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RECENT DEVELOPMENTS IN BUILDING FIRE DETECTION TECHNOLOGIES

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ABSTRACT

Sensing technologies and their application to detecting fires in buildings continue to evolve, and recent advances are summarised in this article. Work being conducted at NIST on characterising smoke and on bench-scale evaluation of multi-element detectors and their response to emulated nuisance sources are discussed, and a full-scale test program to ascertain the performance of modern residential smoke detectors is described. Development trends are extrapolated and the research needed to move emerging sensing concepts into building applications are suggested.

BACKGROUND

Prior to the middle of the 20th century, few office buildings and no residences were protected by automatic fire detection systems of any type, and there was no pull from the construction industry to conduct research to change that situation. The impetus for new technology came primarily from the military and aviation sectors. The invention of the cold cathode tube in the 1940s allowed Meili[1] to produce the forerunner of the modern ionisation smoke detector. Fire detectors are now ubiquitous (in North America and elsewhere) protecting constructed facilities of all types including single family dwellings, commercial and retail buildings, industrial installations, government complexes, and transportation systems. Recent surveys indicate that 95% of U.S. homes have at least one smoke detector installed[2]. The ionisation smoke detector has gone from the scientist's bench to the hardware store, with a purchase cost under five U.S. dollars. Multi-sensor detectors are being installed in commercial facilities, high sensitivity aspiration systems are in use protecting critical equipment, and techniques are being incorporated to reduce the incidence of false alarms through more intelligent signal processing and better communication systems. What do emerging technologies promise for the future, and what obstacles need to be overcome to bring the state of fire detection in constructed facilities to the next level? These questions are discussed in this paper.

The state of fire sensing technologies

The measurable environmental parameters that are affected the most by the presence of a fire are temperature, particulate levels, gaseous species concentrations (CO, CO_2, H_2O, O_2, volatile organic compounds, H_2, NO, HCN, HCl, etc.), and electromagnetic radiation. While the universe of options available to sense these parameters is immense, the conditions under which a fire detector must operate substantially constrain the choices of sensing technologies. Cost, reliability, and maintainability take precedence over selectivity, sensitivity, and time response for most situations.

Operating principles of fire sensing devices have been reviewed a number of times in the literature, beginning with Custer and Bright in 1974[3]. Bukowski and Jason[4], Meacham[5] and Grosshandler[6] provided reviews that expanded and updated the topic through the early 1990s. Sensing technologies specifically aimed at cooking and aircraft fire protection were more recently examined by Johnsson[7] and Cleary and Grosshandler[8], respectively. Pfefferseder[9] discussed a number of techniques useful for sensing a variety of gases produced in a fire environment. Sensors that respond to a fire within a volume, as opposed to at a point, operate on different sets of principles, as described by Willms[10].

The red, green and blue signals from a video camera were used by Kozeki[11] to discriminate flaming fires from other radiant sources. Kozeki extended this work thorough imaging processing techniques to detect smoldering fires, as well[12]. A video-based smoke detection approach, specially designed for tunnel applications, was described by Wieser and Brupacher[13].

A two wavelength, near IR sensor was developed by Lloyd et al.[14] to respond to radiant emission either directly from a small fire or to IR reflected from the walls and ceiling, permitting the system to detect fires not in the line-of-sight or even in the same room. A prototype was constructed and shown to respond properly to the EN54[15] flaming fires, but to be unable to detect the EN54 smoldering fires unless viewing them directly. A fast infrared array spectrometer was used by Kim et al.[16] to view the entire spectrum between 1.8 μm and 4.9 μm and enhance the detection of smoldering fires.

Open-path FTIR methods were examined[17] to determine the trade-offs between the quality of the optics (i.e., price) and the sensitivity of the system to detect different fire and non-fire situations. The rich amount of information in the transformed IR spectrum is sufficient to ascertain a fire from a non-fire, but the investigators have not yet come up with a practical, moderate price detection system suitable for anything other than very specialised industrial applications. A less expensive IR system approach was developed by Goldmeer[18], who based his sensor on a simple absorption cell using mid-IR LEDs and detectors.

