square. There were relatively large unexplained differences of up to 150°C between surface elements made at different times and possibly in different ways. These differences are very likely caused by differences in the true surface area of the alumina or possibly by platinum exposure through the alumina. Elements made in exactly the same way showed little or no differences in behavior.

Some of the practical conclusions are as follows. Materials that melt, soften, or break up mechanically at temperatures less than about 1100°C should not cause ignition by themselves from heat produced by friction unless the surface area heated is so large and shaped so that it constitutes an enclosure for the gas. A fused material can adhere to a metal of high melting point and become heated to the point where ignition can occur without having large heated surfaces. Materials found in mines that can cause ignition by frictional heating are quartz, quartzitic rocks, tungsten carbide, and other hardened materials used for pick tips, grindstone materials such as silicon carbide and aluminum oxide, and steels. Materials which are borderline in ability to ignite gas mixtures from frictional heating are iron pyrites. Clay minerals of shales, carbonate rocks, and copper alloys do not meet conditions for causing ignition by frictional surface heating. Quartz is especially dangerous because it is very hard, nonmetallic and has a low thermal conductivity.

Some materials, such as magnesium, aluminum, and titanium, possess properties which make them hazardous but not by the mechanism discussed in this report. These materials can evaporate and burn as a flame instead of behaving as a inert hot surface. The transport of oxygen to the reaction zone then becomes an important part of the mechanism leading to ignition.

This work has shown that high temperatures are needed to ignite gas mixtures and that relatively few materials are capable of providing these temperatures when exposed to friction or impact. Most important of these materials must be considered to be quartz.

Subject Headings: ***Friction, ignition by; Ignition, by surfaces; Methane, ignition of; Particles, ignition by; Surface ignition.***

L. R. Griffith

Seki, K., Emura, T., Matuura, S., and Tominaga, T. "Incendivity of Coal Dust Clouds by Feeble Electrical Energy," *Journal of Mining Institute of Kyushu* **32,** 252–259 (1964)

This paper describes the ignitability of coal dust by small electric sources.

The apparatus is a vertical tube system. Coal dust from a hopper is directed downward through a vertical 1.2-m-long plastic tube, emerging continuously into the combustion chamber and igniting at a predetermined point.

The ignition sources are heated by thin Ni–Cr wires, or small electric sparks which are discharged in a high-induction circuit.

The following results were obtained:

(1) The minimum ignition temperature of dust is 910°C and lies between the temperature of H_2 and of CH_4.

(2) Minimum ignition energy varies with coal rank. Some coals require 7 to 40 times the ignition energy of CH_4.

(3) The most ignitable concentration lies on the fuel-rich side of a stoichiometric coal dust–air mixture.

(4) Some coals, with low volatile matter or high ash content, cannot be ignited by this source. Readily ignitable coal can be made nonignitable by adding appropriate amounts of rock dust.

Subject Headings: *Coal dust, ignition of; Dust, ignition of; Ignition, electrical; Ignition, of coal dust.*

Authors' Abstract

II. Thermal Decomposition

Roberts, A. F. (Safety in Mines Research Establishment, Buxton, England) "Ultimate Analyses of Partially Decomposed Wood Samples," *Combustion and Flame* 8, 345–346 (1964) (Letter to the Editor)

Knowledge of the average composition of the volatile fraction and of the charcoal fraction separately enables calculation of theoretical air requirements, product compositions, and mass balances at various stages of fires in wood. The samples analyzed were those described in the preceding abstract. Analyses were by British Standard 1016 modified for the higher reactivity of wood than of coal or coke. Carbon, hydrogen, and ash were determined directly, oxygen by difference.

Let $(M_C)_0$ denote carbon content of unheated wood, (M_C) carbon content of sample retaining $100y$ per cent of its initial weight, and $(M_C)_v$ carbon content of evolved volatile matter, then

$$y(M_C) + (1 - y)\,(M_C)_v = (M_C)_0$$

or, rewritten,

$$y(M_C) = y(M_C)_v + [(M_C)_0 - (M_C)_v]$$

so that if $y(M_C)$ is a linear function of y, $(M_C)_v$ must be constant. Similar considerations apply to (M_H), content of hydrogen, and (M_O), content of oxygen. The plots in fact did prove linear and yielded the regression equations:

$$\begin{aligned} y(M_C) &= 39.5y + 8.9 \\ y(M_H) &= 6.9y - 0.9 \\ y(M_O) &= 53.6y - 8.6 \end{aligned}$$

The probability of these equations being due to chance was less than 0.1 per cent. There was no significant correlation between $y(M_A)$ and y, where (M_A) represents content of ash. Hence it was concluded that the average composition of the evolved volatile matter was constant throughout the decomposition.

The average molecular formula calculated for unheated wood, for the evolved volatile matter, and for the charcoal residue, with the theoretical air requirements in grams of air per gram of fuel were: $(CH_{1.5}O_{0.7})_n$, 5.7; $(CH_2O)_n$, 4.6; and $(CH_{0.2}O_{0.2})_n$, 11.2, respectively. These are on the ash-free basis and for assumed yield of 17 per cent charcoal.

Subject Headings: *Analysis, of pyrolysis products of wood; Pyrolysis, of wood; Thermal decomposition, of wood; Thermal degradation, of wood; Wood, pyrolysis of.*

F. L. Browne

Tang, W. K. (University of Wisconsin, Madison, Wisconsin) "The Effect of Inorganic Salts on Pyrolysis, Ignition, and Combustion of Wood, α-Cellulose, and Lignin," *Ph.D. Thesis in Chemical Engineering*, University of Wisconsin, Madison, Wisconsin (1964)

This is an extensive study of the effect on the combustion properties of wood, α-cellulose, and lignin impregnated with various inorganic salts using thermogravimetric and differential thermal analysis. An extensive survey of the literature is included.

The choices of wood, cellulose, and lignin for comparative studies were based on the rationale that the major components of wood are cellulose and lignin, the softer parts of the wood cell being cellulose and the hard-cell walls being predominantly lignin. Thermogravimetric analysis allows a study of the mass loss by a sample due to volatilization and oxidation while differential thermal analysis (DTA) gives information on heat released during pyrolysis or oxidation. The techniques were discussed in an earlier article in Fire Research Abstracts and Reviews.[1]

Studies were made on a number of salts at various concentrations (Table I). The data are treated principally from the chemical standpoint and various potential mechanisms are discussed, particularly those proposed by Browne.[2]

TABLE I

Concentration by weight per cent

Chemical	TGA pyrolysis	DTA pyrolysis	DTA	Combustion
Sodium tetraborate decahydrate	2	2	2	8
NaCl	2	2	2	8
$KHCO_3$	2	2	2	8
$Al_2Cl_6 \cdot 6\,H_2O$	2	2	2	8
$(NH_4)_2HPO_4$	2	2	2	8
H_3BO_4	—	—	2	8
Disodium phosphate	—	—	—	8
Na_2HPO_4	—	—	—	8
$(NH_4)_2SO_4$	—	—	—	8
Ammonium pentaborane octahydrate	—	—	—	8

No firm conclusions were reached as to detailed mechanisms but a start has been made in the understanding of these complex interactions. As indicated by the author, a complete understanding will require much more detailed studies than the over-all heat release and mass loss. Suggested studies include detailed analysis of the products as a function of time and a detailed characterization of the woods both physically and chemically.

References

1. 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).
2. Browne, F. L.: Theories of Combustion of Wood and its Contents, *Forest Products Report 2136*, 1958.

Subject Headings: ***Cellulose, lignin; Pyrolysis, effect of inorganic salts on/in wood, cellulose, lignin; Ignition, effect of inorganic salts on/in wood, cellulose, lignin; Wood.***

R. M. Fristrom

III. Heat and Material Transfer

Freedman, S. I. (General Electric Company, Valley Forge, Pennsylvania) "Heat Transfer with Chemical Reactions," Chapter 4 in *Developments in Heat Transfer*, ed. W. M. Rohsenow. Cambridge: The M. I. T. Press (1964).

An analytical, engineering solution for several heat transfer problems is described. The approach is applicable to similar problems within the specified limitations and associated accuracy.

For convective flow systems involving heat transfer with chemical reactions, the approach was the use of the general diffusion equation,

$$\partial^2\theta/\partial x^2 = a^{-1}(\partial\theta/\partial t),$$

where x and t are linear and time variables; θ the property in question and conserved by the natural laws; and a the diffusivity of heat, mass, or momentum.

The couplings of simultaneous transport processes are expressed in terms of usual nondimensional groups, Prandtl, Schmidt, and Lewis, which are the ratios of any two of the diffusivities. One-step chemical reaction was considered and it was then possible for the heat generated by the reaction to be included in the enthalpy balance for the process.

Total heat transfer was computed on the basis of enthalpy gradient. When Lewis number was unity for all the species involved in the process, this approach offered the simplest analysis. The enthalpy term in the equation could be further split into temperature and concentration terms. In this case, detailed analyses were feasible for cases in which more than one reaction was occurring; that the Lewis number was other than unity, and when any particular chemical constituent was being studied.

Two cases, that of energy transport in a frozen boundary layer with a catalytic reaction zone, and that of local chemical equilibrium, were analysed in detail to show how unity Lewis number simplified the analyses. It was cited that in the first case Lewis number was approximately unity, and in the second case, Lewis number approached unity as a limit. Corrections for Lewis number other than unity was suggested.

As a case of heat conduction with chemical reactions and mass removal in the solid phase, the thermal decomposition of Teflon was treated by a simple first-order reaction model with the decomposition reaction rate,

$$\dot{m} = mB \exp(^{-}E/RT),$$

in which, two adjustable parameters, B and E, were obtained by chemical methods. Several assumptions were made and their validities explained. It was mentioned that the analytical results correlated well with experimental data.

Another interesting case was the Fiberglas-reinforced phenol-formaldehyde resin used as an ablation shield. The gases, formed by the breaking down of the resin at elevated temperatures, emerges into the gas stream after passing through and chemically reacting with a char and a molten glass layer. The analysis for the heat and mass transfer in the solid phase in the presence of gas–carbon–glass chemical reactions was based on a definite ablation surface temperature for the solid phase.

Two simultaneous ordinary differential equations containing six nondimensional groups were obtained and numerical solutions were recommended.

