NISTIR 5555

A Review of Measurements and Candidate Signatures for Early Fire Detection

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January, 1995
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ABSTRACT

The physical and chemical transformations associated with a burgeoning fire are discussed and the results of past experimental measurements of these transformations are summarized. Standard test methods for the current generation of fire detectors and recent developments in detection technologies for which existing standards may not be suitable are described. The literature has been reviewed to determine the extent to which fires have been characterized in their early phase (<100 kW). In particular, measurements of CO, CO_2, H_2O, H_2, O_2, smoke and temperature have been examined. One finds dramatic variations in the measured magnitude and rate of growth of CO concentration in a variety of standard fires. The variation is also large between repeat runs of the same tests. When scaled by estimated mass consumed of fuel, the different standard fires group a bit more systematically. Additional measurements of species, temperature and velocity just above the flame are suggested to get a more complete footprint of each fire type. Similar measurements of non-fire nuisance sources are required in order to discriminate between a fire and non-threatening situation with a high degree of certainty. The concept of a universal fire emulator/detector evaluator (FE/DE) is introduced. The objective is to have a facility that will eliminate the unavoidable run-to-run variations associated with full-scale tests, and to allow more well controlled environments. Computational fluid dynamics could then be used to insert the fire source into the space being protected to guide detector placement and to predict system performance, as well as to compare alternative systems and new concepts on a level, realistic playing field.

A REVIEW OF MEASUREMENTS AND CANDIDATE SIGNATURES FOR EARLY FIRE DETECTION

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Introduction

The current generation of fire detection systems is designed to respond to the smoke, heat, or the electromagnetic radiation generated during smoldering and flaming combustion. Smoke is sensed either by measuring, with a photodetector, the light which is scattered by smoke from a controlled source, or by the change in ion current created by smoke passing through an ionizing radiation field. Heat can be easily sensed by a number of conventional devices, such as compensated thermocouples and thermistors. Both the absolute temperature and rate of temperature rise are used to define alarm conditions. The ultraviolet and infrared portions of the electromagnetic spectrum are typically detected with vacuum tube and solid state photodiodes, photoconductive and photovoltaic cells, thermopiles and pyroelectric cells (Cholin, 1993).

Future developments in early warning fire detection are incumbent upon knowing what is unique about a fire as well as the means to measure those characteristics. The concept of a "fire signature" was defined by Custer and Bright (1974) in their description of the state of fire detection in the early 1970s. Advances in sensing and signal processing have been many over the last two decades, but much remains unknown about what occurs early in an actual fire.

The purpose of this paper is to re-examine the physical and chemical transformations associated with a burgeoning fire and to summarize the results of past experimental measurements of these transformations. Standard test methods for the current generation of fire detectors are reviewed, and recent developments in detection technologies for which existing standards may not be suitable are described. Difficulties associated with evaluating fire detector performance and holes in the data on fire behavior become apparent. Means by which additional measurements of fire signatures can be used for developing new detection systems and evaluating their performance under realistic and unbiased conditions are suggested.

Chemical and Physical Processes in Fires

Equilibrium Combustion: All materials respond to the application of heat. The essence of fire detection is the measurement of this response through direct or indirect means. Thermodynamics tells us that organic compounds exposed to air will inevitably be converted to an equilibrium state consisting primarily of carbon dioxide and water, accompanied by the liberation of heat. Equilibrium thermodynamics, in general, is incapable of predicting the exact composition of gases or the rate at which they are produced, or other secondary effects of the heating; rather, one must rely upon chemical kinetics and analyze the dynamics of the process to gain insight into what is likely to occur in the early stages of a particular fire.

The discussion here is limited to common materials involved in fires in an air atmosphere, with a generic composition of $C_\alpha H_\beta O_\gamma N_\delta X_\varepsilon S_\eta$. "X" may be fluorine, chlorine and/or bromine. The primary equilibrium products from the complete combustion of this material in excess air at atmospheric temperature and pressure are given by the following stoichiometric relation:

$$C_\alpha H_\beta O_\gamma N_\delta X_\epsilon S_\eta + \frac{1}{\Phi}(O_2 + 3.76N_2) = \alpha CO_2 + (\frac{\beta-\epsilon}{2})H_2O + \epsilon HX + \eta SO_2 + 3.76(\Phi + \frac{\delta}{2})N_2 \qquad \textbf{(1)}$$

where $\Phi^{-1} = [\alpha + (\beta-\varepsilon)/4 + \eta - \gamma/2]$, the stoichiometric amount of air.

At room temperature, solid phase carbon is predicted to form at equilibrium for fuel/air equivalence ratios greater than 1.3, as seen in Fig. 1 for a fictional material with a C:H:Cl:S ratio of 5:10:1:1. (The equilibrium concentrations are only slightly affected by the nitrogen and oxygen content of a fuel.) Methane is the only additional gas phase product in excess of 5 ppmv formed from hydrocarbon combustion. If chlorine and sulfur are present, the lower curves in Fig. 1 show high levels of Cl_2 and condensed sulfuric acid under lean conditions. Sulfur condenses out at close to stoichiometric mixtures, and H_2S and HCl are the main products for richer conditions.

Increasing temperature causes the equilibrium concentrations to shift towards smaller gaseous molecules. Figure 2 shows this for the same fuel under stoichiometric conditions. CO_2, H_2O, SO_2 and HCl dominate across the entire temperature range. Carbon monoxide, H_2, and NO are formed in moderate levels only for temperatures in excess of 1500 K. The radical species H, O, OH, Cl and SO also appear at the highest temperatures.

The effect of stoichiometry on adiabatic combustion of the fictional fuel (the reference enthalpy has been taken to be 0.0 kJ/kg) is shown in Fig. 3. Carbon monoxide becomes the dominant species for equivalence ratios greater than 1.5, and the H_2 levels exceed those of both water and CO_2 at the richest condition examined. Nitric oxide is present in large concentration for lean, adiabatic combustion. The lower curves in Fig. 3 indicate that sulfur is present in a number of radical forms, with S_2 the most important. SO_3 is formed in measurable quantities only for the leanest mixtures. The one and two molecule radical species like OH, Cl and SO quickly react to stable products as the mixture cools (refer to Fig. 2).

Transport Processes: The temperature and concentration of chemical species at any point within a fire are the resultant of a balance among sources of energy, mass and momentum, and the diffusive and convective processes responsible for dispersing them. During the early stages of a fire, where fire detection is targeted, the chemical reactions controlling the source of heat and combustion products are usually confined to a volume around the point of ignition which is small relative to the room or space in need of protection. Outside of this volume the source of new chemical species can be neglected, and the source of energy is confined to radiation effects which are relatively small compared to conduction and convection. The momentum source is strongly influenced by the gravitational field and pressure gradients imposed at the boundaries, however, and cannot be neglected.

Because unwanted fires are highly stochastic, the fire detection system must respond in a timely fashion independent of where the ignition occurs. The signature of two identical fire sources will differ in magnitude and rate of change if they occur at different locations relative to the detector. The strength of nuisance signals which have some of the characteristic of a fire signature is also affected by detector placement.

Theoretically, simultaneous solution of the equations governing the conservation of mass, momentum and energy transport could be used to predict the concentration and temperature history at all locations within the protected space for a variety of fire scenarios and interfering sources. Approximate solutions for a limited number of highly restricted fires have been obtained using commercially available computational fluid dynamical partial differential equation solvers. For example, Notarianni and Davis (1993) used a k-ε model of turbulence to track the flow above a large pool fire in an aircraft hangar, and to determine the temperatures and smoke concentration likely to be seen by detectors located in the upper layer. These were compared to full-scale measurements. They also simulated the movement of smoke in a high bay clean room with ventilation to assess the efficacy of the placement of smoke detectors. Satoh (1994) was concerned with the impact of room ventilation on the buildup of smoke for detection purposes. Forney et al. (1993) investigated the impact of ceiling beams on the flow of fire gases to provide guidelines for locating smoke detectors. Baum et al. (1994) used large eddy simulation methods

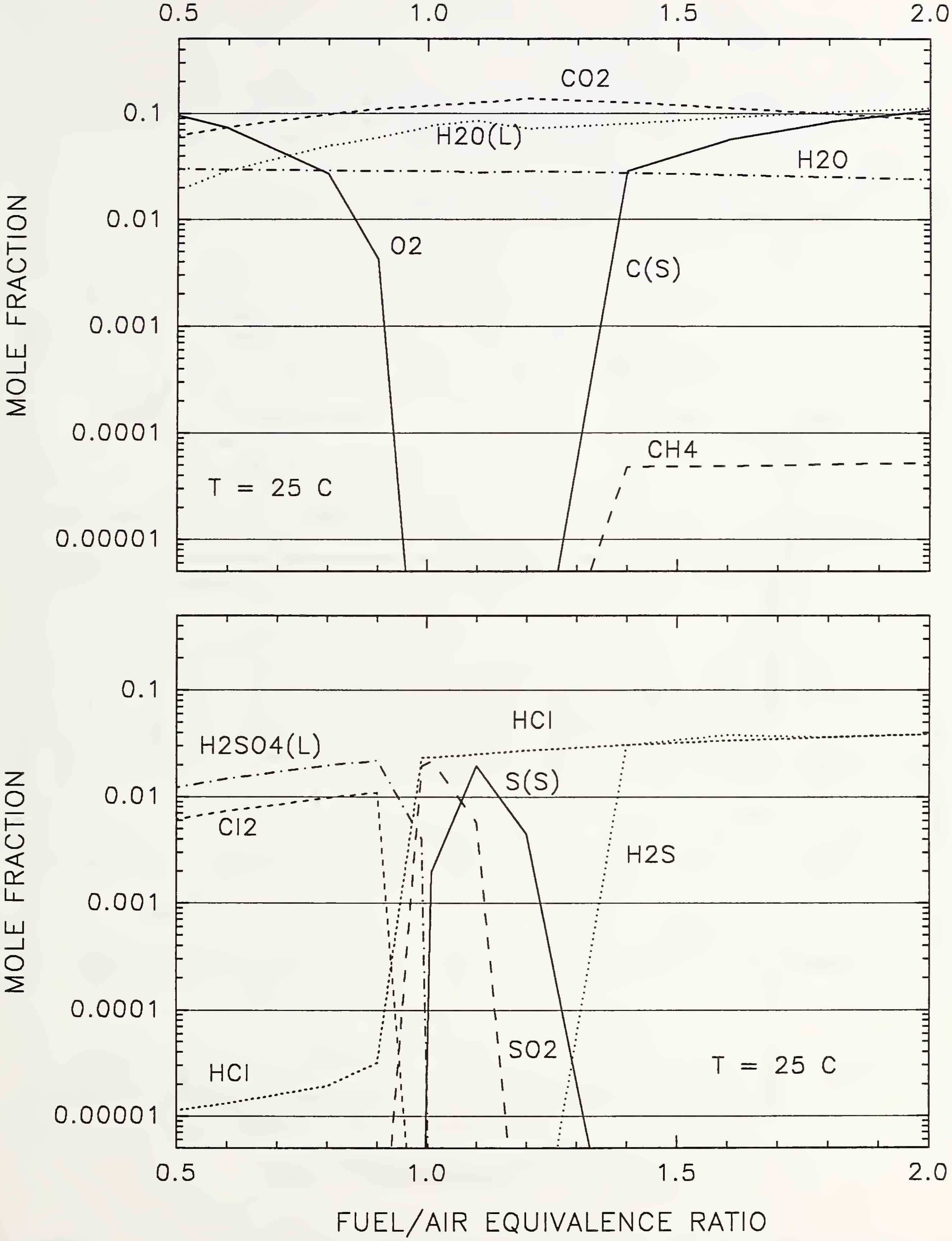

Figure 1. Equilibrium composition of C, H, Cl, S and air mixtures at 25 °C and 101 kPa.