Kaiser and Kempka[19] employed microwave radiation at wavelengths between 3 mm and 10 mm (frequencies between 30 GHz and 90 GHz) to increase the penetration of the beam through smoky environments, and demonstrated the ability to detect the smoldering and luminous EN54 fires.

Fiber-optic coupled diode lasers have been used to sense low concentrations of combustion products (e.g., CO, CO_2, O_2, NO, CH_4). Current research is aimed at determining the limits of multiplexing signals from hundreds of individual fibers so that a single laser can be used to monitor an entire building[20]. This is necessary to bring the cost within reason. Fiber optics also can be used to directly sense a fire. Through the Raman effect, it is possible to locate a hot region along a long fiber to within a few meters, which is particularly useful when monitoring tunnels (occupied or unoccupied) for fires[21].

Micro-fabrication of tin-oxide arrays is a promising technology for sensing multiple gas species. The technique is described by Harms et al.[22], who have demonstrated the technique's ability to sense a fire early and to discriminate fire products from confounding background species.

A number of less conventional mechanisms have been proposed recently for detecting fires. For example, some devices use acoustics to sense the products of a fire. Nebiker[23] developed a photo-acoustic detector based upon a microphone coupled to an IR absorbing gas cell; and da-Silva[24] measured the perturbation of an ultrasonic wave as it interacts with particulate matter in a smoke plume. An ion mobility spectrometer was used by Lenkeit[25] to measure chemical products formed during degradation of a flame retarded polymer.

Indoor air quality (IAQ) sensing technologies are being looked at to improve the reliability and performance of both fire detection and IAQ control systems[26]. Multiple criteria algorithms that consider combinations of threshold values, rate of rise of signals, and statistical characteristics of signals recently have been employed and have begun to appear in commercial products[27-30]. Typically, these detectors are certified via the standard test protocols developed for single-sensor detectors, which include full-scale room fire tests in EN54 part 9, and UL 268[31]. The enhanced benefits of multi-sensor, multi-criteria detectors over single-sensor detectors are not completely established by such tests.

Issues of concern

New sensor technologies do not necessarily, in themselves, lead to new and useful fire protection systems. The usual hindrances to new technology (high first costs, high maintenance, unproven performance in the field, incompatibility with existing systems) are supplemented by the concerns associated with any life safety system. For technologies which operate on qualitatively different principles than the current state, standard test methods may not be adequate to demonstrate the value of the technology, and existing codes may not permit the benefit of the technology (even if demonstrable) to be captured.

A number of issues are being tackled by NIST in the Building and Fire Research Laboratory to better enable the adoption of new fire detection technologies. These include:

- better characterisation of products from fires
- standardisation of nuisance sources
- prediction of the transport of products from the fire to the sensor location
- scientifically-based performance assessment

Three specific projects that address one or more of these issues are discussed in the following sections.

Detector performance assessment

The Fire-Emulator/Detector-Evaluator (FE/DE)[32] was developed at NIST to deal with multi-sensor, multi-criteria detectors and combination IAQ/fire sensors. The FE/DE, shown schematically in Figure 1, provides a controlled environment where sensors can be exposed to fire signatures, indoor air pollutants, and nuisance sources. Increasing temperature, changing velocity, and varying particulate and chemical species concentrations at the detector location are some of the variables controlled. The device has been used to evaluate the smoke entry lag effects of detectors at low to moderate flows[33]. Analog output detectors were exposed to square wave changes in smoke concentration at various fixed velocities and fixed ambient temperature. A two parameter model was developed to capture the time lag which was observed to be substantial at low flow velocities (< 0.05 m/s). The exposure of sensors to nuisance aerosol is also underway[34].

