Fire Physics—Promises, Problems, and Progress

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ABSTRACT

The use of wanted fire leads necessarily to unwanted fires, which are fought by the fire services, designed against by the fire engineers, and observed and explained by the fire sciences. This paper explores the current position of one of those sciences - fire physics, defined as the study of the physical mechanisms by which fire is initiated, grows throughout a system, and is extinguished. The motivations for pursuing given technical areas are examined (promises), the tasks to be performed are described (problems) and the accomplishments to date are summarized (progress). The field of Fire Physics is broken into four broad categories: I.) Fluid Dynamics, II.) Diffusion Flames, III.) Flame Spread and IV.) Compartment Modeling. An inclusive list of topics within each category is presented. Space constraints prohibit a more comprehensive review, however reference is made to many competent reviews already available. Due to the author's linguistic limitations, the English language literature is emphasized.

HISTORY

It is interesting that anthropologists (1) now believe that the use of fire by homonids, i.e. by homo erectus c. 500,000 B.C. in Africa, precedes the evolution of the modern species of man, homo sapien. It is not clear when this use became controlled, i.e., when homonids could ignite fire at will rather than simply conserve it. At 10^6 B.C. it was not controlled; at 10^5 B.C. some evidence for control exists (2). The earliest artifacts indicating the ability to generate fire, flint and massive iron pyrite, date from 10^4 B.C. (3). In a few isolated existing societies ignition processes are unknown and the conservation of fire remains crucial (4). One of these groups, the Andaman Island people regard the possession of fire as the chief distinction between man and animal (5). The pyrolaters of ancient India addressed more hymns to the fire-god, Agni, than to any other pre-Hindu deity (6). During the European Middle Ages, flames were incorporated in heraldry (7). In existing societies the control of unwanted fire remains an important unresolved issue. The magnitude of the problem varies with the particular country (8,9). But all modern societies face the threat of destruction of life and property by escaped fire. Hence the need for fire science.

Several useful reviews of the history of fire science, particularly in the United States, are available (10) extending from pre-history (11) to c. 2300 A.D. (12). U.S. activity prior to 1940 was centered in three locations: the National Fire Protection Association in Boston, the Underwriter's Laboratories in Chicago and the National Bureau of Standards in Washington. S.H. Ingberg's classic work in the 1920's addressed the question, How severe can fires be in buildings? An appropriate inquiry, since the primary problem of the time was to preven the collapse of burned buildings onto adjacent structures or roadways (13). He observed and quantified the variation of fire duration and average room temperature with fuel load (14) thereby laying the empirica foundation for the standard furnace test time-temperature curve (15). Note that he obtained peak temperatures as high as 1050°C within 10 minutes of an "exposure start" with purely cellulosic fuels (see Fig. 6 of Ref. 14). This, primarily post-flashover, temperature history study is fire physics since the measurements were carefully made (with 100 thermocouples arrayed throughout the rooms) over a range of conditions (77 t 440 10^3 BTU/ft^2; 0.8 to 5 MJ/m^2) and the author clearly stated his limitations and assumptions (14).

The National Academy of Sciences played a pivotal role in the 1950' and early 60's by forming the Committee on Fire Research with first H.C. Hottel and then H.W. Emmons as chair. That committee established the seminal journal Fire Research, Abstracts and Reviews, which later contained their recommendations for a fire research program (16) and Hottel's marvelously insightful analysis of Russian pool fire data (17), and published the first book on fire modeling (18).

The period from the late 60's to early 80's was particularly exciting, with the establishment of the Factory Mutual Research Corporation in Boston and the National Bureau of Standard's Center for Fire Research in Gaithersburg, Maryland where the meeting founding the International Association for Fire Safety Science was held in October, 1985.

Parallel growth occurred, primarily independently, in several countries. The effort in the United Kingdom was focused at the Building Research Establishment's Fire Research Station begun in 1948 in Borehamwood. The progress of fire physics can be traced in the Information Papers, Fire Research Notes, journal articles and books (19, 20) authored by the FRS staff. Particularly noteworthy is the recent volume of selected papers by P.H. Thomas covering 35 years of fire physics scholarship from 1951 to 1986 (21). In Canada, the activities of the National Research Council's Division of Building Research predate those of the NBS Center for Fire Research. In Scotland, the University of Edinburgh's Unit of Fire Safety Engineering helped develope an outstanding text on fire physics (22). Australia has had a strong experimental program, including forest and brush fire control.