Subject Headings: *Ablation; Chemical reaction, heat transfer; Heat transfer, chemical reaction; Transport processes.*

A. S. C. Ma

Gaertner, R. F. (General Electric Research Laboratory, Schenectady, New York) "Photographic Study of Nucleate Pool Boiling on a Horizontal Surface," *Journal of Heat Transfer* **87**, 17–29 (1965)

Probably the most common and technologically important type of boiling is nucleate boiling. Heat transfer rates of 20 and 55 million Btu/hr/sq ft, for linear and vortex liquid flow, respectively, have been measured for this process. Yet, no consistent analytical method exists for predicting heat transfer properties.

In this paper, the author seeks to provide an insight into the nature of nucleate boiling, the probable heat transfer mechanisms, and realistic models for analytical study. The approach is experimental; temperature measurements and photographs of pool boiling above a simple flat horizontal surface. Distilled water is the test liquid in the 6-in.-long glass-pipe boiler, and platinum and copper are used and compared as the 2-in.-diam. test surface at the base of the boiler. A special electrical furnace is the heat source.

Measures were taken to achieve steady state prior to data taking. Tests were conducted from incipient boiling to a maximum heat flux (burnout) of 493,000 Btu/hr/sq ft for the copper surface.

At least three, and possibly four, regimes exist in saturated nucleate pool boiling under such conditions. Moreover, the author concludes, any heat-transfer theory or design equation based solely on the dynamics of individual bubbles or any other single heat-transfer mechanism must be in serious error.

Following Gaertner's analysis: the nucleate boiling threshold, at a heat flux q/A of 10,500 Btu/hr/sq ft, marks the changeover from natural convection. In the first 8 per cent of the q/A vs ΔT curve, all "active sites" produce bubbles. The average active site population density n/A is related to heat flux by:

$$q/A = 181(n/A)^{2/3}.$$

The surface temperature T_w controls population density:

$$n/A \propto \exp(-K/T_{w3}).$$

The heat transfer mechanisms of this *discrete bubble* region are: natural convection, evaporation, liquid circulation, and entrainment of superheated liquid in thin wakes. The average bubble diameter at breakoff approximates 130×10^{-3} inches.

The next 7 per cent of the nucleate boiling curve (above 46,000 Btu/hr/sq ft) is designated the *first transition* regime; here, vertical columns of vapor appear. The total heat transfer process is the sum of evaporation, near high active site populations, and the discrete bubble region mechanisms, at low active site locations.

At a heat flux of 80,000 Btu/hr/sq ft., the surface is covered by huge clouds of vapor resting on columnar stems. This *vapor mushroom* regime constitutes the next 39% of the curve. Heat transfer is attributed to latent heat transport at the vapor-liquid interface of the stems and at the base of the clouds.

The slope change of the last 46% of the nucleate boiling curve prompts the author to hypothesize a *second transition* region, where vapor cloud stems are observed to collapse and local vapor patches to exist on the metal surface. At burnout, the entire surface is covered with a vapor film. The researcher believes that vapor patches are formed at locales of critical active site population. The heat transfer mechanism is considered similar to the *vapor mushroom* region, but with allowances for the reduced number of vapor columns available for the latent heat transfer mode.

Subject Headings: ***Boiling, mechanism of nucleate; Heat transfer, in boiling liquids; Photography, of boiling; Nucleate boiling.***

K. M. Foreman

IV. Diffusion Flames

Fendell, F. E. (Aerospace Corporation, San Bernardino, California) "Ignition and Extinction in Combustion of Initially Unmixed Reactants," *Journal of Fluid Mechanics* **21,** 281–303 (1965)

Burning may be defined as involving either a homogeneous mixture of reactants that combine during combustion or a reaction between initially unmixed reactants that combine at the flame. Only slow burning is possible in the unpremixed case considered here, because only those fuel molecules at the flame region are accessible to oxidant molecules.

For unpremixed gases, classical one-component analysis is inadequate; a complete description involves recognition of the multicomponent nature of the flow. Diffusion is then added to the entropy-producing mechanisms of heat conduction and viscosity.

The adequacy of direct one-step chemical kinetics for describing ignition and extinction in initially unmixed gases is studied through the particular case of inviscid axisymmetric stagnation point flow. Oxidant is assumed to flow from upstream infinity towards a nongaseous reservoir of pure fuel at its boiling, or sublimating temperature. Before reaching the reservoir the oxidant reacts with gaseous fuel flowing in the opposite direction to form products and release heat. This heat is in part conducted and diffused to the reservoir interface to transform more fuel into the gaseous state and to continue the steady-state burning. Second-order Arrhenius kinetics for Lewis number unity are examined. A critical parameter characterizing the phenomenon is shown to be the first Damkohler similarity group D_1, that is the ratio of the time for a fluid particle of reactant to traverse the combustion zone to the time for a reaction-inducing collision to occur.

The mathematical analysis of the axisymmetric stagnation point flow problem is present together with the approximations to be made and the effect of burning fuel in the oxidant. Two models of reaction rate are considered; second order Arrhenius kinetics and Burke and Schumann kinetics in which the flame is reduced to a mathematical interface across which derivatives of the dependent variables may be discontinuous. The boundary value problem is examined for the case of each type of kinetic model and a review of the analytical studies of burning in unpremixed gases is presented. The solution using Burke-Schumann kinetics is present in detail together with the numerical integration using a computer program.

Results of the numerical integration for acetone-air data show three regions—weak, intermediate, and intense burning. Arrhenius kinetics have been shown to be able to describe ignition and extinction according to a speculative interpretation of the bifurcated, three-branched steady-state solution of the nearly thin flame condition. The graph of D_1 against maximum temperature shows three regions. For small D_1 the reactants convect away heat without releasing the energy stored in their chemical bonds. Regular perturbation about chemically frozen flow establishes this condition as the weak burning limit. For large D_1 singular perturbation describes a narrow region of intense chemical activity. For infinite D_1 (indefinitely fast rate of reaction) the region is reduced to a surface of discontinuity as in the thin flame kinetics of Burke and Schumann. For intermediate D_1, numerical techniques establish that a solution describing burning of moderate intensity lies between the two previously mentioned asymptotic limits. This intermediate region or intermediate branch of the three-branched steady-state solution of the thin flame condition is physically unstable and rarely observed. Such a system will move towards a weak or strong burning branch, both of which are stable. A system ignites when it jumps from a weak branch to a strong branch, the preferred state suddenly becomes one of intense combustion instead of almost no combustion. Conversely, a system in the strong branch may, under sufficiently strong perturbation, cross over to a weak branch and extinction occurs.

Subject Headings: ***Acetone, diffusion flame; Diffusion flame; Flame, diffusion, theory for; Extinguishment, of diffusion flame; Ignition, of diffusion flame; Reactants, unmixed, in flame.***

G. L. Isles

V. Combustion Principles

Hoynant, G., Duval, X., and Letort, M. (Faculte des Sciences de Nancy et Centre d'Etudes et de Recherches des Charbonnages de France, France) "The Relation between the Combustion Rate and the Specific Surface of Carbon," *Comptes Rendus* **259**, 2827–2830 (1964)

In all gas–solid reactions, there is a fundamental linear relation between the reaction rate V and the real surface S of the solid. Attempts to establish this relation for carbon in air at atmospheric pressure have exhibited errors which could not be attributed to pore diffusion at the experimental conditions used. The authors have observed that minute concentrations (several parts per million) of hydrogenated compounds, especially water, in the combustion air inhibit the reaction to a considerable extent, and these concentrations are variable since the experiments have to be conducted over several weeks. For the tests described, the impurities in the combustion air were first oxidized to CO_2 and H_2O, which were then removed by a long purification train. Finally, the air was cooled in liquid oxygen so that less than 10^{-6} mole fraction of water remained in the air.

In the experiments conducted a 0.5 g sample of carbon particles, ground to pass through a 700 μ sieve (A.S.T.M. 20 and 30) were burned at a temperature controlled to approximately ±1°C until a suitable fraction (x) of the sample had been oxidized. The fraction x, together with the speed of the reaction at that point were determined by infrared analysis of CO_2 and CO in the oxidation products.

At the end of the experiment the sample residue was quenched rapidly, and its surface area S_x measured by adsorption of methane at −196°C. By conducting the experiments for different lengths of time, the curve of V vs S was obtained. In order to prevent diffusion effects interfering with the kinetics of the reaction, the temperature of the reaction had to be kept below 700°C, and consequently the combustion was slow. However, the relation between V and S was a straight line passing through the origin and showed experimental errors less than ±5%.

It was also noted that as the fraction of sample burned increased from 7%–66%, the ratio CO/CO_2 decreased from 1.55 to 0.65.

It was concluded that the catalytic action of the ash, progressively produced during combustion, was responsible for this effect. The activation energy as well as the CO/CO_2 ratio decreased, but the frequency factor in the Arrhenius rate equation increased. Thus, the proportionality between V and S was not affected within the limitations of experimental error, although the reaction mechanism was not identical throughout the experiment.

Subject Headings: ***Carbon, combustion of; Catalysis, of carbon combustion; Inhibition, of carbon combustion.***

P. L. Start

Jost, W. (University of Göttingen, Göttingen, West Germany) "Problems in Flame Convection," *Deutsche Versuchsanstalt fur Luft-und Raumfahrt Ber.* 226 (1962)

Interest in turbulent flames stems from the significant increases in heat output gained by transition from laminar to turbulent mode of flame propagation.

Turbulent flames are ill-defined, therefore, the discussion of convection laws will be limited to laminar flame systems where flame velocity is well-defined. It is defined as the rate of propagation of the flame into the unburned gas with convection effects excluded. The measurement of flame velocity is not possible where convection effects are fully isolated. The effect of pressure on turbulent and laminar flame velocities introduces problems at low pressures with turbulent flames while at high pressures measurements on laminar systems become difficult. The author has begun an experimental program in the measurement of the pressure dependence of the flame velocities of turbulent flames.

Laminar flames can be studied using the soap-bubble method. This is only applicable near atmospheric pressure and does not permit control of the H_2O-vapor partial pressure. In constant-volume environments it is possible to measure the kernel expansions by recording the external (to the bubble) pressure rise. In the soap-bubble technique, however, the igniting spark can reflect pressure pulsations from the walls which can cause havoc with the uniform progression of the combustion wave. The assumptions of uniform one-dimentional aerodynamic conditions can best be met by using large-diameter flat-flame burners or spherically-burning flame holders. To minimize experimental difficulties, the upstream gas flow velocity must be greater than the rate of combustion; otherwise, the flame will flash back. A more involved problem is the relationship between the flame holder and its interaction with the burner. The principal boundary condition affecting the rate of combustion occurs near the burned-gas region, where the state of equilibrium of the products of combustion are ill-defined and complicated, in addition, by the interaction of several independent reactions with coupled equilibria.