Environmental signatures at the sensor location to be emulated in the FE/DE can come from full-scale experiments or numerical simulations of the smoke, gas, and heat transport from a fire or other source. Cleary et al.[35] varied the velocity, temperature, and smoke concentration over time in the FE/DE to demonstrate that a test fire exposure can be emulated in a repeatable manner, and that a multi-sensor, multi-criteria detector's response can be evaluated. For example, TF 4 from EN54 part 9 is a polyurethane foam fire consisting of three mats (50 cm x 50 cm x 2 cm thick stacked on top of one another) that exhibits a peak heat release rate of approximately 50 kW and produces a large amount of smoke. While smoke and temperature values at a standard detector location have been reported in the literature, velocity measurements are not available[36,37]. To overcome this deficiency, computational fluid dynamics calculations of the fire were conducted to predict the velocity profile at the detector location, as well as the time-varying temperature[35]. Figure 2 shows the simulated velocity-time trace and the duct velocity measured in the FE/DE.

The FE/DE light extinction measurements[35] were found to be almost a factor of two lower than values produced in full-scale room tests. This discrepancy was attributed partially to the different light sources used and partially to the limitation in the amount of smoke produced in the propene burner. The measured optical density for six trials is shown in Figure 3.

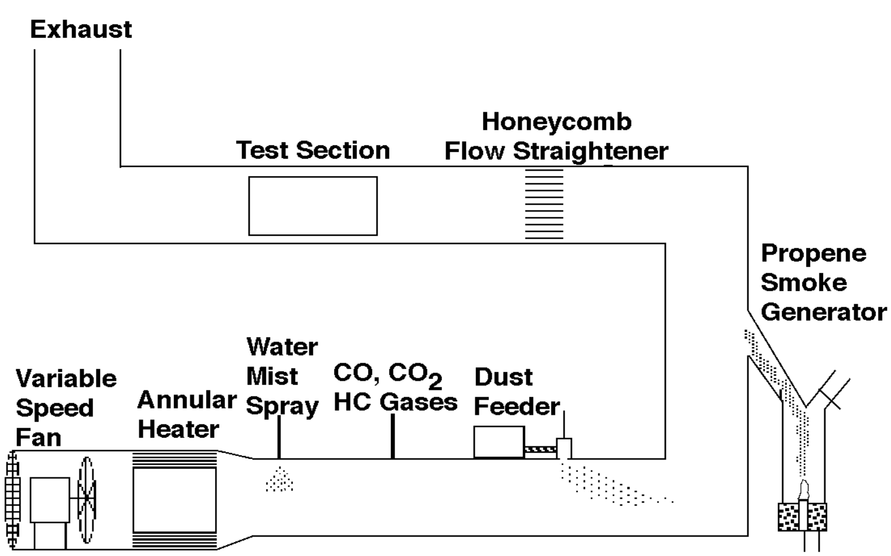

Figure 1: Schematic of the Fire Emulator/Detector Evaluator (FE/DE).

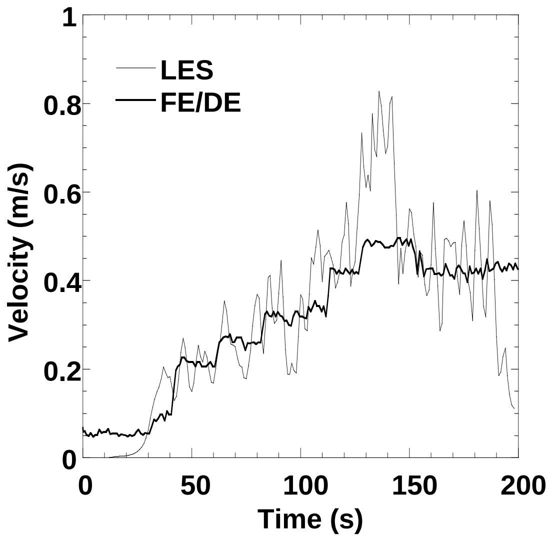

Figure 2: Velocity time trace; FE/DE compared to large-eddy simulation (LES).

