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PRACTICAL COMPARISON OF DOMESTIC SMOKE ALARM SENSITIVITY STANDARDS

ABSTRACT

In 1995 it was proposed that the British Standard for domestic smoke alarms be revised in order to bring the fire sensitivity tests established in the British Standard, BS 5446 : Part 1 : 1990, into line with those in the British/European standard for commercial point-type smoke sensors, BS 5445/EN 54 : Part 9 : 1984 and to reduce nuisance alarms which smoke detector manufacturers considered to be a problem. The UK Home Office wished to be reassured that a reduction in the sensitivity would not constitute a significant reduction in the level of life safety provided by the devices.

A series of eleven tests were conducted to examine the performance of a range of smoke detectors. The fires were selected to closely match the fire sensitivity tests specified in the BS/EN/ISO stand-ards or as representative of realistic fire scenarios. The tests were conducted in a detached three-bedroom dwelling of typical 1970's UK design and construction. Optical and ionisation domestic smoke alarms and commercial analogue addressable smoke sensors, complying with UK and US standards, were installed in four locations within the dwelling; in the lounge, in the hall, on the landing and in a bedroom. The optical density of smoke close to the detectors was also measured.

In each location, the times to alarm for each detector and the time at which the density of the smoke reached a hazardous level were recorded. The time between an alarm and the onset of the smoke density hazard was calculated for each smoke detector. These data were analysed by com-paring the performance of individual smoke detectors, by using standard statistical methods for groups of detectors and by ranking the relative performance of each smoke detector across a range of tests.

For detectors complying with the UK domestic and commercial standards, analogue sensors responded as well as or, in some cases, better than the domestic smoke alarms depending on the type of fire. The overall performance of the analogue and domestic detectors were statistically similar. The ranking analysis indicated that the analogue optical sensors performed better than the domestic optical smoke alarms whereas the ionisation detectors exhibited a similar performance. Therefore, revising the domestic smoke alarm requirements to match the commercial smoke sensor standard would not reduce the life safety effectiveness of domestic smoke alarms.

Analysis of the performance of the detectors complying with the US standards found that the domestic ionisation smoke alarm and the analogue ionisation smoke sensor showed a statistically significant variability. The ranking analysis indicated that the domestic ionisation smoke alarm detected smoke earlier than the analogue ionisation smoke sensor. In the case of the optical devices, the overall performance of the two types was statistically similar. However, the ranking analysis indicated that the analogue optical sensor performed better in some types of fire scenario.

BACKGROUND

Several different test fires have been used to calibrate domestic (or residential) smoke alarms and commercial smoke detectors. In 1995 it was proposed that the British Standard for domestic smoke alarms BS 5446 : Part 1 : 1990 [1], be revised in order to reduce nuisance alarms, which the smoke detector manufacturers considered to be a problem, and to bring the fire sensitivity tests established in the British Standard into line with those in the European standard for commercial smoke detectors, BS 5445 / EN 54 : Part 9 : 1984 [2]. However, the extent of nuisance alarms had not been adequately established in the United Kingdom (UK) and the Home Office wished to be reassured that a reduction in the sensitivity of domestic smoke alarms would not constitute a significant reduction in the level of life safety provided by the smoke alarms.

A series of fire tests were conducted by the Fire Research Station (FRS), on behalf of the Home Office Fire Research and Development Group (FRDG) to examine the performance of smoke detectors complying with UK and United States (US) standards. This paper summarises the study and a full report of the work has been published by the Home Office [3].

Smoke detector standards

At the time of this study, there were separate British Standards that covered the performance of domestic smoke alarms and commercial fire detectors. BS 5446 : Part 1 : 1990 covered the requirements for domestic self-contained smoke alarms and point-type smoke detectors for dwellings. BS 5445, covered the requirements for fire detectors for commercial fire detection and alarm systems.

