

Briefing Paper

Characterising the smoke produced from modern materials and evaluating smoke detectors

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Abstract

The test fires that are used to assess ionisation and optical smoke detectors were developed in the 1980s, but the materials now found in modern service environments have changed since then. There is now a greater use of plastics and flame retardant foams in modern buildings, but little information exists on the response of detectors to smoke generated by the burning or smouldering of such materials.

Twelve approved smoke detectors (commercial and domestic) were installed in a fire test room on the ceiling and the walls. Twenty-nine fire tests were performed using a variety of materials in flaming and smouldering conditions. In tests that produced sufficient smoke, 97.8% of devices responded with an appropriate alarm.

It was confirmed that ionisation and optical smoke detectors are attuned to detecting different types of fires. However, sufficient evidence was found to demonstrate that these detectors nevertheless respond appropriately to a broad range of fires, both within and beyond the limits of the test fires currently used to assess them.

Introduction

The object of this research project was to investigate the smoke profiles generated in fire tests specified in the EN 54-7 (commercial) and EN 14604 (domestic) smoke detector standards, and compare them with smoke produced from burning or smouldering materials commonly found in today's service environment. The intention was to establish whether the current test fires are adequate for assessing smoke detector performance in a broad range of fires involving modern materials, and – if not – to make recommendations.

The research work was conducted in two phases. The first comprised of a review to identify the materials and burning conditions that would be used in Phase 2, during which fire tests were conducted.



Background

Both ionisation and optical smoke detectors are used in commercial and domestic environments. They use different techniques to detect smoke, making them more attuned to detecting different types of fire.

Ionisation detectors use a small radioactive source (americium-241) inside an ionisation chamber that contains charged electrodes. The chamber is arranged to allow a flow of air from outside. As the air enters it becomes ionized, generating an electric current between the charged electrodes. When smoke particles pass into the chamber the ions become attached to them and are carried away, leading to a reduction in the current. More ions are stripped away when there are many small particles, such as those generated during flaming fires. When a material is smouldering it tends to produce fewer but larger particles than it does when in flames. As these cause less current reduction, ionisation detectors are inherently less responsive to the large smoke particles generated during smouldering fires.

Optical smoke detectors typically use a smoke scatter chamber, which contains an LED source with a collimated lens that produces a beam. A photodiode is located at an angle to the beam. As smoke particles enter the chamber they interrupt the beam and the light is scattered and detected by the photodiode. This results in a voltage that can be used to determine an alarm condition. Optical detectors respond to smouldering fires very quickly, as the larger particles generated cause more scattering. Optical scatter chambers are less sensitive to small particles – and become progressively less sensitive as the smoke particle size approaches the LED wavelength used. Therefore optical smoke detectors are slower at detecting the small smoke particles generated from flaming fires. These detectors are less likely to produce false alarms from cooking fumes and steam than ionisation detectors.

As both technologies contain inherent strengths and weaknesses, this research project aimed to determine whether ionisation detectors perform poorly in certain types of smouldering fires, and if optical detectors are less responsive to certain types of flaming fires.

The current test fires

Both EN 54-7 and EN 14604 use the same methodology to identify the most challenging conditions under which to test smoke detectors. Physical tests conducted in a smoke tunnel are used to establish the orientations at which the detector is least sensitive, and to select the four least sensitive detectors from a batch of twenty.

During the fire tests the four worst performing samples are installed in the fire test room (as specified in the relevant standard) at the least sensitive orientation on the ceiling or wall. Four fire tests are then performed as follows: TF2: smouldering wood, TF3: glowing smouldering cotton, TF4: flaming plastics (polyurethane) and TF5: flaming liquid (n-heptane) fire.

The conditions in the fire test room are tightly controlled and the intention is to produce reproducible test fires.

The average smoke profiles produced from the four test fires are shown in Figure 1. The y-axis (m) represents the optical density (measured in dB/m) and indicates the quantities of larger particles generated during smouldering fires. The x-axis (y) is a dimensionless quantity that represents the amount of ionisation taking place and represents the number of smaller particles generated during flaming fires.

The four test fires produce a broad range of smoke types with different properties. These are used to assess the smoke entry characteristics and the sensitivity levels of smoke detectors. Materials such as plastics and flame retardant foams will generate smoke with different properties when flaming and when smouldering – depending on the type of smouldering (e.g. near a radiant heat source or sustained contact with hot surface). The research aimed to establish whether smoke from such fires was effectively covered by existing fire tests, and to assess the performance of ionisation and optical detectors when responding to smoke of this kind.

