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Briefing Paper

The performance of multi-sensors in fire and false alarm tests

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Summary

The early detection of fire is necessary to give building occupants time to escape and to limit the damage to property. Achieving reliable early detection with minimal false alarms over a broad range of applications is a challenge. The detection of smoke-like phenomena commonly found in the service environment, such as steam, aerosols and airborne dust, contribute to the numbers of unwanted alarms. Multi-sensor detectors have been developed in an attempt to meet this challenge, the most commonly used being those incorporating optical and heat sensing technologies.

In theory, detectors incorporating multiple-sensory technologies should provide greater resistance, in terms of reacting later to false alarm sources than detectors using only one technology type. Whilst there are anecdotal accounts [1, 2] of multi-sensor detectors being more resilient to sources of unwanted alarms - particularly those that do not produce heat - more information is needed about multi-sensor capabilities and their variabilities. This study seeks to address some of these by examining the performance of thirty-five optical heat multi-sensor detectors when subjected to a range of test fires, and to assess their resistance to common sources of unwanted alarms.

The multi-sensor detectors chosen are representative of the range available in the marketplace at the time of this study. These detectors were tested alongside two 'reference' single technology optical smoke detectors. Each detector was subjected to a series of ten test fires to evaluate their fire detection performance, and each detector was exposed to five different tests designed to assess their resistance to known sources of false alarm. The multi-sensor detectors were categorised by the complexity of the design to improve their resistance to false operation. The categories were: basic, intermediate and advanced.

As expected, the performance of the multi-sensor detectors and optical smoke detectors in response to test fires was similar. However, during all five false alarm tests the multi-sensors, on average, operated after the single technology 'reference' optical smoke detectors, demonstrating increased resistance to false alarm sources. These results indicate that the sources of unwanted alarm must be present for longer before a fire alarm is triggered, thus providing greater opportunity for user intervention or enough time for a transient cause to die away. Some of the multi-sensors did not respond at all by the end of the false alarm test.

These results demonstrate that multi-sensors have the potential to increase resistance to unwanted alarm sources by delaying the response to transient smoke like phenomena. Typically, this resistance to unwanted alarms increased between the multi-sensor categories, with the 'advanced' category detectors demonstrating the greatest level of resistance. It was noted the multi-sensor detectors set at lower sensitivities operated later in test fires and responded later to the false alarm sources.

The findings broadly support the anecdotal accounts that multi-sensor technology has the potential to reduce certain types of commonly encountered false alarms. However, the degree to which this can be realised depends on the design of the multi-sensor, and in particular the inbuilt features that provide additional resistance to unwanted alarms. It cannot be assumed that use of any multi-sensor detector will impact significantly on the occurrence of false alarms from every form of fire-like phenomena. Not all multi-sensors will provide the same level of resistance.

This research has implications for future product standards and codes of practice. It should be possible and relatively simple to produce a product standard that enables multi-sensor detectors to be graded according to their resistance to specific, commonly encountered phenomena known to result in unwanted alarms. Codes of practice, such as BS 5839-1 [3] (or a supporting Published Document), could then give advice to users on the selection of multi-sensor detectors for specific applications.

Abbreviations and Glossary

The abbreviations list and the glossary are compiled from terms used in this publication. The descriptions in the glossary are not intended to be comprehensive, but to help the reader understand the meaning of terms used in this briefing paper.

Abbreviations

A	Advanced category multi-sensor
ABSSM	Smouldering ABS sheets test fire
B	Basic category multi-sensor
BMKFA	Buckinghamshire and Milton Keynes Fire Authority
CO	Carbon Monoxide
FIA	Fire Industry Association
FRPUFL	Flaming flame retardant polyurethane foam test fire
FRPUSM	Smouldering flame retardant polyurethane foam test fire
KCL	Kings College London
I	Intermediate category multi-sensor
LPCB	Loss Prevention Certification Board
m	Measure of obscuration (in dB/m)
MDFFL	Flaming MDF sheets test fire
RC	Reference commercial smoke detectors
RD	Reference domestic smoke alarm
SD	Standard Deviation
SFRS	Scottish Fire and Rescue Service
TF1	Flaming wooden crib test fire
TF2	Smouldering wood test fire
TF3	Smouldering cotton wicks test fire
TF4	Flaming polyurethane foam test fire
TF5	Flaming N-heptane liquid test fire
TF8	Flaming Decalin liquid test fire
y	Measure of ionisation (dimensionless)

Glossary

Multi-sensor detectors - Fire detectors that use a combination of smoke, heat and carbon monoxide sensors to detect the presence of a fire.

Optical heat multi-sensor detectors – Fire detectors that use a combination of optical smoke and heat sensors only to detect the presence of a fire.

Introduction

Early and reliable detection of fire is vital to alerting people to the presence of a fire hazard and giving them sufficient time to escape. Providing warning before the fire has developed also allows fire suppression strategies to be implemented for the protection of property. Early warnings from fire detection systems are partly responsible for a significant downward trend of fire fatalities in Great Britain from 967 in 1985/6 to 322 in 2013/4 [4].

The products generated by a fire depend on the burning material and levels of oxygen present. The types of smoke produced from different types of fires can be very broad in terms of their characteristics - i.e. optical density, buoyancy and colour. Smoke detectors are expected to respond to all types of smoke. Unfortunately, some of these smoke characteristics overlap with those of airborne particles produced from non-fire sources, such as steam, dust, aerosol sprays etc., the effects of which could be identified by smoke detectors as smoke from fires.

Such phenomena lead to large numbers of false alarms in the UK. Although the fire and rescue services have been producing guidance for the public to help reduce them [5], the losses due to false alarms to UK businesses are estimated to be in the region of a billion pounds per year [6].

Multi-sensor detectors (see example in Figure 1) have been identified as a technology that in the future, with greater implementation, could reduce the number of false alarms from fire detection systems. In essence, by sensing more than one of the types of signature associated with fire - such as smoke as well as heat or carbon monoxide - they give a more reliable warning of a fire.

Common false alarm causes, such as steam, dust or aerosol, produce little if any heat or carbon monoxide. The optical technology within multi-sensor detectors can be configured to be less sensitive when these phenomena are not sensed, but automatically increase their sensitivity to smoke when they are.

Figure 1: Multi-sensor detector

BRE has been involved in two investigations into how false fire alarms can be reduced. The first of these, performed with Kings College London (KCL) and Buckinghamshire and Milton Keynes Fire Authority (BMKFA) [1], was completed in June 2014 and proposed that the greater use of multi-sensor detectors could reduce false alarms significantly. It also proposed a further research study in which a false alarm investigator would accompany fire and rescue service personnel whilst they attended false alarms, and investigate these to identify route causes. The investigator would be a specialist with knowledge of fire detection systems and understanding of false alarm causes.

This led to the second study completed in December 2015, which was performed in collaboration with the Scottish Fire and Rescue Service (SFRS) and a broad range of fire experts [2]. A detailed breakdown of false alarm causes and proportions can be seen in Figure 2, along with false alarms that could potentially be reduced using multi-sensor detectors (highlighted in red).

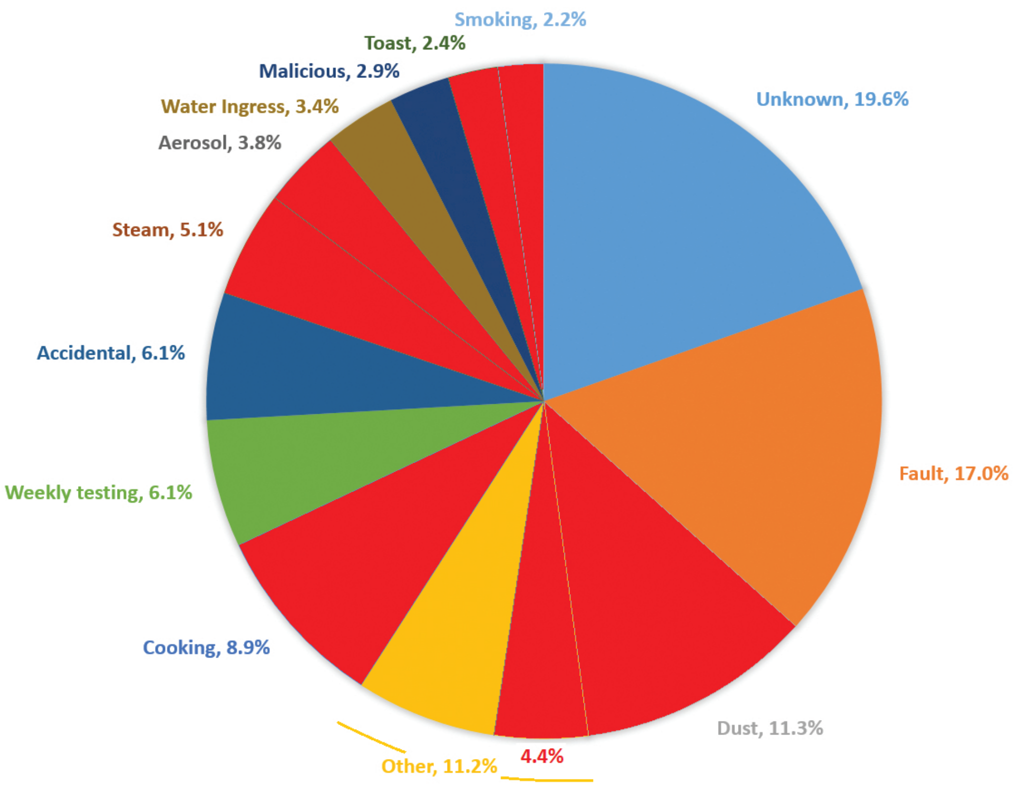


Figure 2: Causes and proportions of false alarms observed and expected reduction using multi-sensor detectors

The self-consumption of solar electricity through EV charging of fleet vehicles can also provide operational savings. In this respect a study has shown how self-consumption could save organisations with a fleet of 10 EVs up to £14,000 per year. The Go Ultra Low campaign has been set up to provide information about EVs and support organisations to convert 5% of their vehicle fleet to electric by 2020.