The interrelationship of temperature, rate of combustion (Λ_0) and time of passage (τ) of the gas through the combustion zone in regard to the width of the combustion zone (δ) is

$$\bar{\tau} = \delta/\Lambda_0$$

where $\bar{\tau}$ is the mean reaction time which is approximately equal to the time needed by the mean heat flux ($\bar{X}$) or mean diffusion current ($\bar{D}$) to "penetrate" to a width δ in the combustion zone.

The values of $\bar{D}$ and $\bar{X}$ are usually not of equal value, but in order to simplify the model they can be equated. Their sharp dependence on temperature is obvious. By way of example, when $\bar{X}$ and $\bar{D}$ are given the values 1 and 10 $cm^2\ sec^{-1}$, the measured rates of combustion (Λ_0) lie between 10 and 10^3 cm sec^{-1} as the limiting values for Λ_0. Thus $\bar{\tau}$ lies between 10^{-1} and 10^{-6} sec. The width of the combustion zone (1 atm pressure) is between 0.01 and 0.1 cm.

The relationship of D and X to the pressure (P) and reaction time ($\bar{\tau}$) at constant temperature is

$$\bar{\tau} = P/P^n$$

where P^n is the reaction velocity of a reaction of order n. It is not clear that we can assign an order to such a series of empirical reactions occurring in a flame; however, the relationships of D and X to P appear to be compatible with experiment.

These findings are, beset by approximations. The reasonable assumption is made that the effective reaction order lies between 1 and 2, and the pressure exponent of the dependence of the latter on the rate of combustion be between $+\frac{1}{2}$ and $+1$. Turbulent systems would not exactly coincide but must be assumed to rest in the same exponential area. If the flame temperature changes with pressure, a further increase in the exponential pressure-dependence is necessary. Experimental substantiation of these pressure factors are seen, for example, in CO–air flames to which has been added small amounts of H_2 or H_2O. Here the mass flux exponent is around $+\frac{3}{4}$.

The spreading of flames in turbulent flow is not easily illustrated by photographic methods. These flames have a very wide illuminated zone that narrows at the burner rim, which is actually an illusion conveyed by the camera since the width is due to rapid fluctuations of a thin zone. To understand the mechanism of the spreading of turbulent flames, it is important to identify a coherent or real reaction zone that actually exists under highly turbulent conditions. One approach is to measure the electrical conductivity of such flames. Wide fluctuations should parallel changes in the shape and size of the luminous zone. Results show no variation in conductivity in the area where the flame zone is supposed to exist. More refined experiments have shown that at high-flow velocities the conductivity varies coherently, indicating the presence of a real luminous zone. When the burned turbulent gases are thrown into the incoming unburned gas stream, it is found that these burning zones disappear. The flow velocities are high enough to cause combustion to proceed at a velocity faster than in laminar flow.

Speeds of turbulent flames are difficult to measure since this involves, among other things, the determination of the flame area. Compositional variations in both laminar and turbulent flames usually have identical over-all effects upon their respective flame velocities.

The composition criteria cited above and the knowledge that the velocity of a stabilized, turbulent flame is actually four to five times greater than the corresponding laminar flame, leads one to the conclusion that the real reaction area of a turbulent flame is much larger than the narrow instantaneous flame zone used for the calculation of this quantity.

No theoretical relationship of variations of burning velocity with burner diameter has been devised as yet. One citation indicated that the flame velocity depends more strongly upon the burner diameter than upon the Reynolds number. Theoretical expressions relating the flame speed, flame area, and burner diameter can be reduced so that the diameter is no longer a factor.

The pressure-dependence of turbulent flame velocities can be reasonably correlated to their laminar analogs. The flame velocities usually increase as the pressure is lowered.

Subject Headings: ***Flame, turbulent; Flame spread, of turbulent flame; Turbulence, flame propagation.***

P. Breisacher

Nichols, O. D., Goodwin, T. C., Muccino, A., and Rice, R. G. (Defense Documentation Center, Alexandria, Virginia) "Flames and Flame Properties—A Report Bibliography," *AD 422 075* (January 1964)

Flames and combustion are broad subjects covering such topics as aerodynamics, theromodynamics, chemical kinetics, fluid mechanics, and thermochemistry. A general picture of the research activities on these subjects can be gained from the recent review articles, "Combustion and Propulsion Research" by S. S. Penner, *Chemical & Engineering News*, January 14, 1963, and "Flame Chemistry" by Robert M. Fristrom, *Chemical & Engineering News*, October 14, 1963. This bibliography on flames and related topics presents approximately 800 citations from the unclassified unlimited DDC collection, and is the first of a series of bibliographies in this general area. The dates of reports referenced cover December 1950 to May 1963. The reports of this bibliography are grouped alphabetically in the Table of Contents. Under the group headings, the reports are arranged alphabetically by corporate author for the purpose of bringing together reports by the same corporate author. Classified and limited reports on flames and flame properties appear in a bibliography numbered AD–334 535.

Future reports accessioned by DDC will be announced in the Technical Abstract Bulletin and the Cumulative Index by subject area, descripton, and originating agency. Instructions on how to request documents listed in this bibliography and a directory of the DDC Offices and the Headquarters Reference Office, where reports or facsimile copies are available for immediate review, are given.

Subject Headings: ***Bibliography, flame; Combustion, bibliography; Flame, bibliography.***

Authors' Abstract

VI. Radiation

Love, T. J. (University of Oklahoma, Norman, Oklahoma) **and Grosh, R. J.** (Purdue University, Lafayette, Indiana) "Radiative Heat Transfer in Absorbing, Emitting, and Scattering Media," *Journal of Heat Transfer* **87**, 161–166 (1965)

In the computation of radiant heat transfer through media containing local inhomogeneities, such as small particles, consideration should be given to the effect of energy scattering. Such media includes smokes, dust clouds, fluidized beds of particles, fogs, and low density insulations. In many instances, the problem of interest will include the effects of partially reflecting boundary surfaces. In most published analyses of such problems, reflecting boundaries and the exact nature of scattering have not been accounted for. The purpose of this work is to present an approximate method for analyzing the problem of radiation heat transfer in an isothermal plane–parallel system of particles which absorb, emit, and scatter radiant energy.

Because of the complicated nature of the integrodifferential equation of transfer, the authors reduced the equation to a simpler form by imposing certain geometric and optical restrictions. The system is assumed to be composed of a uniform plane cloud of particles suspended in a transparent medium and bounded by infinite surfaces which emit and reflect radiation in a diffuse manner. The particles are assumed to be homogeneous spheres of uniform diameter and known refractive index.

The numerical method presented gave consistent results over a range of computations with both third- and fourth-order approximations indicating that the method would be expected to give results satisfactory for most engineering computations.

Although the method of analysis is restricted to plane–parallel axially symmetric geometry, the results may give an insight into the effects for other systems. In particular, the results for optically fixed spacings may be a good approximation for other geometries with large optical dimensions.

It is significant to note that for small optical spacings and for small values of the particle-size parameter, the effect of anisotropic scattering is closely approximated by the isotropic case. This would suggest that the assumption of isotropic scattering may be made with little error for many systems.

Another interesting observation is that infinite clouds of particles which scatter radiation, such as carbon particles, may not be considered black.

Since most clouds of particles may be composed of various sizes and shapes of particles with random orientation and unknown refractive indices, analytical determination of the scattering function may be impossible. However, because of the random nature of the clouds, the scattering may be considered axially symmetric and the authors' analysis would be used with experimentally determined scattering functions.

The authors include a sample problem to illustrate the proper usage of their method and results.

Subject Headings: ***Heat transfer, media, absorbing; Heat transfer, media, emitting; Heat transfer, media, scattering; Heat transfer, radiative; Particles, radiation through.***

E. C. Woodward, Jr.

Snyder, J. W. (Defense Atomic Support Agency, Department of Defense, Washington, D. C.) "Thermal Radiation Bibliography," *DASA-622* (September 1964)

This bibliography includes the most significant and recent work associated with nuclear weapon effects and phenomena reported by United States investigators and a few foreign investigators. The bibliography contains both classified and unclassified listings. The unclassified can be found in Section I and the classified can be found in Section II. The following subject categories are covered: Ignition of Materials, Fire Buildup and Spread, Physical Chemistry, Atmospheric Transmission. Thermal Ablation, Thermomechanical Loading, and Fireball Phenomenology.

Present plans call for a periodic supplement in order to keep it reasonably current. In this respect, the author would appreciate information concerning the existence of any unlisted and related documentation which can be mentioned in the proposed supplement.

Personnel having appropriate security clearances and certified "need-to-know" may review most of the documents listed in this bibliography at the Defense Atomic Support Agency. Individual reports, where available, may be secured from appropriate sources listed in Appendix A.

Subject Headings: ***Bibliography, thermal radiation; Radiation, thermal, bibliography.***

Author's Abstract

VII. Suppression of Combustion

Dewitte, M., Vrebosch, J., and van Tiggelen, A. (University of Louvain, Louvain, Belgium) "Inhibition and Extinction of Premixed Flames by Dust Particles," *Combustion and Flame* **8**, 257–266 (1964)

The inhibiting effect of dusts added to premixed flames of methane–oxygen–nitrogen was investigated. The main objective was to explain the inhibiting of powders so that concentrations of a given powder for complete extinction of a given flame could be predicted. The additive powders were first classified by the authors into two main groups of relatively low or high efficiency of inhibition. As a result of experimental and theoretical studies, the inhibiting action of these two groups was later identified as either thermal heat-sink inhibition (low efficiency) or thermal inhibition in which chain carriers recombined on the dust surface (high efficiency). Among the low-efficiency dusts were alumina, aluminum sulfate, silica, cupric oxide, and magnesium carbonate; high-efficiency dusts were the chromates, carbonates, sulfates, nitrates, and halides of potassium and sodium.

Extent of flame inhibition was determined by noting the critical amount of dust required for flame extinction or the flame temperature and burning velocity changes resulting from dust addition to downward burning flame cones established at the bottom of a vertical water-cooled burner tube of 0.6 cm diam and 60 cm length. The dusts of various types that were fed to the burner top were known only in average sizes that were calculated from extreme dimensions of sieve measurement. Precautionary measures were taken to prevent agglomeration of the flowing dusts by imparting a small electrostatic charge to the particles at a midway position in the tube. Average flame temperatures were measured using the sodium D-line reversal technique, applying appropriate corrections for the amount of light absorbed, reflected, or dispersed by the particles. Burning velocities were determined by the total-area method, basing the flame surface area on the schlieren flame outline. Particle temperature and dimensions did not change much on passage through the flamefront, nor did decomposition or devolatilization occur to any significant degree. Under these circumstances, it was concluded that heterogeneous inhibition is a surface phenomenon, either as a surface cold wall or a surface that adsorbed radicals.