In Japan, several institutes, associations, and societies conducted fire physics research in this time frame. A major focus was at the Ministry of Construction's Building Research Institute first in Tokyo ar now in Tsukuba. The initial progress there centered on experiments on wood cribs (23), room fires (24,25) and smoke generation (26) and on network analyses of smoke movement in buildings (27). The early work of Yokoi, Kawagoe, Saito, Wakamatsu and others, as recorded in the BRI Reports, Occasional Reports and Research Papers, laid the foundation for the current premier fire physics research position held by Japan, as evidenced by many excellent papers in the First and Second International Symposia on Fire Safety Science.

In Europe, Spain and Italy have been regular contributors to the Fire Research Colloquia at the Combustion Institute's biennial International Symposia on Combustion (28). Important fire physics contributions have come from Sweden (Lund Institute of Technology, National Testing Institute, and Fire Protection Association); Germany (Technische Universitat Braunschweig, Universitat Karlsruhe; and Gesamthochschule Kassel Universitat); France (Universite de Poitiers and Centre Scientifique et Technique du Batiment); Denmark (Technical University); Norway (Fire Research Laboratory) and others.

Table 1. FIRE PHYSICS

I. FLUID DYNAMICS

1. Buoyant Flames and Plumes
   - Flow Regimes
   - Transition Criteria
   - Near Field
   - Velocity and Temperature Profiles
   - Far Field
   - Entrainment Rates
   - Coherent Structures and Other Oscillations
   - Droplet Dynamics
   - Interactions with Walls, Ceilings, Layers and Flows
   - Reaction Distributions
   - Flame Base Field
2. Flows Within Compartments
   - Ceiling Layer Formation
   - Two-Layer Temperatures
   - Extended Fire Plumes
   - Ceiling Jets
   - Stratification
   - Corridors
   - Mixing
3. Flows at Openings
   - Doors
   - Windows
   - Ceiling Holes
   - Multiple Openings
   - HVAC Systems
   - Mixing
4. Nondimensionalization

II. DIFFUSION FLAMES

1. Pyrolysis Rates Flame Shapes
   - Laminar Boundary Layers
     - Free, Forced and Mixed
   - Burning distinct from Pyrolyzing
   - Heat Release Rate Databases
   - Turbulent Boundary Layers
     - Free, Forced and Mixed
   - Radiant Augmentation
   - Blockage Effects
   - Liquid and Solid Pools
   - Walls, Ceilings and Corners
   - Cribs, Carpets and Furniture
   - Charring
   - Melting
2. Excess Pyrolyzate
   - Production
   - Composition
   - Accumulation and Flammability Limits
3. Flame Radiation
   - Temperature, Geometry and Composition Effects
   - Heat Release Rate Fraction
   - Wavelength Dependence
   - Soot as % of Fuel Carbon
   - Soot Volume Fraction
     - Measurement
     - Correlations
     - Analyses
4. Nondimensionalization

III. FLAME SPREAD

1. On Solids/Liquids
    - Laminar/Turbulent
    - Thick/Thin
    - Up/Down Vertical Walls
    - Opposed/Assisted Flow
    - Horizontal
    - Surface Tension Effects
    - Transport Mechanisms
    - Radiant Augmentation
    - Oxygen Variation
    - Correlations
        - Damköhler No.
        - Empirical
    - Ignition Temperature
    - Ignition Phenomena
        - Remote Object
        - Piloted/Fire Brand
    - Extinction Phenomena
    - Melting
    - Charring
    - Critical Kinetics-Gas/Solid
2. In Solids (Smoldering)
    - Porous Media Flow
    - Heat and Mass Transport
    - Counter-Current (Diffusion)
    - Co-Current (Premixed)
    - Self-heating to Ignition
    - Surface Reactions
3. In Gases
    - Deflagrations/Detonations
    - Confined/Unconfined
    - Pure Mixtures
    - Vitiated Mixtures
    - Ceiling Layer Limits and Propagation Speeds
    - Ignition/Extinction
    - Stratification
4. Growth Models
    - Exponential/Power Law
    - Doubling Time
    - Smoke Movement
    - Fire Growth Rate Parameter
    - Growth Classification
    - Intensity Classification
    - Threat Variables
    - Escape Time
5. Nondimensionalization