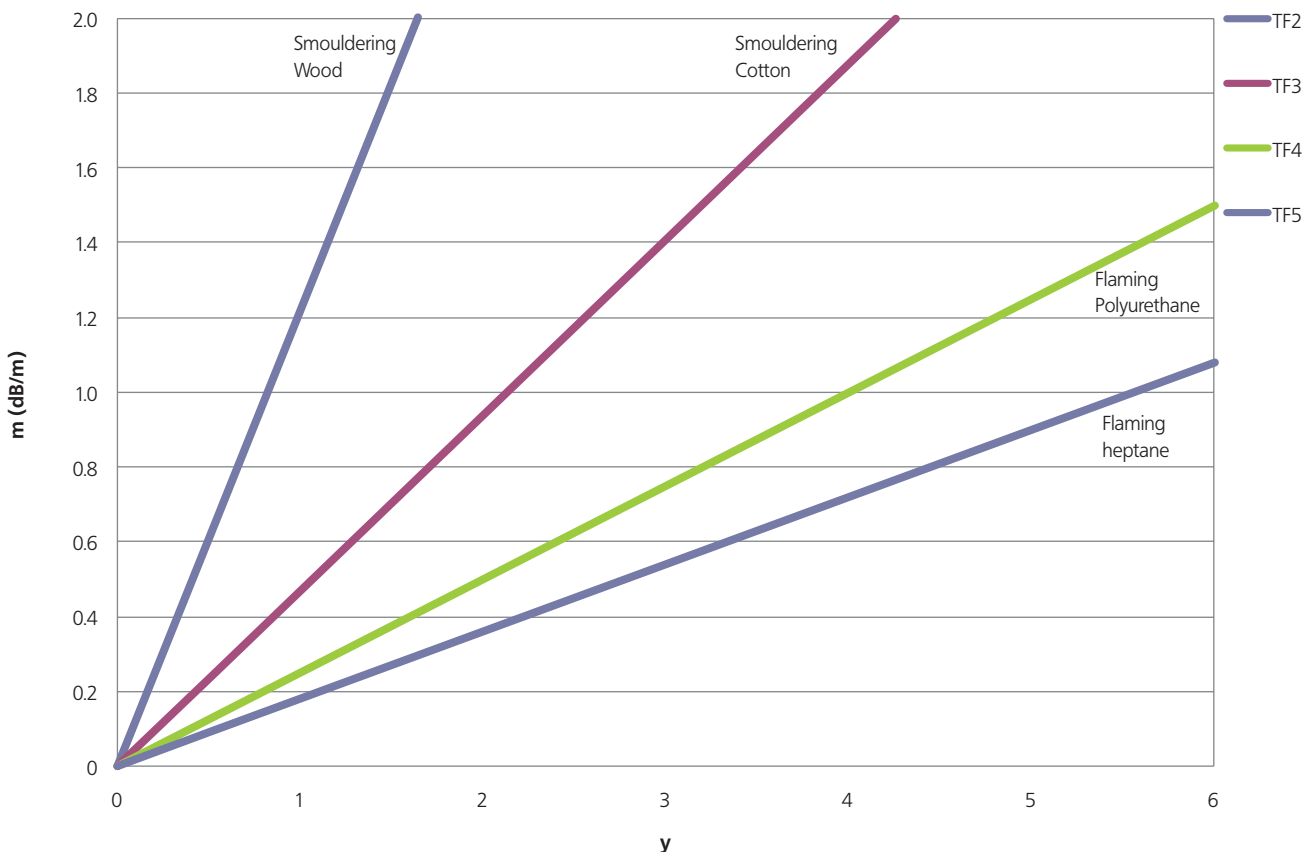


Figure 1: Average m:y profiles of the four currently used test fires

Methodology

During phase 1 papers were reviewed and many experts were contacted to determine whether there were any known cases of detectors not responding to certain types of smoke. The data gathered during this exercise helped to establish the test fires to be performed and the supplementary measuring equipment to be used.