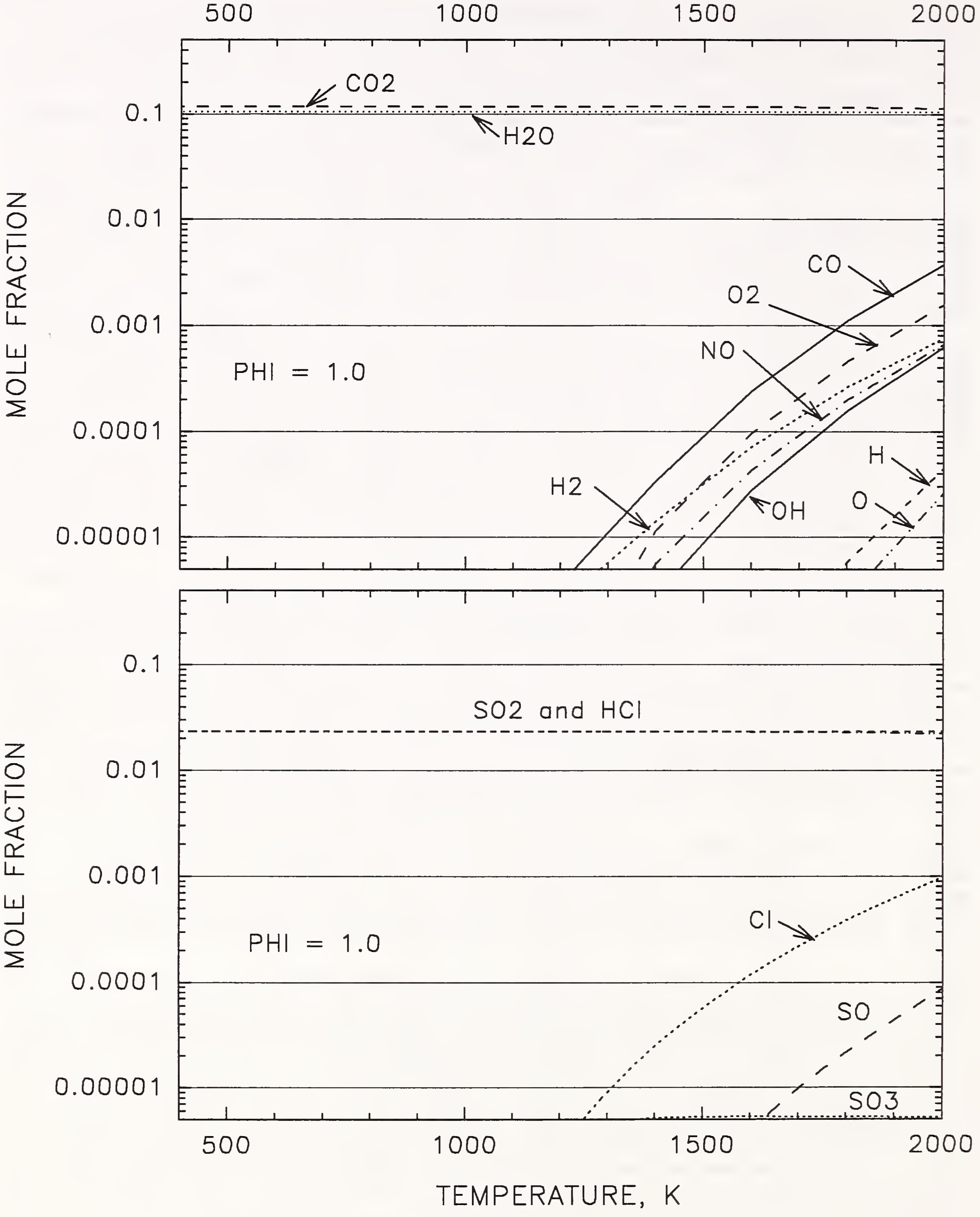

Figure 2. Equilibrium composition of stoichiometric mixtures of C, H, Cl, S and air at 101 kPa as a function of temperature.

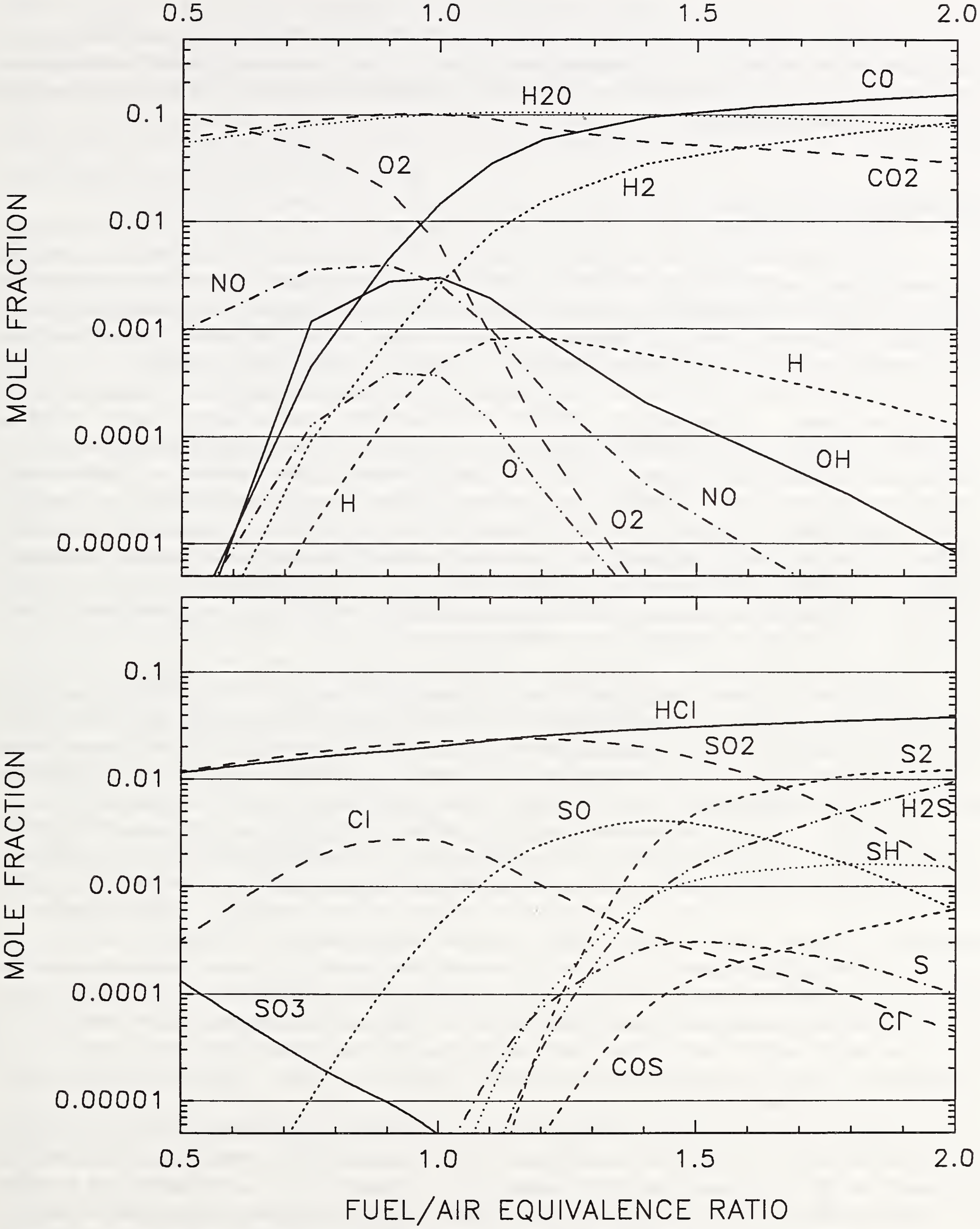

Figure 3. Equilibrium composition of adiabatic C, H, Cl, S and air mixtures at 101 kPa and a reference enthalpy of 0 kJ/kg.

to model smoke flows from three dimensional fires in several different applications.

Increased computational power, a better understanding of turbulence transport, the desire to maximize the investment in fire detection and suppression systems, and the difficulty and expense of conducting full-scale tests will undoubtedly lead to the acceptance of numerical modeling as an essential tool for proper system design.

Measurements of Products

The concentration of a particular species in a fire is dictated by the boundary conditions surrounding the event, the location in the room, and the time since ignition. Even for the major products of combustion the time-dependent amount cannot be predicted to a high degree of certainty from first principles. For trace species and compounds that are formed or destroyed slowly, one must rely on measurements in model systems to estimate what is likely to be formed in an actual fire.

There is a hierarchy of product measurement methods which is inverse to the complexity of the combustion system. At one end are premixed, one-dimensional gaseous fuel/air flames, which are amenable to the most sophisticated probing techniques, and which allow one to follow the formation and destruction of minute and transitory species with submillimeter spatial resolution. Highly accurate measurements can also be obtained in gaseous laminar diffusion flames, and, to a lesser extent, in small-scale non-premixed, axisymmetric turbulent flames. Measurements in buoyant gaseous and liquid-fuel diffusion flames, in solid phase flaming combustion, and in smoldering waves become progressively more difficult. The far end of the hierarchy is reached in full-scale room fires, where even CO_2 levels can be tedious to obtain because of the large three-dimensional volume which has to be probed and the hostile environment to which the analytical instruments are exposed.

Gaseous and Vaporizing Liquid Fuels: The published literature is filled with high quality data taken in laboratory flames, but the extrapolation of these results to predictions of the concentrations likely to be found early in a fire are tenuous. However, because there have been no exhaustive measurements of trace chemical constituents in flaming fires or smoldering combustion, the results from laboratory diffusion flame experiments provide a starting point for identification of possible signature species.

Smyth et al. (1985) measured concentrations of C_2H_2, C_2H_4, C_4H_6, and C_6H_6 within the reaction zone of a laminar methane/air diffusion flame supported on a rectangular slot burner, along with major species (CO_2, CH_4, H_2O, CO and H_2). Absolute concentration measurements of a number of flame radicals (vis. OH, O, H, CH, and CH_3) were later taken on the same burner (Norton et al., 1993). A cylindrical geometry was used by Hamins et al. (1986) to examine the composition of C_2H_2, C_2H_4 and C_2H_6 co-flowing laminar diffusion flames. Their results included profiles of C_2, C_3 and C_4 alkanes, alkenes and alkynes. Not counting the parent fuel, the peak mole fractions of C_2 compounds were generally less than 0.02, with C_3 and C_4 mole fractions 100 times less. The hydrocarbon levels, including those of the CH_4 which is formed earlier in the flame, decrease substantially by the time they reach the flame tip. Acetylene was the dominant hydrocarbon leaving the flame, independent of initial fuel, with a mole fraction less than 0.01 at the tip.

Propane was the fuel in a study by Orloff et al. (1986) using sintered bronze burners with diameters between of 0.19 and 0.76 m. Oxygen, CO_2, CO and total hydrocarbons were measured along the centerline of buoyant turbulent flames ranging from 35 to 283 kW. A correlation was developed between the gaseous product concentrations and the local average elemental mass fraction, and between the average mass fraction and height above the surface which allowed the full range of burner diameters and heat releases to be scaled. Peak mass fractions of CO and CO_2 were 0.04 and 0.09, respectively, and were found to drop by approximately three orders of magnitude at a downstream distance 10 times the burner diameter.

Morehart et al. (1990) used a hood above a natural gas flame to capture the products of combustion simulating the upper layer of a room fire. Depending upon the fuel/air ratio, they found measurable (>0.0001) mole fractions of H_2, CH_4, C_2H_2, C_2H_4, and C_2H_6 for fire sizes between 40 and 68 kW. Pitts (1992) developed the global equivalence ratio concept to explain Morehart's data and performed additional experiments in a reduced scale room to test the robustness of the concept for predicting CO emissions from enclosure fires (Pitts, 1994).

Carbon dioxide, CO, and fuel concentrations were measured by Fischer et al. (1987) in a 73 kW ethanol pool fire. Mole fractions of gaseous fuel less than 0.01 were detected 0.5 m above the pool surface. In a similar experiment burning 0.15 m pools of kerosene, Bouhafid et al. (1988) mapped out the isotherms and time-averaged concentrations of CO and CO_2. Beyler (1986) burned condensed fuels (pine wood, poly(methyl methacrylate), and polyethylene) on a load cell and collected the combustion products from the exhaust hood. He analyzed for H_2O, CO_2, and CO, and found that the condensed fuels produced these gases in concentrations similar to pure gaseous and liquid hydrocarbons, and that oxygen in the fuel tended to increase the amount of CO formed.