IV. COMPARTMENT MODELING

1. Heat Transfer
    - Conduction Losses
    - Thermal Inertia
    - Convection Losses
    - Convection Between Layers
    - Flame Impingement
    - Smoke Layer
        - Visibility
        - Radiation
    - Surface Radiant Exchange
        - Accurately Described
        - Approximations
    - Radiation Rate Pool
2. Pyrolysis and Burning Rates
    - Ventilation Control
    - Vitiation
    - Radiative Feedback
3. Growth to Flashover
    - Ventilation
        - Free, Forced, None
    - Pressure
    - Characteristic Times
    - Temperature Field History
    - Species Field History
    - Computation
        - Zone
        - Field
    - Scale Effects
    - Stratification
    - Oscillations
4. Flashover
    - Definitions
    - Criteria
    - Approximations
    - Stability Analyses
    - Windows Breaking
    - Venting
    - Backdrafts
    - Air Flames
5. Fire Spread to Adjacent Spa
    - Postflashover Intensity
    - Flame Heights Out Windows
    - Flame Propagation and Leng along Adjacent Ceilings
    - Multiple Rooms
6. Nondimensionalization

PROMISES

The session titles at this symposium could serve to identify the branches of fire science. Of interest here is fire physics which can be defined as the study of the physical mechanisms by which fire is initiated, grows and is extinguished. Our goal is to provide life safety from fire by understanding the physics of fire sufficiently to develop mathematical models or empirical correlations which predict the evolution of any fire and, based on these predictions, to suggest test methods or standards which will properly identify fire hazards. The boundaries between fire physics and the other branches of fire science, especially fire chemistry, are blurred and listing problems here does not imply exclusivity but rather partnership, with each area contributing its expertise to the solution of an appropriate sub-problem. Solving complex problems will require cooperation and appreciation, rather than competition, among disciplines.

The promise is basically the same across the fire sciences, i.e., that there exist bodies of fundamental knowledge accrued by science over time which can be applied, directly or with a few small steps advancing the frontiers, to the solution of fire problems. This knowledge is available in universities, industries and government laboratories throughout the world. All that is required is the insight to see and the energy to make the needed connections between the right fundamentals and the fire-related applications. In fire physics, the period 1980-2010 A.D. appears ripe for forging these connections. The fundamental disciplines: fluid mechanics, thermodynamics, transport mechanics, etc., are mature. The required computational power is becoming available. The time for action is now.

PROBLEMS

Table 1 is an attempt to organize the fields within fire physics and to inclusively list all pertinent phenomena. The order is from best to least understood, or in the case of the four main divisions, from most to least mature. Each problem is listed only once, at its first appearance, since its solution is assumed to be available where required further down the table, e.g., "ceiling layer formation" appears under Fluid Dynamics and is not repeated in Compartment Modeling. This concise synthesis can not claim uniqueness and claiming completeness would be rash. But, at the least, Table 1 should have usefulness as a springboard for productive debate. There exist many interconnections among these problems which a one-dimensional list can not display. An appropriate project for the future would be to develop a multi-dimensional Hasemi Diagram (29) or Lighthill Map (30) for fire physics. The individual problems are discussed in the following progress section. Less emphasis than might be expected is placed on future work since that was so well described in the First Symposium invited lecture on fire physics (31). The 141 references cited there are a veritable gold mine of fire physics information. Nondimensionalization is listed at the end of each main division because it does not appear to have yet received the explicit attention it merits. It has been suggested, perhaps incorrectly, that in developing a large precision code (12) for calculating the evolution of a compartment fire, nondimensionalization may not have great utility. However, in practical codes (12), in simplified correlations (32) and in attempts to scale fire phenomena (33,34), identifying the optimum dimensionless groups will be the key problem, just as in the more fundamental branches of physics.

