LARGE BUILDING FIRES

- EXPERIMENT AND ANALYSIS -

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I. INTRODUCTION

Because of its inherent complexity and detail, as well as its rather tenuous relationship to existing combustion theory, the propagation of uncontrolled fires in large buildings remains one of the unsolved problems facing our cities. On October 13, 1969 (see Appendix), a fire in a Los Angeles apartment claimed the lives of eight people and sent more than a score to the hospital for various degrees of burn and smoke inhalation. As the fire developed, flames spread quickly up the main stairwell, blocking exits from apartment units, forcing some to jump from upper floors. Within a matter of minutes, all three floors were so involved in fire that normal escape was impossible.

Our lack of quantitative knowledge about the propagation of building fire has a more widespread effect than such disasters. It is a major factor in preserving archaic and inappropriate building codes; it places a severe limit on architectural innovation because fire hazards in novel structures cannot be evaluated quantitatively. This is a truly serious restriction in an era where low-cost multiple dwellings are in urgent need.

One unique aspect of the large-scale building fire is that attention is directed away from the fire losses in a single room or unit to the role this room plays as a source or carrier of hot gas or flame in the fire spreading process. In many large buildings, it appears possible to regard the fire spreading process as a network problem in which the rooms, passages, air conditioning ducts, behave as passive or active lumped elements in the network. This concept has been introduced by Rockett,* and the implementation of it will constitute a significant part of the present paper. The characteristics of the elements are non-linear, and consequently even a structure of modest size presents a challenging computational problem. In spite of these difficulties, the network concept appears to offer the greatest promise of engineering development, and is discussed in Chapter II of this paper.

The detailed characteristics of the elements to be used in the lumped parameter system are quite complex and depend on a multitude of phenomena. Hence, careful experimental and theoretical investigation of typical elements must be carried out in order that a simple and still meaningful description of the elements can be abstracted for use in the computer program. In Chapter III, a series of investigations is suggested with the purpose of providing the information from which these abstractions can be developed.

Recommendations are given in Chapter IV which set forth the requirements for development of the computer model and supporting information.

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*Rockett, John A., "Objections and Pitfalls in the Simulation of Building Fires with a Computer," Fire Technology, November 1969.

II. BUILDING FIRE AS A NON-LINEAR LUMPED PARAMETER SYSTEM

The possibility of representing the progress of fire in a large complex building rests upon rejection of complete and detailed knowledge of fire in a single room or passage. In the same sense that we approximate detailed response of an inductive coil in a coupled electrical system, certain details of local fire progress cannot be described with accuracy.

Subdivision of the building. We shall assume that the structure may be subdivided into a number of more or less isolated enclosures, such as rooms, hallways, ceiling spaces, etc. These enclosures should be connected only at well-defined junction points, such as doors, windows, ventilating ducts. In general, the junctions will be points at which mass is transferred from one enclosure to the next. In particular, the processes that take place within the room are coupled with corresponding processes in other rooms only by events at the junction points. For example, we cannot consider heat to be transferred through the "wall" of one element to the next. If such a transfer process is significant, a junction point must be established to account for this exchange process within the network scheme.

Conservation at junction points. The conditions to be met at the junction points between elements are, in reality, expressions of the general physical conservation laws. These are:

1) conservation of mass,

2) conservation of momentum,

3) conservation of energy,

4) conservation of chemical species.

Their detailed formulation may be accomplished in the same manner that Kirchhoff's laws follow from electrodynamics. The junction points are assumed to be regular points, without capacitance, resistance, heat exchange, or chemical reaction. Consistent with the detail that is required of the fire propagation problem, these conservation principles may probably be stated respectively as follows:

1) mass flow of air continuous at junction,

2) mass flow of (gaseous) fuel continuous at junction,

3) mass flow of combustion products continuous at junction,

4) temperature of each of the three components continuous at junction,

5) pressure continuous at junction.

This list suggests the necessity of seven dependent variables in the system, and this is probably correct. The presence of independent fuel, oxidizer, and product flow and temperature certainly represents the minimum system so far as chemistry is concerned.

Characteristics of the elements. In its most simplified form, the characteristic of one of the elements corresponds to that of a fluid mechanical pump or compressor. The natural convective potential which arises from the heat addition and geometric configuration is analogous to the head rise. The various losses in the system correspond to inefficiency, and the mass flow rate corresponds to itself. It is convenient to think of a diagram showing pressure difference between inlet and outlet plotted against mass flow for various amounts of temperature rise in the through-flow gas. The first novel aspect is that the mass flow rates for which this relationship is known must extend to negative as well as positive values. The forced draft imposed by other elements of the complete system may drive the flow against the direction of natural convection in a given element. In fact, the flow of air and combustion products may be in opposite directions at any junction.

The second aspect, which requires detailed consideration, is the fact that heat release conditions within a given element are functions of time. The degree of inflammation within the room, the availability of oxidizer, and the changing flow resistance, all vary as the fire proceeds. The greatest problem, however, is the heat storage in the combustible matter, and the consequent rate of fuel vapor production. The heat conduction and storage is fundamentally a transient problem, and cannot, under any circumstances, be considered a quasi-steady one.

These considerations, enumerated in the preceding paragraphs, enter into the problem by determining the heat release, the fuel production, air consumption, and production of combustion gas. These fundamental features enter into the "pumping characteristic" of the room.

A highly simplified analytical model. The qualitative discussion of an element characteristic may be clarified somewhat by the construction of a highly oversimplified analytical model. The advantages of such a model are: 1) the significant assumptions and limitations are made concrete, and 2) the minimum number of parameters are introduced and give some measure of the complexity of the calculations.

Consider a quasi-one-dimensional model that consists (Figure 1) of an inlet junction, 1; an outlet junction, 4; and a connecting chamber of relatively large area in which heat transfer, combustion, and certain momentum losses occur. The processes 1-2, designated the entrance process, and 3-4, the discharge process, need not be described in detail here. We assume that no reaction occurs between these stations and, although certain losses and complications do occur, there is no essential difficulty in describing them.

Our interest centers on the process 2-3, which is the one-dimensional model of the gasdynamic processes occurring within the element. Assume that the flow consists of three concurrent streams:

1) air at constant temperature T_a and density ρ_a,
2) gaseous fuel at constant temperature T_f and density ρ_f,
3) combustion products at constant temperature T_g and density ρ_g.

In keeping with the quasi-one-dimensional model, we assume also that the gas pressure is uniform in planes "normal" to the flow direction; in this

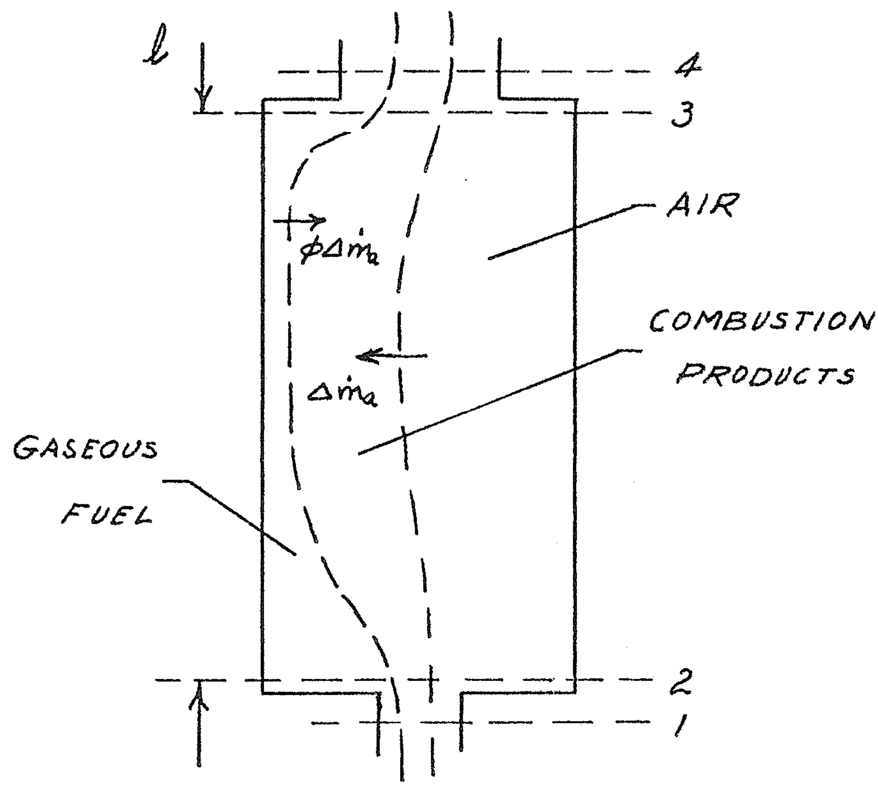

Figure 1. One-Dimensional Model for Room Combustion and Convection.