Solid Fuels: Fires generally involve fuels much more complex than the simple gaseous and liquid hydrocarbons used in most of the experiments just described. The products formed from the combustion of wood vary greatly depending upon the amount of oxygen available, the heating rate, the moisture content and the geometry of the fuel load. O'mara (1974) exposed samples of plywood, pine, oak and Masonite to a radiant heater in air and measured concentrations of methanol, acetaldehyde and acetic acid in the 10 to 100s of parts per million range. Condensed materials formed when pine and oak samples were exposed to radiant heating in an oxidizing environment were analyzed by Ohlemiller et al. (1985) and dozens of compounds were identified. Some of the lower boiling point chemicals condensed out in mass fractions greater than 0.01 included acrolein, methyl propionate, acetic acid, furaldehyde, furfuryl alcohol, 5 methyl furan 2 aldehyde, butyrolacetone, guaiacol, phenol and creosol. A stagnation burner arrangement was used by Hartstein and Forshey (1974) and the product gases from the combustion of pine wood were collected. The following species were found to be present in amounts exceeding 0.5% (mass) of the CO_2 in the effluent: HCl, CH_3OH, CH_2O, C_2H_4O, furfural, $(CH_3)_2CO$, vinyl acetate, and furan.

The behavior of cellulose in a fire environment was exhaustively reviewed by Suuberg et al. (1994). New results were presented for a vertical slab of pressed cellulose exposed in air to radiant heat fluxes in the range of 20 to 60 kW/m^2. The products of pyrolysis were analyzed for CO_2, CO, CH_4, C_2H_4, C_2H_6, and H_2O. The temperature, weight loss, and product emissions were reported as a function of time for heating durations up to an hour.

When Coleman and Thomas (1954) thermally decomposed a number of chlorine containing plastics in air they found the dominant products to be CO_2, HCl and CO, with trace amounts of phosgene ($COCl_2$) detected. Wooley (1971) heated polyvinylchloride (PVC) in air and nitrogen streams and noted 75 components on a gas chromatogram of the effluent. Hydrogen chloride accounted for most of the mass loss; benzene, toluene, xylene, naphthalene and phosgene could be identified. PVC was converted to HCl at the rate of 0.42 g/g_{PVC} when it was burned in the experiments of Hartstein and Forshey (1974). Significant amounts of benzene were measured and methylchloride was also found to a varying degree, depending upon the exact formulation of the PVC. Cured neoprene samples produced chloroprene, CH_3Cl, C_2H_5Cl, C_2H_3Cl, C_6H_6, C_2 - C_4 hydrocarbons, and small amounts of H_2S, CS_2, COS and SO_2. Three different rigid urethane foams were degraded in the absence of air by the same investigators. Ammonia, $C_2H_4Cl_2$, $CFCl_3$, $CHFCl_2$, $C_6H_5NH_2$, C_2H_4BrCl and $C_2H_4Br_2$ were some of the additional compounds identified in the product gases from these anaerobic experiments.

Babrauskas et al. (1991) were interested in assessing the toxic potency of burning materials and measured the CO, NO_x, HCN, HBr, and HCl produced by various polymers exposed in air to radiant heat.

Maximum HCl values of almost 3000 ppm were found from PVC samples. As much as 200 ppm HCN was measured in melamine-type polyurethane foam, and about half that much NO_x. Vinyl fabric exposed to 50 kW/m^2 radiant flux produced about 500 ppm of HCl, and small amounts of HCN and NO_x. Carbon dioxide was produced in these experiments in the range of 1 to 2 g/g_{fuel}, and CO/CO_2 ratios as low as 0.01 and as high as 0.10 were found.

Measurements in the exhaust of waste incinerators may be indicative of some of the products likely to be produced in a ventilated fire of unknown fuel mix. For example, the EPA (Seeker, 1990) has found small quantities of the following substances in the stacks of waste incinerators: benzene, toluene, CCl_4, $CHCl_3$, CH_2Cl_2, C_2HCl_3, C_2Cl_4, chlorobenzene, and naphthalene (along with numerous metal salts and oxides).

Smoke: The term "smoke" refers to an amalgam of condensed carbonaceous materials whose size and hydrogen content vary substantially with the local stoichiometry and temperature history of the mixture. Equilibrium calculations are of no value in predicting the mass fraction or chemical composition of smoke produced in the early stages of a fire. The particle morphology, size distribution, and refractive index are additional parameters which are required to characterize the smoke. Even after leaving the hot regions of the fire, smoke particles continue to agglomerate and act as condensation sites for fuel and water vapors, and for acid gases such as HCl and H_2SO_4.

The formation of soot in flames has received the attention of scientists for over a century, and numerous reviews of the chemistry involved are available (e.g., Haynes and Wagner, 1981; Glassman, 1988). Lee and Mulholland (1977) were concerned with the physical properties of soot and other condensed materials which are indicative of a fire. The mass concentration, volume fraction, and size distribution were identified as key parameters for detection using conventional ionization and optical smoke detectors. Of great importance is the mode of combustion. The size distribution of particulates formed from reacting α-cellulose shifts to diameters about ten times larger when the mode changes from flaming to smoldering. The temperature to which the particles are exposed and the length of time both impact the size distribution. The physical mechanisms responsible for producing different types of smoke properties from smoldering wood were discussed by Mulholland and Ohlemiller (1982).

Bankston et al. (1977) measured the mass concentration as a function of time produced in small flaming wood, polyurethane foam, and PVC fires, and compared the size distribution between flaming and nonflaming conditions. Average values of CO and smoke yields for PMMA, acrylonitrile-butadiene-styrene (ABS), polyethylene, and wood under flaming conditions in a vitiated atmosphere were reported by Mulholland et al. (1991). The smoke yields were found to be insensitive to the degree of vitiation, while the CO production increased a factor of two as the available oxygen in the air was reduced to 14%.

Fire Detection Standards

Standard test methods exist to ensure that a detector performs as designed in an actual fire situation. The test methods vary with the operating principle of the detector, and are generally classified as smoke detector standards, heat detector standards, carbon monoxide detector standards, and flame (or radiation) detector standards. Independent standards have been established by Underwriters Laboratories, Factory Mutual, and the European Committee for Standardization. These are summarized by Luft (1994), from which the following section is liberally excerpted.

Smoke Detector Standards: There are five main standards for smoke detectors:

UL 217 -- Single and Multiple Station Smoke Detectors

UL 268 -- Smoke Detectors for Fire Protective Signaling Systems
UL 268A -- Smoke Detectors for Duct Application
FM 3230-3250 -- Smoke Actuated Detectors for Automatic Fire Alarm Signaling
EN 54 -- Components of Automatic Fire Detection Systems, Part 7

UL 217 applies to smoke detectors that are intended for open area protection in indoor locations of residential units, recreational vehicles, and portable smoke detectors used as travel alarms. UL 268 applies to smoke detectors intended for open area protection and connection to a compatible power supply or control unit for operation as part of a fire alarm system, and intended solely for control of releasing devices such as fire dampers and electromagnetic door holders. UL 268A applies to air duct smoke detectors intended for indoor use within or protruding into a duct in which the maximum air temperature does not exceed 38° C. The FM standard covers a broad range of smoke detectors (depending on the specific number between 3230 and 3250), and applies to any smoke actuated detector that is used as part of an alarm signaling system to warn of an accidental fire. The EN standard applies to self-contained, permanently installed, smoke detectors designed for the protection of life in premises in which regular provision is made for people to sleep.

Underwriters Laboratories evaluates the performance of smoke detectors in reduced and full-scale chambers. Both UL 217 and UL 268 utilize a 1.7 m long, 0.5 m wide and 0.5 m high test chamber into which smoke from a cotton lamp wick ("gray" smoke) and smoke from a kerosene lamp ("black" smoke) are introduced. The detector is mounted at the top of the chamber and a fan causes the smoke-laden air to flow past the detector at about 0.16 m/s. The concentration of smoke is controlled to produce an extinction coefficient between 0.007 and 0.15 m^{-1}. A wind tunnel is used for UL 268A to simulate flow through a 0.3 m square duct at speeds between 0.1 and 1.7 m/s. Smoke is created by heating ponderosa pine sticks on a hot plate and by burning a small pool of heptane.

Five different sources are used to represent fires in a room which is 11 m long, 7 m wide and 3 m high, according to UL 217 and UL 268 (UL 268A does not require this test). The fire is located 1 m off the floor and the detectors are placed near the ceiling about 5.4 m from the centerline of the fire. In test A, 42 g of shredded newsprint is ignited in a metal container; test B is a flaming fire of douglas fir strips in a crib orientation with overall dimensions of 0.15 m by 0.15 m by 62 mm high; 30 ml of gasoline in a small pan is used in test C; a wire mesh cylinder is used to hold 28 g of flaming polystyrene foam packing in test D. The maximum allowed time to response in each of these flaming tests varies from four minutes for A to two minutes for D. Test E is a smoldering fire, created by placing ten ponderosa pine sticks on a hot plate. Seventy minutes is the allowed time limit for detector response to this threat.

Sensitivity to typical aerosols formed during cooking is checked in UL 217 by exposing the detector in a 0.9 m high by 0.4 m square chamber in which 50 g of animal fat, 50 g of vegetable fat and 100 g of beef gravy are vaporized on a hot plate. The smoke detector is not to activate in this situation.

The Factory Mutual smoke detector standard does not specify a fire test. In this test series, smoldering cotton rope is the smoke source. The requirement is that the detector must activate before the extinction coefficient of the smoke reaches 0.13 m^{-1} in order to have the maximum rated coverage of 83 m^2 on a smooth ceiling.

EN 54, Part 7, subjects smoke detectors to fires within a full-scale room and to a prescribed paraffin oil aerosol in a wind tunnel. The room is 9 to 11 m in length, 6 to 8 m in width, and about 4 m high. Different test fires (described in EN 54, Part 9) are located at the center of the room near the floor, and the detectors are placed on the flat ceiling, 3 m from the centerline of the fire. A smoldering pyrolysis fire (TF 2) is created by heating 24 beechwood sticks (10 mm x 20 mm x 3.5 mm) on a hot plate which is capable of attaining 600 °C within 11 minutes after the power is turned on. The test is terminated after flaming begins. A second smoldering fire test (TF 3) consists of 90 pieces of cotton wick 0.8 m long, with a total mass of 270 g. Three sheets of polyurethane foam, each 0.5 m x 0.5 m x 20 mm, are placed on top of each other and ignited with 5 ml of alcohol in TF 4. The final test (TF 5) uses 650 g of a heptane/toluene mixture which is ignited in a 0.33 m square pool. In each fire test the detector must respond before 60 to 80% of the fuel for that test has been consumed.

The response threshold level of the smoke detector is measured in a wind tunnel as specified in EN 54, Part 7. The velocity is set at 0.2 m/s, and a mist of paraffin oil (index of refraction equal to about 1.4) is introduced to produce a polydisperse aerosol with maximum size droplets between 0.5 and 1.0 μm in diameter.

Heat Detector Standards: The standards covering heat detectors are (Luft, 1994)

UL 521 - Heat detectors for fire protective signaling systems
UL 539 - Single and multiple station heat detectors
FM 3210 - Thermostats for automatic fire detection
EN 54 - Components of automatic fire detection, Parts 5, 6 and 8

UL 521 applies to heat detectors for fire protective signaling systems intended to be installed in ordinary indoor and outdoor locations. UL 539 applies to heat activated, mechanically or gas operated heat detectors intended for indoor installation. It does not cover electrically operated heat detectors. The equipment in both standards is exposed to a heat bath and a fire in a standard room. Fixed temperature heat detectors are submerged in a temperature controlled oven filled with water, oil or air. The bath temperature is then increased in 0.6 °C increments until the detector activates. The temperature of the bath at the time of detector operation must be within the rated operating limits. Heat detectors are also tested in a chamber 0.8 m long, 0.25 m wide and 0.4 m high in which the air flow is maintained at about 1.2 m/s and the temperature is increased at a prescribed rate. Any detector that activates in two minutes or less when exposed to this gradient is allowed a spacing rating of 4.5 m. Rate-of-rise heat detectors must respond when exposed to their designed gradient, and should not activate when exposed to a change in temperature at a rate less than 0.11 °C/s until a temperature of 55 °C is reached.