PROGRESS

I. Fluid Dynamics

1. Buoyant Flames and Plumes. This section uses Table 1 as an outline, highlighting available conclusions and noting areas where further efforts are needed. The references cited are examples, meant to provide entry points to the literature in each area. The Emmons Lecture of the First Symposium is required reading in the field of fire fluid dynamics (35). Buoyant flames and plumes are well covered in the other invited fire physics lecture in this symposium (36). Zukoski (35) has identified the governing dimensionless group for large diffusion flames as the enthalpy generation scaled by the buoyant convection of enthalpy, i.e.,

$$Q^* \equiv \dot{Q}/(\rho_\infty c_{p\infty} T_\infty g^{1/2} D^{5/2}) \tag{1}$$

where $\dot{Q}$ is the total heat release rate, D is the fire base diameter, g is 9.8 m/s^2, and ρ_∞, $c_{p\infty}$ and T_∞ are the gas density, specific heat capacity and temperature at ambience. Three flow regimes and two transition regimes have been identified. Transition (IV) to a momentum dominated regime (V) occurs for $Q^* \gtrsim 10^3$. In the range, $1 \lesssim Q^* < 10^3$, the flow is buoyancy dominated (III) and the flame height, at 50% intermittency, in units of the base diameter, is

$$Z_f/D \approx 3.3\ Q^{*2/5} \tag{2}$$

Equation (2) shows that the flame height is independent of the base diameter, as expected for large turbulent buoyant flames where the fuel flow rate, not the diameter, matters. Note that Q* decreases as D increases and as Q* approaches unity, the pulsation normally observed at the flame base grows into strong oscillations (37) initiating the transition (II) to a regime (I), $Q^* \lesssim 0.1$, where the flame column has broken into a ring of separate flamelets.

The adiabatic plume above the fire, or far field, is well understood (38,39) provided the actual distributed enthalpy source can be modeled as a point source. The virtual origin is the device usually chosen to accomplish this (40-42). Let Z_0 be the height of the origin above the flame base, then

$$Z_0/D \approx 0.33\ (2 - Z_f/D) \tag{3}$$

correlates most data (35) giving a virtual origin below the base for tall flames, $Z_f/D > 2$, and above for short flames. Modern mathematical methods are being applied to the whole flow field (43). But for now entrainment rate data (39,42) continue to be useful. Ingenious temperature and velocity field measurements have also been made (44-46). But analyses of reacting flows in these geometries remain undone. Also areas for fruitful future activity are droplet dynamics (47,48) and plume interactions (49,50).

2. Flows Within Compartments and 3. Flows at Openings. The previous section addressed unenclosed plumes and flames. Here confinement, with holes, is added. Zukoski (35,51) explains the formation of two layers, the upper hot and lower cold, in a compartment fire. Stratification is reduced by the recirculation of the hot gas in the upper layer due to entrainment or re-entrainment in the plume and ceiling jet and due to the circular flow path produced by walls and buoyant forces. The soffet or intrados of doors and windows also cause outgasing of the

intermediate temperature material (see Figs. 1 and 10, ref. 35). The history of the two-layer model has been reviewed by Quintiere (52). Both authors (35,52) discuss conditions under which stratifications occur. The unsteady growth to the two-layer condition has been examined (53,54) as have the flows within the ceiling layer (49,55-57). Flow in corridors (31,35,35) and mixing are areas under current study.

Vertical vents, i.e., windows, doors, holes, can be treated as orifices using standard methods (24,31,35) with an orifice coefficient of 0.7 (35,58), within ~ 10%. Horizontal vents are more difficult since both buoyancy and pressure effects can be important producing inherently unsteady flows, but preliminary studies (31,35,59) are available. Some work has been done on forced flow systems (60,61) and multiple openings (62). Further discussion of room fire fluid dynamics is more appropriate under Compartment Modeling.