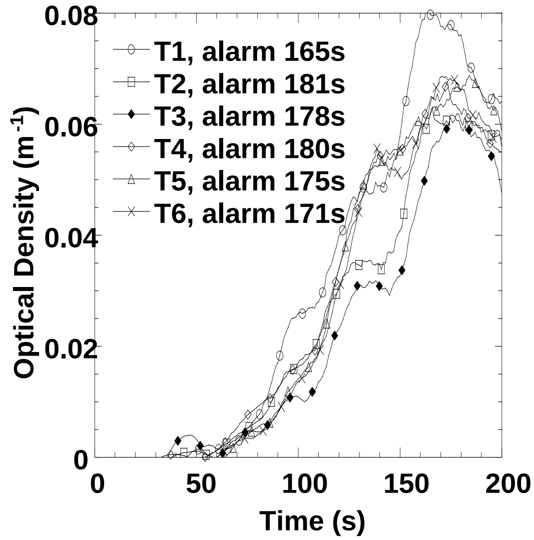

Figure 3: Optical density vs. time using FE/DE (six duplicate tests).

Light scattering properties of smoke particles

A critical concern for the detector community is the ability to discriminate fire aerosols from non-fire aerosols and thus reduce false alarms. A novel aspect of this research is the determination of the magnitude of scattering in terms of the mass concentration of the smoke particles present, which is more easily applied to calculations than dimensionless angular data commonly reported in the past. A light scattering and extinction apparatus (Large Agglomerate Optical Facility) was designed and developed at NIST for examining the extinction cross sections per mass of acetylene and ethene soot particles produced in a co-flow laminar burner[39,40] at red and infrared wavelengths. This apparatus has been adapted[41] to measure angular scattering cross section per mass, $\sigma(\theta)$ [m^2 g^{-1}], of condensed matter at a wavelength of 632.8 nm, over an angular range of 5° to 135°. The smoke particles flow vertically downward in a glass cylinder while the incident laser beam and scattered beam, which define the scattering plane, are orientated horizontally. Polarising optics are used to examine the polarisation specific effects of the scattering.

Smoke particles that have been investigated[42] were wood blocks pyrolysed on a hot plate (EN54 TF2), smoldering cotton lamp wicks (UL217[43] and EN54 TF3[15]), and propene soot from a co-flow laminar burner. All of these smoke particles were generated in the FE/DE and then a sample was transported to the light scattering apparatus for the scattering experiments. A non-fire aerosol, ISO Fine Dust, was also examined in the FE/DE to expose detectors to nuisance alarm aerosols.

Differences in the gradients of the scattering cross sections at small scattering angles were observed due to variations in particle size of the different samples. The size distributions were determined using inertial impaction[44], and were found to be polydisperse as expected. In the case of wood and dust the mean aerodynamic diameter was found to be 1.5 μm and 2.3 μm respectively; the cotton lamp wick smoke has a small mean diameter, 0.3 μm, resulting in scattering at small angles that is both smaller and slowly varying with small increases in scattering angle. The scattering from the propene soot is different because the scatterers are composed of agglomerates, chain-like aggregates of 10 nm to 80 nm primary particles[45,46]. The agglomerates themselves can grow as large as 400 μm[47], but are typically about 20 μm in size[39]. A method of discriminating the soot and non-flaming fire generated smokes based on the ratio of horizontal-horizontal polarised to vertical-vertical polarised light scattering at 90° has been proposed[42,48] and to some extent has been considered as a means of minimising false alarms. Figure 4 is a log-log plot of the angular scattering cross section (vertical-vertical polarisation) as a function of the scattering parameter, q, where $q = 4\pi\lambda^{-1}\sin(\theta/2)$ and λ is the wavelength of the scattered light. The slope for propene soot at $q \geq 12$ μm^{-1} is 1.8 while the values for the other particles are about 3 or larger. Values of less than 2 are universal for soot particles