The equipment specified in the smoke detector standards (thermocouples near the floor and in the arc, obscuration meter and MIC in the arc) was used in the fire test room. In addition the following equipment was installed to gather further data:

- Two flowmeters
- CO measuring equipment
- Secondary obscuration meter
- Ten additional thermocouples

Twelve approved smoke detectors and smoke alarm devices from undisclosed manufacturers were used in the fire tests. These comprised of eight domestic smoke alarm devices (four ionisation and four optical) with two ionisation and two optical devices being installed on the walls and ceiling. Additionally, four commercial smoke detectors (two ionisation and two optical) were installed on the ceiling.

To define end point of the tests, guidance was taken from the EN 54-7 and EN 14604 standards, which specify end of test limits for smouldering and flaming fires that are $m=2$ dB/m or $y=6$ respectively.

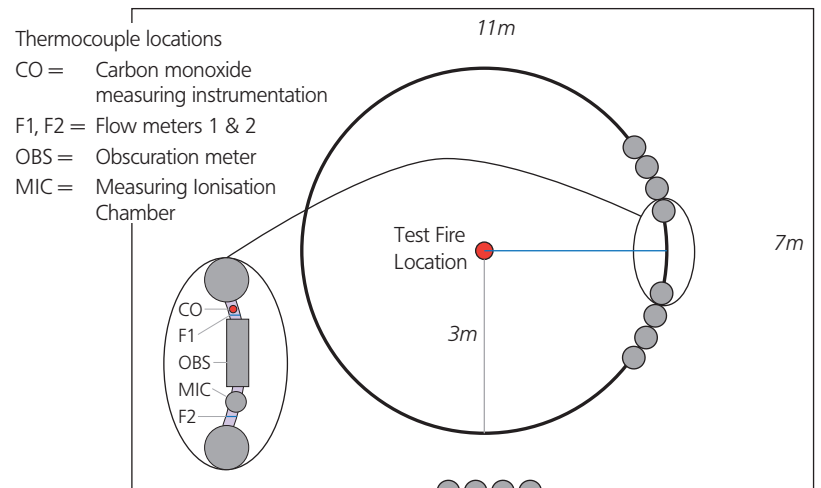


Figure 2: Location of measuring equipment in the fire test room

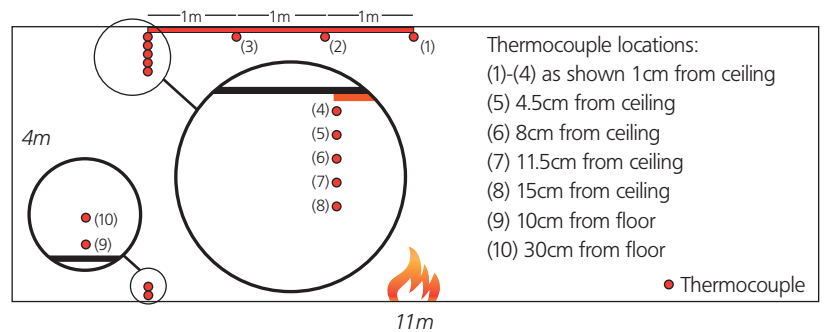


Figure 3: Location of the thermocouples in the fire test room

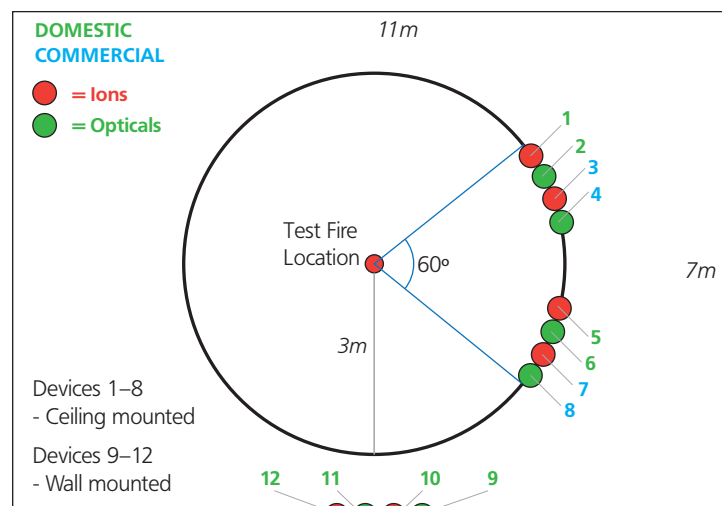


Figure 4: Location of the detectors in the fire test room

Results

Twenty-nine test fires were conducted including the four test fires specified in EN 54-7 and EN 14604. Of these 11 were smouldering fires, 16 were flaming fires and two started off smouldering and went on to become flaming fires (shown as S-F in the table right). The table right summarises the tests that were conducted, the fuels that were used and the mode of smoke production.