Multifunctional solar carports are typically more cost effective than installing the three technologies (i.e. PV, energy storage and EV charge-points) separately, as they share infrastructure and project delivery costs. In addition, solar car parks can reduce operational costs of EV charge-point and increase electricity supply security.

Currently the Office for Low Emission Vehicles (OLEV) are operating a voucher based grant scheme for the installation of EV charge-points for businesses, charities and public sector organisations. The scheme may contribute £300 per charging socket for use by staff and/or fleet vehicles (up to a maximum of 20 per application).

By analysing the causes and considering the use of multi-sensor detectors in those scenarios, it can be estimated that potentially 38.1% of observed false alarms could have been reduced if multi-sensors had been present. Note that of the 11.2% causes reported as 'other', a proportion (4.4% of the entire chart) could potentially be reduced using multi-sensors. Anecdotal accounts from both studies also supported the fact that multi-sensors used in the field had directly led to a reduction in false alarms.

This study proposed thirty-five recommendations for nine stakeholder groups, which could lead to a future reduction in false alarms. One of those recommendations was that further research into multi-sensors needed to be performed to better understand the capabilities and the variabilities of this technology. Depending on the manufacturer's design, processing of sensor data and level of false alarm rejection methods incorporated into the multi-sensor, they can have very different responses to false alarms when compared with other multi-sensors.

At one extreme of multi-sensor design are the most basic types in which there is little more than a rudimentary enhancement in the response to smoke when a heat signature is detected. At the other end of the scale there are very sophisticated devices that perform a multitude of intelligent functions, sometimes using multiple smoke sensors to identify and ignore false alarm causes. Clearly, with such variations in performance capabilities, the effectiveness to detect fires and reject false alarm sources will also vary depending on the level of sophistication incorporated.

There are many types of multi-sensors in the marketplace but the use of optical heat type multi-sensors, using an optical smoke chamber and one or more heat sensors, is prevalent and proper guidance on their selection and use is much needed. It is for this reason the study focussed on optical heat type multi-sensors.

The multi-sensor detectors used were categorised by their design and, together with standard optical detectors, were subjected to a broad range of test fires and false alarm tests. It was not expected that all multi-sensors would be immune to false alarms, but in general multi-sensors should offer greater resistance when compared with single technology detectors.

Background details on the technologies and test methodologies

Detectors

Optical heat type multi-sensor detectors are known by industry experts to have a broad range of performance capabilities. In their simplest form they 'thermally enhance' the signal from the optical (smoke) sensor. For example, when a heat signature is identified the alarm threshold on the smoke sensor is lowered according to the amount of heat increase. This arrangement allows the multi-sensor detector to have an improved response to flaming fires, which typically produce more heat than smoke. The detection performance and resistance to unwanted alarms of an optical heat type multi-sensor detector should in theory, therefore, be better than either a single technology ionisation or optical detector over a broad ranges of fires.

The simplest detectors have been designed with little or no consideration of false alarm resistance. The more complex optical heat type multi-sensor detectors can have a number of additional features that allow them to ignore common false alarm sources. For example:

- robust smoke chambers designed to reject certain types of false alarms,
- spike rejection algorithms that monitor the electrical signals from the sensors and limit immediate responses to a sudden increase from one sensor,
- fuzzy logic analysis examining data from sensors in a more intelligent manner - continuously monitoring and analysing background levels and trends, and examining the combined effects from all sensors before making the appropriate decision.

Standard fire sensitivity tests

Both EN 54-7 [7] and EN 54-29 [8] standards describe the tests used to measure the fire sensitivity of point smoke and combined point smoke and heat detectors. Both standards use the same methodology to identify the worst performing orientations and the four worst performing detectors to assess during the fire tests. Using the worst performing detectors/orientations to demonstrate compliance with detection criteria provides confidence that other detector samples will also meet the performance requirements.

The test specimens are installed in the dedicated fire test room of standard dimensions. The conditions in the fire test room are tightly controlled to produce as repeatable a fire as possible. The test specimens are mounted on the ceiling on a 3m arc, 4m above the fire source. Four test fires are then performed to EN 54-7. These test fires are TF2: smouldering wood, TF3: glowing smouldering cotton, TF4: flaming plastics (polyurethane) and a TF5: flaming liquid (n-heptane) fire. The four test fires produce a broad range of smoke types with different properties, which can be used to assess the smoke entry characteristics and responses of smoke detectors.

There are two additional tests for multi-sensor detectors in accordance with EN 54-29. These tests assess the detectors' responses to more extreme test fires, i.e. TF1: Open Wood Fire and TF8: Low temperature black smoke (Decalin) liquid fire.

Smoke measurement

Two smoke parameters are used in the fire test room to characterise the smoke generated from the different fires. The dimensionless quantity 'y' relates to the smaller and invisible particles, more of which are produced during flaming fires and are measured using an ionisation chamber. The quantity 'm' (obscuration measured in dB/m) relates to larger particles produced during smouldering fires, which are measured using an optical obscuration meter that uses a light beam to measure the amount of light scattered and absorbed by the smoke particles.

The 'm' and 'y' smoke parameters are used during the fire tests to characterise the smoke development generated by the different types of fire.

Methodology

The work programme in this study was agreed by a research group comprising representatives from the Fire Industry Association (FIA), Steve Brown Consultancy, BRE and twelve fire detector manufacturers:

- Apollo
- Argus Security
- C-Tec
- Eaton
- Ei Electronics
- Fike Safety
- Gent
- Hochiki
- Siemens
- Sprue Safety
- System Sensor
- Tyco Fire Protection

Detectors

The different multi-sensors were categorised as follows:

Basic: A detector that uses the signal from the heat sensor to enhance the signal from an optical sensor (to provide quicker warning for flaming fires) and contains no other design features specifically intended to improve resistance to false alarms.

Intermediate: A detector that, in addition to performing the functions of a basic detector, has been designed to enable it to recognise and not respond to some types of false alarm sources, e.g. spike rejection that ignores a transient potential false alarm (e.g. from an aerosol spray).

Advanced: A detector that contains significant design features that allow it to identify and reject false alarms, e.g. devices that have dual sensor detectors, backward and forward scatter optics, or advanced algorithms that enable it to perform complex background monitoring/pattern recognition.

The thirty-five detectors and modes provided by the twelve manufacturers were sorted into these categories. Each manufacturer described how their devices functioned and proposed a suitable category. The proposals were then reviewed and agreed collectively by the FIA and BRE. The performances of these optical heat type multi-sensor detectors were compared against each other, and against the standard optical smoke detectors that acted as references.

All makes and models of detectors are reported here anonymously. The numbers of different multi-sensors used during this study in each category are shown below, along with the abbreviations used to identify them.

Category	Abbreviation	No. of detectors
Basic	B1-B12	12
Intermediate	I1-I12	12
Advanced	A1-A11	11
TOTAL		35

Table 1: Multi-sensor categorisation and sample numbers

The models of smoke detectors to be used were determined by reviewing the data from the test fires performed as part of an earlier research project [9]. For the 23 completed fire tests from that study, those smoke detectors with the most consistent performance were identified, generally operating in the middle of the spread for optical detectors. One reference commercial smoke detector (RC) and one reference domestic smoke alarm (RD) were identified, and selected for this test programme for use alongside the multi-sensors for all false alarm and fire tests.

The ten fire tests and two false alarm tests (toast and cooking) performed in the BRE Fire Test room were always conducted in the same order, and the detectors were replaced periodically as shown below. All multi-sensors and both optical detectors were replaced at the same time, with detectors that were identical in model and mode of operation.

Test	Details of fire test	Code*	Test sample no.
1	Smouldering wood blocks	TF2	1
2	Smouldering cotton wicks	TF3	1
3	Flaming polyurethane foam	TF4	1
4	Flaming N-heptane liquid	TF5	1
5	Flaming wooden crib	TF1	2
6	Flaming Decalin liquid	TF8	2
7	Smouldering flame retardant polyurethane foam	FRPUSM	3
8	Flaming flame retardant polyurethane foam	FRPUFL	3
9	Smouldering ABS sheets	ABSSM	4
10	Flaming MDF sheets	MDFFL	4
	False alarm test		
11	2 slices of white bread in a toaster	Toast	5
12	Chips and sunflower oil in heated pan	Cooking	5
13	Water mist in re-circulating tunnel	Mist	6
14	Dust in re-circulating tunnel	Dust	7
15	Aerosol spray in test chamber	Aerosol	8
* These are the codes used throughout this paper to refer to the different tests.			

Table 2: Samples and codes used for fires and false alarm tests

Fire Tests

In order to assess the performance of the detectors at the extremes more challenging fire tests were applied that were beyond the m:y limits of EN 54-7. These included flame retardant polyurethane foam (Figure 3) and MDFFL fire tests which produced a lot less heat and very low m:y ratios, making detection a challenge for both the optical and heat sensors.

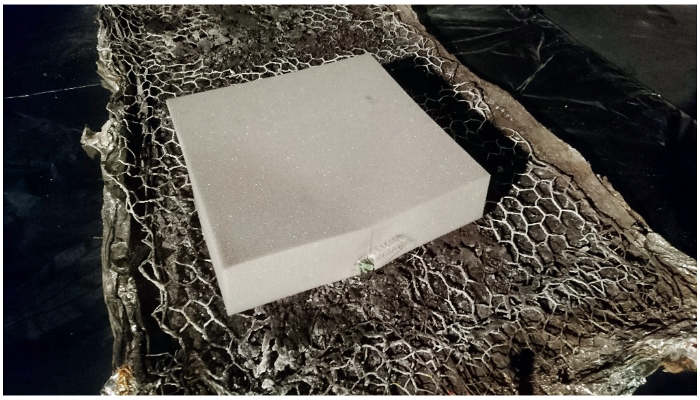


Figure 3: Flame retardent polyurethane foam flaming test

Similarly, the flame retardant polyurethane foam and the ABS smouldering test fire (ABSSM) (Figure 4) produced low heat but with a much higher proportion of large to small particles. These tests were conducted to demonstrate the ability of smoke chambers to respond to relatively larger particles, and confirm that there were no unexpected responses from those used in this study.