To substantiate the conclusions resulting from experimental observations and theory, additional information concerning the particle-size distribution of the powder additives would be desirable. Present assumption of a monodisperse system of average particle size instead of a dust cloud containing a spectrum of particle sizes would be expected to have a considerable influence on many of the experimental conclusions. Knowledge of particle-size distributions are essential for complete assessment of the amount of heat removed by the cold particles and flame-temperature lowering.

However, despite this shortcoming, the authors were able to distinguish very well between thermal and chemical inhibition in several correlations of theory and experiment. Many of the equations utilized in the theoretical development were previously derived in other papers of van Tiggelen. *Thermal inhibition* was shown to be in accord with a model in which the burning mixture is cooled by particles until the mean kinetic temperature (T_{mi}) drops to its limiting value below which no flame can be self-sustaining, or some temperature value that can be predicted on the basis of thermal exchange between gas molecules and solid particles. For thermal inhibition to hold, it was found that: (1) the burning velocity (V_{0i}) of the mixture decreased with T_{mi} so that the plot of (log $V_{0i} + \frac{1}{2}$ log T_{mi}) vs $1/T_{mi}$ was linear with increasing amounts of dust, and (2) thermal inhibitors did not affect the normal value of the flamefront thickness.

For *chemical inhibition* it was found that: (1) the values of T_{mi} were almost invariable on addition of increasing amounts of dust; (2) the critical dust concentration for extinction (W_c) followed the burning velocity (V_0) of the uninhibited flame so that W_c plotted against V_0^2 gave a straight line; (3) the slopes of the linear plot of W_c versus V_0^2 for the same inhibitor with different particle sizes were in the same ratio as the relative average particle radii; (4) the slopes were inversely proportional to the ratios of the relative dust efficiencies for different inhibitors of the same particle size; and (5) the slopes were proportional to the ratios of the weights of the relative chain carriers in each burning mixture when one chemical inhibitor was added to separate flames of methane–oxygen and propylene oxygen. This result was taken to be partial proof of the dependence of efficiency of chemical inhibition on availability on the particle surface of a free valence electron for the colliding radicals.

Subject Headings: *Inhibition, chemical, by particles; Dust, inhibiting effects; Extinguishment, flame, by particles; Inhibition, of flame, by particles; Methane, flame, inhibition, by particles; Particles, inhibition by; Flame, inhibition, by particles; Inhibition, thermal.*

J. M. Singer

Landesman, H., Basinski, J. E., and Klusmann, E. B. (National Engineering Science Company, Pasadena, California) "Investigation of the Feasibility of Synergistic Enhancement of Halogenated Fire Extinguishants," *Air Force Systems Command*, *Wright-Patterson Air Force Base*, *Ohio*, *Technical Report AFAPL–TR–65–10* (March 1965)

This report presents results of a program to test the feasibility of synergistically enhancing the effect of halogenated fire extinguishants with addition of free radical initiators. The effect, previously noted with self-extinguishing plastics by Dow Chemical Company and Koppers Company workers, has been found to be only marginal or nonexistent over the concentration range of initiator–chlorobromomethane mixtures used in this work.

Data are presented from screening for the synergistic enhancement effect by means of (1) flame speed measurements of hydrogen-air flames to which initiator–inhibitor mixtures are added, (2) flammability limits of heptane-air flames to which initiator–inhibitor mixtures are added, and (3) small-scale pan fire tests using initiator–extinguishant mixtures. Results of the experimental program are discussed and attempts made to relate observations to known combustion phenomena.

Subject Headings: *Extinguishants, synergistic effects; Fire, extinguishants, synergistic effects; Fire, extinguishants, halogenated; Synergistic effects, fire extinguishants.*

Authors' Abstract

VIII. Model Studies and Scaling Laws

Kennedy, M. (Safety in Mines Research Establishment, Buxton, England) "The Correlation and Calculation of Temperature Contours Round Small Fires," *British Journal of Applied Physics* 16, 109–114 (1965)

Using a definition of a small fire as being one which generates heat at a rate of less than 100 kW, a device was sought to give an early warning of a mine fire while still small. Factory-type fire detectors, based on temperature rise, are not always suitable for mine fires because of local airflow conditions. Thus, to achieve a temperature needed to trigger the detector (often set to function at 60°C) in the mine, the heat-production rate would be considerably beyond 100 kW.

By using detectors in suitable positions with respect to the fire, the plume of hot gases generated by a small fire might be sensed in ventilated surroundings before the gas temperature was reduced too much by entrained air. It was necessary to conduct experiments to determine the spreading of an ascending current of hot gases from a small source when a side wind was present in order to ascertain the optimum positions for the heat sensors.

Specific quantities of heat were supplied to an airstream in a tunnel in which methylated spirits were burned in shallow trays. Temperatures were recorded downstream of the fire and 60°C isotherms, in a vertical plane parallel to the sides of the tunnel and passing through the center of the fuel tray, were ascertained. Measurements were obtained of the maximum height at which a 60°C temperature was secured for different tray sizes and airspeeds. These data then were interpreted in terms of equations developed by Priestley in 1958. They described the motion of a plume of hot gas issuing from a chimney into a moving atmosphere.

The tunnel used was 8 ft wide and 8 ft high; 19 thermocouples were employed. The fuel trays, 0.5 in. deep, had sides of 6, 9, 12, and 16 in. in length and were weighed continuously during the tests. Airspeeds up to 1,000 ft/min were produced by a fan. The vertical profile of the airspeed was not constant. Averages of the steady temperatures were graphed according to the spatial distribution of the thermocouples. The 60°C isotherms were determined by interpolation.

Results showed that the height of the 60°C isotherm dropped rapidly as the airspeed increased. As the rate of heat production increased, the height of the isotherm increased as expected. When the heat-production rate was 45 kW, for example, the 60°C isotherm was reduced from 30 in. to about 14 in. when the airspeed was increased from 120 to 480 ft/min. For an airspeed of 120 ft/min, the plume height for a temperature of 60°C increased from 16 to 30 in. when the heat production rate was increased from 7.2 to 45 kW.

The author also showed that the plume height for 60°C isotherms, affected by a side wind, can be correlated in terms of Priestley's theory. Correlation was obtained by using a spreading coefficient raised to the 0.75 power. Also, the results showed that smaller areas of heat sources give rise to greater heights of 60°C isotherms for specific values of airspeed and rates of heat generation.

Subject Headings: *Aerodynamics, of fire, small; Fire, aerodynamics; Isotherms, of fire, small; Methanol, of fire, small; Plumes, thermal; Temperature, contours.*

L. E. Bollinger

IX. Atomization of Liquids

Essenhigh, R. H. (The Pennsylvania State University, University Park, Pennsylvania) **and Csaba, J.** (Field Cycle Research Unit, C.E.G.B., Dartford, Kent, England) "The Thermal Radiation Theory for Plane Flame Propagation in Coal Dust Clouds," *Ninth Symposium (International) on Combustion*, New York and London, Academic Press, 111–124 (1963)

The system studied consists of a plane flame front propagating through a monodisperse, uniformly mixed dust cloud of finely ground coal, suspended in air. Heat transfer from the burning zone to the cold cloud is presumed to be predominantly radiative, and diffusion of oxygen towards individual particles is taken to be the principal rate-controlling factor as Nusselt's treatment of pulverized fuel combustion.[1] In the present treatment, in contradistinction to Nusselt's, the rate is primarily determined by the intensity of the incident radiation flux, I_f.

Absorbed radiation serves to heat the particles from the input temperature to the ignition point, but is partially conducted from the particles to the carrier gas. The ignition temperature T_i presumably coincides with the temperature of incipient volatilization of the coal. The flame stabilizes where the burning velocity equals that of the hot cloud. The flame speed is defined as the stationary input velocity v_0 of the cool cloud. In the steady state the flame is maintained at $x = 0$, while the cloud issues from the burners at $x = -L_i$. Relative motion of air and particles is deliberately ignored, but the temperatures of dust T_d and gas T_g are distinguished.

Due to thermal expansion, the following relations hold:

$$\text{velocity, } v=v_0(T_g/T_0);\quad \text{dust density, } D=D_0(T_0/T_g);\quad \text{air density } \rho=\rho_0(T_0/T_g) \tag{1}$$

The radiation intensity attenuates according to

$$dI/dx=kI \tag{2}$$

with

$$k=3D/4aq \tag{3}$$

where a is the particle radius and g the particle density.

Heat transfer from particles to gas is described by

$$dT_g/dt=3D(T_d-T_g)/a^2q, \tag{4}$$

where α = thermal diffusivity of air.

Heat balance of radiation absorbed by the particles is given by:

$$dI/dx=I=Dc_d\, dT_d/dt + pc_v\, dT_g/dt, \tag{5}$$

where c_d is the heat capacity of dust and c_p that of air.

In the steady state $dx=v\,dt$, so that, on account of (1), (5) becomes

$$vkI=v_0(D_0c_d\, dT_d/dt+p_0c_p\, dT_g/dt). \tag{6}$$

Introducing the parameters

$$m=kv=3D_0v_0/4aq,$$

$$K=4m/a^2v_0,$$

and

$$n=(1+p_0c_p/D_0c_d)3D_0/a^2q,$$

all of which are independent of x and t, and of dimension $\sec^{-1}$, integration of Eq. (6) yields solutions for T_d-T_0 and T_g-T_0. Hence, the burning velocity $s=v_0$ is expressed as function of D_0, a, (T_i-T_0), and ignition time $-t_i$.

In applying this result the authors distinguish between "finite" and "infinite" systems, characterized by finite or virtually infinite values of t_i. Two special approximations form the basis of the principal conclusions:

$$\text{Infinite systems, } \alpha=\infty\,;\ s_0=I_f/(T_i-T_0)\ (D_0c_d+\rho_0c_p) \qquad (7)$$

$$\text{Finite systems, } \alpha=\infty\,;\ s=I_f[1-\exp\,(mt_i)]/[(T_i-T_0)\ (D_0c_d+\rho_0c_p)] \qquad (8)$$

Combining (7) and (8) with the substitution $t_i \cong L_i/v_0$, the final approximation is then discussed

$$s=s_0[1-\exp\,(-3D_0L_i/4aq)]. \qquad (9)$$

Here, s_0 is referred to as the "fundamental flame speed" that can be measured only on reasonably large flames, i.e., with L_i of the order of 100 cm. It is anticipated that s_0 has a maximum at stoichiometric concentration. The dependence of s_0 and s on D_0 is graphically represented for concentrations exceeding the stoichiometric and for different values of L_i. It is shown that the peak of s drops and shifts toward higher concentrations as L_i increases.