The two standards had differing requirements for the fire tests used to assess the sensitivity of the two types of smoke detector. BS 5446 : Part 1 : 1990 described four test fires; slow burning wood fire, fast burning wood fire, liquid hydrocarbon fire and polyurethane foam fire. BS 5445 / EN 54 : Part 9 : 1984 described six test fires (designated TF 1 to TF 6); open cellulosic (wood), smouldering pyrolysis (wood), glowing smouldering (cotton), open plastics (polyurethane), liquid (*n*-heptane) and liquid (methylated spirits). At the same time a revised version of BS 5446 : Part 1 [4] had been proposed in which the fire sensitivity tests were the same as some of those tests (TF 2-5) specified in BS 5445/EN54 : Part 9 : 1984.

In the US, UL 217 [5] covered the requirements for domestic smoke alarms and UL 268 [6] covered the requirements for smoke detectors for commercial fire detection and alarm systems. In both of these standards, the fire tests used to measure the performance and sensitivity of the smoke detectors are exactly the same. Six tests are specified; paper, wood, gasoline, polystyrene, smoldering (wood) smoke and (smoldering) cotton wick.

In addition, there was a draft ISO/EN standard [7] being developed under the Vienna agreement. The sensitivity tests TF 2-5 were the same as those specified in EN 54 : Part 9 : 1984 with the addition of test TF 7 which was the same as the smouldering smoke test specified in UL 217/268.

Previous work

A theoretical study to compare the sensitivity standards for smoke detectors [8] was completed. The study compared four standards: Draft ISO/DIS 12239 [7], BS 5446: Part 1 [1], UL 217 [5] and the proposed revision of BS 5446: Part 1 [4] to decide whether the proposed revision of BS 5446 could be accepted in place of the existing BS 5446. The study also reviewed the similarities between the fire test specifications for the existing and revised BS 5446 and also the existing European standard for commercial detectors (EN 54). The study concluded that BS 5445 and BS 5446 (revised) had effectively the same requirements on fire sensitivity. Furthermore, it appeared that BS 5446 (original) required a greater fire sensitivity when compared to BS 5446 (revised). It further concluded that BS 5446 (original) and BS 5446 (revised) could not be directly compared as they used different sets of fire tests and different pass/fail parameters.

EXPERIMENTAL SETUP

The fire tests were selected so as to closely match the fire sensitivity specified in BS 5445 : Part 9 : 1984 [2] (TF 2-5) or the draft ISO standard [7] (TF 7). In addition, two non-standard tests were conducted as representative of realistic fire scenarios that occur in dwellings (Table 1). The fire tests that matched the sensitivity tests are referred to as the ‘standard’ tests and the two realistic fires are referred to as the ‘ad-hoc’ tests. The downstairs dining room (at the rear) and the upstairs bathroom were both sealed. The doors to the other two first floor bedrooms were kept closed for all of the tests. The kitchen door was closed for all tests apart from Test 10. The fire tests were terminated once all detectors had gone into alarm or when it was considered that no more detectors would raise an alarm.

Test number	*Description*	*Location*
1	Smouldering pine	Lounge
2	Flaming polyurethane foam mat	Lounge
3	Smouldering cotton wick	Lounge
4	Flaming heptane	Lounge
5	Smouldering pine	Bedroom
6	Smouldering beech	Bedroom
7	Smouldering cotton wick	Bedroom
8	Flaming polyurethane foam mat	Bedroom
9	Flaming heptane	Bedroom
10	Flaming cooking oil	Kitchen
11	Smouldering/flaming armchair	Lounge

Table 1. Summary of fire test scenarios.

Smoke detectors

The analogue addressable smoke sensors were installed as supplied but minor modifications were made to the domestic smoke alarms. For practical and economic reasons, the smoke detectors were not replaced between each test. This may have resulted in some contamination of the sensing elements but it should be noted that in BS 5445 : Part 7 : 1984 [9] the same set of four detectors are used throughout the procedure of test fires TF 2, TF 3, TF 4 and TF 5. Smoke detectors were located in four areas in the dwelling; the lounge, the downstairs hall, the upstairs landing and the front bedroom. As far as practicable, the devices were mounted in the centre of the ceiling, away from obstructions. Four pairs of smoke detectors were located in the four areas, each pair consisting of an optical and ionisation device (Table 2).