The UL fire test occurs in a room 18 m on a side with a smooth ceiling 4.8 m high. The test fire is located in the center of the room, and the detectors are spaced at 3 m intervals beginning 6 m from the fire centerline. The fuel is ethanol which is placed in a 1.7 m^2 metal pan. The amount used is varied to control the temperature gradient. The minimum performance criterion is tied to the operating time of a reference sprinkler. The detector must activate within 130 s after ignition to qualify for installation at that spacing to which the detector responds prior to sprinker activation.

FM 3210 does not require a specific oven or fire test. It does require that all fixed temperature heat detectors operate within 3% of their intended activation temperature, and at least as quickly as comparably rated sprinklers under similar conditions. All rate-of-rise heat detectors are required to operate at rates between 0.14 and 0.23 °C/s.

The European standard is divided into three parts, each covering a different sensing element operating principle. EN 54 Part 5 deals with point detectors with or without a fusible link designed for standard room temperature conditions and with rated response times up to 54 minutes, with gradients as low as 0.02 °C/s. Part 6 only applies to resettable, heat sensitive rate-of-rise point detectors without a thermostatic element, for which the minimum rated temperature gradient is 0.08 °C/s. For detectors used in high ambient temperatures (up to 140 °C), Part 8 of EN 54 applies. Both resettable and nonresettable devices are covered under this part.

Independent of the sensing element design, the same test facility is used in EN 54 Parts 5, 6, and 8. A wind tunnel produces an average air velocity of 0.8 m/s across a square cross-sectional area 0.25 to 0.30 m on a side. The detector being evaluated is mounted on the inner top surface of the test section and the temperature of the air is increased (with an electric heater) at a specified rate controllable between 0.017 and 0.50 °C/s, with the capability of reaching a maximum temperature of 170 °C while maintaining a constant air velocity. The detector is classified according to a response grade and activation period within the tunnel test.

Carbon Monoxide Detector Standards: Only one CO standard was uncovered in this review (Luft, 1994): UL 2034 - Single and Multiple Station Carbon Monoxide Detectors. The intent of this standard is to cover electrically operated devices designed to protect ordinary locations of family living units, including recreational vehicles and mobile homes, from excessive levels of CO produced in combustion engine exhausts, fireplaces, and abnormal operation of fuel-fired appliances. Carbon monoxide produced in an unwanted fire is not an excluded source, but fire detection is not specifically mentioned as an intended use.

The detector is tested in a 0.75 m^3 chamber in which the air temperature, humidity, oxygen and CO concentrations can be monitored. Carbon monoxide is piped into the chamber and slowly circulated to give a uniform concentration of 100 ppm. This concentration must be established within ten minutes after the start of the test. Additional tests are run with concentrations of 200 and 400 ppm. The activation times for these three levels of CO must be less than 90, 35, and 15 minutes, respectively.

The selectivity is checked by exposing the CO detector to various concentrations of methane, butane, heptane, ethyl acetate, propanol, and carbon dioxide using the chamber described in the previous paragraph. In addition, the response of the CO detector to smoke is checked using the chamber described in UL 217. At no time during any of the selectivity tests should the CO detector activate.

Other Gas-sensing Fire Detector Standards: The detection of the build up of gaseous fuel vapors is used for explosion protection systems, but no UL standard exists for evaluating the performance of fuel gas detectors for fire detection purposes. NFPA Standard 72 (1994) does recognize a role for these types of devices but provides no guidance for testing them in a fire situation. The same statement can be made about other gaseous products of combustion (including CO).

Flame and Radiation Detector Standards: According to Middleton (1989), guidelines are being written by the European standards technical committee for the use of flame detectors in buildings. The expanded area coverage provided by newer, high sensitivity devices is addressed; the susceptibility of the detectors to false alarms is not. Testing is based upon the same series of fires as is used for smoke detectors (TF1 through TF5).

Chapter 5 of NFPA Standard 72 (1994) covers radiation detectors as a category, which includes systems designed to monitor sparks, embers and flames. NFPA states that the detector must be chosen according to the application intended, and refers to parameters such as source wavelength, intensity, and distance from the sensing element. No standard fires to evaluate the performance of the detectors are specified. Radiation-type fire detection devices are not included in Underwriters Laboratories Standards for Safety. Factory Mutual approves these devices based upon standard procedure 3260.

Advances in Fire Sensing

Conventional sensing technologies for the products of fires have undergone incremental developments over the past two decades, but more recently these technologies have begun evolving at an accelerating rate. A bibliographical review of fire detection technologies covering the period from 1975 through 1990 was compiled by Bukowski and Jason (1991). Grosshandler (1992) discussed some of these technologies and assessed novel approaches to advanced fire detection. New sensing techniques were suggested and a number of areas for additional research were mentioned. The UL, FM and EN standards described in the previous section are not designed to measure the performance of many of these approaches.

Examples of technological advances which would be welcome but may not be amenable to current accepted testing procedures include the following:

- non-radioactive ionizing sources for particle detection
- combinations of multiple wavelength, multiple scattering angle, and polarization ratio for enhanced smoke particle discrimination
- electrochemical cell CO detection
- conditioned, multiple, thick-film, metal oxide CO and hydrocarbon gas sensing
- neural network trained, thin-film, surface acoustic wave hydrocarbon gas sensors
- silicon-based, micro-machined, temperature programmed arrays
- species selective fiber optic lasers
- broad-band video detectors combined with pattern recognition software

The following paragraphs describe some of these developments and how they may be used for improved fire detection.

Gas Sensing: Techniques are available for measuring almost any stable gaseous species produced prior to or during combustion that one may want. The tradeoffs in choosing a sensor involve time response, selectivity, sensitivity, complexity, and cost. The conductance of a semiconductor varies as reducing gases come in contact with the surface. Harkoma et al. (1988) have demonstrated the suitability of a Taguchi-type sensor to follow variations in carbon monoxide levels of less than 50 ppm in the exhaust streams of several combustion devices. McAleer et al. (1988) improved on the concept by coating the tin dioxide substrate with sub 10 nm diameter platinum particles. This allowed operation at room temperature, rather than 300 °C, with an encouraging response to several different test fires (Harwood et al., 1989).

Bartlett (Amato, 1991) tailored twelve tin dioxide sensors to respond to different airborne chemicals. By analyzing the relative response of the different sensors, he was able to train the system to detect subtle changes in composition. Using methods of pattern recognition, the device was capable of identifying specific species among a mixture of different alcohols, and of determining the special characteristics of individual smoke from five different tobaccos.

Changes in current, voltage, or conductance in an electrochemical cell created by the reaction of fuels and combustion products can be used to detect a threatening situation (Janata, 1989). Potentiometric, solid-state, electrochemical sensors have been constructed for oxygen, hydrogen, water vapor, carbon monoxide, carbon dioxide, chlorine, and hydrogen sulfide, with detectable partial pressures as low as one part in a million. Operating temperatures as high as 900 °C can be required. Because the sample gas must diffuse into the electrode, the time lag is often of the order of minutes (Weppner, 1987).

Large arrays of micro-machined, silicon-based sensors can be produced which respond to low concentrations of different gas mixtures. Semancik and his coworkers (1993) have demonstrated the potential for these devices by programming the temperature of each individual element. By measuring the changes in conductance of the elements when exposed to a gas mixture, and by connecting the output into a neural network, high sensitivity and selectivity can be simultaneously maintained.

Organic thin film sensors have the potential to measure low concentrations of combustion products. A thin polymeric coating, chosen to react preferentially with a specific class of airborne chemicals, is laid down on the crystal surface. The frequency of the surface acoustic waves (SAW) are affected by the deposition of low concentrations of the species of interest. The U.S. Navy is developing a four-sensor SAW array (Grate, 1991) which has the ability to measure components of chemical warfare agents below one ppm, and has tested the system in a variety of combustion gas atmospheres. Contamination of the active sites by smoke is minimized by placing a Teflon membrane over the sensor.

Under some operating conditions, products of a fire can be detected in less than ten seconds using pattern recognition software to interpret the signals from the four different sensors.

Smoke Detection: New designs in smoke detection are aimed at shortening the response time, discriminating fire-generated particulates from dust and other aerosol sources, and finding non-radioactive ionization sources. Discriminating smoke particles from nuisance aerosols can be enhanced in optical scattering detectors by any of the following methods: (a) increasing the number of scattering angles measured, (b) decreasing the solid angle in the field of view, (c) measuring the polarization ratio, and (d) increasing the spectral selectivity of the light source and detector. Meachem and Motevalli (1992) have proposed to interpret the signal from light scattered at several angles, using the Mie theory, as a means to discriminate among different smoldering materials. Increased discrimination can also be provided by a high voltage ionizing chamber which quantifies the particle size. Litton (1988) found that smoke particles from a fire can be discriminated from Diesel engine exhaust particulates by the smoke's greater tendency to pyrolyze. By comparing the response of an ionization detector to a sample which has been passed through a heated pyrolysis chamber to a sample which is untreated, a major source of false alarms in underground mining operations can be reduced.

Schmidt-Ott et al. (1989) have demonstrated an alternative smoke detector design which utilizes the natural residual charge on the smoke particles remaining after the combustion process. An electrostatic field is established and the current across two electrodes is related to the charge distribution of the aerosol. No ionizing radiation source is required, which allows this design to be used in jurisdictions which do not permit even benign radioactive sources.

Electromagnetic Wave Sensing: Light scattering, absorption, emission and fluorescence can be used to identify concentrations of individual gas species. A source of electromagnetic radiation and a detector are required for these methods. Wide-band sensors operate in the ultraviolet, visible or infrared portions of the electromagnetic spectrum, normally with emission from the fire acting as the source. An inherent advantage of these types of sensors is that a single device can be used to survey an entire room at an instant in time, as opposed to point chemical and smoke sensors which rely on the transport of material from a remote location. In the near infrared ($< 2.0\ \mu m$), IR sensors respond to the continuous emission of the soot particles, and the primary combustion gases (CO_2 and H_2O) emit a substantial signal in bands centered around 2.7, 4.3, 6.3 and 15 μm. Wide-band infrared sensors respond to hot backgrounds in general (such as an exhaust pipe, steam line, or hot electrical machinery), but because fires are inherently an unsteady source of radiation with a characteristic flicker frequency, false signals can be reduced by ignoring the background DC component.

Pattern recognition methods are being applied to interpret the intensities and fluctuations in time and space of the individual red, green, and blue colors of a video camera (Goedeke et al., 1990). The location and size of a burgeoning jet fuel pool fire was detected and discriminated from a false signal within seconds, while a high degree of certainty was maintained. Thermochromic liquid crystal sheets distributed throughout a space to be protected were used to enhance the sensitivity of an inexpensive low resolution video camera to small changes in temperature. Plumb and Richards (1993) made use of this material to locate the rising plume of hot gases and gauge the heat released from a small fire. Pyroelectric vidicon cameras have been in use for fire fighting for several years (Maslowski, 1991), but have not been used as a fire detection device. However, a more recently developed uncooled, barium strontium titanate sensor was unveiled for night-vision enhancement, and is being promoted for application to fire detection.

Selective absorption in the infrared by fuel molecules or combustion products can be used to detect threatening situations. The U.S. Bureau of Mines used commercially available instruments to measure CO and CH_4 levels within coal mines, and combined the method with an optical fiber to permit remote monitoring of methane (Dubaniewicz and Chilton, 1992). Fiber optic lasers are capable of producing monochromatic light at a wavelength controlled by the doping levels of rare earth elements during fabrication (Simpson, 1989). These devices have the potential to be tuned to a wavelength coincident only with the species of interest to fire detection.