Table 2. General Results for Diffusion Flame Species and Enthalpy Fields

	$\leqslant \eta_{f\ell}$	$\eta_{f\ell}$	$\geqslant \eta_{f\ell}$
$Y'_o \equiv Y_o/Y_{o\infty}$	0	0	$1-(1+\phi)J$
$Y'_f \equiv Y_f/Y_{fw}$	$(1+1/\phi)J-1/\phi$	0	0
$h' \equiv h/Q_oY_{o\infty}$	$1-(1-h'_w)J$	$(h'_w+\phi)/(1+\phi)$	$(h'_w+\phi)J$
$Y'_p \equiv (Y_p-Y_{p\infty})/Y_{o\infty}(1+s)$	$1-(1-Y'_{pw})J$	$(Y'_{pw}+\phi)/(1+\phi)$	$(Y'_{pw}+\phi)J$
$Y'_n \equiv Y_n/Y_{n\infty}$	$1-(1-Y'_{nw})J$	$(Y'_{nw}+\phi)/(1+\phi)$	$1-(1-Y'_{nw})J$

Notes: $\leqslant \eta_{fl}$ indicates the fuel side of the reactant sheet and $\geqslant \eta_{fl}$ indicates the oxidant side. Y_i is the species mass fraction, h is gas enthalpy relative to ambient, Q_o is ~ 13 kJ/gm of O_2, s is the stoichiometric ratio ν_fM_f/ν_oM_o, $\phi \equiv Y_{fw}/Y_{o\infty}s$ is the diffusion flame equivalence ratio and

$$J \equiv \left[\frac{Y_f}{\nu_fM_f} - \frac{(Y_o - Y_{o\infty})}{\nu_oM_o}\right] \Big/ \left[\frac{Y_{fw}}{\nu_fM_f} + \frac{Y_{o\infty}}{\nu_oM_o}\right] \equiv \left[\frac{h}{Q} + \frac{(Y_o - Y_{o\infty})}{\nu_oM_o}\right] \Big/ \left[\frac{h_w}{Q} - \frac{Y_{o\infty}}{\nu_oM_o}\right] \equiv$$

$$\left[\frac{(Y_p - Y_{p\infty})}{(\nu_fM_f + \nu_oM_o)} + \frac{(Y_o - Y_{o\infty})}{\nu_oM_o}\right] \Big/ \left[\frac{(Y_{pw} - Y_{p\infty})}{(\nu_fM_f + \nu_oM_o)} - \frac{Y_{o\infty}}{\nu_oM_o}\right] \equiv \frac{Y_n - Y_{n\infty}}{Y_{nw} - Y_{n\infty}}$$

is the normalized conserved Shvab-Zeldovich variable. The subscripts are: f = fuel, fl = flame, n = inert, o = oxygen, p = product, r = fuel reservoir, w = reservoir surface, and ∞ = ambient. Assuming the reservoir surface enthalpy, h_w, is known, it has been shown (66) that $Y_{fw} = (BY_{fr} - sY_{o\infty})/(1+B)$, $Y_{pw} = (Y_{p\infty} + (1+s)Y_{o\infty})/(1+B)$ and $Y_{nw} = (BY_{nr} + Y_{n\infty})/(1+B)$ where $B \equiv (Q_oY_{o\infty} - h_w)/L$, with L the effective latent heat of pyrolysis, is Spalding's mass transfer number (73).

II. Diffusion Flames

1. Pyrolysis Rates/Flame Shapes and 2. Excess Pyrolyzate. Adding reactions explicitly to the fluid mechanics leads to the field of combustion and gives access to the classic studies of reacting boundary layers (63-65). Several reviews are available (66-68). Laminar systems are well understood and serve to identify the parameters important to systems in which energy feedback from the flame provides pyrolysis products for burning. Table 2 gives the enthalpy and species fields in any system to which the fast kinetics Shvab-Zeldovich assumptions (69) apply. Extentions exist to include radiation (70,71) and multiple flame sheets (71,72). These results also supply the far field for applying activation-energy asymptotics (69) to incorporate finite rate kinetics in diffusion flame analyses. Species and temperature fields are obtained from Table 2 by solving the appropriate conservation equations and boundary conditions for $J(\eta)$ (66).