Type	*Sensor*	*Manufacturer*	*Model*	*Standard*
Analogue	Ionisation & optical	Apollo Fire Detectors Ltd	XP95	BS 5445
Analogue	Ionisation & optical	Apollo Fire Detectors Ltd	XP95A	UL 268
Domestic	Ionisation	E.I. Company Ltd	EI 105C	BS 5446
Domestic	Optical	E.I. Company Ltd	EI 100C	BS 5446
Domestic	Ionisation	Dicon Safety Products Inc.	Micro 300	UL 217
Domestic	Optical	Dicon Safety Products Inc.	440	UL 217

Table 2. Smoke detector types installed in test series.

Optical density measurements

Optical density meters were installed in each of the rooms containing the smoke detectors. The optical density meters used a white light tungsten halogen lamp with a broad spectrum. The path length and position below the ceiling was chosen with reference to the BS, UL and Australian [10] standards. The path length was set to a nominal distance of 1.0 m and the transmission and receiver units were located such that their centres were nominally 100 mm below the ceiling. Each optical density meter was located below and central to the installed smoke detectors subject to practical limitations and accessibility. The optical density meters were calibrated using neutral density filters of 0.3 OD and 1.0 OD; in addition, the outputs at full and no obscuration were measured.

ANALYSIS

A comparison of the times to the individual alarms triggering was a logical starting point for the comparison of the different smoke detector types within each room. However, it is not necessarily the time to alarm that is critical but the time between an alarm being raised and the onset of a hazard that is of particular concern.

A study into smoke detection in domestic buildings [11] suggests that an optical density in the range of 0.07 per metre to 0.1 per metre can make escape very difficult. An empirical relationship between visibility and optical density [12] shows that 0.1 OD/m is approximately equivalent to a 10 m visibility. However, if the smoke causes eye irritation, the effective visibility may be significantly reduced. A study of the behaviour of people in fires [13] has shown that smoke density does affect whether or not people move into smoke and once visibility falls below 10 yards (9.14 m) persons moving through smoke will tend to turn back. Furthermore, the (then draft) British Standard for fire safety engineering in buildings [14] suggested that it is unlikely that the tenability limits for mixed toxic products will be exceeded providing the optical density of the irritant smoke does not exceed 0.1 OD/m. Therefore it is appropriate to consider the smoke density in this study as being representative of the principle hazard and an optical density of 0.1 OD/m was chosen as the limiting condition for the analysis.

The theoretical study [8] concluded that BS 5445 and BS 5446 (revised) had the same sensitivity requirements. It is therefore appropriate to assume that the times to alarm from the BS analogue smoke sensors are equivalent to those that would be given by domestic smoke alarms complying to BS 5446 (revised). The relative response of the two was investigated by subtracting the alarm time of each BS domestic smoke alarm from the equivalent BS analogue smoke sensor in each room.

Smouldering pine in lounge, Test 1

It is not possible to present the data for each of the 11 fire tests in this paper. Instead, details are given for a representative smouldering fire test. This test was similar to the TF 7, Smouldering pyrolysis fire (wood) as specified in the draft ISO standard [7]. Nine pieces of pine (75 mm x 25 mm x 20 mm) were arranged on the surface of a hot-plate in a radial star shape. Figure 1 shows the optical density at the lounge, hall and landing locations (the bedroom optical density was not recorded).