All devices were periodically replaced, as exposure to the smoke from a number of tests could cause contamination in the smoke chambers that could potentially affect their response. The second column indicates when all 12 were replaced with brand new devices of the same model, i.e. at tests 1, 10 and 22.

Table 1: The 29 tests conducted in the EN fire test room

Test no.	Device set	Fuel	Mode of smoke production
1	1 of 3	TF2- Beech wood sticks	Smouldering
2	1 of 3	TF4- Non flame retardant PU	Flaming
3	1 of 3	TF5- N-heptane + Toluene	Flaming
4	1 of 3	TF8- Decalin (from ISO 7240-9)	Flaming
5	1 of 3	TF3- Cotton wicks	Smouldering
6	1 of 3	TF1- Wooden sticks (from ISO 7240-9)	Flaming
7	1 of 3	Regular unleaded petrol	Flaming
8	1 of 3	Premium unleaded petrol	Flaming
9	1 of 3	MDF	Flaming
10	2 of 3	TF2- Beech wood sticks	Smouldering
11	2 of 3	PVC cable	Smouldering
12	2 of 3	Flame retardant PU foam	Flaming
13	2 of 3	Flame retardant PU foam	Smouldering
14	2 of 3	Flame retardant PU foam	Smouldering (radiant)
15	2 of 3	Sunflower oil	S-F
16	2 of 3	Newspaper	Smouldering
17	2 of 3	Bedding Polyester	Smouldering
18	2 of 3	Bedding Polyester	Flaming
19	2 of 3	Nylon (small)	Flaming
20	2 of 3	Nylon (medium)	Flaming
21	2 of 3	Nylon	Smouldering
22	3 of 3	Bedding Polyester	Smouldering
23	3 of 3	ABS	Flaming
24	3 of 3	Polystyrene	S-F
25	3 of 3	Polycarbonate	Flaming
26	3 of 3	Polycarbonate	Flaming
27	3 of 3	Polyethylene	Flaming
28	3 of 3	Polyethylene	Flaming
29	3 of 3	ABS	Smouldering

Unless otherwise specified all smouldering fires were conducted in the sustained mode with the fuel in contact with a hot surface that was increasing in temperature throughout the test.

The results from two of these tests are shown in Figures 5 and 6 (right).

Test 9 demonstrates the rapid response of the ionisation detectors (both commercial and domestic) to the small particles generated during the flaming fire. The response from the opticals is slightly delayed until the fire increases in size and the radiant heat leads to more smouldering particles being produced from the MDF. All detectors respond before the defined end of test for a flaming fire ($y=6$) is reached.

Test 24 demonstrates the difference in response between ionisation and optical detectors to a smouldering then flaming fire. At first the polystyrene fuel is smouldering due to the increasing temperature of the steel plate on which it rests. This leads to all 6 photoelectric detectors responding before the defined end of test for a smouldering fire ($m=2$ dB/m) is reached. When the temperature of the polystyrene reaches ignition point (shown as S-F on the chart) the fuel combusts. Within a few seconds the first ionisation detector responds and all ionisation detectors are in alarm before the defined end of test for a flaming fire ($y=6$) is reached.