False alarm tests

The data from two BRE briefing papers [1, 2] were reviewed to identify the most common false alarm causes (shown in column 1 of Table 3), along with the frequency of their occurrence. The false alarm data from the SFRS, BMKFA and KCL are shown in columns 2, 3 and 4

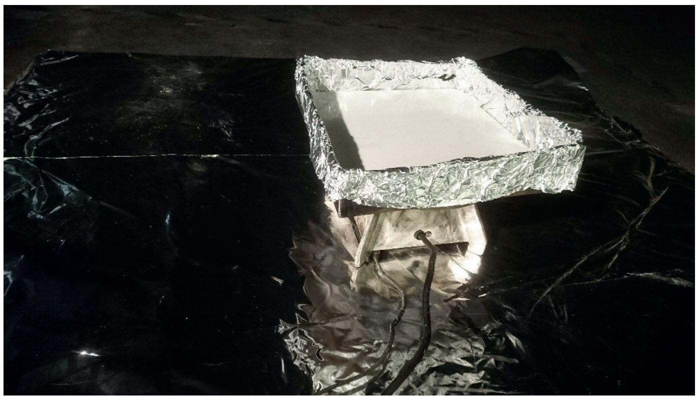


Figure 4: ABSSM test fire

respectively, and are taken from 1908, 6612 and 432 false alarm events respectively.

The latest data from SFRS is probably the most accurate and representative of false alarm causes nationwide, as the form developed by SFRS during the study provided more false alarm details and was completed by suitably trained personnel. Ten false alarm types were explored in detail, with a view to developing or using existing methods to test products to these common false alarm types.

One of the challenges of the study was to determine whether the false alarm tests should exactly replicate reality or whether the focus should be on test repeatability. Trying to replicate what happens in the service environment introduces an element of variability and lack of control. Such a methodology is likely to produce broad responses for the same detector when tested multiple times, and therefore cannot be used for comparative measurements between different detectors. Test methods for all ten false alarm types were considered, and those that could not be developed within the project timescale and those for which test methods were created are summarised respectively in the following two sections.

False alarm type	False Alarms (%)		
	SFRS	BMKFA	KCL
Dust (short term)	11.3	11.1	9.5
Dust (long term)			2.3
Smoke from cooking	9.1	9.4 (including toaster)	14.8
Steam	5.1	2.2	9.5
Condensation			0.7
Aerosols (hairspray/deodorant)	3.9	1.6	1.6
Smoke from toaster	2.4	-	5.8
Cigarette smoke	2.2	0.8	0.5
Synthetic (smoke machines/security cloaks)	1.0	0.4	1.2
Insects	-	1.5	1.9
Total	**35.1**	**27.0**	**47.6**

Table 3: False alarm cause and frequency data from previous studies

False alarm tests not developed

The repeatability of the proposed test methods for long-term dust build up, condensation, cigarette smoke, synthetic smoke and insect ingress was not high enough to perform a meaningful comparison. To avoid the possibility of distorting the results with erroneous data these false alarm types were removed. The specific reasons that these tests were excluded are detailed below.

The long-term dust test was a very difficult test to perform reliably and repeatedly and there was no existing methodology with proven performance.

A condensation test was performed by accelerating the temperature and humidity rates of the existing EN 54-7 Damp Heat test. The six multi-sensors tested did not respond with a false alarm, which demonstrated that the requirements of standards have raised the bar of acceptable performance such that modern detectors pass this test without any issues. A few decades ago the majority of smoke detectors would probably have failed this Damp Heat test. As the test was not effectively challenging the multi-sensors, this false alarm test was not included.

Three cigarette smoke tests were performed but were not repeatable due to a lack of thermal energy (see Figure 5). This test was therefore not used as it would not provide meaningful comparisons of relative multi-sensor detector performance.

Attempts to develop a synthetic smoke test were made with a smoke machine that used a glycerine solution to produce smoke. As with the cigarette smoke test, the synthetic smoke had little energy to produce consistent profiles of smoke growth with time, and therefore this test was not included.

A test using live insects was investigated to assess the smoke chambers' ability to both prevent insects from entering in the first place and, if they entered, to prevent exposure to the critical parts that influence smoke detection. Whilst methodologies were explored and developed, it was concluded that the insect test would lack repeatability - as the activity and behaviour of insects would not be consistent at different times of the day or year - and was therefore not included.

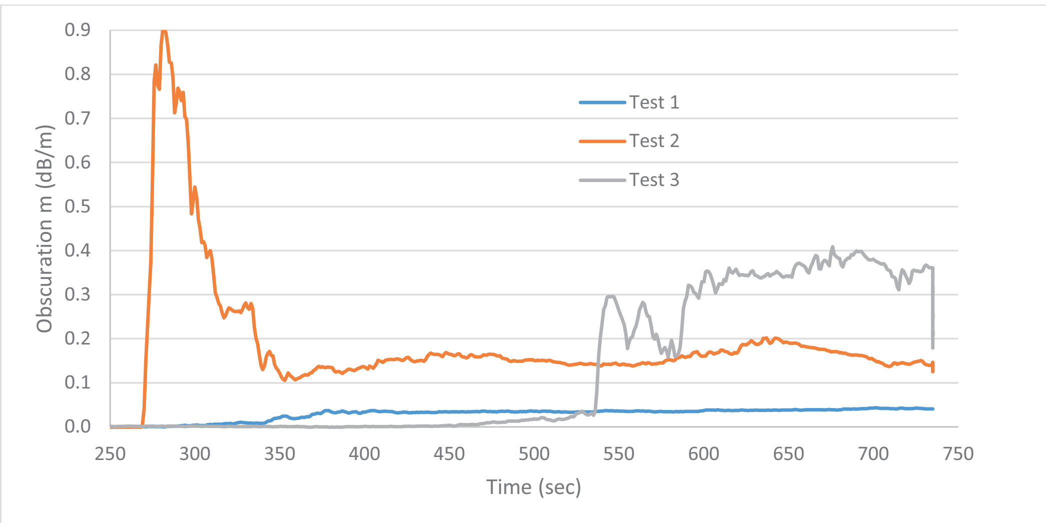


Figure 5: Observed inconsistency in the cigarette false alarm test

False alarm tests developed

The short-term dust build up, cooking, steam and burning toast tests were developed as detailed below. The test methods strayed somewhat from real life, such as using water mist instead of steam. This gave a much more repeatable test whilst accurately replicating the false alarm phenomena.

For the short-term dust test, the methodology developed by Duisburg University and reported in 'Apparatus for the Test of Fire Detectors in Dusty Environments' [10] was used. All tests were repeated three times after a purge of the apparatus.

The cooking test was developed by BRE during this programme (see Figure 6). It used 100g of frozen chips and 200g of sunflower oil in a frying pan that was gradually heated on an EN 54-7 TF2 hotplate in the BRE fire test room.

To replicate a false alarm due from steam, the water mist test methodology developed by Duisburg University and reported in 'Apparatus for the Test of Fire Detectors in High Foggy Environments' [11] was used. The water mist conditioning was sufficiently representative of the effects of steam. All tests were repeated three times after a purge of the apparatus and at least a five minute stabilisation time.

Figure 6: Cooking false alarm test

The aerosol test methodology was developed by Duisburg University and specified in AS 8036 Aviation SAE Standards [12]. The deodorant aerosol 'Nivea Men 48h fresh active' was used as this has been shown (in previous unpublished work by Duisburg University) to produce particle sizes with a tight diameter distribution, and remains airborne for comparatively longer than other deodorants.

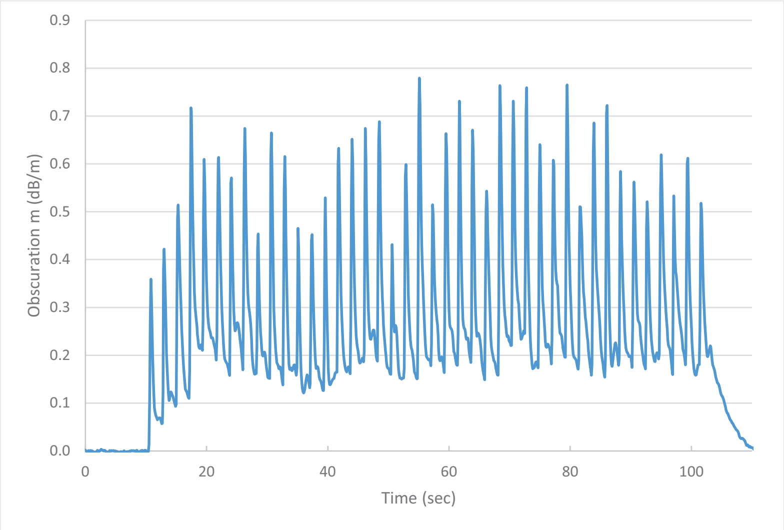


Figure 7: Smoke obscuration from pulses of aerosol

The spray test provides pulses of aerosol at around two second intervals, which lead to spikes in the levels of obscuration (see Figure 7) measured by the obscuration meter positioned next to the detector being tested. The aerosol concentration within the smoke chamber of the detector is known to gradually increase with each pulse. At some point the concentration reaches a level to activate the detector into alarm. The methodology for reporting a measurement of the response is to integrate the obscuration pulses with time and note the integrated value (measured in sec. dB/m) at the time of alarm.

Smoke produced when food items are being toasted is responsible for many false alarms, which are often caused when fire is not present. As the bread progressively toasts more smoke is produced. Detection is preferred when the concentration of smoke is visible, but with sufficient time to allow for investigation and intervention before the toast ignites. The burning toast test (Figure 8) was developed by BRE during this programme. It comprised two fresh slices of medium sliced white Warburton's bread placed in a toaster (of two slice capacity) on the maximum setting, with the automatic cut off switch set to permanently on.