Abstracter Comments

The theory as presented, though apparently consistent within itself, suffers from the shortcoming that it leaves the burning zone out of consideration. This leads to the belief that, for a given concentration, the incident radiation intensity I_f remains unaffected by changes of input velocity. True, the maximum (adiabatic) flame temperature is thus fixed. However the location of this maximum at some distance, L_m on the positive X axis is not. This distance is proportional to the burning time, i.e., it depends on Nusselt's rate-determining step. Consequently, the radiation incident at $x=0$ varies with the attenuation and with the temperature profile in the burning cloud.

Reference

1. Nusselt, W.: V.D.I. *68*, 124, 914 (1924).

Subject Headings: ***Coal dust, clouds; Clouds, of coal dust; Dust, clouds; Flame, propagation, dust; Flame, particles, coal dust; Radiation, in dust flame; Radiation, thermal, in dust clouds; Radiation, thermal, in flame propagation.***

H. M. Cassel

Kuznetsov, V. R. (U. S. S. R.) "Rate of Chemical Reaction and Its Effect on the Process of Droplet Combustion," *Inzhenerny i Zhurnal* 2, 344–349 (1962) Translation AD 419229 FTD–TT 63–653 Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

This paper presents an approximate solution to an equation derived by Agafonova.[1] The equation is intended to describe the burning of a spherical fuel droplet in a gaseous oxidizer stream. It appears that the objective of Agafonova's theory was to account for the influence of a finite chemical reaction rate on the evaporation rate of the droplet, on the fraction of vaporized fuel that ultimately reacts, and on the conditions governing blowoff of the diffusion flame from the forward stagnation region. Some assumptions involved in Agafonova's model are listed by Kuznetsov, although he does not describe the model. The nature of the model is probably best characterized by the first assumption, which states that "the boundary layer on the droplet is equivalent to a certain given film, with identical thickness everywhere." Agafonova's second-order, ordinary differential equation (for temperature as a function of radial coordinate) appears to consist of a heat conduction term equated to a chemical heat release rate term. Kuznetsov's contribution is to approximate the heat release rate as a rectangular-shaped step function and the temperature profile as a continuous triangular-shaped function, thereby extracting algebraic solutions for the fraction of vaporized fuel that burns and for flame blowoff conditions. These two results were compared with experiments (again reported by Agafonova) on ethyl alcohol and gasoline droplets. The predicted blowoff conditions agreed well with experiment, but the predicted fraction of fuel vapor burned agreed poorly (because the effect of wake burning is neglected in the theory, according to Kuznetsov).

This theoretical work appears to be mathematically inferior to current Western theoretical work on the problem. However, there is a considerable amount of excellent work being done in Russia on combustion theory, and much of this is not translated into English. On the other hand, the Russian authors exhibit familiarity with the Western work (e.g., Kuznetsov quotes Spalding).

Readers interested in turning to the literature to obtain more details of this work may appreciate the following warnings:

1. Agafonova's paper does not appear to have been translated.
2. Kuznetsov's paper is written in such an abbreviated style that it is difficult to follow in translation.

Reference

1. Agafonova, F. A., Gurevich, M. A., and Tarasova, Ye. F.: "Conditions of Stable Combustion of Single Liquid Fuel Droplets," Third All-Union Conference on the Theory of Combustion, Vol. 2 (Moscow, 1960).

Subject Headings: ***Droplets, burning of; Ethyl alcohol, droplet burning; Gasoline, droplet burning; Reaction rate, effect on droplet burning; Rate of reaction.***

F. A. Williams

X. Meteorological Interactions

Thyer, N. (University of Washington, Seattle, Washington) "Valley Wind Theory," *Final Report-Part B Contract AF 19(604)–7201, Geophysics Research Directorate, Air Force Cambridge Laboratories, Bedford, Massachusetts* (July 1962)

This report is the fourth of a series on valley and mountain winds. The first three parts describe field studies; the report reviewed here is a theoretical study of valley winds. In otherwise calm conditions a wind will often blow up a valley in the daytime and down the valley at night. While a number of authors have tried various theoretical models to predict valley winds, none has been particularly successful because of the complicated interaction of natural convection with a pressure gradient. The approach here is to use a digital computer to obtain solutions to the full equations.

There is no particular difficulty in writing the appropriate conservation equations once an eddy viscosity and eddy thermal conductivity have been introduced. The region considered is a V-shaped valley, closed at one end and at the other end opening on to a level plain. The computer program starts with the atmosphere at rest, a disturbance is introduced by heating the air at the surface, the time history of the resulting flow is obtained.

Clearly the computer solution to such a three-dimensional, unsteady problem is difficult. This report is largely a summary of the difficulties encountered. First a rather loose grid network is used. Several assumptions are made on the original equations. Despite the rather rough approach, the results seem remarkably satisfactory. Several features of the wind observed in nature are reproduced; a thin layer of slope wind, updrafts over the ridges, valley wind below ridge level having a maximum speed near the trough, and an anti-wind layer of about the same thickness near the ridge height.

The use of computers to determine solutions to meteorological problems certainly seems to offer a lot of promise. This report should be of interest to anyone involved in such an effort.

Subject Headings: *Valley wind; Wind, valley, theory of.*

D. L. Turcotte

XI. Operational Research Principles Applied to Fire Research

Phung, P. V. and Willoughby, A. B. (USR Corporation, Burlingame, California) "Prediction Models for Fire Spread Following Nuclear Attacks," *Final Report for Office of Civil Defense under Contract OCD–PS–64–48* (January 1965)

The prediction method for fire spread following nuclear attacks is stated as likely to involve a representation of the fire in time and in space and require data on rate of spread, burning time of fuel, igniting capability, and ignition susceptibility. It is suggested that a semi-empirical approach seems to be most appropriate. The study develops two families of mathematical models: fire front and fuel state.

In the fire-front model, the entire fire area or fire front is pictured as a random walker moving along a strip of fuel area divided into small square sections called cells. At any moment, one of three possible events may take place: either the fire front is burned out, or it moves one cell forward, or it stays where it is. Mathematical relations based on this mechanism give the probability of finding the fire still burning and that of finding the fire burned out at a given location and a given time. In addition, the mean rate of spread in terms of cells per hour is readily calculated.

With slight modifications, the mechanism can be applied to a strip of fuel area in which the cells differ significantly with respect to fuel characteristics or to cases in which, by the process of long-range spotting, the fire can jump over one or more cells.

The fuel-state models describe, by guess or by fact, the events in each cell of the fuel area. At any time, a cell is in one of three states: the unignited state, including the early phase in which the cell (though ignited) is still incapable of igniting other cells; the flaming state, in which the burning intensity is sufficient to ignite other cells; and the burnout state. Whether and when a cell passes from one state to the next depends on the particular set of fuel, weather, and topography variables. All transitions and derived quantities can be analytically related to the burning time of the cell (not of the entire fire) and to the mean rate of spread in cell widths per unit times.

The study attempts to analyze 71 cases of recorded fire spread in urban areas which have, over the years, appeared in reports of fires. In this analysis, "fuel type" is put into four classes: "light wooden structures," "heavy wooden structures," "light stone or concrete structures," and "heavy stone or concrete structures." It can be observed that a fire-protection engineer would question whether "light" and "heavy" structures can be differentiated. Fire spread between all-wood buildings and between buildings which have brick or masonry outside walls is sufficiently different to be long recognized.

The analysis also uses the term "fuel density" to describe the ratio of roof area to ground area, sometimes called "builtupness." Fuel density is measured for four classes: below 20, 20 to 29, 30 to 39, and over 40 per cent.

The analysis differentiates between ground spread and "spotting." "Spotting" is simply the spread of fire by flying brands which may spread fire without actually igniting all of the intervening buildings.

Fire-protection engineers would recognize two vastly different classes of fire spread where all-wood buildings are involved, depending on whether the buildings had wood-shingle roofs. Wood-shingle roofs are not even mentioned in the analysis, although they probably were referred to in the reports on which the analysis was based. The analysis reveals this factor but explanation of the phenomena seems backhanded to a fire-protection engineer. An important result— "at first startling"—is reported, that observed rate of spread increases rapidly as fuel density decreases. The report then goes on to say, "The explanation is that for fires which do not go out in low density fuel, the relative tendency for ground spread decreases much faster than the tendency for spotting." Wood-shingle roofs are found on wood residences which would not generally be in areas 30 per cent or more built-up.

Studies of the U.S. Strategic Bombing Survey relating to spread probability in cities receives comment. These studies deal with the efficiency of 37 linear miles of firebreaks of various widths. Fire was stopped over 34.8 per cent of the total length of breaks in the width range from 65 to 150 ft and 75 per cent of the total length for widths ranging from 150 ft upwards. This seems to indicate that for a spacing of 107 ft (midpoint between 65 and 150 ft), the probability of spread is approximately 0.65, and for some spacing beyond 150 ft, it is 0.25. This spacing is probably not far from the point at 200 ft, halfway between 150 and 250 ft.

With these two points and the fact that fire spread is certain when spacing is zero, a curve of probability-of-spread versus distance could be drawn. Such a curve should be considered as an upper limit of the probability of spread for two reasons: first, fires were not considered stopped in places where burned structures were found on both sides of the firebreak, although both sides of an adequate firebreak might have been hit directly by incendiary bombs; second, fire might have jumped across a firebreak at one point and spread along some distance on the other side of the break.

Also mentioned is examination of fire-spread data in incendiary-attacked German cities which has led to the conclusion that under normal fire conditions, a 10-ft space between two brick buildings had about 50 per cent chance of preventing fire spread. This value and the fact that fire spread is certain when spacing is zero allows a second curve to be drawn which is obviously a lower limit for a fire-spread curve.

A curve drawn between these two limits is presented as a best guess to yield acceptable results when applied to urban fuel in general. This derived curve shows probabilities at 50, 100, 150, and 200 ft as approximately 80, 35, 12, and 4 per cent, respectively.