case, we interpret this as meaning in planes normal to the gravitational field. In passing from station 2 to station 3, fuel and air may combine in the mass ratio 1:ϕ, the ratio being fixed and known. In each of the air and fuel streams, the appropriate Bernoulli constant varies only because of frictional or other resistive losses. Then if ℓ is the characteristic vertical dimension of the element and C_f is a common, appropriately defined loss coefficient, a reasonable statement for the Bernoulli integral for each of these streams is

$$p_2 + \frac{1}{2}\rho_a u_{a2}^2 = p_3 + \frac{1}{2}\rho_a u_{a3}^2 + \rho_a g \ell + \frac{1}{2}\rho_a \left[(u_{a2}+u_{a3})/2\right]^2 C_f \qquad (2.1)$$

$$p_2 + \frac{1}{2}\rho_f u_{f2}^2 = p_3 + \frac{1}{2}\rho_f u_{f3}^2 + \rho_f g \ell + \frac{1}{2}\rho_f \left[(u_{f2}+u_{f3})/2\right]^2 C_f \qquad (2.2)$$

These, of course, are independent of the fact that air and fuel may be reacting to form combustion products. In addition to these two relations, we have a momentum integral for the entire process 2-3. If we designate by A the cross-sectional area of the structure and by A_a, A_f, A_g those portions of this area which carry air, fuel, and combustion gas, respectively, then the momentum integral is

$$
\begin{aligned}
p_2 A &+ \rho_a u_{a2}^2 A_{a2} + \rho_f u_{f2}^2 A_{f2} + \rho_g u_{g2}^2 A_{g2} \\
&= p_3 A + \rho_a u_{a3}^2 A_{a3} + \rho_f u_{f3}^2 A_{f3} + \rho_g u_{g3}^2 A_{g3} \\
&\quad + (M_a + M_f + M_g) g \\
&\quad + \frac{1}{2} C_f \left\{ \rho_a [(u_{a2} + u_{a3})/2]^2 + \rho_f [(u_{f2} + u_{f3})/2]^2 + \rho_g [(u_{g2} + u_{g3})/2]^2 \right\}
\end{aligned} \qquad (2.3)
$$

In this relationship, the quantities M_a, M_f, and M_g are the total masses of air, gaseous fuel, and combustion products within the structure.

In addition, there are continuity or conservation relations for each of the gas streams, and they may be written as follows:

$$\rho_a u_{a2} A_{a2} - \Delta \dot{m}_a = \rho_a u_{a3} A_{a3} \qquad (2.4)$$

$$\rho_f u_{f2} A_{f2} - \phi \Delta \dot{m}_a + \mu_f = \rho_f u_{f3} A_{f3} \qquad (2.5)$$

$$\rho_g u_{g2} A_{g2} + (1+\phi) \Delta \dot{m}_a = \rho_g u_{g3} A_{g3} \qquad (2.6)$$

Here, $\Delta \dot{m}_a$ is the mass of air per unit time that is being converted to combustion products, and μ_f is the mass production rate of fuel gas caused by pyrolysis of combustible material. Because $\Delta \dot{m}_a$ is the mass rate of consumption of air, $\phi \cdot \Delta \dot{m}_a$ is the mass consumption rate of fuel, and $(1+\phi) \Delta \dot{m}_a$ is the mass addition rate of combustion products. The mass of fuel μ_f produced is considered to be added to the system at zero momentum and at the total pressure appropriate to the Bernoulli integral (2.2). Consequently, this mass addition to the fuel does not appear in either Bernoulli equation for the fuel or the overall momentum relation. Finally, it is clear that the areas always sum to the known cross-sectional area A,

$$A_a + A_f + A_g = A \tag{2.7}$$

Now suppose for the moment that the conditions at station 2 are known, for example, from matching with the output from the preceding element. Then the equations (2.1) - (2.7) may be employed to determine u_{a3}, u_{f3}, u_{g3}, p_3, A_{a3}, A_{f3} and A_{g3}, provided the quantities ℓ, C_f, $\Delta \dot{m}_a$ and μ_f are known. We assume that the total mass "capacitances" M_a, M_f, M_g of the system are determined by integration over time.

Implications for a real element. Although the characteristic length ℓ, and mean loss coefficient C_f, are reasonably obvious in the present model, their counterparts in an actual element require some well-directed experimentation. Similarly, although we can easily formulate an air consumption rate $\Delta \dot{m}_a$ based upon turbulent mixing and a gaseous fuel production rate μ_f controlled by transient heat conduction to the walls, experimental determination of their counterparts for a real element poses rather challenging problems.

An additional difficulty that must be coped with is also well illustrated by the example. To assure that the characteristics of the element were determined, we assumed that conditions at the lower station were (in some sense) known. Clearly, this may not be true. For example, conditions may exist where the combustion products discharge through the upper part, while air flows in the opposite direction and discharges through the lower part. Then the nature of prescribed quantities changes: some are prescribed at one junction of the element and some at the other. Formally, this is no serious difficulty; it is simply an extension of the observation that the nature of the prescribed quantities changes; some are prescribed at one junction of the element and some at the other. The difficulty in the present problem is that the element is not linear; or more explicitly, it may behave in a quite different way when the gas streams are countercurrent. Although this feature presents a formidable problem in network computation procedures, the fundamental difficulty is that of determining those characteristics experimentally.

The model is simplified in another manner that requires extension for actual elements. Although we have considered an element with two junctions, many natural elements will have more than two junctions. The manner in which the gas streams divide between the various junctions is strongly influenced by the internal structure of the element. If this internal influence is sufficiently strong, a given room or enclosure may be artificially divided into several elements, each of which has only two junction points. It is evident, however, that this device is not always applicable and that the severe experimental problem of determining the response of such a system must be considered carefully.

Implementation of lumped parameter model. The principal aim of the foregoing discussion was the clarification of analytical and experimental work required to implement the lumped parameter model. As has been indicated, the experimental obstacles are both numerous and difficult. Generally speaking, they can be divided into 1) the ignition, flame spread, and combustion rate of rooms and their contents; and 2) the forced and natural convective motion of the gas stream through the room. These are discussed in some detail in the following section, and a series of fairly well-defined experiments is suggested. The convection problem is a difficult one which is not too easily broken down into elementary parts and the results of which are open to question when experiments are performed in small "laboratory-sized" equipment. To obtain these vital results in large-scale equipment and to perform the measurements necessary to understand the gas and heat flow patterns, a fairly sophisticated facility is required. It appears that the most promising facility for this purpose would be a large room, at least 10 feet on a side, of metal and fire brick structure, with considerable flexibility of available openings. Preferably, the heat source would be propane or methane burner arrays which could be located flexibly in a manner to simulate various actual combustion processes. The gas supply to various areas may be programmed as a function of time to simulate the natural development of fire. Because of the coupling problem with other elements, natural convective flow will not suffice; the facility will require air and combustion product feed systems capable of driving the convective flow of these gases in a variety of manners. Thus, the entire facility has the character of a large compressor testing rig, capable of operating over all possible ranges of flow. Because detailed temperature, pressure, and velocity measurements will be required in some instances, the controlled heat release is greatly to be preferred over a natural (and non-reproducible) combustion process.

Such a combustion study facility has been considered by the National Bureau of Standards; it appears to be an item requiring considerable time to construct and not inexpensive to operate. However, it is certainly the key piece of large equipment essential to implementing the program for larger building fires.

III. BASIC RESULTS AND SUGGESTED EXPERIMENTS RELATED TO BUILDING FIRES

Discussions of a possible analytical model for building fires have revealed certain requirements of experimental information to insure both the qualitative realism and quantitative accuracy of the model. The most urgent requirement may be divided roughly, into two parts: 1) the convective gas flow through complex building structures at various stages of burning, and 2) the fundamental factors required to describe the progress of fire within a single enclosure. The first of these, the convective gas flow, is basically a fluid mechanical problem and, in many instances, does not depend intimately upon the details of combustion, but rather on fairly gross characteristics. The second, however, is directly involved with many sensitive details, some of which are rather poorly understood. In a very substantial manner, the utility of the network concept rests upon the possibility of describing the essential burning processes in a room with innocent simplicity. If the description is too complex, the network calculation will be either prohibitively laborious or insufficiently accurate.