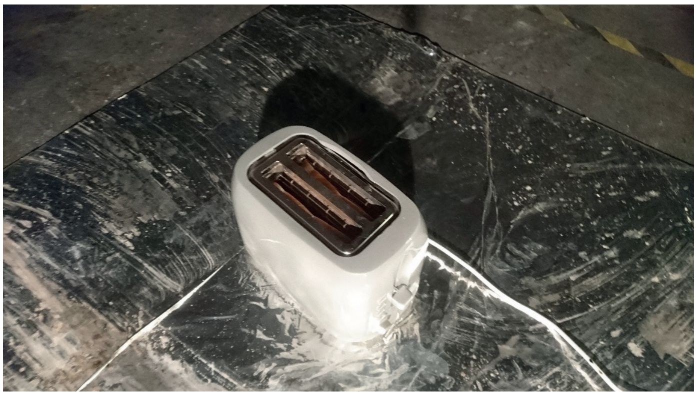


Figure 8: Toast false alarm test

Results from fire and alarm tests

Summary of fire sensitivity test data

Five sets of fire tests were performed on thirty-five optical heat multi-sensors, and five domestic optical and five commercial optical type smoke devices. A summary of the mean m:y ratios of small to large particles for all test fires is shown below and arranged in increasing order. The four new test fires (shown in bold) produce particle distribution ratios that are outside the EN 54-7 standard TF2 to TF5 fires.

Test Fire	Mean Ratio m:y (dB/m)
MDFFL	0.056
TF1	0.083
FRPUFL	0.140
TF5	0.171
TF4	0.240
TF8	0.286
TF3	0.379
TF2	1.085
FRPUSM	1.243
ABSSM	3.872

Table 4: Mean m:y ratios for all test fires

The mean responses of time, change in ceiling temperature, m and y for the thirty-five multi-sensor detectors to all the test fires, are shown below.

Test Fire	Time (sec)	Delta t (°C)	m (dB/m)	y
TF2	515	0.3	0.78	0.70
TF3	347	0.2	0.43	1.03
TF4	141	8.8	0.72	2.83
TF5	56	17.5	0.52	2.51
TF1	308	21.3	0.54	6.29
TF8	258	3.9	0.75	2.70
FRPUSM	1170	1.0	0.66	0.57
FRPUFL	192	2.3	0.45	3.49
ABSSM	724	0.7	1.82	0.50
MDFFL	394	21.4	0.16	3.73

Table 5: Mean responses of multi-sensors during test fires

The FRPUFL fire produced very little heat for a flaming fire which, together with a low m:y ratio, makes this a challenging fire to detect. Profiles of the 'm' verses 'y' and 'm' verses 't' during the FRPUFL fire are shown in Figures 9 and 10 to demonstrate the consistency of this test fire.

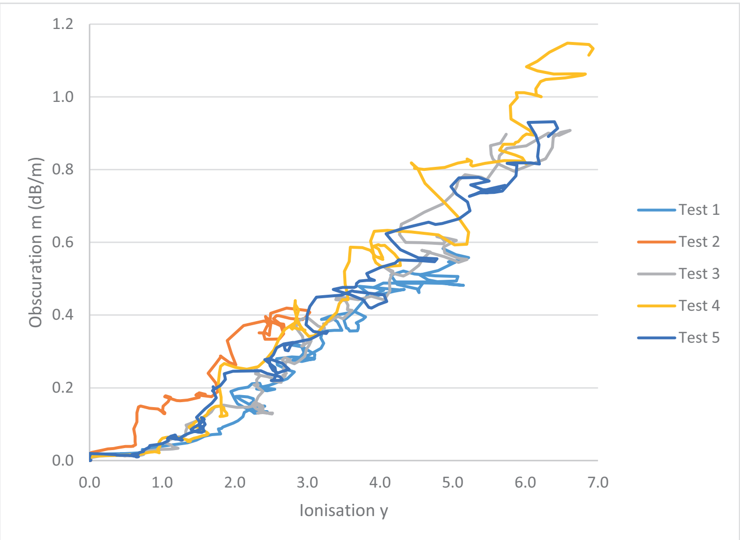


Figure 9: m V y profile of the FRPUFL fire

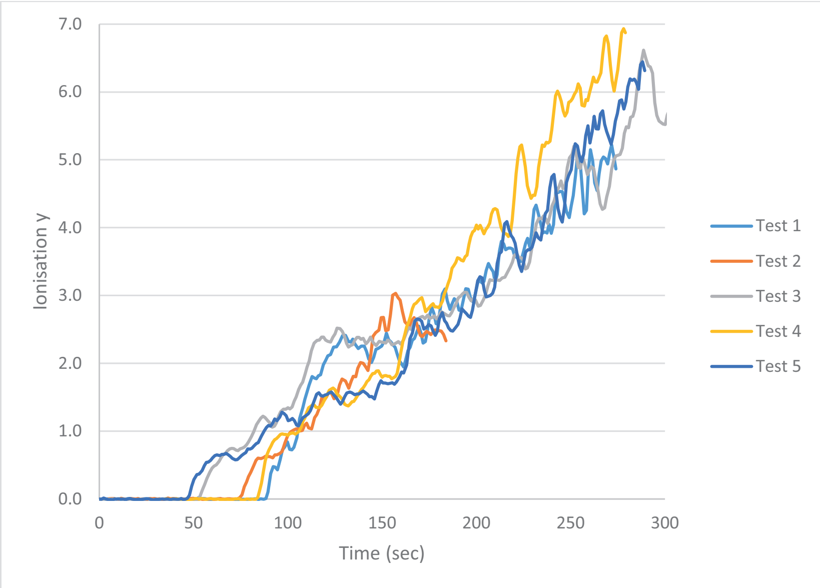


Figure 10: m V t profile of the FRPUFL fire

For smouldering fires, both the ABSSM and FRPUSM tests produced very little CO as well as very little heat, which could potentially make them challenging fires for multi-sensors incorporating CO sensors to detect. The MDFFL fire produced both a lot of CO and considerable heat, but unfortunately not consistently as the fire profiles were highly variable.

Seven detector responses (two reference, three intermediate and two basic) to the fourth FRPUFL test fire are shown in Figure 11.

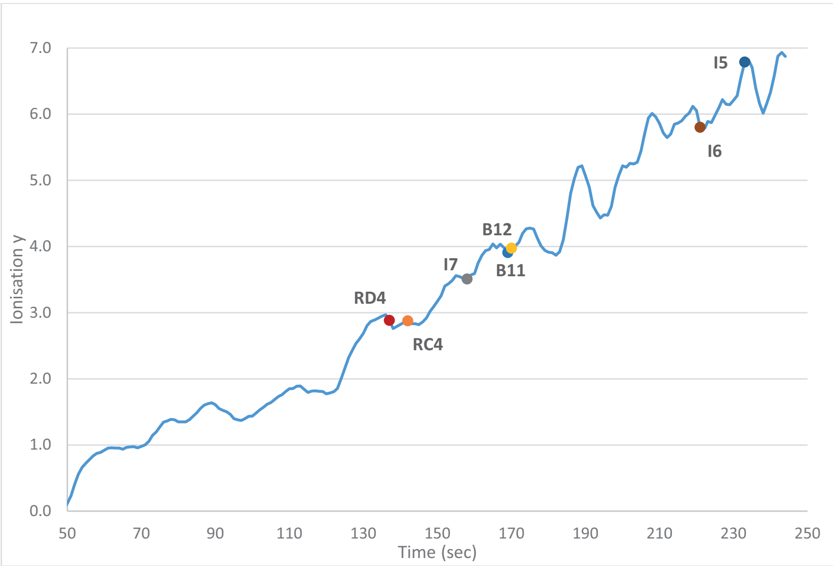
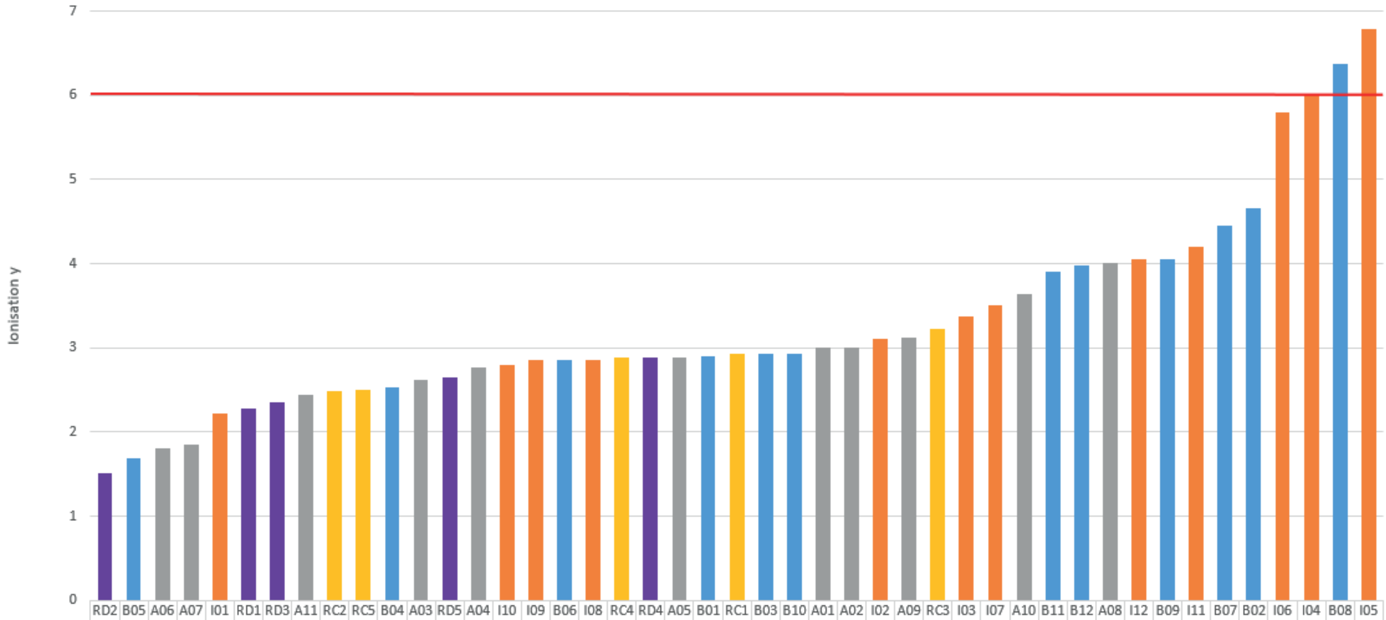


Figure 11: Detector responses during the fourth FRPUFL test

For this particular test it can be seen that the reference domestic smoke alarm (RD4) responds firstly, closely followed by the reference commercial smoke detector (RC4). The basic and intermediate multi-sensors respond later, with Intermediate multi-sensor (I5) signalling an alarm after the end-of-test condition for a flaming fire is reached (y=6).