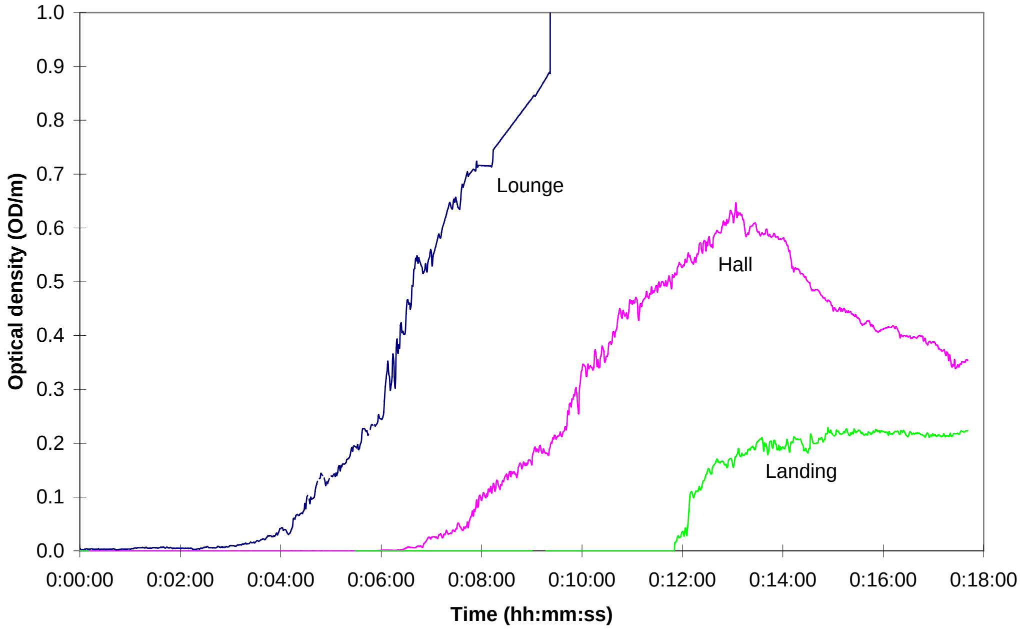

Figure 1. Optical density of smoke in lounge, hall and landing, Test 1.

Table 3 shows the detection-to-hazard times for each detector. It was noted that UL analogue optical sensor gave the greatest time in the lounge whereas it gave the least time in the hall. In general, optical detectors gave better detection-to-hazard times than ionisation detectors.

Alarm sequence and detection-to-hazard times

The alarm sequences showed the analogue smoke sensors responded quicker as a group compared to the domestic smoke alarms in the same room particularly in the standard flaming and ad-hoc fire scenarios. In these tests it was found that the last analogue sensor to respond was always ahead of the of the last domestic smoke alarm.

The detection-to-hazard times showed the difference in performance of the two types of smoke detector in different types of fire. For the standard smouldering fire tests, in general optical detectors gave higher detection-to-hazard times than ionisation detectors. In the standard flaming fires, ionisation detectors provided the longer detection-to-hazard times. The results from the two ad-hoc fire tests did not demonstrate any particular performance differences from the two types of smoke detector.

Location	Time to 0.1 OD/m (h:mm:ss)	Detector type		Domestic smoke alarm detection-to-hazard time (h:mm:ss)	Analogue smoke sensor detection-to-hazard time (h:mm:ss)
Lounge	0:04:32	Ionisation	BS	-0:01:26	-0:01:59
		Optical	BS	-0:03:29	0:00:42
		Ionisation	UL	-0:00:48	-0:01:08
		Optical	UL	0:00:20	0:00:53
Hall	0:07:57	Ionisation	BS	-0:01:52	-0:01:04
		Optical	BS	0:00:09	-0:01:30
		Ionisation	UL	-0:00:13	-0:02:53
		Optical	UL	-0:00:44	-0:04:17
Landing	0:12:09	Ionisation	BS	-0:01:28	-0:01:07
		Optical	BS	0:00:28	-0:00:43
		Ionisation	UL	0:00:43	-0:01:21
		Optical	UL	-0:00:41	-0:01:09

Table 3. Detection-to-hazard times, Test 1.

Comparison of BS 5445 / BS 5446 (revised)

In the standard smouldering fire tests the performance of the BS detectors was mixed. There were cases of a domestic smoke alarm raising the alarm before its equivalent analogue smoke sensor in one test and yet in another the response was reversed. The response of pairs of equivalent BS detectors also varied by location. For example, in Test 3 the lounge the BS domestic optical smoke alarm raised the alarm before the BS analogue optical smoke sensor whereas in the bedroom the response was reversed.

In the standard flaming fire tests, it was found that the time differences between the response of any pair of equivalent BS domestic smoke alarm and BS analogue smoke sensor was small. However, it was generally found that the BS analogue smoke sensor, particularly the optical type, would give an alarm before the equivalent BS domestic smoke sensor. In the two ad-hoc fire tests, the BS analogue sensors generally raised an alarm before the equivalent BS domestic smoke alarm.