In order to build the fundamental knowledge and understanding requisite to a relatively simple description, certain well-defined areas have appeared to be particularly significant. In the following sections, the current status of these subjects is reviewed and experimental investigations are outlined. It is felt that the results of these investigations would demonstrate whether the network fire model could be made realistic and would provide a substantial amount of the information required to make it quantitatively correct.

A brief bibliography is given at the end of each of the following paragraphs of the more important material studied during the review.

1. Ignition and Pyrolysis

When a combustible solid is heated to a high enough temperature, volatile materials are given off which can burn when mixed with a suitable quantity of air. If the surface temperature of the solid is high enough, burning in the gas phase may occur without the requirement of a secondary ignition source, such as an open flame. The processes by which the gas phase compounds are generated from the solid and are further decomposed in the liquid or gas phase is called pyrolysis, and the processes leading to initiation of burning in the gas phase is called ignition - spontaneous ignition when no secondary ignition source is present, and piloted ignition when an ignition source is present. Under some circumstances, the heat transferred from the burning gases to the solid material from which they are generated by pyrolysis may be large enough to sustain the pyrolysis. The reaction zone formed by regions of gas phase (and perhaps surface phase) combustion and solid (and perhaps gas phase) pyrolysis make up a flame zone which can spread across a solid surface. This process is called flame spread.

Under many circumstances, the process of ignition and flame spread cannot be distinguished in a useful manner. For example, when hot gases from a room fire flow rapidly across a combustible ceiling, the initiation of pyrolysis is independent of the combustion of the pyrolyzed material, and burning in the gas phase could be called by either of the above terms. However, in discussing phenomena such as room flashover or ignition by thermal radiation, the concepts are useful and are used as described above in the following paragraphs.

Emphasis is placed here on experimental work, since the mathematical apparatus required to carry out computations is well in hand. What is needed is a physical model which gives an adequate description of the important phenomena. The model must be developed in conjunction with experiments which are designed to elucidate key points.

Because of the number of experiments already carried out in this field, a survey in greater depth than that attempted here (for example, with visits to see experimental apparatus) would be desirable before additional work is started.

Ignition by radiation. Ignition of cellulosic materials by thermal radiation pulses has been studied by a number of investigators, e.g. refs. 1.1 to 1.18. In the typical experiment, a sample of the test material is held vertically, by a support system which does not obstruct local convective currents, and is irradiated by a source of thermal radiation such as an arc lamp. The radiation is usually of constant intensity, and the duration of the pulse is continued until ignition of some sort is obtained. In some experiments, a pilot flame is located in the convection column above the sample and serves as an ignition source (piloted ignition), and in others no pilot is present (spontaneous ignition). A second differentiation is made between flaming ignition (a condition in which the products of pyrolysis burn visibly while under the influence of incident thermal radiation but do not burn when the radiation is withdrawn) and sustained ignition (a condition in which combustion is initiated and continues after the radiant flux is withdrawn).

The series of tests in which the most extensive measurements of temperatures and surface properties was made are reported in refs. 1.1, 1.8, and 1.9. Unfortunately, these measurements were carried out for thermal radiation conditions typical of these expected from nuclear explosions, and the radiant fluxes are roughly ten times those to be expected from building fires. The series of reports of Simms and co-workers (1.9 - 1.12) covers the radiant fluxes of interest, but contains less complete documentation of temperatures and surface properties. In addition, Simms' primary measurement is the time required for flaming ignition as a function of radiant flux level.

Table I (following the bibliography) gives a brief summary of the experiments and comments on some of the important parameters. In brief, Simms analyzed his data by use of a model in which it was assumed that 1) the heated surface was cooled by natural convection; 2) no chemical reaction occurred in the solid phase; and 3) flaming ignition occurred when the surface temperature reached a certain value. Neither the convective cooling rate nor the surface temperature was measured, and both values were picked to get the best correlation of the data. This correlation of the data is questionable, because both convective heat transfer rates and temperature are adjustable parameters. Other experimenters do not find that the suggested values of either of these parameters fit their data, e.g. ref. 1.5 and Table I.

The experimental results of the NRDL were examined without reference to any model of the process and were correlated by plotting the data as a function of $Q/\rho c \ell$ versus $\sqrt{\alpha \tau}/\ell$, where the symbols are defined as:

Q	irradiance (cal/cm^{2}sec)	
ρ	density (gm/cm^3)	of solid sample
c	specific heat (cal/cm$^\circ$C)	of solid sample
ℓ	depth (cm)	of solid sample
α	thermal diffusivity (cm^2/sec)	of solid sample
τ	time of irradiation (sec)	

The problem with this representation is that $Q/\rho c \ell$ ($^\circ$C/sec) is not a dimensionless parameter and that for large values of $\sqrt{\alpha \tau}/\ell$, the thickness of the sample enters the presentation of the data. Hence, it is clear that this representation is not complete and does not offer a completely satisfactory empirical representation of the data.

In none of the experiments reviewed were all of the important parameters measured and reported. Hence, the data reported are suspect as test results which are directly applicable to fire situations. In addition, the data reported are not sufficient to lead to a general theory of surface ignition by radiant heat transfer for the wide range of materials present in typical building fires.

Finally, these experiments are also unsatisfactory in that they deal with step function application of thermal radiation alone. In general, ignition in a room fire will occur after a sample of material is exposed to a gradually increasing radiant and convective heat transfer, and at present no model exists which allows results obtained for a step function flux distribution in time to be correlated with data for a more realistic distribution.

Convective ignition. Only one convective ignition study was found during this review, ref. 1.20, and it is subject to similar criticisms as the radiant ignition studied. In particular, it did not lead to a convincing identification of the important parameters or an elucidation of the important mechanisms.

Proposed ignition experiment. The question arises here, as in all of the areas studied, concerning the accuracy required of theoretical and experimental work to make it useful in the present context. In areas where little understanding of complex processes exists, tests must be carried out in a manner which exactly duplicates the problem to be studied. As the dominant processes are identified, requirements for test conditions can be relaxed somewhat and more abstract tests can be used.

In the area of ignition, a large body of data has been obtained, and in many instances, different investigators hold conflicting opinions concerning such concepts as ignition temperature. Hence, it is recommended that further experiments be carried out in the areas of ignition by radiation and convection with the primary aim of elucidating the important mechanisms which govern the ignition process. The collection of more data suitable for use in a handbook is not recommended. The experiments must be designed in conjunction with general models of the process and should be used to investigate the validity of the key hypotheses in the models. If possible, the model should be developed before new experimentation and in conjunction with a thorough review of existing experimental results.

The experiments should include the following features:

1) Radiant and convective heat fluxes should cover the range 0.2 - 4.0 cal/cm^{2}sec. It is desirable that the radiation should have a spectral distribution typical of low-temperature solid body radiation, and gas temperatures of convective flows should cover the range between 200° and 2000°C. (Variation of spectral distribution for a constant heat flux will also be useful.)

2) Sufficient measurements should be made that an accurate heat balance can be made for the sample. Measurements should include emissivity, absorptivity, and temperature at or near the surface, and convective heat transfer rates. A measure of heat given off during the ignition transient in a calorimetric measurement of some sort would be

highly desirable.

3) Measurements of the temperature distribution in the body of the sample should be made as a function of time.

4) Chemical analysis should be made of the products of pyrolysis.

5) Schlieren and other visualization and measuring techniques (such as hot wire velocity probes) should be used to examine the flow field set by the radiant heating of the sample.

6) Flaming and sustained ignition limits with and without pilot flame should be determined. Onset of ignition in experiments made with appreciable convection may be hard to identify, and the criteria may be more usefully defined as the time at which net heat is added to the flow.

In addition to these features, most of which have already been used in previous work, it is suggested that the following parameters be varied:

7) Moisture content and other properties such as chemical composition, thermal conductivity, and density.

8) Orientation of sample and adjacent walls or structures. Sample size, in directions parallel and normal to incident radiation.

9) Nature of heat pulse, e.g. a continuously increasing flux rate instead of the usual square wave.

10) Convective and radiant heating should be used separately and simultaneously.

These experiments and the accompanying synthesis should lead to the identification of the important processes and parameters which characterize them. In addition, we should obtain a resolution of some of the present inconsistencies in the published data, a better understanding of the critical heat flux and ignition temperature ideas, and better estimates of room flashover times.