For each of these charts the detector identification and smoke response at the alarm point were taken and combined with the same data from the remaining tests of that test fire type. These were then plotted on single bar charts to demonstrate the response of all detectors for each test fire (see example in Figure 12). The 45 responses are presented with the smoke response on the y axis, and with the detector identification on the x-axis being arranged in order of increasing response. The limit for the test fire appears as a horizontal red line.

The abbreviations used in the charts are: RC= Reference commercial, RD = Reference domestic, A= Advanced, I = Intermediate and B= Basic. As the smoke detectors were tested five times each, these are reported as RC# of RD# where # represents the test number. For the multi-sensors references as A#, I# or B#, the # represents the identification of that device in terms of manufacturer, model and mode.



	RD2	B05	A06	A07	I01	RD1	RD3	A11	RC2	RC5	B04	A03	RD5	A04	I10	I09	B06	I08	RC4	RD4	A05	B01	RC1	B03	B10	A01	A02	I02	A09	RC3	I03	I07	A10	B11	B12	A08	I12	B09	I11	B07	B02	I06	I04	B08	I05
R Dom	1.5					2.2	2.3						2.6							2.8																									
R Comm									2.4	2.5									2.8				2.9							3.2															
Advanced			1.8	1.8				2.4				2.6		2.7							2.8					3.0	3.0		3.1				3.6			4.0									
Inter					2.2										2.7	2.8		2.8										3.1			3.3	3.5					4.0		4.2			5.8	6.0		6.7
Basic		1.6									2.5						2.8					2.9		2.9	2.9									3.9	3.9			4.0		4.4	4.6			6.3	

Figure 12: Alarm responses from all detectors during the FRPUFL test

By analysing this data and considering the responses for all detectors types tested, the ratio (max:min) response, the mean and standard deviations (SD) were noted.

Type	Ratio (max:min)	Mean	SD
Basic Multi-sensor	3.79	3.60	1.23
Intermediate Multi-sensor	3.06	3.96	1.47
Advanced Multi-sensor	2.22	2.83	0.66
Reference Commercial Smoke Detector	1.30	2.80	0.31
Reference Domestic Smoke Alarm	1.91	2.34	0.52

Table 6: Detector type responses for the FRPUFL test

These alarm response charts and summary tables were then used to make general observations for each of the tests such as:

- In general multi-sensors respond after optical smoke detectors.
- The basic multi-sensor detectors have the largest spread (max:min=3.79), i.e. greatest variability in response.
- Two intermediates and one basic multi-sensor fail the test (responded after y=6).

The reasons why the three multi-sensors failed this particular test were not investigated, but such observations were useful when the overall responses to all tests were considered and used to draw general conclusions (see Table 12).

Whilst the single-sensor technologies in this test have performed sooner than the multi-sensors, a more comprehensive review of the detector type responses was also conducted (see 'Combined Responses') to compare the overall capabilities of each detector type. In a particular test a specific detector type may appear to perform early, but only by looking at the averages to all fire and false alarm tests is it possible to draw overall conclusions about the performance of the different detector types.

The sensitivity levels of the different multi-sensors were noted for each of the test fires (e.g. FRPUFL in Figure 13).

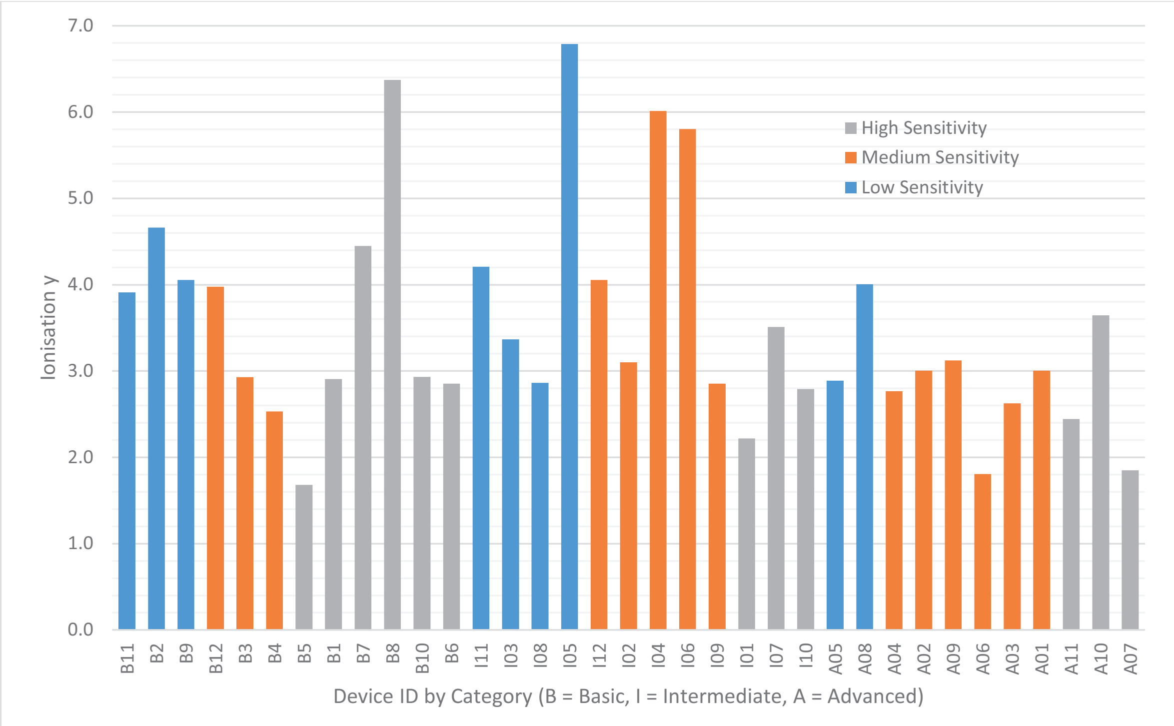


Figure 13: Summary of overall FRPUFL sensitivity responses

Figure 13 shows that the high sensitivity devices did not always signal an alarm before the low sensitivity ones. That is because manufacturers had set their alarm thresholds at different levels which, together with the detector design, determine their response. This is observed over all the basic, intermediate and advanced categories. If the averages of each sensitivity are taken for the three categories and the ten test fires, the following table results:

CATEGORY	Basic			Intermediate			Advanced		
SENSITIVITY	Low	Medium	High	Low	Medium	High	Low	Medium	High
TF2	1.29	0.31	0.80	0.86	0.83	0.75	1.03	0.69	0.51
TF3	0.27	0.52	0.32	0.55	0.47	0.30	0.46	0.57	0.28
TF4	3.467	3.474	2.26	3.78	3.03	1.72	3.05	2.99	1.74
TF5	2.06	2.37	2.08	3.17	2.81	2.78	2.39	2.56	1.91
TF1	6.54	7.94	6.57	7.77	6.85	5.27	5.53	5.88	2.98
TF8	1.06	0.78	0.76	0.89	0.84	0.45	0.68	0.77	0.46
FRPUSM	0.83	0.69	0.52	0.46	0.78	0.52	0.64	0.93	0.47
FRPUFL	4.36	3.15	3.53	4.34	4.37	2.84	3.45	2.72	2.65
ABSSM	2.86	1.92	1.21	2.00	1.92	1.48	1.63	2.42	1.12
MDFFL	4.63	5.82	3.34	4.07	3.27	3.14	3.11	4.21	2.82

Table 7: Mean responses in dB/m for smouldering and y for flaming fires

The series of figures highlighted in red demonstrate the expected result, i.e. quicker response with increasing sensitivity. Note that over the three categories and ten tests (thirty possibilities) the expected response was only observed thirteen times, demonstrating that in this case there is no correlation of multi-sensor sensitivity and response performance.