A standard set of statistical analyses of the detection-to-hazard times for all 11 test fires was conducted. The analysis compared the variances and means of the detection-to-hazard times from the pair of BS ionisation detectors and the pair of BS optical detectors in all rooms. The comparison of the variances was carried out by using the *F-Test* with a 95% confidence limit. The comparison of the means was conducted using the *t-Test* also with a 95% confidence limit. The *F-Test* comparison of each BS detector pair found that their variances were common. The *t-Test* analyses for the detector pairs found that the mean detection-to-hazard times were not statistically different. Thus, the performances of equivalent BS domestic and analogue detectors in the 11 test fires were similar.

It was found that the BS analogue smoke sensors tested to EN54 gave detection-to-hazard times similar to or better than the BS domestic smoke alarms tested to BS 5446. Thus, domestic smoke alarms that are be tested to the revised version of BS 5446 would perform as well as the domestic smoke alarms tested to the earlier standard.

Comparison of UL detector responses

In the standard smouldering fires it was found that the UL domestic smoke alarms generally responded earlier than the equivalent UL analogue smoke sensor. However, there were cases, such as in Test 7, where there were significant variations in favour of the UL analogue smoke sensors. In the standard flaming fires the difference in response between equivalent detector pairs was small. The UL analogue optical smoke sensors were found to be marginally more responsive than their equivalent UL domestic optical smoke alarm. In the ad-hoc fire tests, it was found that with the exception of a number of isolated cases, the response times of UL detector pairs were close together.

As for the BS detectors, a statistical analysis of the performance of the pairs of UL ionisation detectors and UL optical detectors was performed using the *F-Test* and the *t-Test*. The variances for the UL analogue and domestic ionisation detectors indicated that the performance of the UL domestic ionisation smoke alarm and UL analogue ionisation smoke sensor was not similar. However, the mean detection-to-hazard times for the UL optical detector pair were statistically similar.

Ranking analysis

The initial analyses of the results calculated and compared the average hazard-to-detection times for each smoke detector type in each room. However, when a detector failed to raise an alarm in a test in which the optical density reached 0.1 OD/m it was not possible to assign a detection-to-hazard time. Omitting such detectors from the overall analysis may have skewed the conclusions away from those detector types that did not give an appropriate alarm. Therefore, an additional method of ranking was developed to ascertain the relative performance of the different types of smoke detector.

Each individual detector was ranked in decreasing order of detection-to-hazard times. Detectors that raised an alarm where the optical density never reached 0.1 OD/m were ranked equal top. Thereafter a detector with the highest detection-to-hazard time was ranked next and detectors with equal detect-ion-to-hazard times were given an equal ranking. Where the optical density in a room reached 0.1 OD/m and the detector failed to raise an alarm the detector was ranked last. However, where a detector did not raise an alarm and the optical density did not reach 0.1 OD/m, the detector was omitted from the ranking since was not possible to infer the performance level from such a circumstance. For each test, an average rank for each detector type, regardless of location, was calculated and these averages ranked. Thus, the eight detector types were ranked in order of performance for each test fire and these rankings were used as a basis of further analysis.

Clearly, unlike the analysis of the actual detection-to-hazard times, the ranking analysis does not account for the time differences that will exist between ranking levels. A detector in a specific test will be ranked higher than another whether it gave alarm several minutes or merely seconds before. The ranking analysis also does not differentiate between cases where the detection-to-hazard was a positive time and where it was a negative time. However, the technique does allow a method of reducing the test data into a format that aids the overall analysis.

Standard smouldering fires

Figure 2 shows the spread of rankings for each detector type in the standard smouldering fire tests. It is clear that there was a considerable amount of variability between tests as shown by the wide spread in rankings for most of the smoke detector types.