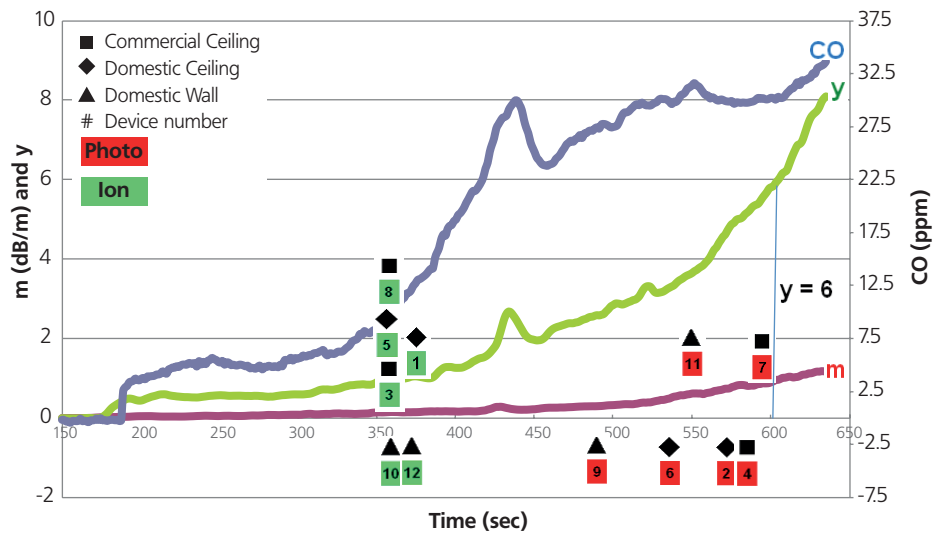


Figure 5: Test 9- MDF in flaming mode

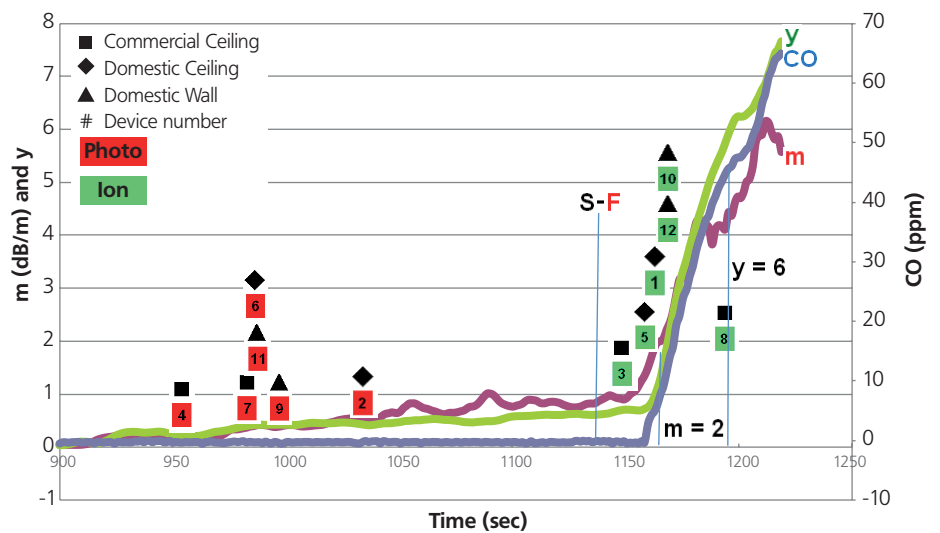


Figure 6: Test 24- Polystyrene first smouldering then flaming



Figure 7: Tests 1 & 10- Smouldering beech wood sticks (TF2) in the fire test room