The key dimensionless group is the diffusion flame equivalence ratio,

$$\phi = Y_{fw}/Y_{O\infty}s \qquad (4)$$

where the notation is defined in the notes to Table 2. The equivalence ratio has long been a useful measure of fuel richness associated with premixed flames (69). ϕ emerges here as also applicable to diffusion flames and the richer the flame, the greater the hazard. Table 3 shows the effects of chemical properties on flame heights, $x_{f\ell}$, normalized on the pyrolyzing fuel height, ℓ (66). A free flame length of 2.4 for cellulose means that the flame exists 1.4ℓ above the fuel, as typically observed for a fireplace log. Polyurethane produces flames three times as long as cellulose and thereby presents a greater fire spread hazard.

Low stoichiometric ratios, s, and latent heats of pyrolysis, L, produce high surface fuel mass fractions, Y_{fw}, and high equivalence ratios, ϕ. High ϕ means much fuel is being generated which must reach out to find the oxygen required to burn. Hence high ϕ's correspond to long flames which travel along ceilings, out doors and down corridors spreading the fire as they go. Alternatively, in closed systems, at high

Table 3. Flame extensions and properties for foam polymers (74,75)

Material	s	L(kJ/g)	B	Y_{fw}	ϕ	$x_{f\ell}/\ell$
Polystyrene, GM-49 $C_8H_{8.4}O_{0.03}$	0.33	1.3	1.7	0.6	8.3	12.0
Polyurethane, GM-25 $C_{3.1}H_{5.4}ON_{0.22}$	0.46	1.2	1.5	0.6	5.3	7.5
Polyisocyanurate, GM-41 $C_{5.3}H_{5.2}ON_{0.57}$	0.43	4.5	0.4	0.2	2.3	2.8
Cellulose, filter paper $C_6H_{10}O_5$	0.84	3.5	0.8	0.3	1.7	2.4

ϕ much fuel is being pyrolyzed which is not being burnt. That fuel has been called excess pyrolyzate (76). As the excess pyrolyzate accumulates, combustible mixtures form which can lead to rapid gas phase fire spread once venting occurs (77,78). While the results in Table 3 are from laminar calculations (66,79), the same relative ranking persists for turbulent systems (80,81) which have shorter flames (82) and are dominated by radiation (83,84).

A considerable literature on pool fires is available (37,67,85-88). Substantial heat release rate databases are being produced by Babrauskas of the NBS Center for Fire Research (89-91) and by Tewarson at Factory Mutual Research Corporation (74,92). Descriptions of pyrolysis rates and flame shapes for practical systems are listed under Fire in the cummulative subject indices of the International Symposia on Combustion (93,94).

3. Flame Radiation is recognized as the dominant energy transport mechanism in full scale fires (95,96). The emergence of radiation with increasing scale, over the convection dominant at small scale, prohibits scaling fire phenomena from bench top to real size. The fundamental influences of temperature, geometry and composition are well known (97-99). Efficient application to practical fires is the problem. Orloff (87) suggests an effective radiation flame temperature of 1260 K for small pool fires. The mean beam length approach appears to suffice for physical path calculations (95-97) and soot is the primary radiator (95-99). Non-homogenities in the temperature and species fields may be important (86,87,99-101). A useful simplification has been to express the flame radiation as a fraction of the heat release rate, ~ 1/3, (95,100) and assume isotropy. Tien and co-workers have examined the spectral distribution of flame radiation (96) and its absorption by pyrolyzate (101).

Since the wavelengths of infrared flame emission are large (~ 3 μm), compared with the circumferences of most soot particles ($\lesssim$ 0.3 μm), absorption dominates scattering and the detailed soot size distribution does not affect flame radiation. It is only necessary to know the soot volume fraction, f_v, i.e., the fraction of the flame volume occupied by soot. The soot volume fraction is $\sim 10^{-6}$ (95-105), which corresponds to the conversion of ~ 5% of the pyrolyzed fuel carbon to soot (104). The soot emissivity (96,104) can be approximated by

$$\varepsilon_s = 1 - \exp(-\kappa L), \qquad (5)$$

where L is the flame mean beam length and the effective soot absorption coefficient is

$$\kappa \approx 1.27\times10^3 f_v T_f, \ (\mathrm{m}^{-1} \text{ for } T_f \text{ in K}). \qquad (6)$$