The emission from a blackened surface near the tip of a fiber can act as an optical analog to a thermocouple. Increased sensitivity at lower temperatures can be obtained by measuring the change in interference pattern that occurs when a small gap placed at the end of the fiber varies its thickness due to thermal expansion (a miniature Fabry-Perot interferometer). Raman scattering within the optical conductor can also be used to measure the temperature distributed along the fiber optic cable (Whitesel, 1990).

The motion of ions produced in flames can be sensed from the Doppler signal created by the interaction with transmitted radio waves. Berman et al. (1992) used a modified microwave motion detector to demonstrate the feasibility of this device for monitoring the presence of a flame within a multi-burner natural gas furnace. The application of this method to fire detection has not been explored.

Acoustic Sensing: The heating of gases from a fire changes the local speed of sound and gives rise to characteristic pressure waves. Techniques for measuring these changes in acoustic behavior were reviewed in the article by Grosshandler (1992). Another approach to acoustic detection of fires is to take advantage of the knowledge that acoustic emission occurs from objects which are thermally stressed, and that the relieved stress can be detected with a piezoelectric transducer which is coupled to the object or a structure on which the object is directly mounted. This technique was shown (Grosshandler and Jackson, 1994) to be sensitive enough to detect within a minute when beams made of wood, gypsum board, and plastic were exposed to an open flame. Further tests (Grosshandler and Braun, 1994) in a simulated full-scale room indicated that measuring acoustic emission could be more effective in detecting a hidden smoldering situation and an open natural gas fire than measuring temperature or smoke concentration.

Standard Fire Signatures

The products of combustion formed in the different experimental arrangements discussed above encompass most of what is likely to be emitted in the early stages of a fire. Because no two unwanted fires are alike in all aspects, the quantities and rates of production of heat and chemical species vary significantly, making generalization difficult. Added to this is a randomness associated with detector placement vis a vis the source of ignition and initial fire growth. The deterministic aspects of fire generated products needs to be separated from stochastic, geometric vagaries.

The fires prescribed in the UL and EN standards have been chosen ad hoc to produce a range of conditions over which current smoke and heat detectors are likely to be exposed. The fires have not been scientifically established as representing any actual event, but are accepted by consensus as being reasonable models. While the fuel, ignition and duration of the fire is specified, the heat release rate and the products of combustion are variables which are not independently controlled, but which define the unique signature of anyone of them.

A limited amount of data has been taken to characterize these fires. Pfister (1983) examined the time-varying composition at the ceiling above the center of five fires ignited in a standard EN 54 room. An open wood fire, a nonflamming wood fire (TF2), a smoldering cotton wick (TF3), a nonflamming paper fire (UL 217), and an overheated transformer test developed by Cerberus were chosen for the investigation. The open wood fire was designed after TF1 in EN54 part 9. Seventy beechwood sticks, 10x20x250 mm, were arranged in a crib and ignited with 5 ml of ethanol. Measurements were made of CO, CO_2, H_2, and total hydrocarbons in each of these fires, and the alarm points of radiation, ionization,

Table 1. Approximate peak concentrations and alarm response times for standard fires (Pfister, 1983).

Parameter	Flaming Wood (TF 1)	Wood Pyrolysis (TF 2)	Smoldering Cotton (TF 3)	Smoldering Paper (UL 217)	Overheated Transformer (Cerb. AG)
Peak Conc. (ppmv)					
CO_2	> 1800	880	1560	1360	640
CO	> 90	> 100	> 90	> 100	> 100
H_2	65	12	58	30	25
Total Hydrocarbons	24	26	45	66	42
Time to Peak (seconds)					
CO_2	> 120	640	470	220	180
CO	> 560	> 500	> 120	> 70	> 130
H_2	720	610	360	240	180
Total Hydrocarbons	120	640	> 470	215	> 200
Time to Alarm (seconds)					
Radiation	60	> 640	no response	255	200
Ionization	200	520	230	230	190
Light Scattering	479	550	380	220	220
Thermal	340	no response	no response	no response	no response

thermal, and light scattering detectors were noted. The peak concentrations, the time after ignition to reach the peak, and the time to detector response are listed in Table 1.

Peak CO levels exceeded the maximum range of the NDIR instrument (100 ppmv) in all cases, CO_2 was of the order of 1000 ppmv, and the hydrogen and hydrocarbon levels each averaged close to 45 ppmv in these tests. The average time required to reach the maxima varied with the test, ranging from around 180 s for the overheated transformer to over 600 s for the pyrolyzing wood. In some cases the test was terminated before the peak was reached either because the specified mass of fuel had been consumed or the mode of combustion changed (i.e., from smoldering to flaming). No radiation nor temperature measurements were reported; however, the thermal detector responded only for the flaming wood test, and the radiation detector reached the alarm state in all but the smoldering cotton test.

Jackson and Robins (1994) recently reported measurements that they made in the standard EN fires, including an ethanol pool fire designated as TF6. Gases were sampled at the ceiling, 3 m from the centerline of the fire, which is where the detector is located using the standard EN method. In addition to CO, they measured the change in relative humidity, oxygen level and gas temperature as a function of time after ignition, and also kept track of the fuel which was consumed. Optical and ionization detectors were used to monitor the smoke density. Table 2 summarizes their results, and includes an estimate of the maximum rate of fuel consumption.

The flaming fires produced between 16 and 46 ppmv CO, and the smoldering fires produced about

Table 2. Approximate conditions measured near end of test in EN standard fires (Jackson and Robins, 1994).

Parameter	TF1: Flaming Wood (t=720 s)	TF2: Wood Pyrolysis (t=720 s)	TF3: Smoldering Cotton (t=540 s)	TF4: Flaming Polyurethane (t=140 s)	TF5: Flaming Heptane (t=180 s)	TF6: Flaming Ethanol (t=360 s)
Max gas levels						
CO	46 ppmv	105 ppmv	350 ppmv	45 ppmv	30 ppmv	16 ppmv
ΔH_2O, R.H.	10%	n.d.[1]	n.d.	10%	30%	40%
H_2	4 ppmv	n.d.	28 ppmv	n.d.	n.d.	n.d.
ΔO_2	-2500 ppmv	n.d.	n.d.	-2400 ppmv	-8000 ppmv	-8000 ppmv
Max temperature						
ΔT	48 °C	1 °C	< 1 °C	25 °C	58 °C	54 °C
$\Delta T/\Delta t$	0.11 °C/s	.003 °C/s	< 0.002 °C/s	0.28 °C/s	0.49 °C/s	0.32 °C/s
Max extinction coeff.[2]	0.21/m	0.63/m	0.69/m	0.40/m	0.34/m	0.03/m
Mass consumed						
change	-70%	-60%	-40%	-68%	-90%	-75%
maximum rate	-0.28%/s	-0.14%/s	-0.08%/s	-1.1%/s	-0.68%/s	-0.21%/s

[1] not detected

[2] [(ln 10)/10]•(dB/m)

eight times more. Only the smoldering cotton and flaming wood produced measurable amounts of H_2. No significant changes in temperature, relative humidity or oxygen levels were measured in the wood pyrolysis and smoldering cotton tests. The highest extinction coefficient was measured in the smoldering fires and the minimum in the alcohol fire. Polyurethane was consumed the fastest (1.1%/s); the two smoldering fuels were gasified at a rate about ten times slower.

By plotting the values measured by Jackson and Robins (1994) and Pfister (1983), one gets a feel for the wide range of conditions to which a fire detector is expected to respond. Figure 4 shows the CO levels as a function of time for all the fires listed in Tables 1 and 2. The concentration often exceeds 100 ppmv, and in no case does it not exceed 20 ppmv; however, the times required to attain this threshold vary from 20 s to 500 s. Hydrogen levels are more difficult to predict. Some fires produce no measurable H_2, while in one test more than 100 ppmv was measured as shown in Figure 5. Ceiling temperatures are plotted in Fig. 6. The high rates-of-rise exhibited by the polyurethane and liquid pool fires are due to the much greater heat release rates when compared to TF1-TF3.

Heat release rates can be estimated from the mass loss data once the initial mass and an energy density are known. Table 3 is an estimate of the initial mass based upon the description of the test fires in EN 54. Also included are estimates of the mass of fuel and average heat release rates for the UL test fires. The UL fires can be seen to involve considerably less fuel than the EN fires. The average heat release rates over the duration of the tests varied between 2.3 kW for the smoldering wood (TF 2) and 130 kW for the heptane pool fire, TF 5. The heat release rate reached its peak near the end of each test, which, for the polyurethane fire, was almost three times higher than the average.

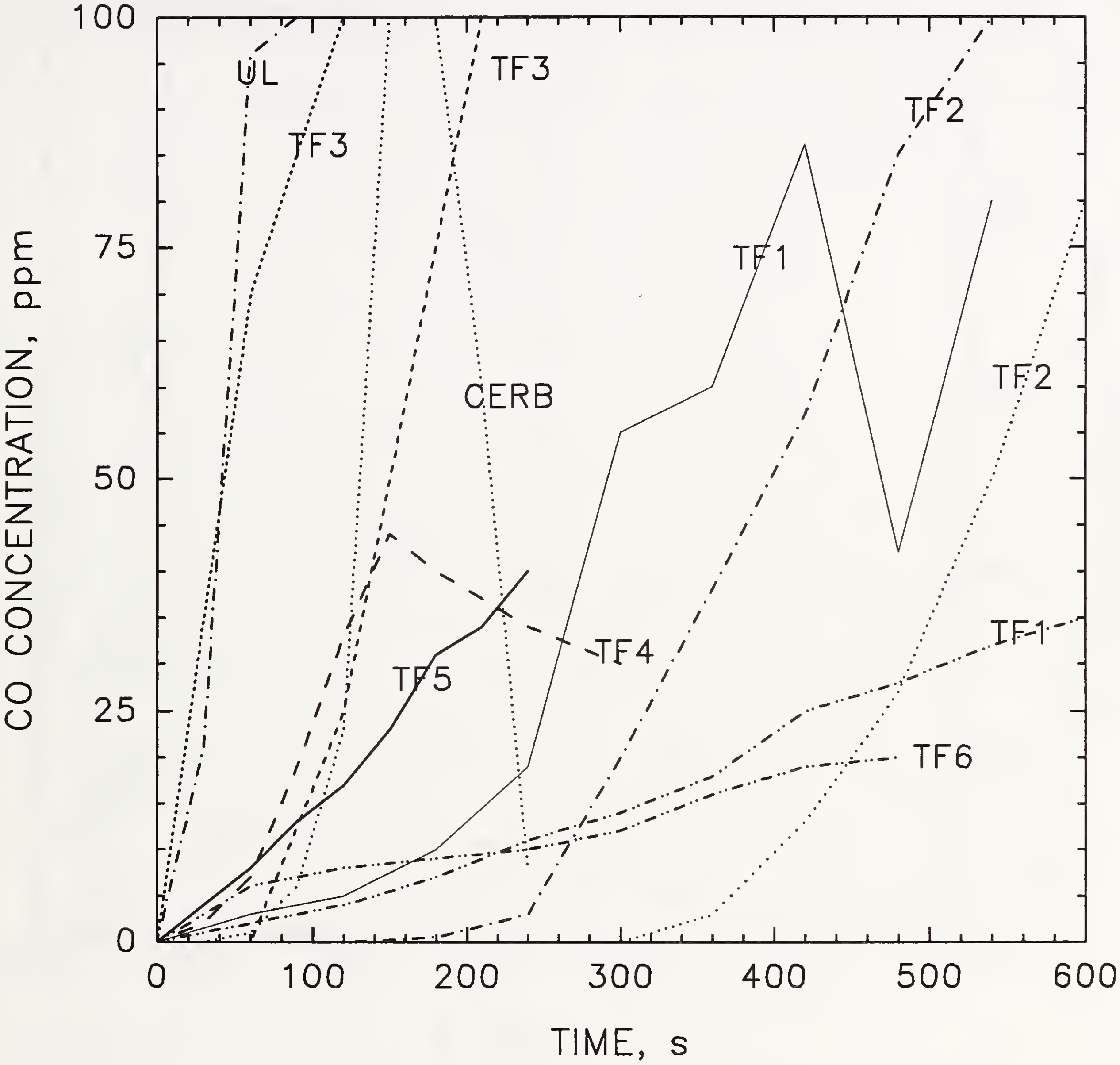

Figure 4. Concentrations of CO measured in standard test fires (Pfister, 1983; Jackson and Robins, 1994)