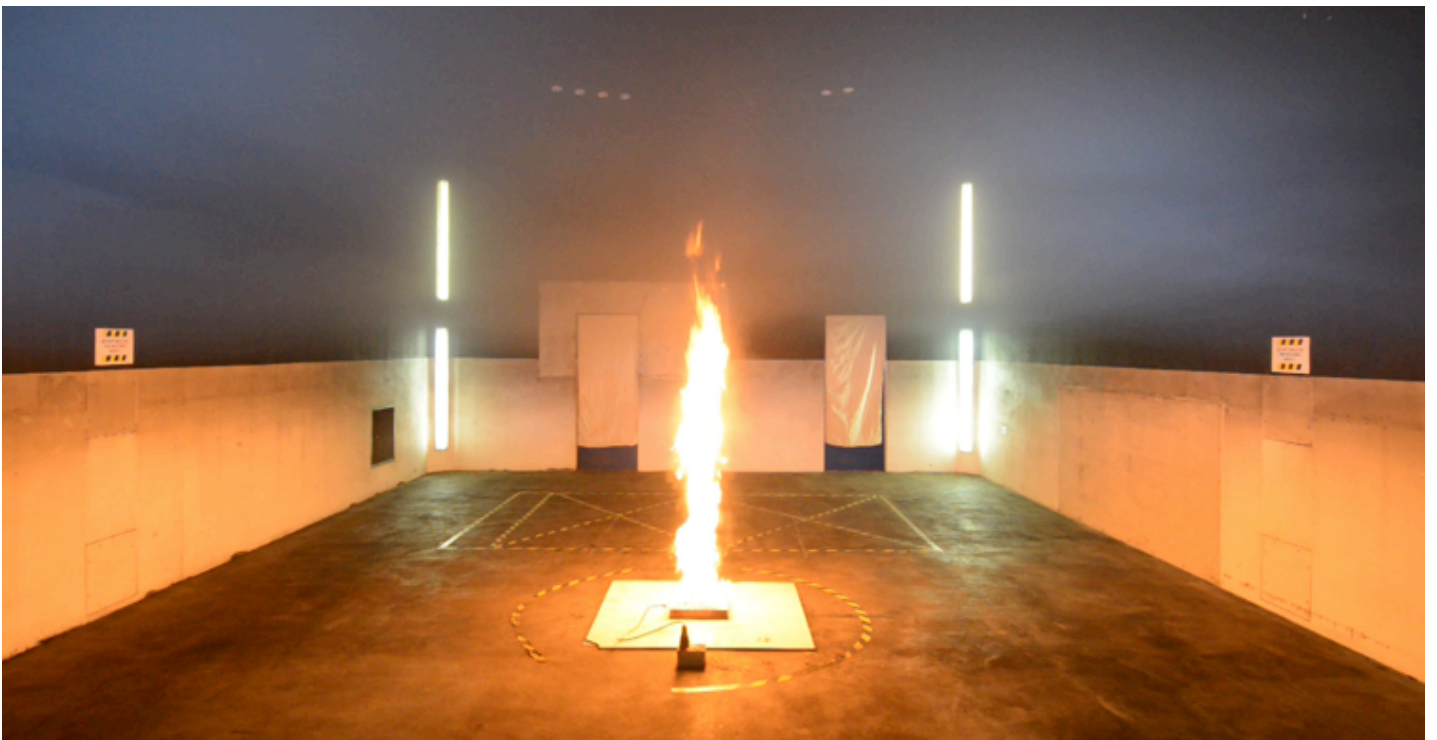


Figure 8: Test 3- Flaming n-heptane fire (TF5) in the fire test room

Analysis

Of the 29 test fires conducted five (shown in Table 2) produced too little smoke (17 Polyester smouldering, 18 Polyester flaming, 19 Nylon, 25 Poly-carbonate and 27 Polyethylene); these were repeated with more fuel.

In this context too little smoke would be considered to be either well before $m=2$ dB/m or $y=6$ or if all devices that would be expected to respond had not responded.

The results from the remaining 24 tests are arranged in order of increasing $m:y$ and are shown in Table 3.

Sixteen of the 24 test fires (shaded in the table) fall within the m/y limits specified by the TF2-TF5 test fires from EN 54-7. From these tests only two negative responses were recorded with 190 positive responses.

For the four tests that had a high mean m/y ratio, the detectors responded for all fires except for domestic wall ionisations 10 and 12, which did not respond to test fire 13, and domestic ceiling opticals 2 and 6 that did not respond to test fire 29.

Table 2: Tests that produced too little smoke

Test	Type	Final m*	Final y*	Mean m/y	No. of device alarms
17	Polyester (S)	0	0	0	0
18	Polyester (F)	0.06	0.23	0.2715	1
19	Nylon (F)	0.11	0.42	0.2126	6
25	Polycarbonate (F)	0.12	0.44	0.2733	6
27	Polyethylene (F)	0.38	1.58	0.2032	8

* These values indicate the m and y levels achieved after the last device operated or when the test was abandoned.

Table 3: Tests that produced sufficient smoke

Test	Type	Final m*	Final y*	Mean m/y	No. of device alarms
6	TF1 (F)	1.27	16.4	0.0794	12
12	FR PU (F)	0.47	4.56	0.0938	12
9	MDF (F)	1.18	8.1	0.148	12
20	Nylon M (F)	0.17	1.23	0.1679	7
2	TF4 (F)	1.32	7.71	0.1962	12
16	Paper (S+F)	0.17	0.62	0.1991	12
7	Petrol L (F)	2.19	10.72	0.2094	12
3	TF5 (F)	1.7	8.07	0.2164	12
8	Petrol S (F)	0.94	3.8	0.2308	12
28	Polyethylene L (F)	1.51	5.36	0.2596	11
4	TF8 (F)	0.9	3.29	0.2665	12
26	Polycarbonate L (F)	0.35	1.14	0.2726	12
5	TF3 (S)	2.08	5.27	0.3429	11
15	Oil (S,F)	1.33	3.98	0.4911	12
23	ABS (F)	2.66	4.14	0.583	12
11	PVC (S)	1.16	1.73	0.7063	12
10	TF2 #2 (S)	1.53	1.66	0.8226	12
24	Polystyrene (S,F)	5.58	7.67	0.8435	12
14	FR PU (S-R)	1.67	1.59	0.8516	12
1	TF2 #1 (S)	2.32	2.29	0.9384	12
22	Polyester (S)	1.23	0.95	1.58	12
21	Nylon (S)	2.48	1.5	1.67	12
13	FR PU (S-S)	1.34	0.97	1.88	10
29	ABS (S)	6.53	2.24	3.04	10