Summary of false alarm test data

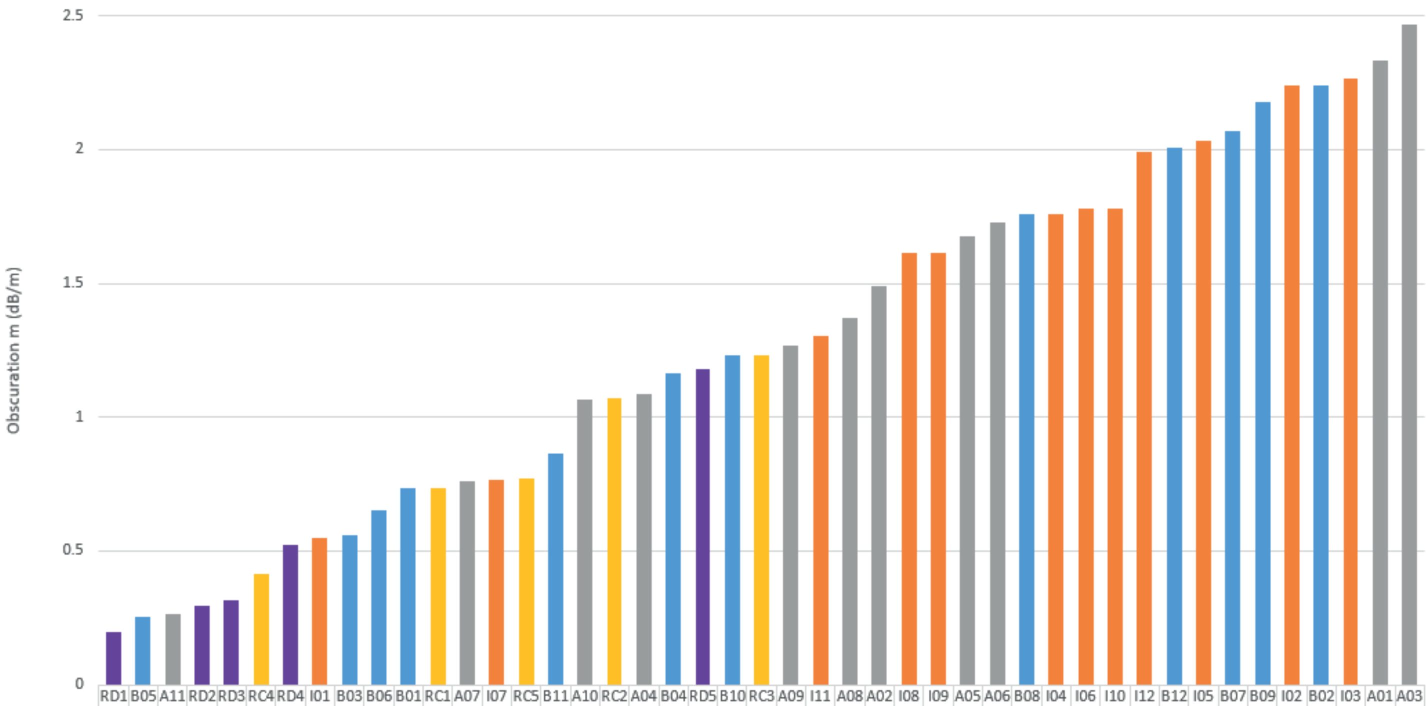
The burning toast and cooking tests were performed in the BRE fire test room, and the water mist, dust and aerosol tests at Duisburg University - all are reported here. Note that Intermediate detectors I5, I6 and I7 could not be configured for the tests performed at Duisburg University and therefore appear absent in the relevant graphs.

The burning toast test was performed five times and the time difference between the last operating smoke/multi-sensor and the toast igniting are shown in the table below. Smoke was typically produced five minutes after the start of the test and lasted for around three and half minutes before the toast ignited. A latter response is preferred to avoid false alarms, but operation before the toast ignites, with sufficient time to intervene, is critical.

Test Number	Time between last detector operating and toast igniting (sec)	
	Multi-sensor	Smoke Detector
Test 1	80	116.7
Test 2	38	82.6
Test 3	87	97.2
Test 4	47	90.0
Test 5	54	110.0
Average	61.2	99.3

Table 8: Smoke and multi-sensor response times from toaster smoke before ignition

It can be observed that multi-sensor detectors were operating typically around 40 seconds after the smoke detectors, but around a minute before the toast ignited. The detector responses are shown in Figure 14 where the early response of smoke detectors and latter response of multi-sensor detectors can clearly be observed.



	RD1	B05	A11	RD2	RD3	RC4	RD4	I01	B03	B06	B01	RC1	A07	I07	RC5	B11	A10	RC2	A04	B04	RD5	B10
R Dom	0.2			0.3	0.3		0.5														1.1	
R Comm						0.4						0.7			0.7			1.0				
Advanced			0.2										0.7				1.0		1.0			
Inter								0.5						0.7								
Basic		0.2							0.5	0.6	0.7					0.8				1.1		1.2

	RC3	A09	I11	A08	A02	I08	I09	A05	A06	B08	I04	I06	I10	I12	B12	I05	B07	B09	I02	B02	I03	A01	A03
R Dom																							
R Comm	1.2																						
Advanced		1.2		1.3	1.4			1.6	1.7													2.3	2.4
Inter			1.3			1.6	1.6				1.7	1.7	1.7	1.9		2.0			2.2		2.2		
Basic										1.7					2.0		2.0	2.1		2.2			

Figure 14: All detector responses during toast test

The ratio (max:min response), the mean and standard deviations (SD) were noted.

Type	Ratio (max:min)	Smoke obscuration (dB/m)	
		Mean	SD
Basic Multi-sensor	8.83	1.31	0.71
Intermediate Multi-sensor	4.14	1.64	0.54
Advanced Multi-sensor	9.39	1.41	0.64
Reference Commercial Smoke Detector	2.96	0.84	0.32
Reference Domestic Smoke Alarm	5.97	0.50	0.40

Table 9: Detector type responses for the toast test

Although there is no clear correlation between the multi-sensor category and sensitivity, the overall (mean) response time of the multi-sensors is later than commercial and domestic single technology optical type smoke devices.

The cooking test produced quite variable responses from one test fire to another, which may be due to the distribution of chips in the pan and water adsorption during the preparation process. In general the observations were similar to the toast test with no clear correlation between the multi-sensor category and sensitivity. The same overall response order of domestic smoke alarms operating first, then commercial smoke detectors and multi-sensors last was observed.

Type	Ratio (max:min)	Smoke obscuration (dB/m)	
		Mean	SD
Basic Multi-sensor	11.99	0.41	0.27
Intermediate Multi-sensor	5.11	0.29	0.14
Advanced Multi-sensor	27.92	0.54	0.55
Reference Commercial Smoke Detector	2.74	0.28	0.11
Reference Domestic Smoke Alarm	8.21	0.21	0.22

Table 10: Detector type responses for the cooking test

The detector responses during the water mist test are shown in Figure 15 with the mean response shown as a horizontal orange line for all multi-sensor categories.

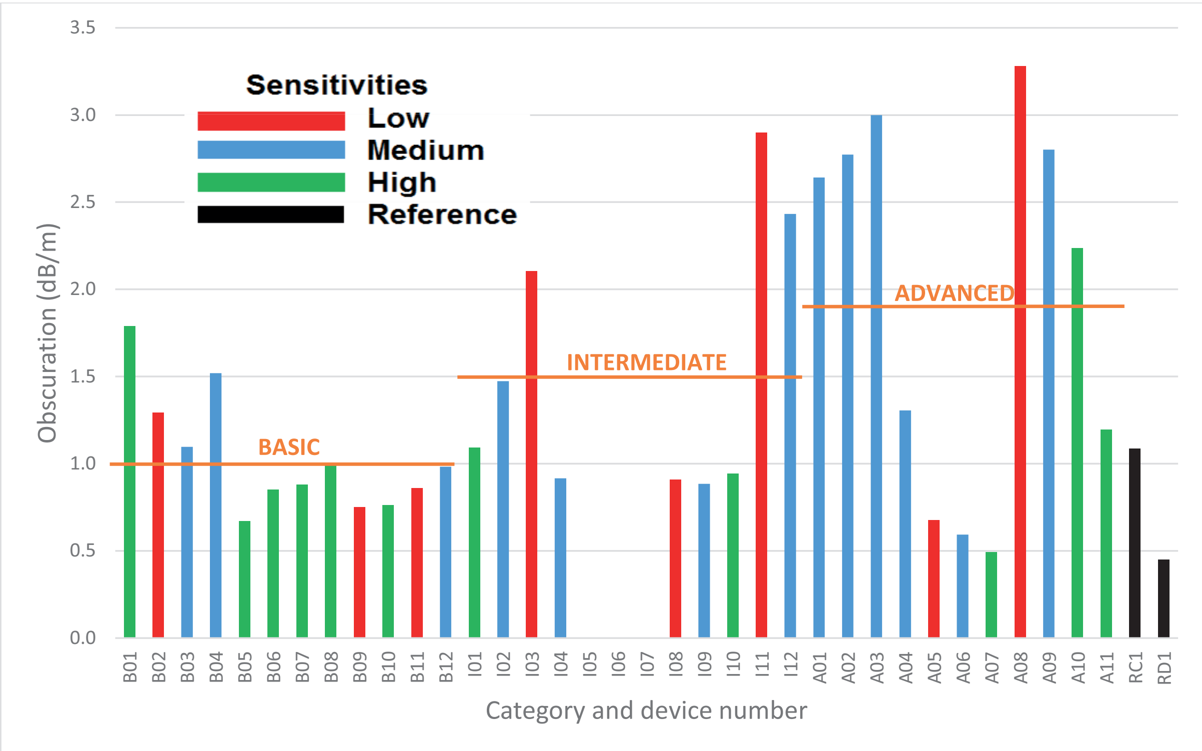


Figure 15: All detector responses during the water mist test

During the water mist, dust and aerosol tests performed at Duisburg University, I5, I6 and I7 could not be configured and therefore no data can be shown in Figure 15. The key observations based on the water mist test results were:

- 9 intermediate and advanced category multi-sensors alarmed after m=2 dB/m, demonstrating that these devices were going into alarm after the fire test limits had been met for a smouldering test fire. Thus if a multi-sensor is responding with an alarm to smouldering tests before m=2dB/m has been achieved, but responds after m=2dB/m during this false alarm test, it demonstrates that the multi-sensor is recognising the false alarm phenomenon and holding off signalling an alarm.
- 'Advanced' category multi-sensors respond later than 'intermediate' which respond later than 'basic'.
- Average response of all multi-sensors is later than the reference commercial smoke detector, which responds later than the reference domestic smoke alarm.
- None of the multi-sensors operated before the single technology optical type domestic smoke alarm.

The mean responses of all combined and individual multi-sensor categories and the smoke detectors are shown in the table below.

Type	Mean response		
	Water mist (dB/m)	Dust (dB/m)	Aerosol (sec. dB/m)
Overall Multi-sensor	1.47	0.460	17.3
Basic Multi-sensor	1.04	0.300	8.83
Intermediate Multi-sensor	1.52	0.889	16.7
Advanced Multi-sensor	1.91	0.285	26.9
Reference Commercial Smoke Detector	1.09	0.244	3.50
Reference Domestic Smoke Alarm	0.45	0.127	13.2

Table 11: Combined response of all detector types to water mist, dust and aerosol tests

The key observations for the dust tests were:

- 9 multi-sensor devices alarmed after an m=0.5 dB/m; 2 'basic'category, 6 'intermediate' category and 1 'advanced' category. This demonstrates that those devices operating at the latter stages of this test were all multi-sensors.
- No correlation for the average responses of multi-sensor categories
- Average response of all multi-sensors is later than reference commercial smoke detectors, which is later than reference domestic smoke alarms
- None of the multi-sensors operated before the reference domestic and commercial smoke devices.