It is concluded that additional studies of urban-area fire spread would be desirable for use of the models proposed. Two methods of obtaining additional data on fire spread are suggested which would be helpful for both wartime and peacetime purposes.

One idea is that the probability of no spread can be studied by examining maps of burnout areas in World War II incendiary-attacked cities or in any large-scale urban fire. For a given type of fuel area, the pairs of burned and unburned structures with a given spacing would be counted and tabulated. It is expected that it can be shown that the distribution of spacings (a characteristic of the area, not of the fire) must be combined with these data to give the probability of no spread.

An alternative and more basic study suggested is to determine the maximum spacing required for ignition to occur for each narrow range of responsible factors. Among those suggested for study are type of structural materials, fire load and size, to obtain the probability of spread as a function of distance. This, of course, is what fire-protection engineers have traditionally done with past fire experience and approval of the methodology should be welcomed.

Subject Headings: *Fire spread, nuclear attack; Models, fire spread; Nuclear attack, fire spread.*

H. Bond

XII. Instrumentation

Cucchiara, O., Rex, R., and Donaghue, T. (Parametrics, Incorporated, Waltham, Massachusetts) "The Development of an Instrument for the Detection of Hazardous Vapors," *Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, Technical Report AFAOL–TR–65–50* (June 1965)

A prototype model of an instrument which is capable of detecting low concentrations of hydrogen, fluorine, and fluorine-containing oxidizers was developed.

The instrument provides an audible alarm within 3 to 5 sec after exposure to near hazardous concentrations of these gases. The alarm concentrations are either 0.5 or 1.0 per cent hydrogen, and 0.025 ppm of fluorine, chlorine trifluoride, or oxygen difluoride. Other detection levels (both higher and lower) could be set if required.

The instrument is portable, simple to operate, and reliable, and it incorporates the technique of radiochemical exchange using kryptonates. Selectivity is achieved by the utilization of different kryptonated sources for the various gases. Other gases can be detected with this instrument by using appropriate kryptonate homologs.

Subject Headings: *Detector, radioactive, for hazardous vapors; Vapors, hazardous, detector for; Krypton, radioactive, detector, for hazardous vapors.*

Authors' Abstract

XIII. Fire-Fighting Techniques, Equipment

Countryman, C. M. (Pacific Southwest Forest and Range Experiment Station, U.S. Forest Service, Berkeley, California) "Mass Fires and Fire Behavior," *U.S. Forest Service Research Paper PSW–19* (1964)

Mass fires in heavily populated areas or wildlands pose major threats to life, property and natural resources. In attempting to establish fire characteristics and the factors influencing mass fire, the need has been recognized for quantitative data from planned large field-test fires.

Countryman's report is a well-documented comprehensive summary of the design and results of six series of field tests simulating mass fires and conducted during a period of over two years in U.S. National Forests of the Pacific Southwest region. In addition, the report includes a status report (1964) on knowledge of free-burning fires.

Categorizing the two classes of mass fires, i.e., fire storms and conflagrations, the author procedes to describe the two types of fire environments (open and closed) and their three major components (fuel, topography, and air-mass characteristics).

The test series involved four general fuel types and a large variety of geometric and environmental conditions. In addition to photographic documentation of each test fire, continuous pressure, temperature, and radiation data were taken, and intermittent samples were made of CO, CO_2, and O_2 concentrations.

The author draws a number of significant conclusions from the experimental program. It is determined that wildland fuel types are satisfactory for simulating many urban (building) fire conditions and, thus, this permits conducting fire research on a practical, relatively inexpensive scale. In addition, the field-scale fires are reasonably capable of being duplicated to allow verification of earlier observed phenomena.

Contrary to the widely held misconception, the air flow into the fire area is found to come from above the fire base and increase in rate with height. In fact, the hot fire deflects ambient air flow in much the manner of a bluff body. The spread of fire appears unaffected by flame radiation and more a matter of mass transport of burning particles (firebrands) to the unburned fuel sites.

Of great consequence to attempts at fire modeling is the fact that test data suggests that small-scale or laboratory fires are not representative of large- or field-scale fires because the air flow into and supporting the combustion zone is at a considerably higher temperature for the latter set of conditions After an initiation phase, the fire breaks up into several hot spots, each with a highly turbulent convective column which eventually merges into an over-all thermal convective flow. The temperature of the merged flow is much lower than in the primary combustion zone, indicating a high rate of heat loss to the entrained air. The pressure in the wake of the fire is found to be negative in contrast to the highly positive pressure of the combustion region. The development of fire whirlwinds is observed in areas where unstable air mass conditions (such as opposing air currents and eddy circulation) occur. (This fact may lead to predictive estimates of possible situations leading to fire storms.)

Of significance to human survival in fire shelters are the measurements of lethal concentrations of gaseous combustion products and reduced oxygen content which occur within and immediately adjacent to fires at almost the same time. Furthermore, intolerable heat conditions are reached in a fire area within a few minutes after ignition.

For future investigation, the recommended areas are: extension of tests to much larger fires in order to verify current conclusions and extrapolations, instrumentation techniques for larger-scale test fires, a detailed study of ignition and fire pattern and fire-generated vortices, and the exploration of characteristics of slow- or long-burning fires usually associated with large massive buildings.

Subject Headings: ***Conflagrations; Fire storm; Fire, mass, simulation of; Fire, urban, simulation of; Simulation, of urban fire; Fuel, wildland, simulating urban fire.***

K. M. Foreman

Pickard, R. W., Bigmore, R. H., and Hird, D. (Joint Fire Research Organization, Boreham Wood, England) "Gas Temperatures beneath Ceilings due to Steadily Burning Fires in Buildings," *Institution of Fire Engineers Quarterly* **24**, 230–259 (1964)

Heat-sensing detectors are commonly used for fire alarms and automatic sprinkling systems. Since the operation of the detector depends upon its temperature rise, its actuation in the early stage of a building fire is dependent upon the temperature and velocity of the stream of hot gases at the point where the detector head is placed. Detectors must be placed so that wherever a fire may start, the heat transfer to at least one head is sufficient to ensure early operation. The temperature and velocity of the hot gases and, therefore, also the heat-transfer rate to the detector are dependent upon the size of the fire, the distance to the detector, the distance between the detector and the ceiling, and the size and characteristics of the ceiling.

Local temperature and velocity measurements were made for various types of buildings and ceilings with controlled experimental alcohol fires of constant heat output. The types of full-scale buildings and ceilings investigated were:

1. A rectangular corridor, closed at one end where the fire was located, and open at the other end.
2. A clerestory roofed building with windows open on one side; the fire located near an end wall.
3. Building with a north-light roof (sawtooth window bays); the fires located at one side wall and at the center of the bay.
4. Building with a large flat ceiling; the fire located at the center of the building at several heights from the floor.
5. Building with flat ceiling and joisted roof beams: the fire at an off-center position at floor level.

Data of temperature and velocity are given for various locations along the ceiling and at different heights below the ceiling. The data are correlated with a semi-empirical mathematical expression for the temperature distribution directly above and at some distance from a rising column of hot gas. From these experimental results the minimum size of fire (in terms of heat-release rate) to operate detectors under various conditions and locations are established for both low-and high-sensitivity detectors. Important conclusions are that ceiling height has a very large effect, while detector spacing up to about 25 ft has a small effect, on the size of fire which can be detected.

Subject Headings: ***Ceiling, temperature beneath during fire; Detector, thermal, for fire; Fire, detector; Temperature, beneath ceilings during fire.***

R. W. Ziemer

XIV. Miscellaneous

Fahnestock, G. R. and Hare, R. C. (Southern Forest Experiment Station, New Orleans, Louisiana) "Heating of Tree Trunks in Surface Fires," *Journal of Forestry* 62, 799–805 (1964)*

Temperature patterns in a longleaf pine stand in southern Mississippi were studied during surface fires. Temperature measurements were taken at the bark surface on the lower trunk of seven longleaf pines and cambial temperatures on six of these pines. Study trees were located on either headfire plots or backfire plots. Air temperatures were also measured on three additional plots (two headfires and one backfire). Fuel concentrations averaged 14 tons per acre around the perimeter of the

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* See page 174 this issue for "Simulating Forest Fires for Research" by R. C. Hare.

study trees and 21 tons per acre immediately adjacent to the tree trunks; fuel consisted mainly of pine litter.

Iron-constantan thermocuuples were used as sensors in all the temperature measurements. Pairs of the thermocouples were placed on the lee and windward sides of five trees—one couple on the bark plate, the other in a fissure between plates—at 0, 1, 2, and 3 ft above ground surface. Air temperatures were measured at 5-in. intervals up to 75 in. A 16-pen potentiometer was used for recording the bark surface and air temperatures.

Cambial temperatures were measured at 1 ft above ground on the lee side of five trees and on the windward side of the sixth. The couples used were in flexible metal tubes and positioned beneath the external bark-plate couple. Temperatures were read from a portable potentiometer.

All plots were burned under comparable weather conditions. Headfires which generally moved faster than backfires consumed 8.7 tons of fuel per acre in comparison to 5.7 tons for the backfires. These values are, respectively, 60% and 49% of preburn means. Flame heights averaged 3 to 4 ft in headfires, 1.5 ft in backfires. Maximum flame heights were at least twice these averages.

Average external time–temperature curves for both type fires and for all sensor locations were determined by dividing the time scale of all fires into proportional parts and averaging the time and temperature values at these points. A registered temperature of 100°F at the groundline on the lee side constituted exposure to the fire and ended when the temperature dropped to 200°F.

Both types of fires and all sensor locations showed essentially similar-shaped curves. Groundline temperatures on the windward side of headfires began the steep rise and reached maximum temperature more than a minute earlier than the leeward side. Further up the trunk, temperature increases tended to occur simultaneously on both sides of the tree. Differences in time of reaching maximum bark-plate temperature on the lee and windward side decreased with increasing height; coincidence occurred at 3 ft.

In the backfires the leeward side registered low-intensity radiation preheating for several minutes before the flames reached the tree. Temperatures at upper-trunk levels were higher than at groundline during this period. On the lee side the main rise in temperature was abrupt, on the windward side more gradual. The time lag between temperature peaking on the lee and windward sides was approximately the time the base of the flame took to back around the tree.

Free-air temperatures were generally much lower than bark-surface temperatures. However, at groundline and at 10 in. above ground, air temperatures corresponded closely to those at groundline adjacent to the tree trunk and those at the 1-ft level on the windward side of trees, respectively.