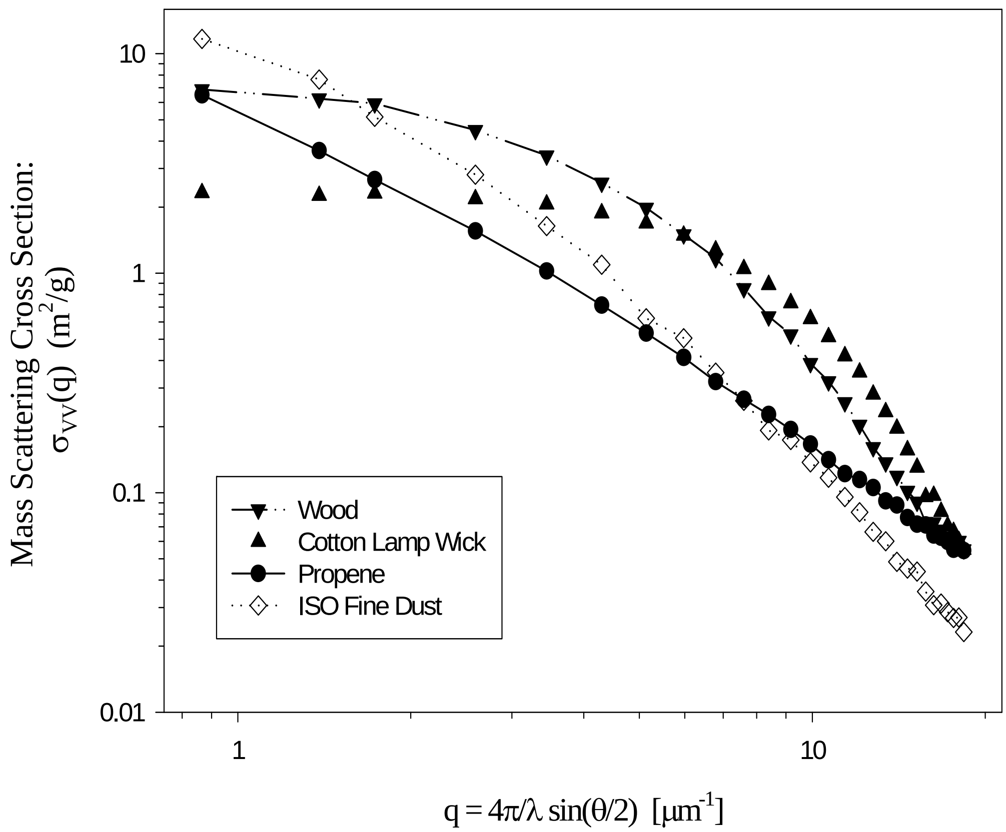

Figure 4: The mass scattering cross section plotted as a function of the scattering parameter, *q*.

due to the mechanisms that lead to the primary particle forming agglomerates. In fact, the slope of the soot result is related to the fractal dimension characterising the mass distribution in the agglomerate and is in the range of 1.7 to 1.85 for all soot[47]. The difference in slope between the soot and non-flaming fire generated smokes has been proposed as a possible means of discriminating between the two types of smoke particles[42]. The extension of these approaches to non-fire aerosols is being examined. However, the morphology difference between the non-flaming fire generated particles and nuisance alarm particles is not as substantial as that between soot and non-flaming fire smoke particles.

Home smoke alarm research project

There is little incentive for industry to produce and install better residential fire alarms until performance improvements can be demonstrated through objective, realistic, and accurate testing. In co-operation with several North American governmental and non-governmental agencies, NIST is coordinating the evaluation of current and emerging smoke alarm technology responses to common residential fire scenarios and nuisance alarm sources. The purpose of the project is to determine if different types of fire alarms can respond to threatening residential fire settings in order to permit egress of typical groups of occupants.