Pyrolysis experiment. In addition to the above experiment, a similar experiment to that described above should be carried out in an inert atmosphere where the pyrolysis process itself can be studied in isolation without the complication of gas phase combustion. Lack of understanding of this process is the primary difficulty in developing any general theory of ignition and burning of solids. The primary aim of this experiment and synthesis would be to determine the important chemical reactions, and the corresponding heats of reaction and rate constants which dominate the pyrolysis process in the combustion of cellulose or a simpler material if a suitable one can be found for study.

A number of pyrolysis experiments have been performed with very thin materials with the aim of keeping the temperature of the whole sample substantially constant. These experiments have not been successful to date, and it may also be useful to study pyrolysis under transient conditions such as those given by uniform heating of a semi-infinite slab. The work of Murty and Blackshear, ref. 1.21, is of interest here.

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ref. no.	1.1	1.2	1.3	1.4	1.5	1.6
materials	α-cellulose newspaper	wood (several types)	wood (fir, mahogany, oak, etc.)	wood	cotton fabric	wood, asphalt, shingles
size	not given	7.6 cm x 7.6 cm x (1.3-2.5)	3.9" x 3.9" x (1/2, 5/8, 3/4")	4" x 4" x $\frac{1}{2}$" [226]	not given	8 cm x 16 cm, thickness not given
radiation source	tungsten lamp	radiant panel	flame (pool)	flame	tungsten lamp	radiant panel
range of radiation (cal/cm^2 sec)	1 - 100	0 - 1.8	.275 - .85	.275 - .85	.4 - 10.0	.2 - .6
emissivity & absorptivity	not given	not given	not given	not given	calculated [64]	not given
moisture	10, 20% [9]	0, 20, 40, 60 %	not given	not given	not given	not given
convection	not given	not measured, assumed 8.0×10^{-4}	took h from ref. 1.2 (i.e, 8×10^{-4}) [287]	took h from ref. 1.2 (i.e., 8×10^{-4})	not given	not given
pilot and position	not given	1.25 cm above [378]	1/4" above [284]	1/4" above	1/2" above [60]	0.6 cm above [47]
surface ignition temperature	600-650 [15]	pilot-380°C spon-545°C	280-495°C	280-495°C	not given	not given
minimum ignition irradiation (cal/cm^2 sec)		0.31-pilot 0.74-spon [377]	not given	not given	~.4 from graphs [60]	~.35 from Fig. 2 [48]

Numbers in brackets refer to page in reference cited: check these pages for additional information.

TABLE I.

ref. no.	1.9 and 1.12	1.10 and 1.11	1.16	1.18	1.20
materials	wood (several types)	cellulose solids	concrete brown clay fire brick	pine	hardboard α-cellulose
size	5 cm x 5 cm x 1.9	(.02 - .065 cm) and >1 cm -- just thickness given	32 in.^{2}	cylinders - 5" x 3/8" dia.	12 cm x 14 cm x (0.3 - 2 cm)
radiation source	radiant panel	radiant panel, tungsten lamp, carbon arc	furnace	electric furnace	furnace - convective heating
range of radiation (cal/cm^{2}sec)	.25 - 1.5 [254]	0 - 12		not given	680°K to 830°K (furnace)
emissivity and absorptivity	not given	mentioned, but no data given		not given	not given
moisture	not given			1.5 %	not given
convection (h)	not measured	not given		not given	velocity given
pilot and position	0.94 to 1.9 cm above [254]	theoretical rather than experimental		not given	glow-wire, position not given
surface ignition temperature	pilot-340°C spon-525°C	525°C		650°F	900°C, spontaneous ignition [905]
minimum ignition irradiation (cal/cm^{2}sec)	0.3 [259]	.6 [299]		not given	not given

Numbers in brackets refer to page in reference cited: check these pages for additional information.

TABLE I (continued)

2. Surface Spread: Flaming Propagation

Recent reviews of the spread of flames through a matrix or across a sheet of combustible material show that little systematic work has been done in these areas and suggests that spreading or propagation rates are sensitive functions of a number of parameters, including the material geometry, the angle the surface makes with respect to the horizon, thickness and composition, juxtaposition to other bodies, and flow conditions at the surface. For example, see the review by Friedman, ref. 2.1.

As in the case of ignition phenomena, experiments and synthesis are required here which will identify the dominant processes and the appropriate characteristic parameters. A large number of new tests are not needed.

An investigation concerning spread in a relatively quiet atmosphere should include experiments in which the influence of the above-mentioned parameters is clarified, but should first concentrate on making a careful heat balance to the solid surface at the flame front, which will include radiant and convective heat transfer, and a detailed delineation of the natural convective flow. Some work should be done with materials for which information on pyrolysis has been or is being obtained. Flow visualization techniques should be very helpful in studying the convective heat transfer processes.

In addition, some tests should be carried out to determine the influence on flame spread of: 1) radiant heat fluxes which are appreciable fractions of the minimum ignition value, 2) material temperatures near that at which pyrolysis reaction rates begin to be important (e.g. 300°C for some woods and cellulose), 3) high ambient gas temperature and reduced oxygen content, and 4) forced air flows across the burning surface which overpower natural convection effects produced by the flame. These experiments will aid in understanding flame spread under conditions of room fires in which no strong gas flows are present.

2.1 Friedman, R., "A Survey of Knowledge about Idealized Fire Spread over Surfaces," Fire Research Abstracts and Reviews, V. 10, No. 1 (1968), pp. 1-8.

2.2 Anderson, H. E., "Mechanisms of Fire Spread Research," Progress Report No. 1, U. S. Forest Service Research Paper INT-8 (1964).

2.3 Fons, W. L., H. B. Clements, P. M. George, "Scale Effect on Propagation Rate of Laboratory Crib Fires," Ninth Symposium on Combustion, Academic Press, New York (1963), pp. 860-866.

2.4 Thomas, P. H., "The Size of Flames from Natural Fires," Ninth (International) Symposium on Combustion, Academic Press, New York (1963), pp. 844-859.

2.5 Levy, Marshall M., "A Simplified Method for Determining Flame Spread," Fire Technology, V. 3 (February 1967), pp. 38-46.

2.6 Anderson, H. E., "Fire Spread and Flame Shape," Fire Technology, V. 4 (February 1968), pp. 51-58.

2.7 Welker, J. R. and C. M. Sliepcevich, "Burning Rates and Heat Transfer from Wind-blown Flames," Fire Technology, V. 2 (August 1966), pp. 211-218.

2.8 Welker, J. R. and C. M. Sliepcevich, "Bending of Wind-blown Flames from Liquid Pools," Fire Technology, V. 2 (May 1966), pp. 127-135.

2.9 Rios, J., J. R. Welker, and C. M. Sliepcevich, "Interaction Effects of Wind-blown Flames from Wood Crib Fires," Fire Technology, V. 3 (May 1967), pp. 129-136.

2.10 Welker, J. R., O. A. Pipkin, and C. M. Sliepcevich, "The Effect of Wind on Flames," Fire Technology, V. 1 (May 1965), pp. 122-129.

2.11 Roberts, A. F. and G. Clough, "The Propagation of Fires in Passages Lined with Flammable Material," Combustion and Flame, V. 11 (October 1967), pp. 365-376.

3. Burning Rates

Once a fire has been ignited and has spread to involve a complete combustion element, one must determine whether or not adjacent elements will become involved. Hence, the burning element must be looked upon as a source of hot gas, combustible gas, or thermal radiation which can influence the ignition or combustion of adjacent elements. The element under consideration may be a collection of burning material within a room, a whole room, or a whole building.

If we consider a burning fuel element within a room, one must be able to predict the rate of heat and gas generation, and the thermal radiation characteristics of the fuel as a function of time for a particular environment. The description of a burning element must include its chemical composition and its geometric arrangement and location with respect to adjacent structures. Important environmental characteristics are thermal radiation field and the local flow speed, temperature, and gas composition.

The burning rate is obviously intimately connected with the pyrolysis mechanism, and this investigation can be considered as an extension of the pyrolysis work discussed in paragraph 1. However, the pyrolysis investigation was aimed primarily at the elucidation of the chemical processes involved, whereas the present study is related to combustion of large pieces of fuel. In this study, the influence of the char layer and the processes occurring in it also become important. In addition, it appears to be possible to obtain results here which will be immediately useful in making a mathematical representation of a burning room, even if the pyrolysis work does not yield a satisfactory description of the detailed chemical processes involved in combustion.