The highest bark-surface temperature recorded was 1555°F. This occurred 3 ft above ground on the lee side of a tree in a headfire. Other comparable temperatures were also recorded in other fires. The authors state that more temperatures near 1600°F probably occurred but were undetected. A summary of findings showed:

1. A higher temperature was recorded at some point in every headfire than at any point in any backfire.
2. Generally, lee-side maxima exceeded windward-side maxima in both headfires and backfires.
3. In headfires, maximum temperatures occurred at groundline on the windward side, above groundline on the leeward side.

4. In backfires, maximum temperature generally occurred at groundline on both sides of the tree.
5. Maximum bark-plate temperatures generally exceeded adjacent fissure temperatures.

Groundline-temperature durations on the leeward side were quite similar in headfires and backfires; on the windward side high temperatures persisted longer in headfires. Temperatures above 200°F persisted appreciably longer in backfires at all levels; 600°F temperatures persisted longer in headfires. The authors suggest that backfires and headfires are equally damaging at groundline with headfires causing more upper-trunk injury. Bark-plate temperatures generally were higher and persisted longer than fissure temperatures.

Estimates of total heat emphasized the finding that headfires and backfires in heavy litter fuels cause identical leeward side heating at the groundline, while on the windward side backfires cause less heating than headfires. Total heating decreased with increase in height on both sides and fissure heating was less than bark-plate heating.

Temperatures inside the bark and their relation to external temperatures were quite variable. Differences in bark thickness and incorrect placement of the sensors were possible causes for the variation. Lethal temperatures (130°–140°F) were exceeded in the cambial region of four trees. In the other trees only sublethal temperatures were recorded. Maximum internal temperatures lagged external maximums by 60 to 150 seconds, then declined at varying rates which were inconsistent with external cooling rates.

Scorching of crowns occurred in all headfire plots with as much as 46% of the pines in these plots losing 95% to 100% of their foliage. No scorching occurred in the backfire plots. Because of the convection effect, bark scorching was higher on the leeward side averaging 2.5 times the scorch height of the windward side. On some trees in headfires, charring on the leeward side at the groundline did not take place. Apparently, relatively cool spots can occur here in spite of the fact that this location receives maximum heating on an average.

Cambial mortality occurred in varying lengths along the trunk from a few inches to several feet. Some trees with little or no crown scorch had extensive damage. Bark thickness appeared to limit the amount of damage and, depending on the type of fire and whether on the windward or leeward side, injury varied from little to extensive. Heat lesions were mostly above groundline on the leeward side and at or near groundline on the windward side.

Eight general conclusions are reached by the authors from this study:

1. In pine-litter fires, heating is greatest at groundline and decreases with height.
2. High temperatures of 1600°F occur when flames contact the bark but these temperatures are very temporal.
3. Irregularities of the bark surface affect the heating of the surface. Bark fissures are generally heated less and reach lower maximum temperatures than the bark plates.
4. Leeward side heating is more intense than on the windward side and the difference increases rapidly with height.
5. Under similar weather conditions, headfires and backfires in litter fuel heat trunks at the groundline to essentially the same degree.

6. With increasing height much more heat is applied to the lee sides of trees by headfires than by backfires; on the windward side the difference is much smaller.

7. Inner bark temperatures tend to rise and fall with bark surface temperatures but at a much lower level and with a considerable time lag.

8. Headfires cause more damage than backfires due to greater intensity of heating.

Subject Headings: ***Fire, heating of tree trunks; Tree trunks, heating by fire.***

W. Y. Pong

Marcy, J. F., Nicholas, E. B., and Demaree, J. E. (Federal Aviation Agency, Washington, D.C.) "Flammability and Smoke Characteristics of Aircraft Interior Materials," *Systems Research and Development Service*, *Federal Aviation Agency Technical Report ADS-3* (January 1964)

Summary

Flammability and smoke characteristics of interior materials were determined from a selection of 109 materials representative of present usage in the aviation industry. A comparison was made of the flame-resistant characteristics exhibited by the different materials on the basis of: (1) test method, (2) thickness, weight, composition, and backing, (3) fire-retardant treatment, and (4) degradation from use and cleaning. By employing test methods defined in FAA Flight Standards Service Release 453 and Federal Specification CCC–T–191b, burning characteristics were obtained in terms of burn rate, burn length, and self-extinguishing time. A Flame-Spread Index and smoke factor also were obtained by making use of the Radiant Panel Test Apparatus.

Conclusions

Based on an analysis of the test results obtained on 109 different aircraft-interior materials and from a comparison of the four test methods to achieve these results, it is concluded that:

1. The FSS Release 453 Test Method is not a suitable test procedure for materials other than fabrics.
2. There are many materials presently available and in use today which are self-extinguishing and which far exceed the flame-resistant characteristics required by a 4-in./min maximum burn rate.
3. On the basis of the tests conducted, the vertical test method is a satisfactory alternate to FSS Release 453 as a test method for fabrics that are self-extinguishing.
4. The Radiant Panel Test Method is capable of covering the entire flammability range of the interior materials tested, thus providing Flame-Spread Index ratings indicative of the degree of flame resistance.
5. The large number of interior materials containing vinyls or other plastics produce greater quantities of smoke during burning than do the cellulose-derived materials of the same flammability range.

6. The effect of the condition of the material (whether new, used, or cleaned) on the flame resistance of the fabrics and rugs tested was not significant.

Subject Headings: *Aircraft, flammability, of interior materials; Aircraft, smoke index, interior; Flammability, aircraft, interior materials; Flame resistance, aircraft, interior materials; Flame spread, index, aircraft interior materials.*

Authors' Abstract

Rogowski, B. F. W. and Lewis, A. S. (Joint Fire Research Organization, Boreham Wood, England) "References to Scientific Literature on Fire," Part XIII (1961)

This bibliography lists titles of articles published during 1961. The material is cross-referenced under author and subject. Classification is under the following topics:

A. Occurrence of Fire
    Incidents; casualties; material loss; statistics
B. Fire Hazards
    Industries and materials
C. Initiation and Development of Combustion
    Experimental studies
D. Fire Precautions
    (including means of escape)
E. Fire Resistance (including structural protection)
    Structures; building materials; fire-retardant treatments
F. Fire Fighting
    Appliances; equipment, including technique; extinguishing media; personnel protection
G. Nuclear Energy
    Hazards and precautions
H. General
    Works of reference, etc.

Subject Headings: *Bibliography, on fire; Fire, bibliography.*

R. M. Fristrom

BOOKS, PAMPHLETS, AND NEW JOURNALS

Thompson, N. J. *Fire Behavior and Sprinklers.* Boston: National Fire Protection Association (1964)

Mr. Thompson, who retired in 1959 as director of the laboratories of the Engineering Division of the Associated Factory Mutual Fire Insurance Companies, had 33 years experience in investigations of industrial fire protection. In this volume, he attempts to explain some of the fundamentals of fire behavior and to relate these to sprinkler protection.

First, he discussed the properties of combustibles that have a direct bearing on their relative fire hazard. Ordinarily, fires and explosions occur from reaction taking place only in the vapor or gaseous phase. Exceptions can be found, of course. Combustibility and the rate of fire spread are highest in mixtures of gases or vapors with air as compared to atomized liquids and finely divided solids (provided they do not detonate). Most common, solid combustible materials are cellulosic in nature. Their relative susceptibility to fire is covered. Various fibers and metals are considered; aluminum and magnesium fires are most prevalent. After a modest discussion of liquids and gases, he lists the most significant fuel properties: physical state, volatility, heat of vaporization, melting point, heat of fusion, heat of decomposition, specific heat, heat conductivity, heat of combustion, auto-oxidation, flash and fire points, and moisture content.

Chapter 2 is devoted to the thermal decomposition (pyrolysis) of combustibles, emphasizing wood. Some details are given concerning the ignition mechanism of wood and the air temperature required for ignition. Studies have shown that most types of solid wood species ignite spontaneously when heat is applied at the rate of 135 Btu/ft^2/min. Below 400°F, the gaseous products of pyrolysis are largely water vapor. Other products are produced above 400°F and the pyrolysis becomes exothermic above 536°F. Following discussions of the total heat developed and the spreading of flames, various wood structures and their relation to fires and fire spreading are covered. Some data on insulated steel deck roofs are presented.

For general fire-protection purposes, fire intensity generally is thought of in terms of British thermal units per square foot of floor area. A more accurate expression would involve British thermal units per unit volume of the fire. The intensity depends on the characteristics and properties of the combustibles together with the physical state and arrangement of the fuel, the surrounding temperature conditions, and many other factors. Detailed presentations are given concerning the physical state and arrangement, air supply, temperature of the exposing atmosphere (very important), oxygen-deficient atmospheres, combustible height, and radiation. Thick fogs can be very helpful in reducing the radiant heat.

If possible, the combustion fire products will rise almost vertically because of their reduced density. An understanding of the travel direction and temperature gradient in combustion products is essential when the best position of sprinklers is to be selected. Prompt operation of the sprinklers is necessary to minimize damage. Data are given of the temperature as a function of distance from the center of the fire for various rates of heat release from a gasoline pan fire. Low ceilings cause a steep temperature gradient when compared to high ceilings.

An intense fire generates vertical velocities ranging from 10 to 30 ft/sec. Beams and ceiling joists cause lateral flow of the hot gases. Over the years, a nominal standardized formula for heat-venting stacks has been devised.

$$A=\frac{\mathcal{Q}}{0.24(t_2-t_1)d_2K\{2g[(d_1-d_2)/d_2]H\}^{\frac{1}{2}}},$$

where A = vent area (ft^2); $\mathcal{Q}$ = heat to be vented (Btu/sec); H = stack height (ft); K = orifice coefficient of vent opening; t_1 = outside air temperature (°F); t_2 = vented gas temperature (°F); d_1 = outside air density (lb/ft^3); d_2 = vented gas density (lb/ft^3). For the usual values of t_1 (about 70°F), d_1 (0.075 lb/ft^3), and K (0.8), the formula reduces to

$$A=\frac{[0.375(t_2+460)\mathcal{Q}]}{[H^{\frac{1}{2}}(t_2-t_1)\ (t_2-t_1)^{\frac{1}{2}}]}.$$

These formulas give rise to rather large vent areas. Results of numerous heat-venting experiments are given, including data for vents in combustible roofs.

Sprinkler systems have reduced the annual waste from fire damage substantially. Industrial fire losses were cut from about 50 cents to two or three cents per hundred dollars of insured property as improvements have been made over nearly 100 years. Thompson gives a brief history of sprinkler systems with primary emphasis on atuomatic systems.