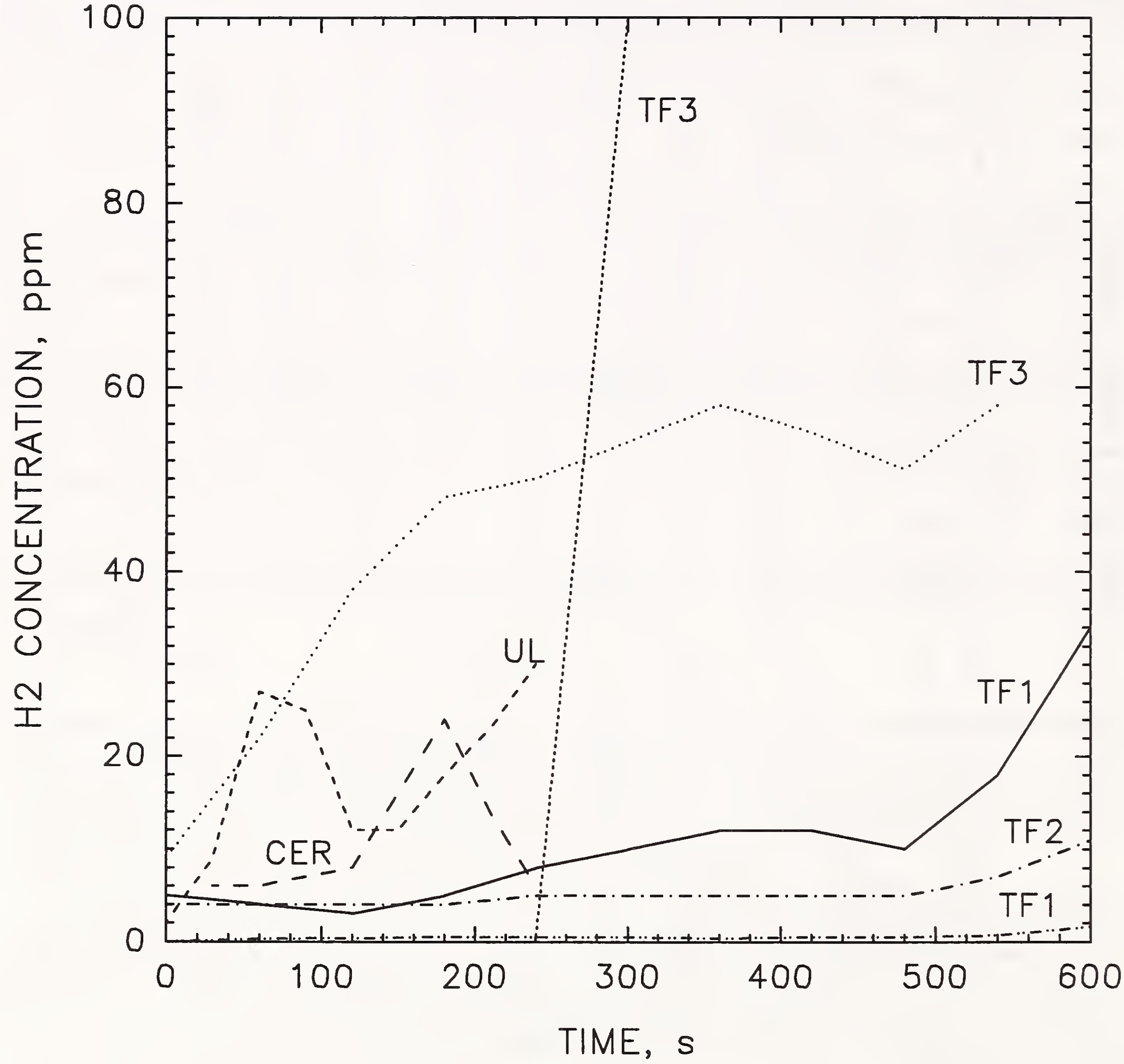

Figure 5. Concentrations of H_2 measured in standard test fires (Pfister, 1983; Jackson and Robins, 1994)

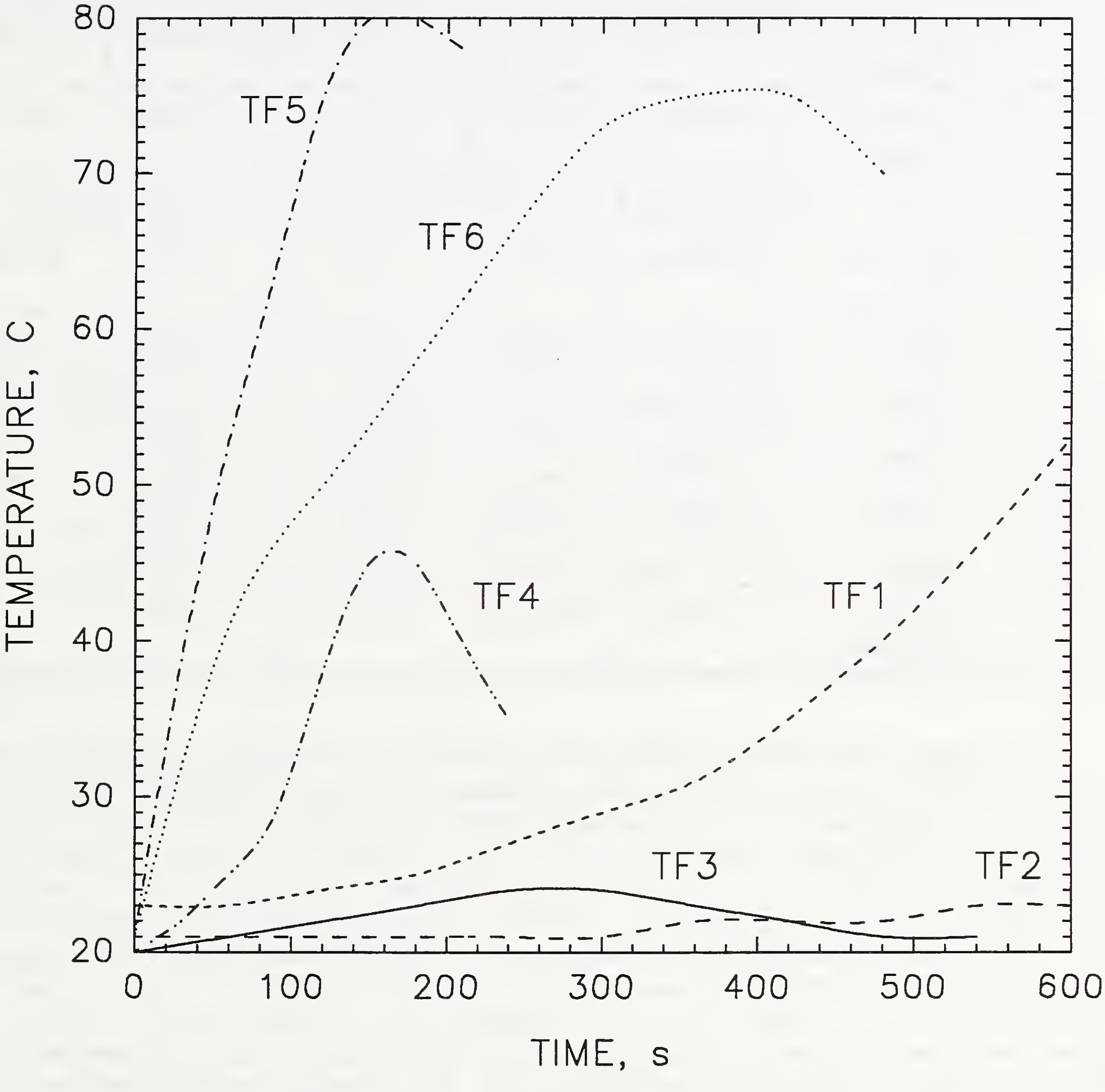

Figure 6. Temperatures measured in standard test fires (Jackson and Robins, 1994).

Table 3. Approximate fuel loss and heat release rates of standard fire tests.

Test Fire	Fuel	Enthalpy of Combustion	Initial Mass	Average Consumption Rate	Average Heat Release Rate	Maximum Heat Release Rate
TF 1	dry beechwood (80 kg/m^3)	20.7 MJ/kg	2.8 kg	2.7 g/s	56 kW	145 kW
TF 2	dry beechwood (80 kg/m^3)	20.7 MJ/kg	0.13 kg	0.11 g/s	2.3 kW	3.8 kW
TF 3	cotton	16.7 MJ/kg	0.27 kg	0.19 g/s	3.2 kW	3.6 kW
TF 4	polyurethane (20 kg/m$_3$)	25.6 MJ/kg	0.30 kg	1.2 g/s	30 kW	84 kW
TF 5	heptane	48.5 MJ/kg	0.65 kg	3.1 g/s	150 kW	214 kW
TF 6	ethanol	29.7 MJ/kg	2.0 kg	4.0 g/s	120 kW	125 kW
UL A	newsprint	17.5 MJ/kg	0.043 kg	0.18 g/s	3.2 kW	--
UL B	dry firwood	21 MJ/kg	0.593 kg	2.5 g/s	52 kW	--
UL C	gasoline	47.7 MJ/kg	0.025 kg	0.13 g/s	6.2 kW	--
UL D	polystyrene (30 kg/m3)	25.5 MJ/kg	0.025 kg	0.20 g.s	5.1 kW	--

Voigt and Avlund (1980) reported the mass consumed in fires designed after the TF series but run in a room of different geometry, and found the time required to consume the prescribed amount of fuel to be higher than that reported by Jackson and Robins (1984). An exception was the polyurethane, which they attributed to differences in composition and the point of ignition. The average heat release rates in this earlier study were 48, 1.1, 1.4, 44, 131, and 119 kW, respectively, for the TF 1 through TF 6 fires. Figure 7 is a plot of the mass loss as a function of time for the EN fires (Jackson and Robins, 1984). Using these instantaneous consumption rates and the heating value of the fuel, the temperature increase as a function of the energy released is shown in Fig. 8. Note that TF 1 and TF 4 have been corrected for the energy content in the 5 ml of ethanol used for ignition purposes. The spread in temperatures is greatly reduced by using energy scaling, with the early stages of the smoldering fires behaving similarly to the liquid and plastic flaming fires. The temperature increases much less steeply in the flaming wood fire, which might be attributable to water loss and endothermic reactions early in the heating.