Although experiments have been carried out in which the mass loss history of burning samples such as isolated wooden dowels, e.g. ref. 3.4, have been determined, these data do not cover the whole range of variables desired here. These experiments should be extended to cover conditions of intense thermal radiation and convective heating which would simulate conditions in completely involved room fires with strong gas flows.

Time dependent measurements should be made of: 1) heat balance for the burning sample, which includes net heat loss by convection and radiation; 2) such internal characteristics of the sample as composition, pressure, and temperature; 3) generation rate and composition of hot gases and rate of mass loss; and 4) convective plume characteristics, such as heat release distribution, flow speeds, temperature, and geometry. Parameters to be varied in examination of an isolated element should include: a) radiant flux from outside sources (up to several calories/cm^2 sec); b) local gas flow field parameters, such as velocity (up to many feet/sec), composition, and temperature (up to $2000^{\circ}K$); c) geometry, composition, and initial temperature of the combustible material. Although carried out for a different purpose, the work of Grumer and Strasser (ref. 3.5) makes a reasonable starting point for these experiments.

3.1 Blackshear, P. L., Jr., and K. A. Murty, "Heat and Mass Transfer to, from, and within Cellulosic Solids Burning in Air," Tenth Symposium (International) on Combustion, The Combustion Institute (1965), pp. 911-923.

3.2 Blackshear, P. L., Jr., and K. A. Murty, "Pyrolysis Effects in the Transfer of Heat and Mass in Thermally Decomposing Organic Solids," Eleventh Symposium (International) on Combustion, the Combustion Institute (1967), pp. 517-523.

3.3 Roberts, A. F., "An Analogue Method of Estimating Wood Pyrolysis Rates," Eleventh Symposium (International) on Combustion, the Combustion Institute, Pittsburgh (1967), pp. 561-565.

3.4 Tinney, E. Roy, "The Combustion of Wooden Dowels in Heated Air," Tenth Symposium (International) on Combustion, The Combustion Institute (1965), pp. 925-930.

3.5 Grumer, Joseph and Alexander Strasser, "Uncontrolled Fires -- Specific Burning Rates and Induced Air Velocities," Fire Technology, V. 1 (September 1965), pp. 256-268.

4. Convective Flow and Heating from a Combustion Plume in an Enclosure

One of the important steps leading to a room flashover condition is the conduction of heat from a natural convection plume to walls, ceilings, and combustible materials. Because thermal radiation flux from small fires in a room tends to be small compared with a critical value close to 0.3 cal/cm^2 sec, and because radiation from hot or burning gases is most often small compared with this value, the radiation from heated surfaces such as ceilings can play a very important role in ignition by radiation. (For example, a ten foot square ceiling heated to a temperature of about 1200°F can cause ignition of cellulose on a floor ten feet distant.)

Motion of plumes and heat transfer from plumes impinging on walls and ceilings are understood in a general way, but methods of estimating either for turbulent plumes in enclosures are not now available. Experimental data for the plume impinging problem and for the influence of vertical walls on plume motion were not found during the present review.

In some previous experiments, e.g. ref. 4.3, the height of flames from various sources has been emphasized in studying buoyant diffusion flames. Although these studies look at part of the problem, they do not investigate the whole plume behavior.

Plume characteristics of very large fires burning on a flat surface can be predicted reasonably well some distance above the surface, where the flow resembles a turbulent jet (see refs. 4.1 and 4.2). However, near the surface, where the entrained flow must turn from a horizontal to a vertical flow direction, analytic predictions are not satisfactory. The influence of walls, low Reynolds numbers due to reduced scale, and large temperature variations across the plume cannot be assessed with present models. Hence, it is recommended that a study be made of plume motion within enclosures where enclosure surfaces form important constraints on the motion of the gas and of the heat transfer to enclosure surfaces resulting from the plume motion. It would seem necessary to carry out studies involving experiments for at least a few examples, either as separate experiments or as parts of more complete investigations, involving simulation of room fires.

Experiments in this area should include delineation of the flow field set up in a room by heat release patterns similar to those found in small room fires. Transient behavior of the convective flow field and heat transfer from the plume to the walls and ceilings should be measured. One experimental scheme is to use a gas burner of known characteristics to simulate a fire so that the source characteristics will be known. That is, the burner can be programmed to give the desired time varying heat and mass release rate.

Experiments in which room scale is changed substantially (i.e., by factors of 2 to 10) should also be carried out so that scaling laws can be developed, and hopefully, small scale tests may be used for most of the work.

These data should be carefully compared with existing computational schemes for plume motion with the aim of establishing approximate values for parameters governing mixing which occur in these analyses. It may then be possible to establish simple and rapid computational schemes for plume motion and heat transfer. Again, one major aim of this study should be the development of scaling procedures.

4.1 Morton, B. R., Sir Geoffrey Taylor, and J. S. Turner, "Turbulent gravitational convection from maintained and instantaneous sources," Proc. Roy. Soc. A, V. 234 (January 1956), pp. 1-23.

4.2 Lee, Shao-Lin and H. W. Emmons, "A study of natural convection above a line fire," Journal of Fluid Mechanics, V. 11 (Aug.-Dec. 1961), pp. 353-368.

4.3 Thomas, P. H., C. T. Webster, and M. M. Raftery, "Some Experiments on Buoyant Diffusion Flames," Combustion and Flame, V. 5 (December 1961), pp. 359-367.

4.4 Fay, J. A., M. P. Escudier, and D. P. Hoult, "Plume Rise Measurements at Industrial Chimneys," Discussions, Atmospheric Environment, Pergamon Press (1969), V. 3, pp. 311-315.

4.5 Lee, Shao-Lin and Chi-Hai Ling, "Natural Convection Plume above a Circular Ring Fire," Eleventh Symposium (International) on Combustion, the Combustion Institute (1967), pp. 501-506.

4.6 Yokoi, S., "Study on the Prevention of Fire-Spread Caused by Hot Upward Current," Fire Research, V. 3 (Sept. 1961), p. 217.

4.7 Thomas, P. H., "Buoyant Diffusion Flame," (letter), Combustion and Flame, V. 4 (1960), pp. 381-382.

4.8 Smith, R. K., "Radiation Effects on Large Fire Plumes," Eleventh Symposium (International) on Combustion, the Combustion Institute, Pittsburgh, Pa. (1967), pp. 507-518.

4.9 Batchelor, G. K., "Heat Convection and Buoyancy Effects in Fluids," Quart. J. Royal Meteorological Society, V. 80 (1954), p. 339.

5. Thermal Radiation from Burning Solids

Computational methods are well developed for determination of radiant energy transfer between solid surfaces separated by transparent gases, e.g. ref. 5.1, and by gases which are weakly absorbent when the radiant surface properties are known. Calculations for highly absorbent gases which are hot enough to re-radiate appreciably are more complex, but can be carried out so long as the gas properties can be defined adequately. Hence, radiant transfer is well in hand: what remains is the testing required to obtain useful approximations for absorption properties of typical combustion gases in burning enclosures and surface emissivities and absorptivities as a function of wavelength for typical surfaces which have been modified by the changing environment produced by combustion or by heating prior to combustion.

Measurements of these properties can be obtained during tests described in paragraphs 1, 4, and 7 of this section of this report.

5.1 Nelson, Harold E., "Radiant Energy Transfer in Fire Protection Engineering Problem Solving," Fire Technology, V.4 (Aug. 1968), pp. 196-205.

5.2 Heselden, A.J.M and P.L. Hinkley, "Measurements of the Transmission of Radiation through Water Sprays," Fire Technology, V.1 (May 1965), pp. 130-137.

6. Room Flashover

The concept of room flashover can be illustrated in the following simplified manner. A fire in an enclosure heats the ceiling by convective transfer. Radiative transfer then occurs between the ceiling and other parts of the room. Studies of thermal ignition show that a combustible material such as cellulose can be ignited when a minimum threshold of thermal radiation is exceeded. Hence, when the flux from the ceiling plus any convective heating exceeds this critical limit, combustibles in the rest of the room will begin to burn at very nearly the same time. This more or less sudden ignition in large parts of the room is called flashover, and it marks an important stage in the development of a room fire.

The development of a model from which flashover times (time between start of a small room fire to the envelopment of the whole room in flames) can be calculated appears to be necessary if the history of fire spread in a building is to be predicted. Tests carried out at IIT by Waterman (6.1, 6.2) were aimed at studying flashover and the scaling laws for experiments used to investigate this process. Any future investigations should start with a careful study of this work beyond that possible from the two short published papers available during this review.