* These values indicate the m and y levels achieved after the last device operated or when the test was abandoned.

For the four tests that had a low mean m/y ratio the detectors responded for all fires except for five optical devices that did not respond to test 20. This is most likely due to the relatively small size of the fire, as the peak m and y values generated during this fire were significantly lower than the other three fires.

It is suspected that if enough smoke had been generated during test fire 20 then all 12 devices would have responded. However this result has not been qualified, so from the results of the remaining 23 fires we effectively have six no responses and 270 responses. This represents positive responses 97.8% of the time. The six no responses are attributed to the inconsistent response of one particular type of detector and suspected contamination for the remaining ones.

Even though no statistical data was gathered by repeating the same tests, the results do provide evidence of the response characteristics for the types of detectors (optical or ion) to a variety of smoke types produced in smouldering and flaming modes.

Data gathered from the additional equipment installed in the fire test room suggests that the limits specified in EN 54-7 in terms of the working volume and temperature distribution are adequate and do not need to be refined. However, the following recommendations are made:

- Assess whether the number of directional dependence measurements should be increased for domestic smoke detectors due to the asymmetrical design.
- To improve reproducibility between test laboratories, the location at which the temperature near the floor is measured should be more clearly specified in EN 54-7.

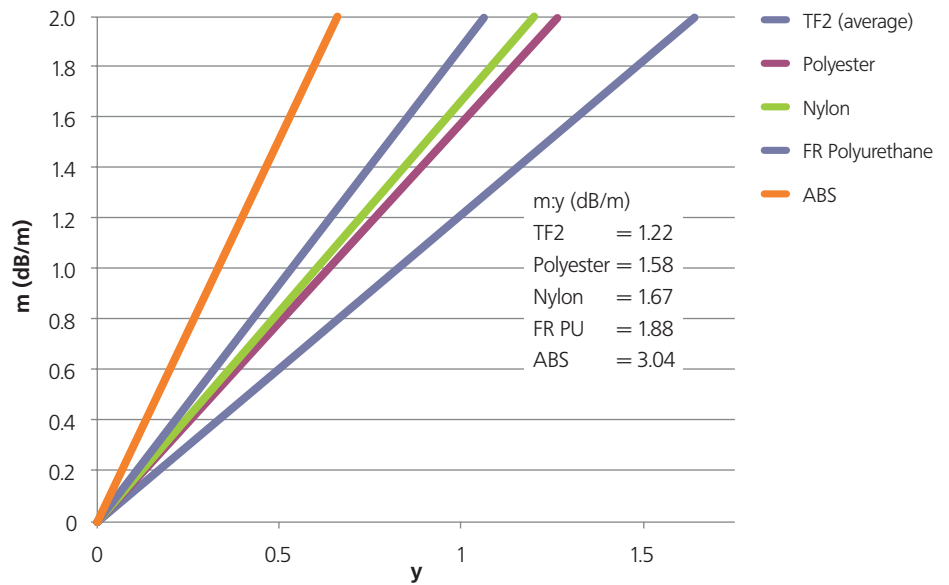


Figure 9: The four smouldering fires with m/y values outside the TF2 range

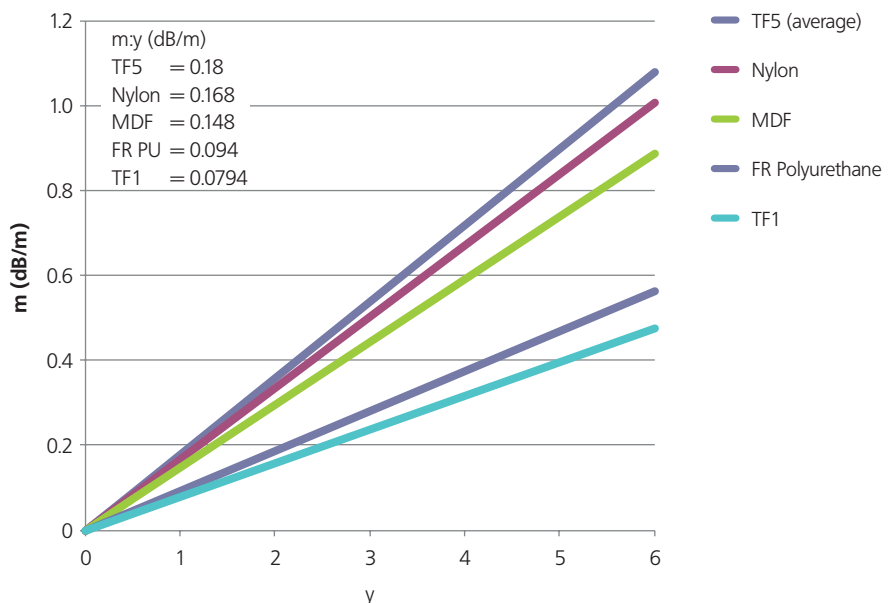


Figure 10: The 4 flaming fires with m/y values outside the TF5 range

Summary of results

Of the 29 test fires, five were considered to be too small and had to be repeated with more fuel. Of the completed 24 test fires:

- 16 were found to be within the m/y range of smoke types bounded by TF2 and TF5;
- four smouldering fires were found to be beyond the (m/y) limits for a TF2;
- four flaming fires were found to be beyond the (m/y) limits for a TF5.

The m/y ratio for the TF1 flaming fire was found to be the worst case of all the flaming fires. This indicates that a defined fire exists for the flaming test fire limit assuming m/y is the appropriate measurement.

For the smouldering tests carried out beyond the TF2 limit, no defined test exists. The m/y ratio for the smouldering ABS fire (29) was significantly higher than the others.

