



Towards the Development of a Universal Fire Emulator–Detector Evaluator

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(Received 20 July 1995; revised version received 10 April 1996; accepted 15 April 1996)

ABSTRACT

Past measurements are examined of CO, CO₂, H₂O, H₂, O₂, smoke and temperature produced in standard fires of the UL and EN type. Additional measurements just above the heat release zone are suggested to obtain a more complete footprint of each standard fire, and the concept of a universal fire emulator–detector evaluator (FE–DE) is introduced. The objective of the emulator is to produce more well-controlled environments that eliminate the unavoidable run-to-run variations associated with full-scale tests. Numerical fluid dynamic computations are recommended to insert the fire source into the space being protected as a guide for detector placement and to predict system performance under realistic conditions. Published by Elsevier Science Ltd.

1 INTRODUCTION AND BACKGROUND

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. 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 Bright¹ 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,² but much remains unknown about what occurs early in an actual fire.

Organic compounds exposed to air will inevitably be converted to an

equilibrium state consisting primarily of H_2O and CO_2 , accompanied by the liberation of heat. At room temperature, solid phase carbon is predicted to form at equilibrium for fuel/air equivalence ratios greater than 1.3. Methane is the only additional gas phase product in excess of 5 ppmv formed from hydrocarbon combustion. If chlorine and sulfur are present, high levels of Cl_2 and condensed sulfuric acid are produced under lean conditions, SO_2 is plentiful near stoichiometric conditions, and H_2S and HCl are significant products for richer mixtures. Increasing temperature causes the equilibrium concentrations to shift towards smaller gaseous molecules. CO , H_2 and NO are formed in moderate levels only for temperatures in excess of 1500K.³

The actual concentration of a particular species in a fire is controlled by the rate of the competing chemical reactions. The kinetics are strongly influenced by the time since ignition and the boundary conditions surrounding the fire. Even for the major products of combustion the time-dependent amounts 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. A more detailed discussion of these measurements can be found elsewhere.³

During the early stages of a fire 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. However, the momentum source is strongly influenced by the gravitational field and pressure gradients imposed at the boundaries, and cannot be neglected.

Approximate solutions to the equations governing the conservation of mass, momentum and energy for a limited number of highly restricted fires have been obtained using commercially available, fluid-dynamical partial differential equation solvers, e.g. Refs 4 and 5. Increased computational power, a better understanding of turbulence transport, the desire to optimize 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 integral tool for system design.

2 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 Laboratory, Factory Mutual and the European Committee for Standardization.

Underwriters Laboratory evaluates the performance of smoke detectors in reduced and full-scale chambers.⁶⁻⁸ 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. 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 for the detector to respond in each of these flaming tests varies from 4 min for fire A to 2 min for D. Test E is a smoldering fire, created by placing 10 ponderosa pine sticks on a hot plate. The allowed response time for this threat is 70 min.

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 to the emissions from 50 g of animal fat, 50 g of vegetable fat and 100 g of beef gravy vaporizing on a hot plate. The smoke detector is not to activate in this situation.

The Factory Mutual smoke detector standard⁹ 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.

The European standard, EN 54 Part 7,¹² subjects smoke detectors to fires within a full-scale room and to a prescribed paraffin oil aerosol in a wind tunnel. The room is 9–11 m in length, 6–8 m in width and about 4 m high. Different test fires (described in EN 54 Part 9)¹⁴ 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 (TF2) is created by heating 24 beechwood sticks (10 × 20 × 3.5 mm) on a hot plate which is capable of attaining 600°C within 11 min after the power is turned on. The test is terminated after flaming begins. A second smoldering fire test (TF3) 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 × 0.5 m × 20 mm, are placed on top of each other and ignited with 5 ml of alcohol in TF4. The final test (TF5) 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 60–80% of the fuel 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.

UL 521¹⁵ applies to heat detectors for fire protective signaling systems intended to be installed in ordinary indoor and outdoor locations. UL 539¹⁶ 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. 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 metal pan. The amount used is varied to control the temperature gradient. The minimum performance criterion is tied to the operating time of a sprinkler which would be used to protect the same space. The detector must activate within 130 s after ignition.

FM 3210¹⁷ 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.

Independent of the heat sensing element design, the same test facility is used in EN 54 Parts 5, 6 and 8.^{10,11,13} A wind tunnel produces an average air velocity of 0.8 m/s across a square cross-sectional area 0.25–0.30 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.

Only one CO standard was uncovered in this review, UL 2034.¹⁸ 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 m³ 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 10 min after the start of the test. Additional tests are run with concentrations of 200 and 400 ppm. The selectivity is checked by exposing the CO detector to various concentrations of other gases. 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.

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 72¹⁹ 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).

Guidelines are being written by the European standards technical committee for the use of flame detectors in buildings. Testing is to be based upon the same series of fires as is used for smoke detectors (TF1–TF5).

Chapter 5 of NFPA Standard 72 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 3260.²⁰

3 STANDARD FIRE SIGNATURES

The products of combustion formed in the different testing 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-à-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 any one of them.