The results reported by Waterman indicate that small-scale experiments with room height of order of 1 to 2 feet can be used in flashover tests. Verification of this result either by analysis of his data or by direct tests similar to Waterman's should be the first step in any future extension of this work.

Should a new experimental program be started, as seems likely, at least some part of the experimental program should be carried out in large rooms, i.e., rooms with dimensions of 10 feet on a side or more, in order to furnish a baseline for the small scale work. The use of gas-fired burners to simulate room fires offers the advantages of a low-cost and flexible device by which precise control of heat release as a function of time can be obtained.

Measurements to be made in the large room tests and smaller scale tests should include time histories of the following parameters: 1) temperature distribution in the room gases; 2) composition of gas, including a search for unburnt hydrocarbons; 3) heat transfer rates to walls, ceiling, and to combustible samples in various parts of the room due to radiant and convective transfer processes; 4) motion of hot gas plume above simulated fires by use of simple photography and other flow visualization techniques, and velocity measurements; 5) ignition times for various samples in the room, i.e., times required to initiate flaming combustion of various fuel elements in the room not in direct contact with other burning materials; 6) weight measurements of any burning items; and 7) influence of ventilation system parameters, such as flow rate, open areas, and location of openings.

It is clear from the above discussion that the large room tests offer an excellent opportunity to carry out tests described in previous sections and to relate isolated test results to conditions which more closely simulate a real fire. Hence, these large room tests will offer the opportunity of making a valuable check on the relevance of the isolated and smaller scale tests. Adequate instrumentation should be made available to insure that full use is made of such tests. Large room test facilities would also be useful in carrying out experiments discussed in the following two paragraphs, and in these tests too, the use of gas-fired burners to simulate room fires appears to be very attractive.

6.1 Waterman, T. E., "Room Flashover -- Criteria and Synthesis," Fire Technology, V. 4 (February 1968), pp. 25-31.

6.2 Waterman, T. E., "Room Flashover -- Scaling of Fire Conditions," Fire Technology, V. 5 (February 1969), pp. 52-58.

6.3 Thomas, P. H., "Some Studies of Building Fires Using Models," International Symposium on the Use of Models in Fire Research, W. G. Berl, editor. Publication 786, National Academy of Sciences - National Research Council (1961), pp. 150-185.

7. Combustion Rates in Fully Developed Room Fires

In addition to the determination of flashover, the progress of the fire in an enclosure should be studied subsequent to flashover as a function of fuel characteristics and loading, and ventilation parameters. These experiments should include studies of unventilated room fires and their behavior when ventilation is suddenly started by opening a door or window, since the almost explosive burning which can occur under these circumstances is a common cause of death among firemen.

Once a room has become completely enveloped in fire, it is most productive to consider the fire as an ignition source for adjacent parts of the structure or adjacent structures. Hence, the room must be characterized as: 1) a hot gas generator which produces convective heating of adjacent combustibles; 2) a radiant energy source; and 3) a source from which flame can spread directly through or along connecting elements such as walls. The first of these characteristics has been least studied, and appears to be the one requiring the most additional work. The second can be treated once the state of the room is defined,and the ignition of adjacent structures by flames propagating through walls and other structural members has been the subject of a great deal of experimental work on fire endurance of structural elements. Additional tests in this area will not be discussed here.

Characterization of the room as a hot gas generator depends largely on the ventilation of the room, room openings such as doors and windows, and fuel characteristics at the time of flashover. Experiments have been carried out with fires in real fuel elements and also with gas burner simulation to determine the burning rates as a function of ventilation, e.g. ref. 6.2. These experiments should be reviewed and extended to include the influence of forced air flows from air conditioning systems and the influence of such fuel parameters as fuel loading density, surface to volume ratio, and thickness of fuel elements.

The primary aim of this investigation should be the development of a model for prediction of the history of the room fire as a hot gas generator. The analytic work will involve the integration of experimental data on burning rates and convective flows discussed under paragraphs 3 to 6 into a calculation scheme which can describe the flow and heat release patterns of the burning enclosure. Parameters to be described include: 1) conditions at the ventilation opening -- velocity, density, composition, and temperature; 2) combustion rates of typical fuel elements (weight as a function of time) at various positions in the enclosure; 3) local environment near fuel elements in the room -- gas temperature, composition, and velocity, convective heat transfer rates, and radiant energy flux to and from fuel elements; and 4) heat balance for room and hot gas plume leaving ventilation openings.

Clearly, such a detailed picture will not in general be desirable, and hence the calculation must be based on a simplified picture of events in the enclosure ; experimental work will be necessary to show how to simplify the description. Tests should be devised which make possible the measurement of the parameters listed above. Although it may be possible to carry out most of these tests in small scale rooms (i.e., one or two feet on a side), and with simulated fires, it is highly desirable to have some realistic data to act as a check on smaller scale tests. Hence, investigation of fires in real fuels and in large room configurations (ten foot scale) should be carried out.

Again, tests of the sort discussed above will allow measurements on the combustion and ignition of fuel elements obtained in the isolated tests of Sections 1 - 5 to be compared with those obtained under more realistic conditions. In particular, the radiation characteristics of a room fire, discussed in Section 5, depend on surface temperature, emissivity, and absorptivity of walls and of the gas in the room, and on the geometry of the room, ventilation openings, and the plume outside the openings. These characteristics can be studied here under realistic simulation of a real fire. Hence, measurements of these variables should be made in addition to those discussed above.

It will be useful here to give a simple example of the type of test which could lead directly to the information required for proper formulation of the computational model. Consider a test room, 10 foot scale, with a distribution of gas jets located to simulate furniture. Let the room have two openings, pressurized by outside blowers which can produce flows both in and against the natural convection flow direction. A single gas burner in the room is ignited to start the fire, and others are ignited later as a function of the output of sensors located adjacent to the individual burners and responding to temperature, heat flux rates, or other suitable parameters. Similarly, the flow rates to the burners can be programmed to simulate the combustion of typical fuel elements in response to the sensor signals and a pre-set program designed to simulate the history of the combustion of fuel elements as a function of temperature, etc. During the development of the fire within the room, the blowers can be programmed to simulate conditions in adjacent rooms by fixing either pressure levels or flow rates; the state of inflowing gas must be conditioned to give the desired composition and temperature.

The response of the room can now be determined for the simulated fire. That is, the state of gas flow at the two openings and the history of the fire within the room (gas jet operation) can now be measured.

There are two categories of experimental programs of this type that should be undertaken with the gas-fired facility. The first of these is a series of experiments to demonstrate whether, regardless of the detail that must be given about the burning process, such a room may be treated as an element in the sense that we have described it. To do this, a specific room combustion program should be employed with a large range of inlet conditions. The resulting outlet gas state and the resulting course of the fire in each instance would be compared for consistency, for steadiness, and for reproducibility. The attempt would be made to organize these results into an element characteristic. It is not obvious that this can be accomplished. The results may not be reproducible or may change discontinuously with the variations of inlet state. If this is so, some detailed investigations must be undertaken to find the source of the difficulties.

The second category of experiment concerns the response of the element to changes in room geometry, fuel loading, and fuel character in the room. The aim would be to investigate a sufficient number of configurations that the possibilities of simplifying the results would present themselves. Hopefully, the pumping and gas generating characteristics of the room would be insensitive to certain details of the fuel location, could be normalized with respect to the total fuel load, etc. If this proves possible, then the element may be characterized by a few parameters, and these may be employed in the computer program. If the simplification proves impossible, then the entire computation is of questionable feasibility.

7.1 Salzberg, F. and T. E. Waterman, "Studies of Building Fires with Models," Fire Technology, V.2 (Aug. 1966), pp. 196-203.

7.2 Gross, D. and A. F. Robertson, "Experimental Fires in Enclosures," Tenth Symposium (International) on Combustion, the Combustion Institute, Pittsburgh, Pa. (1965), pp. 931-942.

7.3 Putnam, A. A. and C. F. Speich, "A Model Study of the Interaction of Multiple Turbulent Diffusion Flames," Ninth Symposium (International) on Combustion, Academic Press, New York (1963), pp. 867-877.

8. Motion of Combustion Gases and Smoke in a Building

During a building fire, motion of gas will be set up within the building and outside it by the generation of large volumes of heated gas by combustion processes and the resulting natural convection effects. Measurement of this hot gas can lead to ignition of fresh combustible products and is a chief source of fire spread. In addition, smoke can hinder fire suppression efforts. Hence, any prediction of the history of a building fire must depend heavily on the ability to predict the motion of hot combustion products and the much cooler air supply.