Tasks that are underway include the identification of conditions representative of current fatal residential fires; evaluation of the efficacy of current requirements for number and location of smoke alarms; development of standard nuisance alarm sources to be included in the test program; examination of other fire detection technologies in combination with smoke alarms; collection of data on the potential for improvements in performance by new technologies;

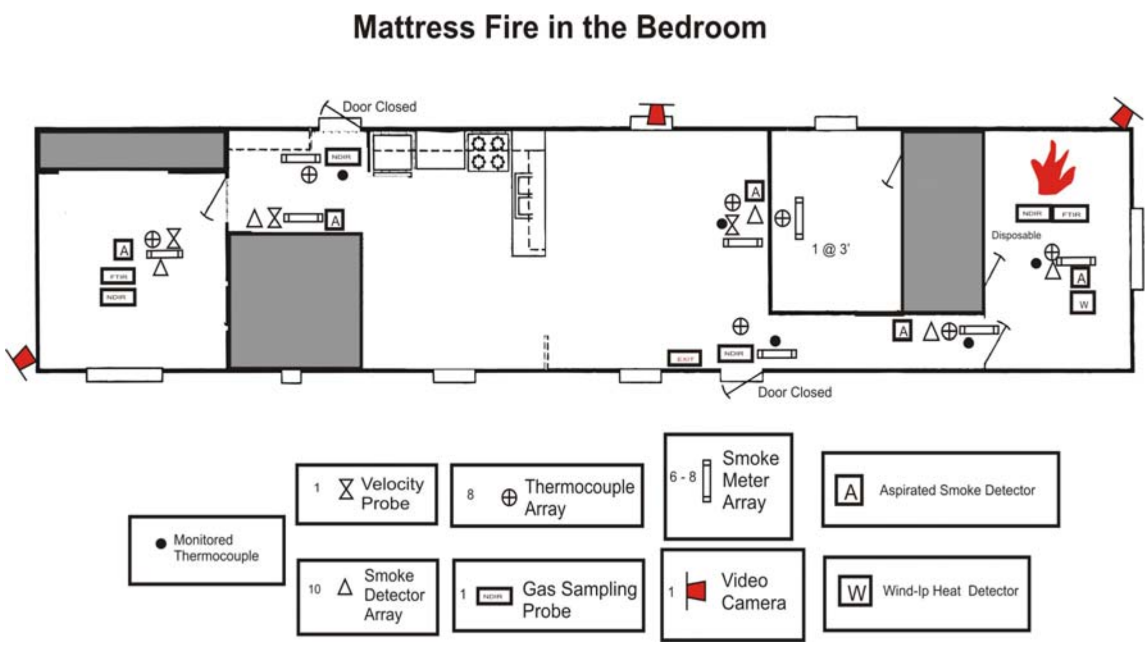

Figure 5: Plan view of manufactured home configuration for smoke alarm tests. The overall length is 20.1 m and the width is 4.2 m.