A limited amount of data has been taken to characterize these fires. Pfister²¹ 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 nonflaming wood fire (TF2), a smoldering cotton wick (TF3), a nonflaming 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 9.¹⁴ Measurements were made of CO, CO₂, H₂ and total hydrocarbons in each of these fires, and the alarm points of radiation, ionization, thermal and light scattering detectors were noted.

Peak CO levels exceeded the maximum range of the measuring instrument (100 ppmv) in all cases, CO₂ was of the order of 1000 ppmv, and the hydrogen and hydrocarbon levels each averaged close to 45 ppmv in these tests. The average times 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 or 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 Robins²² 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. The flaming fires produced between 16 and 46 ppmv CO, and the smoldering fires produced about eight times more. Only the smoldering cotton and flaming wood formed measurable amounts of H₂. 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 fastest (1.1%/s); the smoldering fuels were gasified at a rate about 10 times slower.

By examining the values measured in the above experiments, one gets a feel for the wide range of conditions to which a fire detector is expected to respond.³ The concentration of CO 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 to 500 s. Hydrogen levels are more difficult to predict. Some fires produce no measurable H₂, while in one test more than 100 ppmv was measured. The high rates of temperature 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 calculated from the mass loss data once the initial mass and an energy density are known. Table 1 includes 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 vary between 2.3 kW for the smoldering wood (TF2) and 130 kW for the heptane pool fire, TF5. The heat release rate reaches its peak near the end of each test, which, for the polyurethane fire, was almost three times higher than the average.

Voigt and Avlund²³ reported the mass consumed in fires designed after the TF series, but run in a room of different geometry, and reported the time required to consume the prescribed amount of fuel to be higher than that found by Jackson and Robins.²² An exception was the polyurethane, which has been 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 TF1–TF6 fires.

Grosshandler³ plotted the mass loss as a function of time for the EN fires of Jackson and Robins.²² 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. 1. Note that TF1 and TF4 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 2 and 3 compare the CO and H₂ concentrations as a function of the mass of C or H released. This is estimated from the mass loss assuming the following weight percentages in the different non-homogeneous fuels: wood—49% C, 6% H, 44% O, 0.7% N; cotton—44% C, 6% H, 49% O; and polyurethane—20% C, 2% H, 54% O, 24% N. The grouping of the smoldering fires and the flaming fires is more evident when scaled with mass loss rather than when plotted vs time.³ 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.

TABLE 1
Approximate Fuel Loss and Heat Release Rates of Standard Fire Tests

Test Fire	Fuel (density, kg/m ³)	Enthalpy of combustion	Initial mass	Consumption rate	Average heat release rate	Maximum heat release rate
TF1	Beechwood (80)	20.7 MJ/kg	2.8 kg	2.7 g/s	56 kW	145 kW
TF2	Beechwood (80)	20.7 MJ/kg	0.13 kg	0.11 g/s	2.3 kW	3.8 kW
TF3	Cotton	16.7 MJ/kg	0.27 kg	0.19 g/s	3.2 kW	3.6 kW
TF4	Polyurethane (20)	25.6 MJ/kg	0.30 kg	1.2 g/s	30 kW	84 kW
TF5	Heptane	48.5 MJ/kg	0.65 kg	3.1 g/s	150 kW	214 kW
TF6	Ethanol	29.7 MJ/kg	2.0 kg	4.0 g/s	120 kW	125 kW
ULA	Newsprint	17.5 MJ/kg	0.043 kg	0.18 g/s	3.2 kW	—
ULB	Dry firwood	21 MJ/kg	0.593 kg	2.5 g/s	52 kW	—
ULC	Gasoline	47.7 MJ/kg	0.025 kg	0.13 g/s	6.2 kW	—
ULD	Polystyrene (30)	25.5 MJ/kg	0.025 kg	0.20 g/s	5.1 kW	—

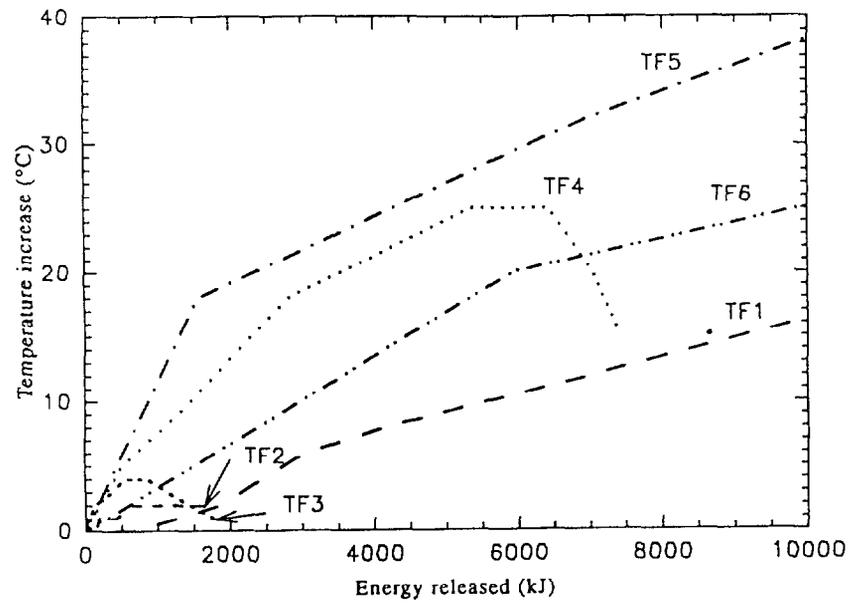


Fig. 1. Temperature increases measured in test fires of Jackson and Robins²² vs energy released.