Figures 9 and 10 compare the CO and H_2 concentrations as a function of the mass of C or H released. This is estimated from Fig. 7 assuming the following weight percentages in the different fuels:

wood -	49%(wt) C, 6%(wt) H, 44%(wt) O, 0.7%(wt) N
cotton -	44%(wt) C, 6%(wt) H, 49%(wt) O
polyurethane -	20%(wt) C, 2%(wt) H, 54%(wt) O, 24%(wt) N

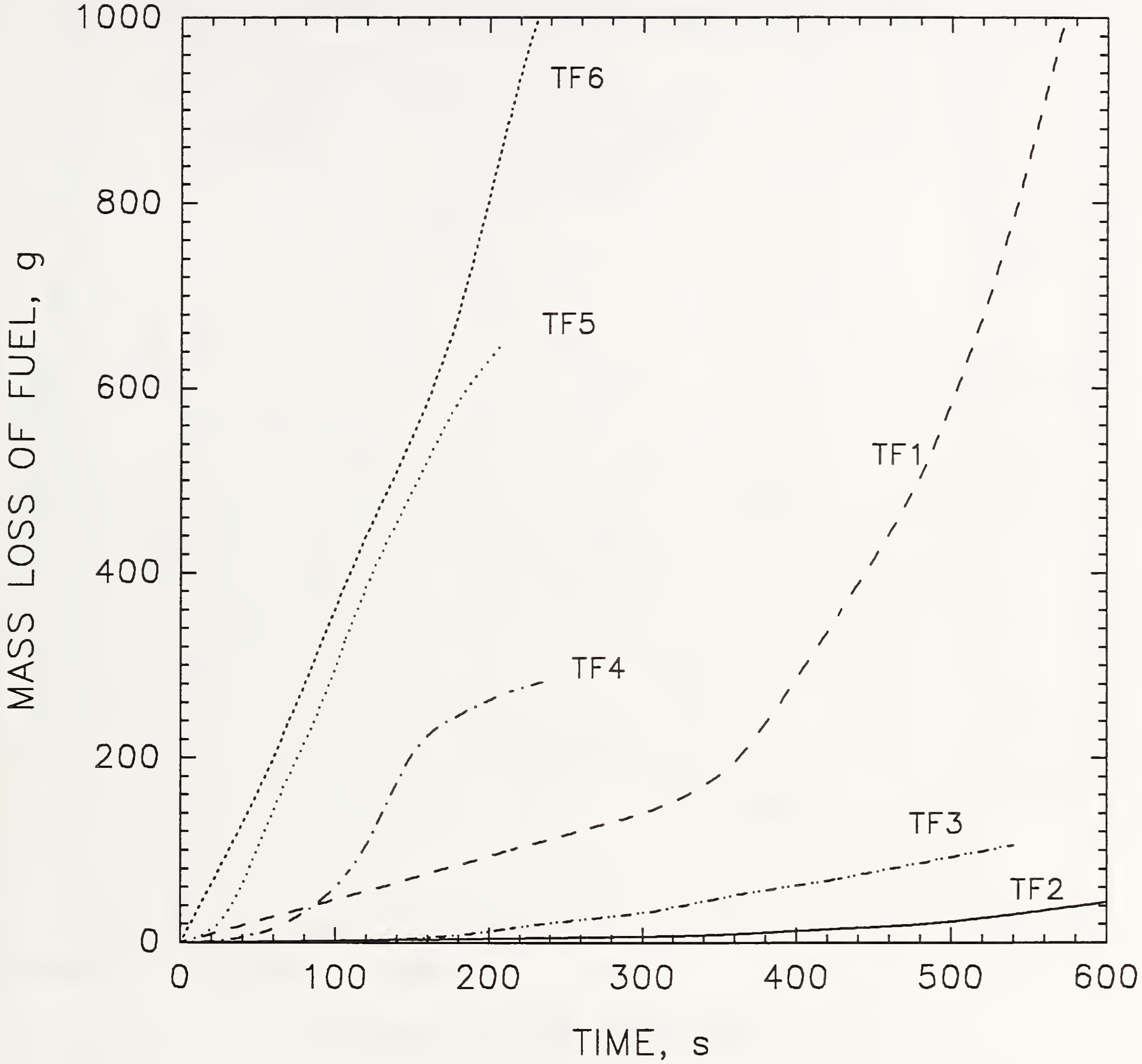

Figure 7. Mass loss of fuel in standard fires estimated from data of Jackson and Robins (1994).

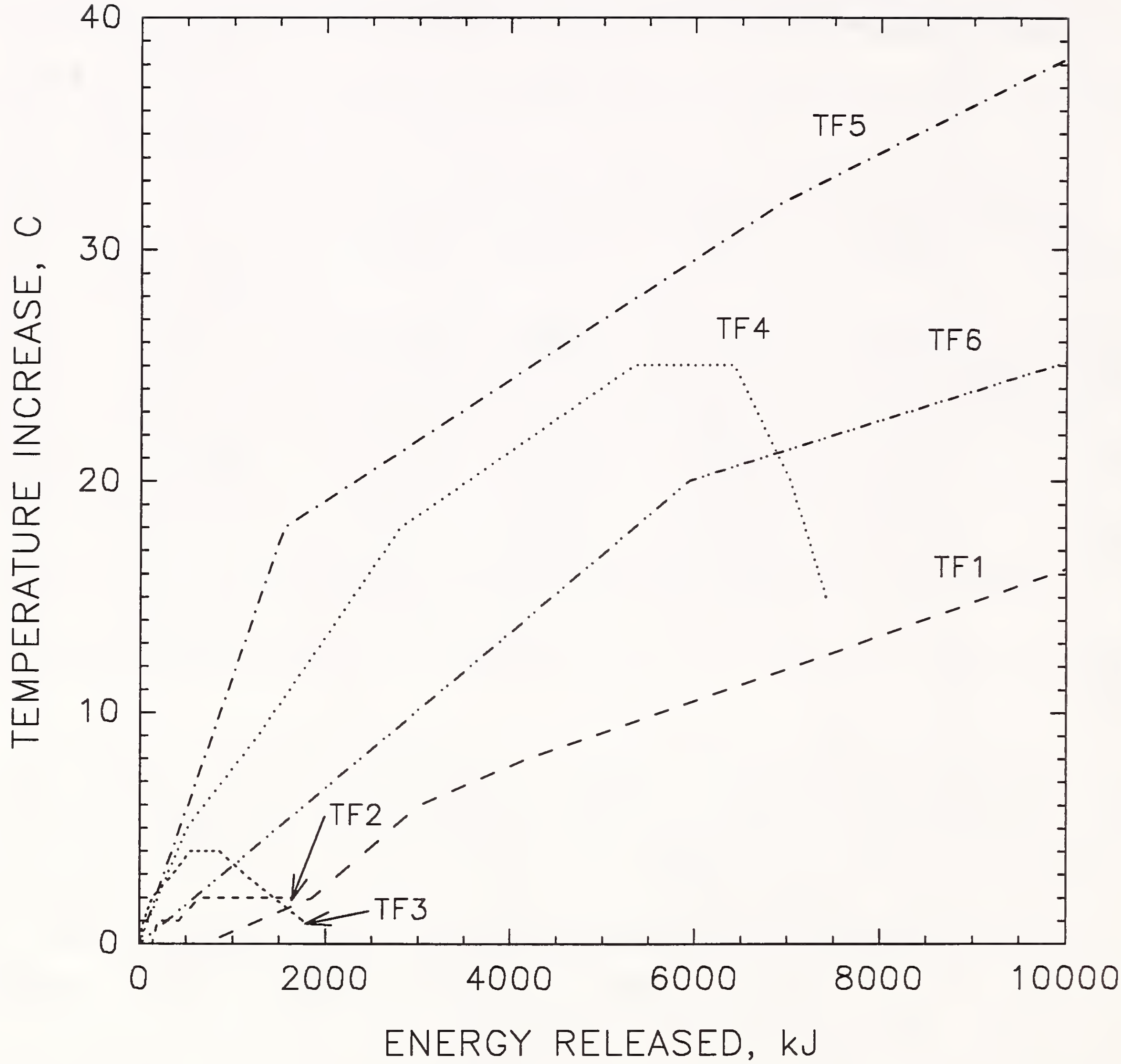

Figure 8. Temperature increase in test fires as a function of energy release, based upon data of Jackson and Robins (1994).

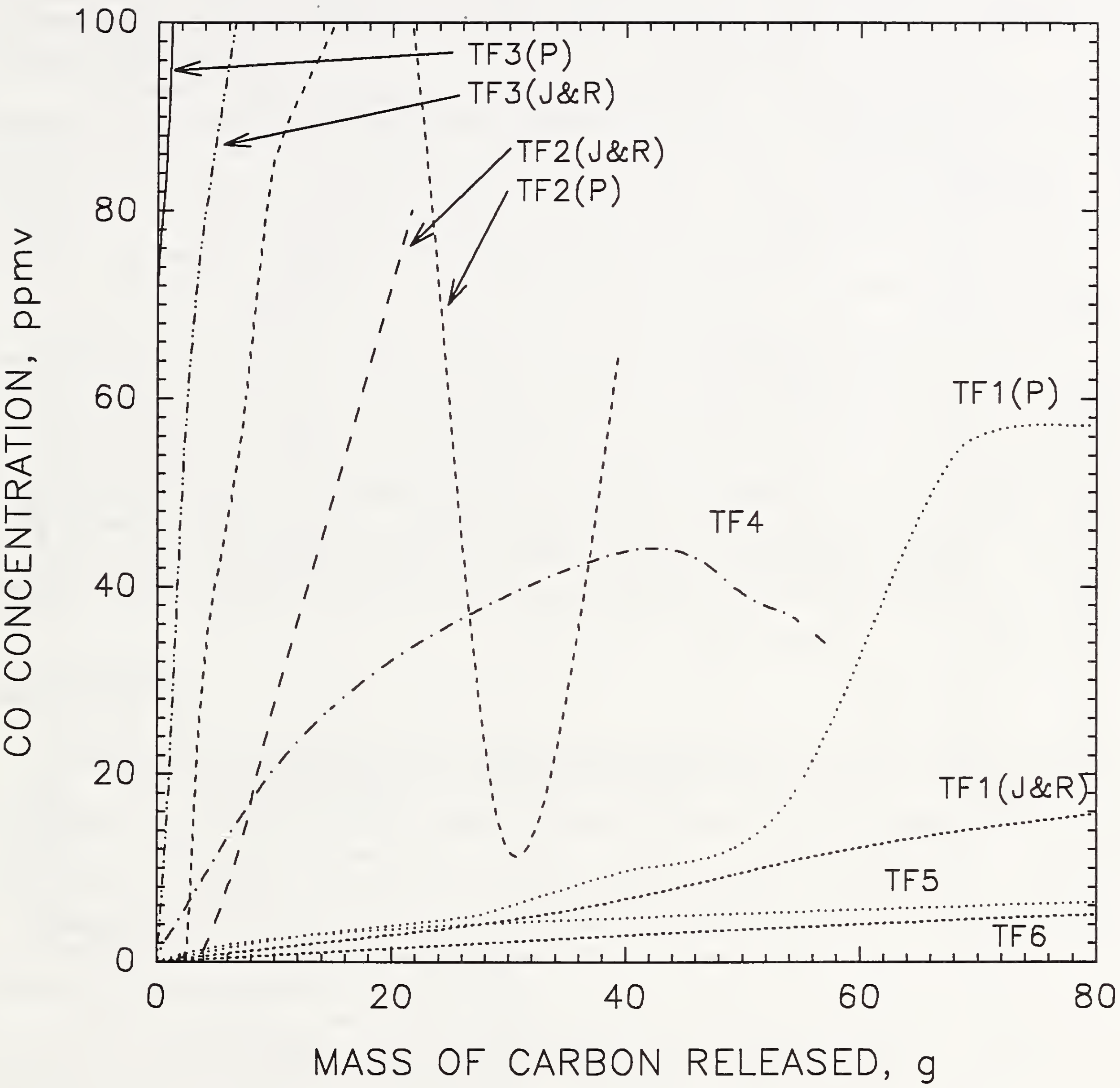

Figure 9. CO emissions measured by Jackson and Robins (1994) and Pfister (1983) in test fires normalized by estimated mass of carbon consumed.