It has been suggested that for pool fires, the soot volume fraction scales with optical path as

$$f_v/f_{v\,\max} \approx 1.5\ (\kappa L)^{1/3}, \text{ for } \kappa L < 0.3. \qquad (7)$$

For $\kappa L \geqslant 0.3$, $f_v = f_{v\,\max}$, a fuel property determined experimentally to range from ~ 0.2 ppm for ethanol and ~ 0.6 ppm for wood to ~ 0.9 ppm for polyurethane and ~ 4 ppm for polystyrene (104). Several diagnostic techniques are available to measure f_v in situ (102,103), but the unraveling of the mechanism of soot formation remains one of the great unsolved combustion problems (102,105).

III. FLAME SPREAD and IV. COMPARTMENT MODELING

A thorough review of each of these divisions could easily occupy all 15 allowed pages. But my allotment is already exceeded, so I will only cite a few reviews for flame spread (20,69,77,93,94,106-117) and compartment modeling (14,21,24,32,51-62,118-130) and carry forward one thread from the fire physics invited lecture at the last symposium. Professor Emmons identified window breaking as a key unresolved problem (31) and gave, in his usual way, sufficient physical insight to make a solution tractable. A window breaks in a fire for the same reason that an ice cube cracks when placed in liquid. Thermal expansion places the cooler portion in tension. The exposed window heats and expands placing its cooler shaded edge in tension until it cracks at a small defect, usually at the top inner edge. The pressure difference across the window is sufficient to remove it within milliseconds after the crack is initiated. Glass can only stand a small tensile stress, $\sigma \sim 4\text{x}10^{7}$ N/m^{2} ($\sim$ 6000 psi) (131). The stretch modulus for glass is $E = 7.8\text{x}10^{10}$ N/m^{2} ($1.1\text{x}10^{7}$ psi) (132). So the strain, $\varepsilon = \sigma/E$, required to crack the glass is $\sim$ 0.05%. The temperature rise needed to produce that strain is $\Delta T = \varepsilon/\alpha \approx 58°\text{C}$ (104°F), since the coefficient of linear thermal expansion for glass is $\alpha \approx 9.2\text{x}10^{-6}\ °\text{C}^{-1}$ ($5.1\text{x}10^{-6}\ °\text{F}^{-1}$) (132). My fracture mechanics colleagues at Berkeley ran the two-dimensional, unsteady version of this problem (133) on the Cray computer and got $\Delta T = 60°\text{C}$ (108°F) for the same property values. The 2°C increase in the window temperature rise at fracture is due to conduction into the cooler edge region. These results appear to be independent of scale. So compartment modelers may assume windows act as vents after the glass reaches $\sim$ 80°C. The energy transport between flame, smoke layer and glass remains to be modeled.

CONCLUSION

An in-depth review of fire physics as originally envisioned requires a book rather than an article. And like the painting of our Bay Bridge, the book would take sufficiently long to write, that it would be necessary to start all over again when it was finished. What a delightful position for a researcher to be in.

Much has been accomplished in fire physics. Our long range goals are clear (12,29,31). Our short range goals should include better communication with our colleagues - both those on the practical side who bear the responsibility for implementing these results as improved test methods and codes and those on the fundamental side whose expertise we need to advance the frontiers of fire physics. It may be that the problems are too complex, too dependent on detail, too terrible in their physical and legal consequences, to allow us to succeed in the short term in replacing specification codes with performance codes. Perhaps we need to be content with smaller goals such as suggesting improvements in current designs and standards. One appropriate step is to apply what is now known to model accidental fires after they have occurred to reconstruct the details and thus identify fruitful directions for future research (78,134).

ACKNOWLEDGEMENTS

The support of the U.S.D.O.C. National Bureau of Standards - Center for Fire Research under Grant 60NANB5D0552 is most appreciated. The author apologizes to those authors who should have been included in this review, but were not, due to the author's ignorance and the editors' length restrictions.

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