The test fires TF2-TF5 do cover most general purpose applications as a real fire is unlikely to involve only a single type of material. As more materials with different smoke characteristics are involved in the fire the likelihood of detection increases.

However, it should be noted that smouldering fires can continue for a long time with only one material being involved, potentially leading to the production of toxic gases in fatal concentrations. An example of this would be bedding in contact with a heat source such as a lit cigarette. In this case an ionisation detector may not respond and therefore should not be sited in locations where such a scenario is possible. In contrast a flaming fire will eventually produce sufficient heat that will radiate onto other materials and lead to the production of smouldering smoke to which the optical detectors would be expected to respond.

Twelve smoke detectors, eight of which were installed on the ceiling and four on the wall, were exposed to the smoke from a variety of test fires and responded with a 97.8% pass rate.

Conclusions and recommendations for further research

The aim of this research was to measure the smoke characteristics of a number of test fires using modern materials, and assess them against the test fires specified in EN 54-7 and EN 14604.

The research has demonstrated that commercial and domestic approved ionisation and optical smoke detectors respond to a broad range of fires with m/y ratios within and beyond the fire test limits of EN 54-7 and EN 14604.

The fire tests specified in EN 54-7 and EN 14604 are considered to be appropriate and are sufficiently wide in terms of distribution of smoke characteristics.

Both ionisation and optical smoke detectors are attuned to detecting certain types of fire. In order to ensure that the most appropriate type of device is installed, guidance on the appropriate use of ionisation and optical smoke detectors should be sought from relevant codes of practice.

Recommendations for further work

- Assessment of the performance of a variety of optical heat multi-sensor detectors to some of the fires conducted during this research programme.
- Research into a repeatable smouldering fire with an m/y ratio > 3.0 dB/m with a better m/y profile.
- Research into an alternate realistic flaming fire with an m/y ratio < 0.1 dB/m such as flaming flame retardant poly-urethane.

References

- (1) EN 54-7: 2000 + A1 June 2002 + A2 July 2006. Fire detection & fire alarm systems Part 7: Smoke detectors – point detectors using scattered light, transmitted light or ionization. European Committee for Standardisation. Central Secretariat, Rue de Stassart 36, B-1050 Brussels.
- (2) EN 14604: 2005. Smoke alarm devices. European Committee for Standardisation. Central Secretariat, Rue de Stassart 36, B-1050 Brussels.
- (3) ISO/TS 7240-9:2012(en) Fire detection and alarm systems – Part 9: Test fires for fire detectors.

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