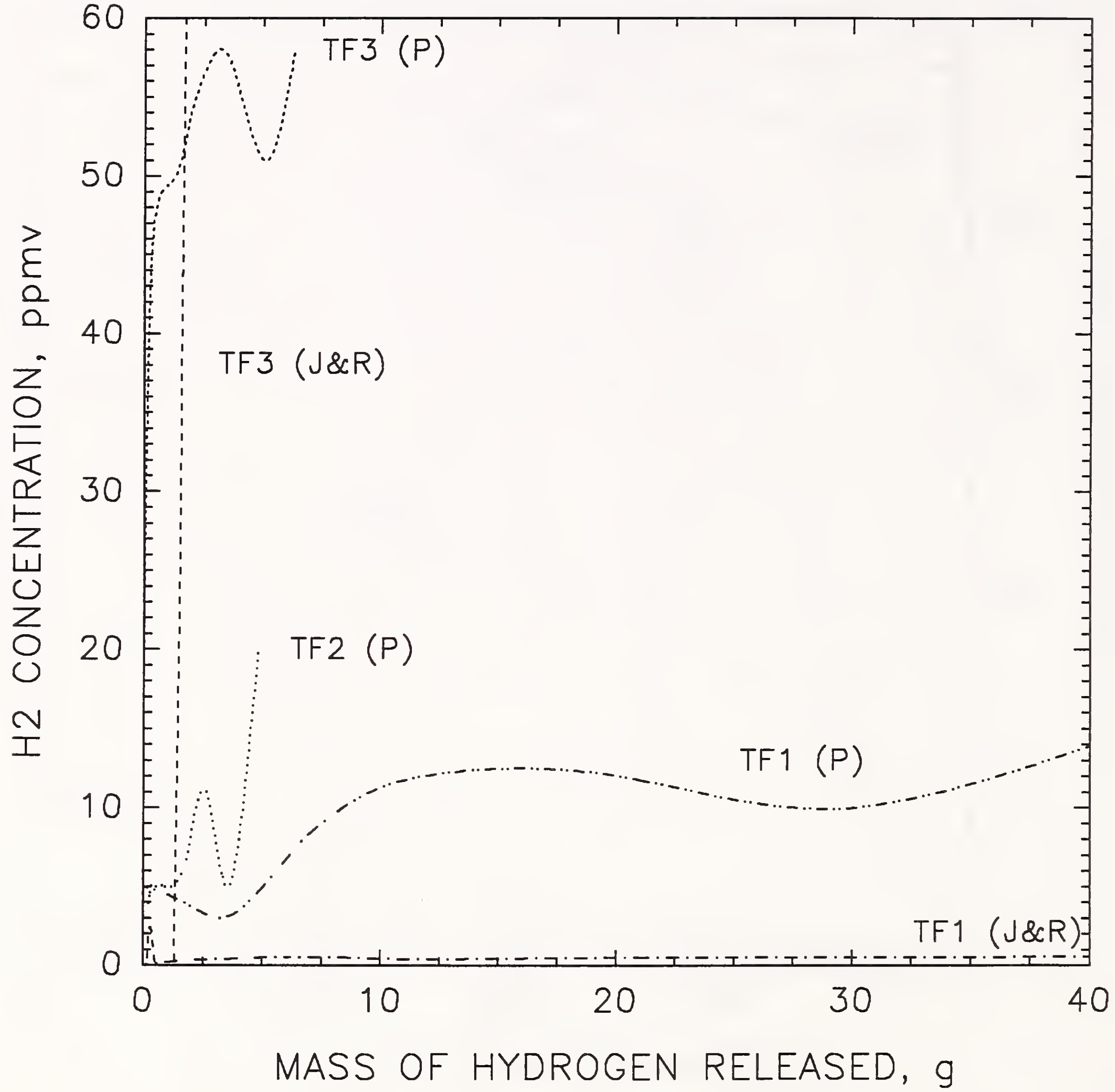

Figure 10. H_2 emissions measured by Jackson and Robins (1994) and Pfister (1983) in test fires normalized by estimated mass of hydrogen consumed.

heptane -	84%(wt) C, 16%(wt) H
ethanol -	52%(wt) C, 13%(wt) H, 35%(wt) O

The grouping of the smoldering fires and the flaming fires is more evident when scaled with mass loss rather than when plotted versus time (compare to Figs. 4 and 5). The flaming wood and liquid fires produce approximately the same amount of CO during the early portion of the event. The polyurethane is in between, producing early CO levels similar to the smoldering situation and later levels closer to the less sooty flaming fuels.

The concentrations measured by Pfister (indicated with a "P" in Figs. 9 and 10) are considerably higher than the values measured by Jackson and Robins (J&R). The latter authors attribute this to the increased distance from the fire that their sampling probe was located. Taking 20 ppmv as a threshold for CO, the additional time required to reach the probe located 3 m off of the centerline ranges between 85 and 150 s. It takes about 180 s for similar amounts of H_2 to be detected in TF 3. If convection can explain the differences, than the velocities at the ceiling must be between 0.017 and 0.035 m/s.

A difference in position can not explain all the observed behavior because the hotter flaming wood fire generates a much higher buoyant flow, but the time lag in the TF 1 fire is greater than in the cooler smoldering cotton fire, TF 3. Also one would expect the velocity of the hydrogen to be, on average, higher than the CO because of the buoyant forces on the very light molecules. But the hydrogen time lag is larger than the CO time lag. If, on the other hand, the sampling volume in Pfister's experiments was closer to the ceiling, the structure of the boundary layer would suggest that the local concentration of combustion products would be higher. The strong tendency for hydrogen to diffuse laterally as well as in the streamwise direction would contribute to the lower readings experienced by Jackson and Robins. It could also be that the differences are due almost entirely to experimental variation. There were no replicates reported in either article so that it is not possible to assess the magnitude of this effect.

Future Directions

The choice of candidate chemical species and physical responses to detect a fire in an early stage is large. The measurements made over the past decades indicate where one should be looking. Temperature rise, infrared radiation, carbon dioxide and water always accompany a flaming fire in abundance. Carbon monoxide and smoke can also be counted upon, but the quantities vary considerably with fire type. Hydrogen, a number of low and high molecular weight organics, NO, HCl, and SO_2 will be present in many situations in detectable levels, but are strongly fuel and fire dependent. The visible and uv portions of the electromagnetic spectrum and acoustic radiation may provide useful auxiliary signatures for specialized detection situations.

What is needed is a test protocol which will permit fire sensor designs to be evaluated and compared in a uniform manner. The relevant aspects of the test must be tightly controlled and highly repeatable, and not restrict new technologies or innovation. The procedures must be thoroughly documented to allow any interested laboratory to duplicate a test with no change in outcome.

A number of critical milestones can be identified on the way to developing an appropriate test protocol:

1. Characterize the types of fires one wishes to detect.
2. Develop a suite of laboratory fires which captures the essence of the threats.
3. Measure all significant physical and chemical parameters in these laboratory fires and quantify the mean, standard deviation, and frequency response of each as a function of time.
4. Design a facility to generate the key chemical and physical responses to emulate the suite of

fires.

5. Mathematically model the space to be protected to determine the stimulus created by the fire at the desired site of detector placement.
6. Measure the response of the detector to the fire emulator which has been programmed to simulate the stimulus at the detector site.

Step 1 may vary with one's perspective, but general consensus has been obtained within the European Community that the six fires described in EN54 part 9 do capture the essence of many expected threats. The test fires include synthetic and natural fuels, liquid and solid fuels, smoldering and flaming conditions, heavy and light smoke levels, and a variety of heat release rates. Additional tests are required to simulate fires in electrical equipment, and fuels which contain elements other than C, H, O, and N (e.g., F, Cl, Br, and S).

The published measurements of species concentration and temperatures in the EN54 test fires (Pfister, 1983; Jackson and Robin, 1994) are a valuable step towards milestone 3. Additional measurements should focus in the region close to the fire origin but outside the exothermic reaction zone. The hypothesis is that each fire can be considered a source of momentum, heat and chemical species which grows in a unique manner, and that no further chemical reactions occur among the gases or condensed matter beyond a well defined point in the plume. This implies that the species, velocity and energy fields can be predicted throughout the room using conventional computational fluid dynamics.

For the pool fires (TF 4 through 6), the well defined point lies between two and five pool diameters above the surface. The fires with wood and cotton will need to be examined closer to the source. Care is necessary to maintain a consistent ignition sequence, fuel source (especially density and water content), and to eliminate external air currents and wall effects. There is no advantage to conduct the experiments in the EN54 standard room. For each fire configuration the following parameters need to be measured in order to properly specify the source:

- fuel weight loss
- temperature
- vertical and horizontal components of velocity
- CO_2, H_2O, CO, H_2, major gaseous fuel components, THCs, NO, O_2
- aerosol mass concentration, scattering coefficient, absorption coefficient, particle size distribution
- uv, visible and ir intensity distribution
- acoustic intensity distribution

The velocity, temperature and CO distributions (in the streamwise and transverse directions) can serve to identify the point in the plume where the remainder of the data should be collected. Conventional fine wire thermocouples and anemometers (laser and/or hotwire) have sufficient time response to follow the unsteady motion of the plume as well as the evolution of the fire, but some attention must be paid to the CO measurements to be sure to capture the nuances of fire development. The open path Fourier transform infrared spectrometer (OP-FTIR) could be ideal for this, especially since it can also be used to quantify CO_2, H_2O, various hydrocarbons, and soot volume fraction along a line-of-sight. The diatomics (H_2 and O_2) and NO could be measured with a few second response time using mass spectrometry, or in the tens of seconds time frame using grab samples or continuous flow process instruments. Standard instruments for measuring the radiation and acoustic fields exist with subsecond response times. Simultaneous records of as many signals as possible would permit cross-correlations to be developed, which could figure important for intelligent signal processing. The experiments should be repeated enough times to generate meaningful uncertainty statistics.

With the signature of each designer fire established, the range of composition, temperature, radiation levels, and velocities likely to be encountered in the field can be determined with the aid of computational fluid dynamics. The task of actually designing the fire emulator can then begin. Two basic units are envisioned: one for point detectors which builds upon the closed circuit wind tunnel designs described in EN 54 parts 5 through 8; and a second for line or volume detectors which uses a buoyant, free jet.

To be complete, similar measurements of non-fire nuisance sources are required in order to discriminate between a fire and non-threatening situation with a high degree of certainty. Once developed, a universal fire emulator/detector evaluator (FE/DE) could be programmed to emulate either a fire or interfering signal. This would then provide a reliable test bed for signal processing algorithms as well as system hardware. Support for such a facility and the general approach is sought from the fire protection industry and regulating organizations.

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U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

MANUSCRIPT REVIEW AND APPROVAL

(ERB USE ONLY)	
ERB CONTROL NUMBER	DIVISION
PUBLICATION REPORT NUMBER NISTIR 5555	CATEGORY CODE
PUBLICATION DATE January 1995	NUMBER PRINTED PAGES

INSTRUCTIONS: ATTACH ORIGINAL OF THIS FORM TO ONE (1) COPY OF MANUSCRIPT AND SEND TO THE SECRETARY, APPROPRIATE EDITORIAL REVIEW BOARD.

TITLE AND SUBTITLE (CITE IN FULL)

A Review of Measurements and Candidate Signatures for Early Fire Detection

CONTRACT OR GRANT NUMBER

TYPE OF REPORT AND/OR PERIOD COVERED

AUTHOR(S) (LAST NAME, FIRST INITIAL, SECOND INITIAL)

Grosshandler, W.L.

PERFORMING ORGANIZATION (CHECK (X) ONE BOX)

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Building and Fire Research Laboratory/Fire Science Division

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The physical and chemical transformations associated with a burgeoning fire are discussed and the results of past experimental measurements of these transformations are summarized. Standard test methods for the current generation of fire detectors and recent developments in detection technologies for which existing standards may not be suitable are described. The literature has been reviewed to determine the extent to which fires have been characterized in their early phase (<100 kW). In particular, measurements of CO, CO_2, H_2O, H_2, O_2, smoke and temperature have been examined. One finds dramatic variations in the measured magnitude and rate of growth of CO concentration in a variety of standard fires. The variation is also large between repeat runs of the same tests. When scaled by estimated mass consumed of fuel, the different standard fires group a bit more systematically. Additional measurements of species, temperature and velocity just above the flame are suggested to get a more complete footprint of each fire type. Similar measurements of non-fire nuisance sources are required in order to discriminate between a fire and non-threatening situation with a high degree of certainty. The concept of a universal fire emulator/detector evaluator (FE/DE) is introduced. The objective is to have a facility that will eliminate the unavoidable run-to-run variations associated with full-scale tests, and to allow more well controlled environments. Computational fluid dynamics could then be used to insert the fire source into the space being protected to guide detector placement and to predict system performance, as well as to compare alternative systems and new concepts on a level, realistic playing field.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

fire detection; fire detectors; fire gases; fire plume; fire research; fire tests; smoke detectors; test fire

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