The detector responses during the aerosol test are shown in Figure 16, with the mean response of the different multi-sensor category being shown as a horizontal orange line.

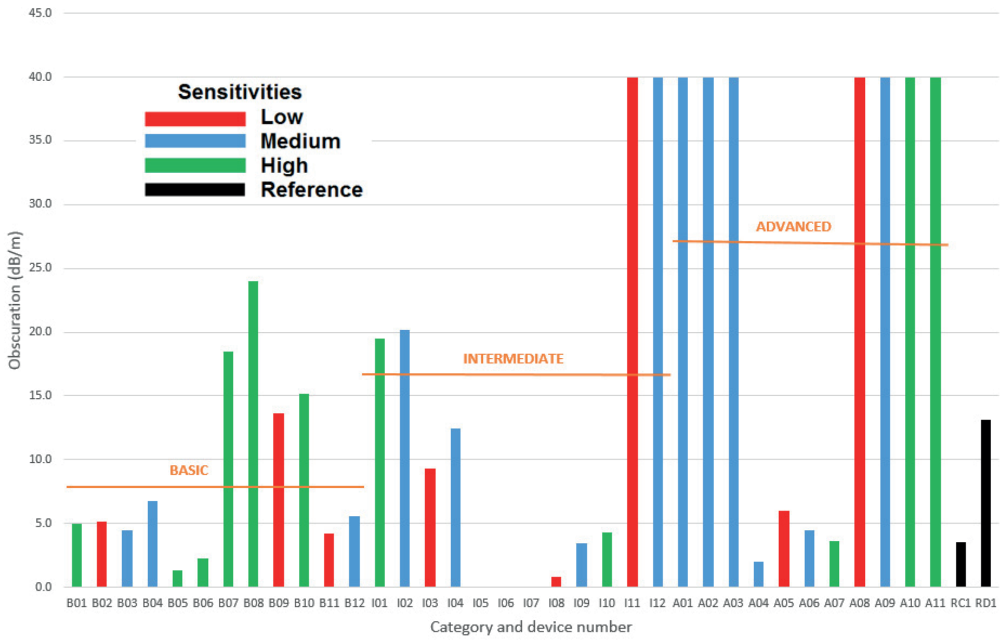


Figure 16: All detector responses during the aerosol test

The key observations for the aerosol tests were:

- 9 multi-sensors did not alarm, which demonstrates great resistance to aerosol (2 'intermediate' category and 7 'advanced' category).
- 'Advanced' category multi-sensors respond later than 'intermediate' which respond later than 'basic' (non-alarming devices were weighted with a score of 40).
- Average response of all multi-sensors is later than reference domestic smoke alarms, which are later than the reference commercial smoke detectors.

Findings

Fire sensitivity tests

Fire sensitivity tests of the EN 54 standards were performed as the means of comparing the detection performance of the various categories of multi-sensor with the performance of the single technology optical smoke detectors. The purpose of performing the suite of additional fire tests was to create fires with more challenging smoke and heat characteristics with limits outside of the standard test fires, to observe if all of the multi-sensor detectors would respond with an alarm. The additional fire tests performed all had m:y profiles outside the existing TF2-5 limits.

The FRPUFL fire was very consistent in terms of the smoke profile repeatability between fires and for a flaming type of fire producing very little heat which, together with a low m:y ratio, made this a difficult fire to detect. The test produced very little CO which made it a challenging test for optical heat multi-sensors incorporating CO sensors. For smouldering fires both the ABSSM and FRPUSM tests produced very little CO as well as very little heat, which could make them quite challenging for multi-sensors incorporating CO sensors. Of these two types of fire, ABS produced the highest m:y ratio with an average temperature increase at the time of alarm of only 0.7°C.

The end of test fire limits of y=6 and m=2 dB/m from the EN 54 series of standards have been used and applied to the additional fire tests. Whether these limits are appropriate for these new test fires has been questioned as the same limit may not necessarily represent untenable conditions, in terms of visibility, for all tests fires. For example, the smoke from smouldering fires when m=2 dB/m from two different materials may look completely different from one another and have different limits of visibility. This visibility limit is dependent on the material that is burning, the type of smoke that it produces and how our eyes are able to see through it. To state limits of m=2 dB/m for all smouldering fires and y = 6 for all flaming fires is simplifying a complex issue. Future research to investigate the untenable visibility limits from different materials under smouldering and flaming conditions is recommended.

Detector responses to test fires

Multi-sensors defined as 'basic' category devices demonstrated the widest max:min response on seven out of the ten fire sensitivity tests, indicating that the variabilities of 'basic' devices is significantly higher than those categorised as 'intermediate' or 'advanced'.

A broad range of responses had been observed for devices with the same sensitivity and in the same category, which may be due to the different approaches that manufacturers had taken during the development of the detectors. For example, some manufacturers would have taken the approach of lowering detection sensitivity to reduce false alarms, whilst others will have incorporated sophisticated algorithms to analyse the heat and smoke signatures. It would be expected that high sensitivity detectors would, on average, respond sooner than medium sensitivity detectors, which would in turn respond sooner than those of low sensitivity. However, this order of expected responses was only observed 43% of the time, due to the manufacturers setting these thresholds at different levels.

Test Fire	Number of multi-sensor failures			
	Basic	Intermediate	Advanced	Total
TF1	7	8	4	19
TF2	0	0	0	0
TF3	0	0	0	0
TF4	0	0	0	0
TF5	0	0	0	0
TF8	1	0	0	1
FRPUFL	1	2	0	3
FRPUSM	0	0	0	0
ABSSM	2	5	5	12
MDFFL	1	3	0	4
Total	**12**	**18**	**9**	**39**
Number of models tested	120	120	110	350
Failure rate	**10%**	**15%**	**8%**	**11%**

Table 12: Number of multi-sensor failures observed during each test fire and overall failure rate

100% of multi-sensors and 100% of optical detectors passed the test fires TF2-TF5. Table 12 shows the number of multi-sensors that had not responded by the time the end-of-test conditions had been reached, for each of the ten test fires for all multi-sensor categories. All thirty-five multi-sensors in the ten sets of fire tests operated with an 89% (311/350) success rate, in terms of operating with an alarm, before the end-of-test conditions were reached. The ten optical smoke detectors tested over the ten test fires had a success rate of 90% (90/100). This shows that multi-sensors and optical smoke detectors had similar pass rates for the test fires - as expected - but their responses during the false alarm tests will reveal any differences in performance (see below). The advanced category multi-sensor detectors had the lowest failure rate.

Detector responses to false alarm tests

For the toast test it was observed that multi-sensors alarm later than optical smoke detectors, which demonstrates their later response to this common false alarm source. For all five toast tests the fuel ignited, on average, one minute after the last device had alarmed, demonstrating their operation before a flaming scenario was present.

The results of the cooking test show the 'advanced' category multi-sensor detectors grouped at either end of the scale, either operating quickly or late into the test. A contributing factor may be the lack of consistency of this type of test. However, the results of this test have been used to provide an overall comparison of performance with the other tests. Further development of the test fire is needed, perhaps better replicating typical real-world scenarios where the cooking pan is in closer proximity to the ceiling mounted detectors.

In the false alarm tests of water mist, dust and aerosols, the 'advanced' category multi-sensors in general operated after 'intermediate' category devices', which operated after the 'basic' category devices. On average, the response from all the multi-sensors was later than the single technology reference commercial smoke detectors and the reference domestic smoke alarms.

As can be seen in Figure 17, during each of the five false alarm tests the multi-sensors, on average, operated after the single technology reference smoke detectors. With reference to Figure 17, the mean response of the multi-sensor detectors has been normalised to the response of the single technology smoke detectors for each false alarm tests, to demonstrate the increase in smoke density required to trigger the multi-sensors.

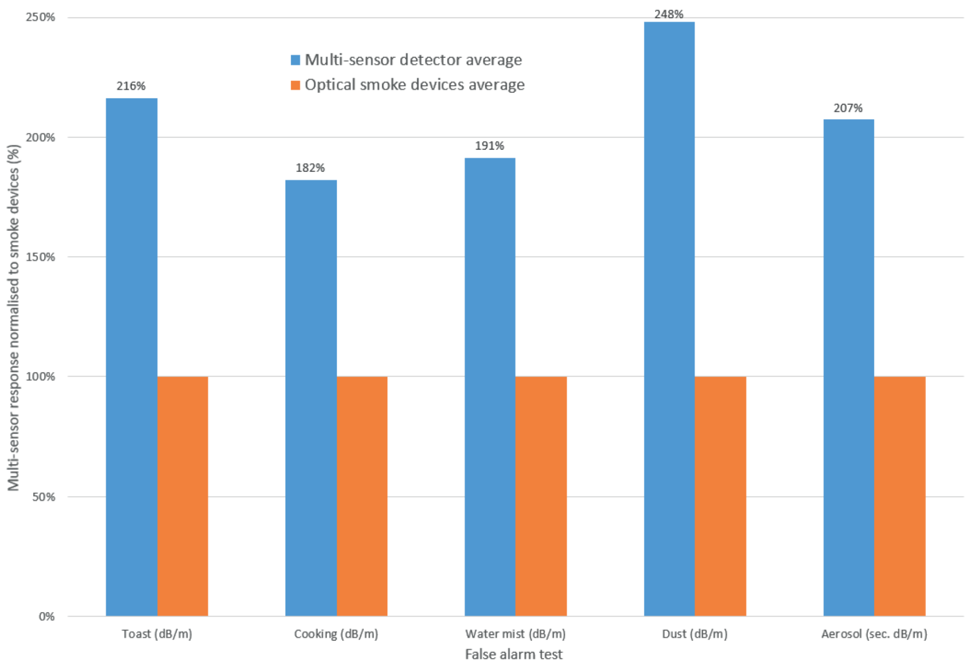


Figure 17: Response of multi-sensor detectors normalised to smoke devices for all false alarm tests

Combined responses

Figure 18 shows the mean response of each multi-sensor category, together with the mean response of the single technology reference optical smoke detectors, normalised to maximum value for both the fire sensitivity tests and the false alarm tests.