He then goes into the detailed mechanism by which sprinklers act on fires. The four beneficial effects from water sprays from sprinklers are direct wetting and cooling of combustibles, cooling of the atmosphere, cooling of exposed building elements and contents, and reducing the oxygen content in the air. Operating times of sprinklers vary considerably even though they have the same temperature rating. The variation results from the difference in thermal lag of the temperature-sensitive element. The sprinkler having the highest ratio of surface area to mass in the temperature-sensitive element will operate most quickly under the same fire conditions. Sprinkler-operating time is significantly influenced by the rate of hot air movement, higher velocities reducing the operating time, of course.

The distance between the ceiling and the sprinkler is an important factor in determining the effectiveness of protection when a fire occurs. When sprinklers are close to the ceiling, they operate faster. Except for smooth ceilings, however, close spacing can result in serious interference to the lateral distribution of water. Optimum clearance is from 7 to 10 in. unless the ceiling is broken up badly by beams, etc. Data are given regarding the effects of water pressure and clearance between the sprinklers and the combustibles. Many additional details are presented on protection against severe exposure, protection by directed sprays, water supplies, and building construction. Additional comments are made on the 1963 NFPA sprinkler standard.

Thompson gives a good introductory survey of the mechanism of fire behavior and sprinkler operation that will be useful to those in the fire-protection field. Shortcomings of the book are the inadequate discussion of explosion hazards and the absence of any discussion on detonation hazards and the potential damage.

Subject Headings: ***Fire, behavior; Sprinklers, history of; Sprinklers, use in fire extinguishment.***

L. E. Bollinger

Walsh, C. V. (New York City Fire Department, New York, New York) *Fire Fighting Strategy and Leadership*. New York: McGraw-Hill Book Co., Inc., (1963)

This book is an introduction to the principles of fire fighting. It is aimed at firemen and their officers. The level is that of a first-year college course in the fire-fighting science. The book is clearly written and covers most of the topics which one might think desirable for the novice fire fighter and prospective fire officer to become acquainted with. The subject material is well described by its table of contents which is reproduced below.

Part 1. *Combustion and Extinguishment*

1. Heat and Flame
2. Extinguishing Fires
3. Fire-extinguishing Agents

Part 2. *Ascertaining the Problems and the Order of Solution, or Sizing Up the Situation*

4. The Approach
5. The Pertinent Factors
6. Effects of Building Construction
7. Building Occupancy
8. Effects of Weather

Part 3. *Fire Fighting Strategy*

9. The Plan of Action
10. Engine Companies
11. Ladder Companies
12. Rescue and Squad Companies
13. Equipment and Apparatus
14. Unusual Fires

Part 4. *Leadership*

15. Management Techniques
16. Direction and Command
17. Issuing Orders
18. Planning and Policy Making

Since only the first and parts of the second and third chapters are devoted to the scientific background of the fire problem and no preparation in science or mathematics is presumed, the level of science is, and the reviewer thinks should be, elementary. As a result, the fire-research scientist will find little or no new material. The remainder of the book is devoted to problems, objectives, and management techniques in fire departments. It is this section which would make worthwhile reading for many fire researchers who (as is the case with the reviewer) do not have direct contact with practical fire-fighting activities. The book contains a wealth of the practical information and suggestions which the novice fire fighter must accumulate in order to function effectively and be able to direct fire-fighting activities intelligently.

A reading of these sections might help to put the academic research man in closer contact with what firemen know and think they know and what many of the practical day-to-day problems are. It might help give the researcher a concept of and sympathy with the needs and problems of the fire fighter, for it should be remembered that the understanding of fire phenomena is a long term means to an end and it is the effective use of scientific developments and ideas by the firemen which is the ultimate goal of all fire research.

Subject Headings: ***Fire fighting, leadership in; Fire fighting, strategy in.***

R. M. Fristrom

Science Periodicals from Mainland China. National Federation of Science Abstracting and Index Service, Washington, D.C. Volume 1, No. 1 (1965) Quarterly.

"This new quarterly journal is designed to enable the reader to obtain current information about what is being published in the major Mainland China science journals being received by the NFSAIS. Photo reproductions of the tables of contents of each issue received of each journal during the quarter are given. Photocopies or microfilms of articles or entire journals are available from the Federation headquarters."

There were no titles of interest to the fire-research field in the first issue, but this should be an interesting field to watch. For further information, contact Raymond A. Jensen, National Federation of Science, Abstracting and Indexing Services, 324 E. Capitol St. Washington, D.C. 20003.

The journals listed in Vol. 1, No. 1, were:

Primary Journals

Acta Anatomica Sinica, Vol. 8, No. 1, 1965
Acta Astronomica Sinica, Vol. 12, No. 2, 1964
Acta Automatica Sinica, Vol. 3, No. 1, 1965
Acta Biochemica et Biophysica Sinica, Vol. 4, No. 5, 6, 1964; Vol. 5, No. 1, 1965
Acta Biologiae Experimentalis Sinica, Vol. 9, No. 4, 1964
Acta Chimica Sinica, Vol. XXXI, No. 1, 1965
Acta Entomologica Sinica, Vol. XIV, No. 1, 1965
Acta Geodetica et Cartographica Sinica, Vol. 8, No. 1, 1965
Acta Geophysica Sinica, Vol. 14, No. 1, 1965
Acta Horticulturalia Sinica, Vol. IV, No. 1, 1965
Acta Mathematica Sinica, Vol. 15, Nos. 1, 2, 1965
Acta Meteorologica Sinica, Vol. 35, No. 1, 1965
Acta Microbiologica Sinica, Vol. 11, No. 1, 1965
Acta Palaeontologica Sinica, Vol. 13, No. 1, 1965
Acta Physica Sinica, Vol. 21, Nos. 1, 2, 3, 4, 1965
Acta Physiologica Sinica, Vol. 27, No. 4, 1964; Vol. 28, No. 1, 1965
Acta Psychologica Sinica, No. 1, 1965
Acta Zoologica Sinica, Vol. 17, No. 1, 1965
Chinese Medical Journal, Vol. 84, Nos. 1, 2, 1965

Fangzhi Jishu (Textile Technique), No. 12, 1964; Nos. 1, 3, 1965
Huaxue Tong Bao (Chemistry Bulletin), Nos. 1, 2, 3, 1965
Jianzhu Zuebao (Chinese Journal of Architecture), No. 11–12, 1964
Kexue, Dazhong (Popular Science), No. 1, 1965
Kexue Tong Bao (Science Bulletin), Nos. 1, 3, 1965
Scientia Silvae, Vol. 10, No. 1, 1965
Scientia Sinica, Vol. XIV, Nos. 1, 2, 3, 1965
Shengwuxue Tong Bao (Bulletln of Biology), No. 1, 1965
Shuili Xuebao (Journal of Hydraulic Engineering), No. 1, 1965
Tumu Gongcheng Xuebao (Chinese Journal of Civil Engineering), Vol. 11, Nos. 1, 2, 1965
Wuxiandian (Radio), No. 1, 1965
Zhongguo Nongye Kexue (China's Journal of Agricultural Science). No. 11–12, 1964; Nos. 1, 2, 3, 1965
Zhong-Guo Zao-Chuan (China's Shipbuilding), Vol. 57, No. 1, 1965

Secondary Journals

Abstracts of Articles Published in Japanese Scientific and Technical Periodicals, No. 6, 1964
Science Abstracts of China—Biological Sciences, Vol. II, Nos. 5, 6, 1964; Vol. III, No. 1, 1965
Science Abstracts of China—Earth Sciences, Vol. II, Nos. 3, 4, 1965; Vol. III, No. 1, 1965
Science Abstracts of China—Mathematical and Physical Sciences, Vol. II, Nos. 3, 4, 1964; Vol. III, No. 1, 1965
Science Abstracts of China—Medicine, Vol. II, Nos. 4, 5, 1964; Vol. III, No. 1, 1965
Science Abstracts of China—Technical Sciences, Vol. II, Nos. 5, 6, 1964

Subject Headings: ***China, periodicals; Periodicals, Chinese.***

Proceedings of the Thirty–Fourth Annual West Virginia Fire School (1964) *West Virginia University, Morgantown, West Virginia Extension Bulletin No. 44* (Edited by R. E. Hanna, Jr.)

Contents

Foreword
Fire School Program
Why Are You Here?—Donald M. O'Brien
How to Get Leadership—G. L. Sartain
Firefighting Foam—W. C. Tamburro
Better Fire Protection Through Research—Arthur B. Guise
Radiation Hazards—M. L. Zickefoose
Fire Service Extension Classes, 1963–64
Fire Service Short Courses, 1964
Fire School Registration

Subject Headings: ***Fire school, West Virginia University.***

Fourth Quinquennial Symposium on Fire Fighting Foams, Campobello Island, New Brunswick, Canada (August 11, 12, 13, 1964) *The Mearl Corporation*, *Ossining*, *York. New*

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- A New Vapor-Securing Agent for Flammable-Liquid Fire Extinguishment
  - R. L. Tuve—U.S. Naval Research Laboratory
- Light Water Systems
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- Effect of Perfluorinated Surfactants on Detergent Foams in Extinguishing Petroleum Fires
  - A. F. Ratzer—Chemical Concentrates, A Division of Baker Industries, Inc.

Second Session

- High Expansion Foam on Hydrocarbon Fires
  - Milton Lambert—U.S. Naval Applied Science Laboratory
- High Expansion Foam for Structural Fires
  - J. F. O'Regan—Bliss-Rockwood Company
- Developments in England
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    - Part I Gas Turbine-Foam-Operated Generator for Experiments in Aircraft Fire Control
    - Part II Foam Compatibility with Dry Chemicals
    - Part III The Use of Inert Gas and Inert Gas Foams to Control Fires in Buildings
- More Fire Fighting Capability per Man through Equipment Development
  - Marvin C. Tyler—Systems Engineering Group, U.S. Air Force

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- Petroleum Fire Extinguishments by Fire Fighting Foam
  - D. N. Meldrum—National Foam System, Inc.
- Fighting Fires in Ruptured Petroleum Pipelines
  - Lester A. Eggleston—Southwest Research Institute
- Use of Air Foam to Control Oil Slicks
  - John Boyd—A. K. Peters Co.
- Specification Testing of Mechanical Fire Fighting Foam Liquids
  - L. E. Rivkind—The Mearl Corporation

Subject Headings: ***Foam, in fire fighting; Fire fighting, use of foam.***

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