At present, there are some analytic results for flows induced by or strongly influenced by density gradients under conditions for which (a) density differences are small, (b) the flow is laminar, (c) the variation of density due to molecular diffusion can be ignored, and (d) the geometry of the boundary surface is simple.

In problems involving turbulent flows, fewer solutions are available. A typical example is the solution obtained for a turbulent plume rising from a steady source (4.1 and 4.2). These solutions are not easily extended to cover the case of hot gas rising up a stairwell (either open or closed at the top) under conditions such that a large part of the well is filled with hot gases.

Flows which simulate horizontal motion of natural convective flows in buildings have been studied under the heating of "gravity currents" or "stratified flows." A typical example is a paper by Macagno and Rouse (8.6), which contains a good set of references to this field. Unfortunately, these papers do not give much help in analyzing the problem of interest here, since all of these solutions depend upon ad hoc assumptions concerning the turbulent transport phenomena, and in none are density differences larger than a few percent considered. Since the magnitude of the density variation is important here, there is good evidence that mixing between streams with large density differences is inhibited. This effect is marked in growth currents where density differences of only 5 - 10 percent are involved, and in the present case where differences of 300 - 500 percent are included, this effect may greatly reduce mixing and thereby contribute to the spread of hot gas.

In making an analysis, the principal problems are (a) to make a reasonable representation of the turbulent transport coefficients in flow fields with large density variations (due to large temperature variations), and (b) to treat complex two- or three-dimensional flow fields.

One approach to solving such problems is to investigate a few relatively simple configurations experimentally and theoretically with the aim of developing (a) simple techniques for estimating turbulent mixing coefficients, and (b) analytic methods of treating the effects of large density changes in the fluids. The first tests should be made with simple, small-scale configurations, and their purpose should be to examine the mixing phenomena which occur in natural convection flows with very large (e. g. 5 to 1) density ratios. The scale of these tests should be large enough that turbulent flow can be established, but small enough that apparatus will be inexpensive to build and easy to modify. A duct with a cross-section of 1/4 to 1 square foot may be large enough. To obtain large density differences, use of gases of different densities (e. g. hydrogen flowing into nitrogen or nitrogen flowing into sulfur hexafluoride) should be considered in place of high and low temperature streams of air.

Also, the use of air at 530°R and very cold nitrogen (say, 150°R) may also form an attractive pair of gases for test purposes. A vertical (stairwell simulation) or horizontal (hallway simulation) duct of rectangular cross-section would make a useful geometry for the first tests.

Parallel with this approach, an investigation of scale effects should be carried out. Experimental investigation of natural convective flows with similar geometries and boundary conditions, but with scales varying from one foot to ten feet, should be carried out to determine what effect, if any, scale changes will have on the flow field and on turbulent mixing in particular. Analysis of data obtained in these tests will further increase information on turbulent transport phenomena and will serve to check the conjecture that scale effects are not very important in turbulent flows of this type.

The experiments discussed above should include the following features: models which simulate typical building configurations should be investigated and relatively simple geometries should be used in early tests. Scale changes should cover the range from one-foot to ten-foot room heights, with a lower limit fixed by turbulent flow requirements. Flow visualization techniques, including schlieren or interferometric photography, should be used to observe gas motion and to measure density gradients. In early tests, density differences can be obtained by use of different gases rather than different temperatures in the same gas.

Efforts should be made to account for heat conduction to the walls and to scale wall conduction properties as the scale is changed. Measurements of the flow field properties should include mean temperature, pressure, and composition fields. Hot wire and helium tracer techniques should be used to investigate local turbulent fluctuations and mixing rate characteristics. Finally, the influence on internal flows of pressure and flow fields external to the building and of internal flows set up by air conditioning equipment could be examined in model tests. Note that these experiments are similar to those discussed in paragraph 4 and would make use of similar experimental techniques. In addition, the large-scale test facility described in paragraph 7 could, with addition of suitable hallways, etc., be used to study the motion of gas in large scale situations.

Should modeling prove feasible, small-scale (and therefore inexpensive) tests would be possible for complex buildings, and models could be used as analog computers.

The major problem remains of connecting the motion of gas in the model with the rate of combustion in the room which is acting as the hot gas source. Combination of the results of this and the previous paragraph should make this possible.

8.1 McGuire, J. H., "Smoke Movement in Buildings," Fire Technology, V. 3 (August 1967), pp. 163-174.

8.2 McGuire, J. H., "Control of Smoke in Building Fires," Fire Technology, V. 3 (November 1967), pp. 281-290.

8.3 Seigel, L. G., "The Projection of Flames from Burning Buildings," Fire Technology, V. 5 (February 1969), pp. 43-51.

8.4 McGuire, J. H., "The Flammability of Exterior Claddings," Fire Technology, V. 3 (May 1967), pp. 137-141.

8.5 Nelson, Harold E., "Room Fires as a Design Determinant," Fire Technology, V. 1 (August 1965), pp. 197-203.

8.6 Macagno, Enzo Oscar, and Hunter Rouse, "Interfacial Mixing in Stratified Flow," Journal of the Engineering Mechanics Division, Proceedings of the A. S. C. E., Vol. 87, EM 5 (October 1961), pp. 55-80.

8.7 Streeter, V. L., editor, Handbook of Fluid Dynamics, McGraw-Hill Book Co., New York (1961), Chapter 2.

8.8 Taylor, G. I., "Fire Under Influence of Natural Convection," The Use of Models in Fire Research, W. G. Berl, editor. Publication 786, National Academy of Sciences - National Research Council (1961), pp. 10-31.

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IV. RECOMMENDATIONS

1. Computational procedures for the treatment of building fires by means of a non-linear network analysis should be developed. This approach appears to be the only one capable of treating this problem in any degree of generality. It is of the utmost importance to maintain the strictest simplicity, in the description of the elements and in the construction of the network, that is commensurate with a realistic model of the building fire.

2. As the most essential factor to implement the rational analysis of large building fires, it is recommended that a facility be constructed for the purpose of carrying out controlled experiments directed toward the determination of unit characteristics for the network analysis. The facility should provide rooms with scales varying from one to at least ten feet on each side that permit detailed simulation of the ignition, convection, and burning processes. They should permit a wide variety of geometrical configurations, natural or forced convection of air and combustible gas, and external heaters to simulate a supply of hot and combustible gas. The fuel gas could be methane or propane supplied through gas jets distributed over interior surfaces of the room to allow non-destructive simulation of the room fire. These gas jets should permit programming to give a desired profile to the fire. The facility should permit the measurement of convection velocities, gas throughflow, exhaust composition,

and temperature distribution, as well as various parameters describing conditions inside the rooms.

3. In order to follow the course of the fire with an acceptable degree of realism, the network analysis must account for the continuity of: i) mass flow, ii) gas temperature, iii) gas pressure, iv) chemical composition, from one element to the other. The elements themselves must therefore be considered as centers of production for each of these quantities. We must determine, therefore, what possible output states a room, hallway, or ventilating duct will provide as a function of time, under a wide variety of flow inlet conditions. The element may be considered as a very complicated "pump and gas generator" and we need to know its pumping characteristics. That is, for a given inflow of gas mass, what changes in temperature, pressure, and composition does the "pump" provide from inlet to outlet. Extensive systematic experiments must be carried out to determine these characteristics.

In the actual fire, the pumping characteristics of an element depend upon time; that is, they are strongly influenced by the instantaneous fire involvement of the room. Thus, the experiments must contain this element of change as an inherent part of the characteristic; that is, the pumping characteristics involve the integrated history of the fire. This is analogous to the representation of charge on a condenser in an electric circuit as the integrated current flow.

This program may be carried out more expeditiously utilizing the "gas-fired room" than with one utilizing real fuel. However, the control of local gas jets must be effected by measurements of corresponding wall temperatures and heat flux rates. This feedback arrangement will permit direct utilization of fundamental information on surface combustion in simulating the room fire. Then the effects of specific parametric changes may be observed and experiments may be repeated with some degree of convenience. It is obvious that, as the "room burning facility" is developed, comparison between actual room burns and simulated room burns must be made to improve the degree of simulation and to expose basic faults in the system.

Experiments must cover a wide range of throughflow conditions for any given room geometry and fuel loading. Clearly, where a given element is placed into the complicated network representing the building, the actual direction of gas flow may be opposite to that which would occur under the action of normal convection. In this circumstance, the element, considered as a pump, may be "stalled" and its performance, which may be non-steady, will require an experimental rather than analytical description.