For fire tests for which no response was observed, this has been fixed at a level of 120% of the worst performing device. The performance of all devices has been normalised to the worst performing device for each test and then the average of the device types across all fire or false alarm tests has been taken. Normalising in this way illustrates, on average, how detectors compared with the worst performing device operated for the false alarm and fire tests.

With reference to the test fires (shown in blue) a higher y-axis value demonstrates a later response. Similarly, a higher y-axis value for the false alarm tests indicates a later response and greater resistance to the false alarm sources. Whilst the data shows no significant difference in the detection performance between multi-sensors categories, improved resistance to unwanted alarms is visible. The best resistance, in decreasing order, is provided by multi-sensors in the 'advanced' category, compared with the 'intermediate' category, the 'basic' category, and the single technology reference commercial smoke detectors and then domestic smoke alarms. It was noted that the single technology domestic optical smoke alarms had the fastest average response to the fire sensitivity tests, but it was also quickest to respond to the false alarm stimuli.

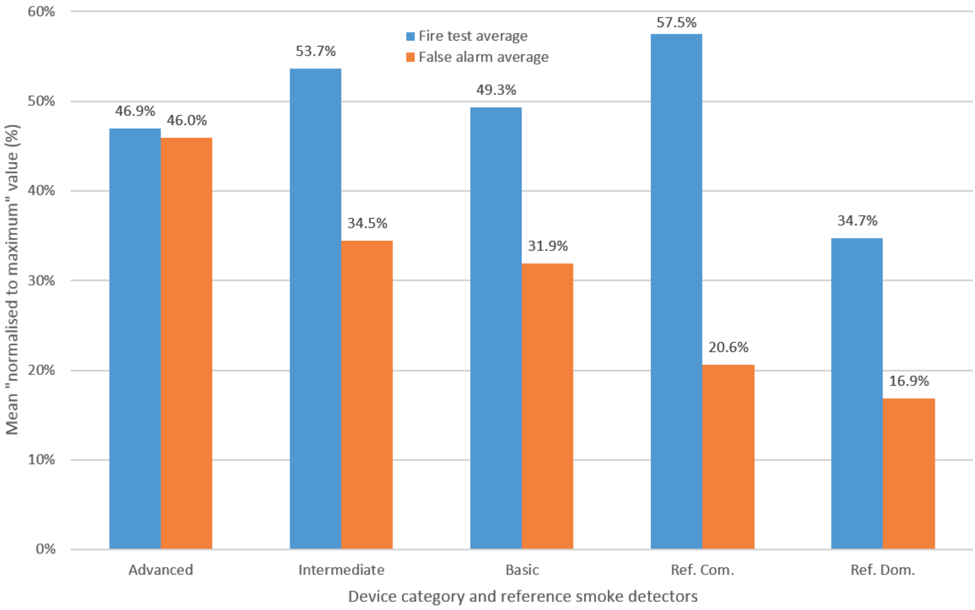


Figure 18: Category and smoke detector averages for all false alarm and fire tests

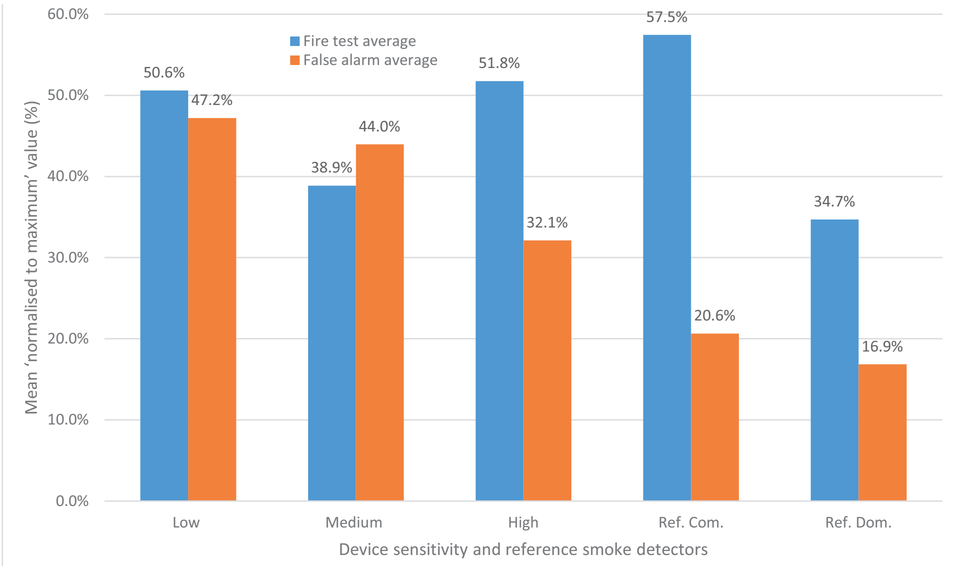


Figure 19: Sensitivity and smoke detector averages for all false alarm and fire tests

The improved resistance to false alarm phenomena observed from of the multi-sensors in the 'advanced' category, indicates that the product design features intended to improve false alarm resistance were effective. Some of the operating modes included in the tests have been designed to resist specific types of false alarm stimuli, but for the purposes of this study, their performance has been assessed across a relatively broad spectrum of false alarm sources.

The mean responses of the multi-sensor devices (by sensitivity) together with the mean responses of the single technology reference optical smoke devices for both the false alarm tests and fire sensitivity tests, are shown in Figure 19. The same methodology reported previously has been used for deriving the 'average' false alarm and fire test responses of each detector. The average of these has then been calculated for all sensitivities and both optical smoke detectors.

This chart demonstrates that the lower the sensitivity of the multi-sensor, the later it responds to the false alarm source. However, for the group of medium sensitivity multi-sensors, the response to the test fires was found to be significantly quicker than the other sensitivities. An investigation of this revealed that 6 of the devices from the medium sensitivity group were from two manufacturers that had set their medium sensitivity at a higher level than the other makes of multi-sensor. This had the effect of reducing the overall average response. If these detectors are removed from the assessment the average becomes 47.7%, which is consistent with the findings associated with the low and high sensitivity groups.

Conclusions

Thirty-five different optical heat multi-sensor detectors representing the full range of those available in the marketplace today, were tested alongside two reference optical smoke detectors to a series of ten test fires and five false alarm tests. These tests were intended to demonstrate any benefits of multi-sensor detectors over optical smoke detectors, and also the performance capabilities of multi-sensor detectors - depending on the complexity of their design. Whilst these multi-sensor detectors were compliant with relevant standards, they were not necessarily claiming to be compliant with the latest EN 54-29 standard.

Before summarising the benefits of multi-sensors that were demonstrated, it is worth making the following general observations:

- The sources of false alarms, in the majority of circumstances, tend to be present for a limited period of time before dispersing - e.g. steam from a shower room.
- Fires, in contrast, will typically tend to develop with increasing concentrations of smoke and heat and continue to grow over time.

During the false alarm tests it was observed that the multi-sensor detectors, on average, responded much later than the single technology optical smoke detectors. The resultant delay in operation is essentially where the benefits of multi-sensors are revealed. The delay allows time for any transient false alarm sources to disappear before the multi-sensor fire threshold is reached, thereby avoiding an unwanted alarm. There is also more time for building occupants to discover and respond to the false alarm source before a fire alarm is triggered.

The use of multi-sensors is unlikely to eliminate all of the 38.1% of false alarms reported earlier, but the additional delay in response may have prevented a significant number of those events from developing into false alarms.

Furthermore, the detection performance of the multi-sensors to valid fires was found to be comparable to that of the single technology optical type smoke devices tested.

On average, the multi-sensors responded one minute before the toast ignited during the toast test, but forty seconds after the optical detectors responded with an alarm. This demonstrates that the multi-sensors require the alarm source to be present longer before triggering a fire alarm - but they still operate before a fire is created. During the water mist, dust and aerosol tests, in general the 'advanced' category multi-sensors operated after the 'intermediate' devices, which operated after the 'basic' devices. On average, the response from all the multi-sensors was later than the reference commercial smoke detectors, which in turn was later than the reference domestic smoke alarms. The development of other false alarm tests, namely the long-term dust build up, condensation, cigarette smoke, synthetic smoke and insect ingress tests, was explored but abandoned due to difficulties with developing repeatable tests.

In the course of this study four new test fires were developed, the most consistent of which was the flame retardant polyurethane foam flaming fire. Similar pass rates for the ten test fires were observed for multi-sensor detectors and optical smoke detectors, but crucially, during all five of the false alarm tests, the multi-sensors typically operated after the reference smoke detectors. On average, the false alarm resistance increased between the nominated categories, with the 'advanced' category detectors demonstrating the greatest resistance. As expected, multi-sensor detectors set at lower sensitivities operated later in test fires, and to false alarms.

To conclude, this research has shown that, the use of multi-sensor technology has the potential to reduce certain types of commonly encountered false alarms. However, the extent to which this can be realised depends on the particular implementation of features designed to improve false alarm immunity. It cannot be assumed that use of simply any multi-sensor detector will impact significantly on the occurrence of false alarms from every form of fire-like phenomena.

Regarding the implication of this research to future product standards and codes of practice, it should be possible and relatively simple to produce a product standard that will enable multi-sensor detectors to be graded according to their resistance to specific, commonly encountered phenomena that result in unwanted alarms. It is anticipated that LPCB will produce a Loss Prevention Standard for the purpose of product certification in relation to the resistance to false alarms. On that basis, codes of practice, such as BS 5839-1 (or a supporting Published Document), could give advice to users on the selection of multi-sensor detectors for specific applications.

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