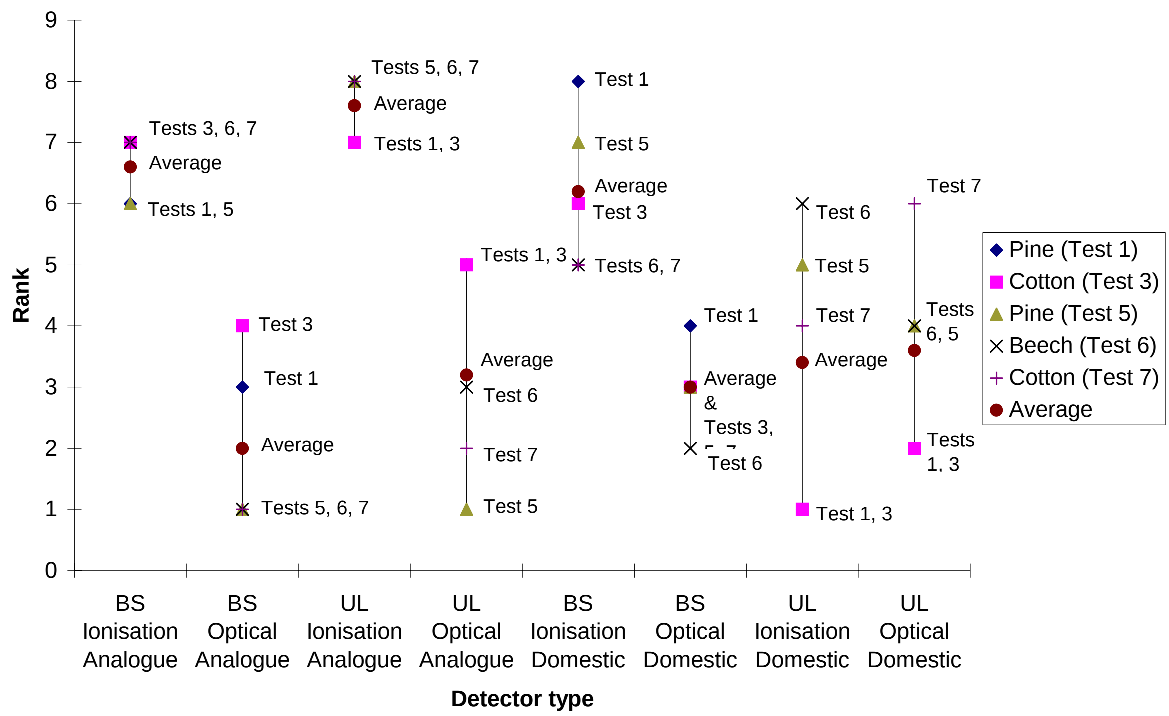

Figure 2. Ranking analysis for the standard smouldering fires.

Comparing the BS domestic and BS analogue detectors it is found that there are three cases of the BS analogue optical smoke sensor ranked 1 and three cases of the BS domestic optical smoke alarm ranked 3 thus suggesting a better performance from the analogue optical smoke sensor. For the ionisation smoke detectors, three cases were at ranks 5 and 6 for the BS domestic ionisation smoke alarm and three cases at rank 7 for the BS analogue ionisation smoke sensor. However, the BS domestic ionisation smoke alarm shows a wider spread.

The rankings of the UL domestic and UL analogue detectors were also compared. The ranking patterns of the UL domestic ionisation and UL domestic optical smoke alarms are similar, both exhibiting a wide spread between ranks 1 and 6. However, the UL analogue ionisation and UL analogue optical smoke sensors show a distinct difference. The UL analogue ionisation smoke sensor cases are all clustered in the ranks 7 and 8 whereas the UL analogue optical smoke sensor is spread between ranks 1 and 5. The UL analogue optical smoke sensor and UL domestic optical smoke alarm ranking spreads are similar whereas the UL domestic ionisation smoke alarm always ranks better than the UL analogue ionisation smoke sensor.

Standard flaming fires

Figure 3 shows the spread of rankings for each detector type in the standard flaming fire tests. There is less variability in these tests when compared with the standard smouldering fires. Comparison of the BS domestic smoke alarms and BS analogue smoke sensors rankings revealed a similar result as for the standard smouldering fires. The analogue optical sensors performed better than the domestic optical smoke alarms whilst the analogue ionisation smoke sensors and domestic ionisation smoke alarms showed a similar performance. The ranking of the UL smoke detectors indicates that UL domestic ionisation smoke alarm performed more effectively than the UL analogue ionisation smoke sensor. However, the analogue optical smoke sensor performed better than the domestic optical smoke alarm.