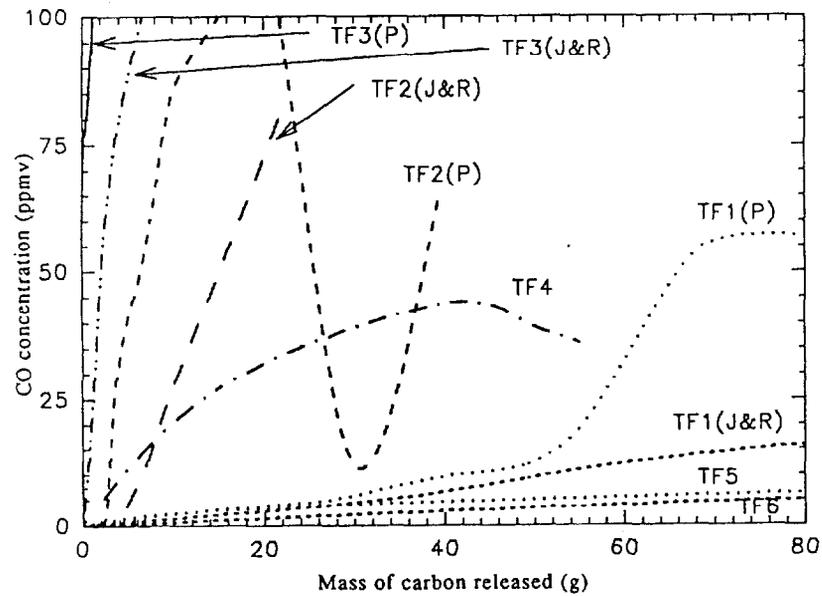


Fig. 2. CO emissions measured in Pfister²¹ and Jackson and Robins²² vs estimated mass of carbon consumed.

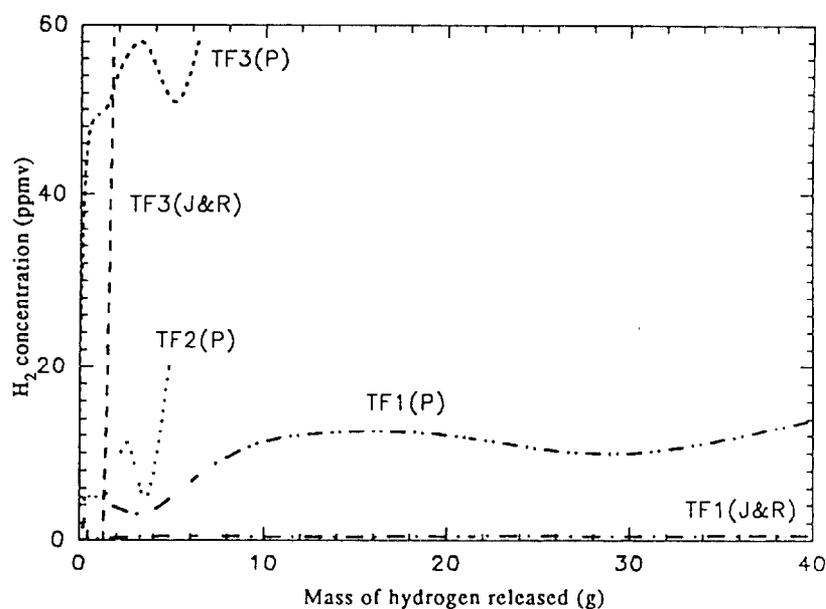


Fig. 3. H_2 emissions measured in Pfister²¹ and Jackson and Robins²² vs estimated mass of hydrogen consumed.

The concentrations measured by Pfister²¹ (indicated with a 'P' in Figs 2 and 3) are considerably higher than the values measured by Jackson and Robins²² (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 TF3. If convection can explain the differences, then 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 TF1 fire is greater than in the cooler smoldering cotton fire (TF3). 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. However, the H_2 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.

4 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, CO₂ and H₂O always accompany the 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 SO₂ will be present in many situations in detectable levels, but are strongly fuel and fire dependent. The visible and u.v. 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. The following critical milestones can be identified on the way to developing an appropriate 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 EN 54 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 EN 54 test fires^{21,22} 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 (TF4–TF6), 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 EN 54 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; CO₂, H₂O, CO, H₂, unburnt hydrocarbons, NO and O₂; scattering coefficient, absorption coefficient, and particle size distribution; u.v., visible and i.r. intensity distribution; and acoustic intensity distribution. The measurements 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 5–8; and a second for line or volume detectors which uses a buoyant, free jet.

To be complete, similar measurements of nonfire nuisance sources are required in order to discriminate between a fire and nonthreatening 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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