4. The large-scale tests described above will obviously be expensive, and it is very desirable to investigate the possibility of reducing this expense by use of smaller scale tests. If small-scale (one foot scale rooms) tests prove technically feasible, reduction in expense will probably

result from smaller capital costs of room construction and blower equipment, and perhaps smaller costs for operating personnel. However, instrumentation costs will not be greatly reduced if the same data are sought from large and small scale tests.

In none of the problem areas described in Section III have scaling laws been developed in a satisfactory manner. It is vital that they should be, not only because small scale tests may be cheaper, but more importantly, because they are necessary if experimental data are to be made generally useful. Hence, the development of scaling laws should be an important part of any investigation undertaken during this program.

5. Experimental research and analysis should be carried out to aid quantitative understanding of the physical phenomena governing the mechanisms of burning in rooms and other elements.

In Section III, the phenomena involved in a room fire were subdivided and experiments were proposed which aimed toward increasing our ability to predict the course of the fire. None of the phenomena appeared to be well understood, and all deserve further study. However, it is possible to pick areas which are in more need of attention than others and which are of more immediate interest from the point of view of the room fire situation. Two areas appear to require further study if the approach to building fires discussed in this report is to be successfully utilized.

The first is the study of the motion of hot combustion products in a building (Section III-8). Although everyone "knows" that hot gases rise, the rate of movement of hot, turbulent gas through a complex building due to natural convection and the manner in which the gas temperature decreases with distance from the source are not well understood. Model studies of this problem appear to offer the best first look at this problem, even though some experimental verification of the validity of modeling is certainly required.

The second is the study of the behavior of fully-developed fires in rooms (Section III-7). Small-scale experimental work may be of use here, but considerable testing at the 10-foot room scale appears to be required in order that a tractable model can be constructed.

In addition, at a lower priority, we suggest that the other investigations suggested should be approached in the following order.

Room flashover (Section III-7) appears to have been studied by Waterman (7.2) with considerable success. His work should be reviewed and further work carried out if necessary.

In order to be able to describe the gas-generator properties of a burning room, a description is needed of the burning rate of thick fuel elements in an environment which includes high radiation intensity, hot gases, and reduced oxygen content. The small-scale experiments discussed in Section III-3 were suggested to supply this information and will support the large-scale room experiments in a most valuable manner.

A better understanding of natural convective motion within the burning room itself (Section III-4), and of the heat transfer produced by it, is also required if the development of the room fire to flashover point is to be described quantitatively.

Studies of ignition of heated surfaces primarily by convection (Section III-1) and spread of flames under conditions of considerable convective flows (Section III-2) are required to complete the overall study of fire spread.

Finally, characterization of the ignition by radiation (Sections III-1 and III-5) should be studied to illuminate the process of spread to a whole room when part is ignited by spread from an adjacent burning room.

APPENDIX

Los Angeles Times Mon., Oct. 13, 1969

8 Killed, 7 Injured as Fire Sweeps L.A. Apartment House

BY NOEL GREENWOOD
Times Staff Writer

A predawn fire swept through a three-story apartment house near downtown Los Angeles Sunday, killing eight persons—including two children—and injuring seven.

At least 30 more persons escaped death by leaping from windows of the apartment house or climbing down firemen's ladders.

Some residents slid down makeshift ropes of blankets and sheets. Others threw out mattresses and jumped onto them.

Firemen said the death toll equaled the highest loss of life ever recorded in a Los Angeles residential fire.

Arson investigators said the fire was of "suspicious" origin and might have been deliberately set.

Save Boy First Thought Dead

Firemen saved the life of one boy —first thought to be dead—when they noticed a slight movement of his body and administered mouth-to-mouth resuscitation.

Seven of the dead were found crumpled on the floors of their apartments, apparently overcome by smoke while trying to escape through windows.

The eighth victim died of injuries suffered when she leaped from her third-floor window to the pavement below.

The fire broke out in the basement of the Bromley Apartments, 320 S. Rampart Blvd., at about 4:40 a.m.

It swept quickly up a stairway connecting all three floors and engulfed the central hallways in flames.

Residents awakened by the smell of smoke tried to flee down the halls but were forced back by the flames. They escaped through windows instead.

In one third-floor apartment, firemen found the bodies of Anthony and Ina Porter, both about 25, and their daughter, Tammy, 3.

Lying unconscious near the bodies of his parents was Anthony Jr., 6.

Fireman David Smith and Capt. Jack Bennett noticed slight movement in the boy's body, and Smith began mouth-to-mouth resuscitation.

The boy was revived in the room, given further resuscitation outside, then taken to County-USC Medical Center where he was reported in good condition, recovering from smoke inhalation.

Three Bodies Found

In another third-floor apartment firemen discovered the bodies of Edgar Soto, 55, his wife, Maria, 48, and their son, Eugene, 10.

The seventh person to die in the fire was Mrs. Mary Morrison, 70, found in her second-floor apartment.

Succumbing to internal injuries suffered when she jumped from her third-floor apartment was Mrs. Rose Cordova, 22. She was taken to County-USC Medical Center, where she died at 6:50 a.m.

She was three months pregnant.

Her husband, Michael, 21, and his brother, Gabriel, 20, were injured when they jumped from the same apartment.

Both were taken to County-USC Medical Center, where Michael was in serious condition with multiple fractures and his brother was in fair condition, suffering from bruises.

Lita Cunanan, 25, and Dely Lorenzo, 25, were injured when they leaped from a window in their second-floor apartment.

Miss Cunanan was treated for a broken back at Kaiser Hospital and Miss Lorenzo was taken to County-USC Medical Center with broken heel bones.

Also injured in jumps from the second floor were Mrs. Javier Gamboa, 68, who suffered minor injuries, and Blanca Reyes, 18, who sustained a broken pelvis. At County-USC Medical Center, Mrs. Gamboa was released after treatment and Miss Reyes was reported in fair condition.

It was not certain how many persons escaped the fire. Firemen said they rescued about 30, and there were several more who escaped on their own.

The 24-unit apartment house was fully rented at the time of the fire, but apartment manager Joseph G. Davis said he did not know the total occupancy.

Davis said that when he awoke in his first floor apartment, there were flames coming through his door. He said he tried to get the door open to get at a fire hose in the hallway, but was driven back by the flames.

He smashed a window and jumped clear of the building.

Many of the ground-floor windows were covered with steel bars as a protection against burglars. Smashed window panes and torn screens gave evidence of futile attempts to get past the bars.

But there were no

deaths on the ground floor, and firemen said it was probably because the fire was most intense in the front portion of the building, allowing residents to flee through a rear door.

A front fire escape was useless because it was engulfed in flames. Some second- and third-floor occupants managed to flee down a rear stairway.

Mrs. Mildred Beardsley, a second-floor occupant, was awakened by the screams of others. She tried to open her hallway door but couldn't.

"My room was completely filled with smoke," she said. "I couldn't breathe. I kicked out the window screen.

"Someone hollered to me to make a rope out of my bedspread and sheets. But I couldn't tie it, and it wouldn't hold me."

Then, she said, firemen got a ladder to her window and she climbed down.

Those who jumped to safety had to survive about a 15-foot drop from the second floor and a 25-foot drop from the third floor.

Some were partially caught or had their falls broken by neighbors and spectators who gathered.

Luis Zuleta, 20, who lives in an apartment house across the street, said that when he arrived at the fire, "people were pounding on the windows trying to get out."

He said he and another man broke the fall of one woman by holding a mattress between them.

The apartment house, estimated to be 40 years old, was of wood and masonry construction.

Firemen said its open interior stairway type of construction was common in past years, but is no longer an approved type in Los Angeles.

"The stairway acts like a chimney and sucks the fire up throughout the building," said one Fire Department spokesman.

The blaze began in a storage area of the basement. Damage was estimated at $50,000 by firemen.

The owner of the apartment house, who refused to give his name to newsmen, said the building was insured.

It took firemen a half-hour to control the blaze. About 50 firemen and 16 pieces of equipment were summoned. The building was enveloped in flames when firemen arrived.

The only other Los Angeles residential fire to claim eight lives occurred in December, 1968, when flames swept a two-story frame house in Watts. Six of the eight victims were children.

The Fire Department said the city's other major fires in terms of lives lost were a hotel blaze in 1963 that killed seven persons and a barroom fire in 1957 that claimed the lives of six.