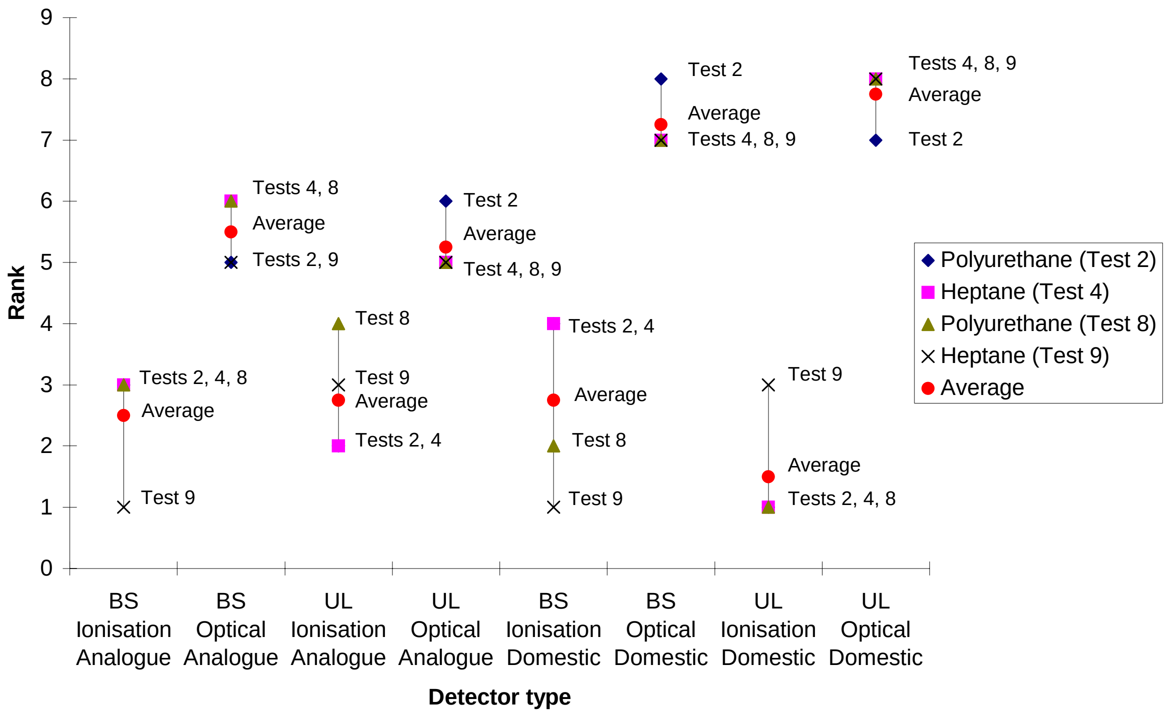

Figure 3. Ranking analysis for the standard flaming fires.

Examination of the rankings of equivalent sensor types indicated that the BS and UL analogue optical smoke sensors are very similar as are the BS and UL domestic optical smoke alarms. The ionisation smoke detectors show a wider variability in rankings but again are relatively similar across the four types with the UL domestic smoke alarms being the most effective.

Ad-hoc fires

For the two ad-hoc fires the rankings matched closely with all four optical detectors achieving the same rank in every test. Examination of the BS analogue and BS optical smoke detect-ors again showed a significantly improved detection performance from the BS analogue optical device over the BS domestic optical device. The BS analogue ionisation sensor showed a greater variability when compared with the BS domestic device but on average it performed marginally better. Comparison of the UL smoke detector rankings showed that the UL analogue optical smoke sensor was more effective than the UL domestic optical smoke alarm whilst the UL analogue and UL domestic ionisation detectors were similar.

Effect on life safety

The analysis of the fire tests demonstrated that the proposed revision to BS 5446 : Part 1 would not lower the life safety potential of domestic smoke alarms. This conclusion was based on the comparison of the hazard-to-detection times obtained by the BS detectors and the ranking analysis. It was shown by interpretation and statistical analysis that the detection-to-hazard times from analogue smoke sensors tested to EN 54 were similar to domestic smoke alarms tested to BS 5446. Furthermore, the ranking analysis suggested that analogue optical sensors tested to EN 54 perform generally better than domestic optical smoke alarms tested to BS 5446 and analogue ionisation sensors tested to EN 54 perform as well as domestic ionisation smoke alarms tested to BS 5446.

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