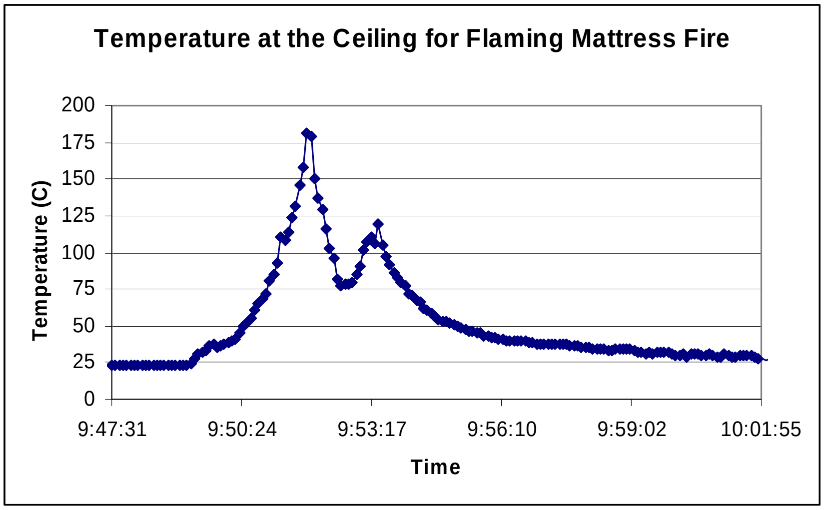

Figure 6: Temperature traces taken in the room of fire origin during the manufactured home smoke detector tests.

characterisation of test detectors and alarms in a consistent manner to facilitate comparisons; and utilisation of fire models to extend the applicability of the test arrangements and test instrumentation; and the distribution of data collected to interested parties.

Measurements are being conducted in three different facilities: a two-story brick house (165 m^2 floor space, with an operating forced air heat pump) slated for demolition; a manufactured home located within the NIST Large Fire Laboratory; and the NIST FE/DE apparatus. Figure 5 is a plan view of the manufactured home configured for testing a mattress fire scenario, which was chosen due to the frequency and number of fatalities resulting from mattress fires. A residential mattress (twin size, pillow top design) allows for smoldering and flaming tests. The igniter is constructed of a nichrome wire loop on a ceramic insulator powered from a variable voltage AC transformer to generate a smoldering condition. Figure 6 shows an example of the temperature reached at the ceiling of the bedroom in the manufactured home test. A final report on the project is expected in 2002.

FUTURE TRENDS

Continued research into fire detection is motivated by one or more of the following needs:

- to increase the ability of fire detectors, based upon current sensor designs, to discriminate a fire threat from a non-threatening change in the environment;
- to adapt emerging sensor technologies to extend capabilities of current fire detection systems;
- to better protect special hazards; and
- to improve certification and predictive capabilities for detection systems.

The main drive from the building industry is for proven fire detection technologies that can be installed and operated at lower cost; enhanced performance capability is a lower priority, especially if the enhancement is associated with some risk. The global move to performance-based codes is resulting in increased dependence on detection, however, creating a demand for higher reliability and more predictable performance. Fire alarm system manufacturers are following closely advances in sensor technologies, and would like to know more about the signatures of fires and nuisance sources, but are wary of radical departures from the conventional ionisation and photoelectric smoke detector designs. The industries providing the major impetus for research into new detection technologies are those with special hazards or those impacted by changing regulations. Telecommunication central offices, computer network systems, aircraft cargo holds, manned space craft, and hazardous storage areas are examples of applications pulling for innovative fire protection solutions. A technology push is coming from smaller companies and aerospace industries previously unassociated with fire detection. These are typically companies at the cutting edge of sensor design and manufacturing, companies with expertise in information technology and communications, or companies who are pushing a technology originally developed for the military into a new, civilian application.

Current knowledge is insufficient to predict the performance of existing detection technologies in anything other than idealised situations. Innovative systems cannot be designed, certified, or installed if it is not possible to predict their behavior in the field. For this we need to understand the following: material behavior under heating and flaming conditions; dynamics of fire growth and smoke movement prior to and during suppression counter-measures; how to sense and discriminate low levels of emissions from pyrolysing and burning materials; and how to sense and discriminate background sources of the same emissions. The viability of computational experiments has been demonstrated using CFD codes to examine detector performance under complex geometries and air flows[49]. This approach, coupled with a small number of confirming experiments promises to provide significant insights into complex phenomena at substantially less cost.

Research is required to overcome barriers to the implementation of unconventional but promising new technologies, and to provide answers to complex, interrelated questions like, What can be gained by sharing information among other building systems such as indoor air quality, heating and cooling, and/or security? Can sensing be used to actively control fire counter-measures during suppression and clean-up? or, How does one evaluate an integrated detection/suppression (and building control) system?

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