

# **SMOKE DETECTION PERFORMANCE AND FDS MODELLING FOR FULL-SCALE FIRE TESTS**

Yun Jiang<sup>1</sup>  
Xtralis Pty Ltd  
Bentleigh East, VIC 3165, Australia  
Peter Massingberd-Mundy  
Xtralis (UK) Ltd

## **ABSTRACT**

Fire engineering designs require quantified performance of fire detection systems to comply with “deemed to satisfy” (DtS) or “performance based design” (PBD) requirements. Nominal sensitivities/thresholds specified by the manufacturers are usually adopted to determine the detection times in various calculations and computer modellings. Challenges are continuing raised on certainty of detectors’ performance in real fires, and accuracy of computer modelling of the fire detection systems. As a principle participator in the Firegrid research project, Xtralis undertook full-scale fire tests of the real performances of various fire detection systems, including conventional point type detectors and Air-sampling (aspirating) Smoke Detection (ASD) systems. Furthermore, validation of computer modelling on the detection was achieved from the in-situ tests.

This paper presents major test and simulation results of fire detection from two sets of full-scale fire tests conducted in the Firegrid project. It reveals performance differences between the various detection systems studied and also the accuracy of predictions generated using computational fluid dynamics (CFD) models. The results show that Fire Dynamics Simulator (FDS) simulation on the ASD system generated quite high accuracy of performance prediction in those tested scenarios, while significant inconsistencies exist between the experimental and simulation results for the conventional point type smoke detectors. In the tests the smoke levels observed at the time of alarm of the photoelectrical detectors exceeded the manufacturer’s nominal sensitivities by more than 220 to 580%. The simulated average alarm times of the point detectors are between 30 to 56% of the tested. These inconsistencies are believed to be attributed to a combination of the uncertainty of point detector response in complex fire environments and an over-estimated soot level developed in big fires by the FDS simulations.

## **INTRODUCTION**

Point type smoke detectors, including photoelectrical (optical) and ionisation types, are fire detectors widely adopted in commercial and residential use. However their detection performance is frequently questioned when quantified detection performance is required in fire safety engineering designs. While their basic response to different fires (selective detection) is well understood, (ionisation detectors being more responsive to flaming fires and photoelectrical detectors to smouldering fires), a major issue remains as to the predictability of their response in real fire situations. These issues have been highlighted in a number of recent researches<sup>[1] [2]</sup>, and the reported errors relative to detectors’ nominal sensitivities published can be high as 1000%<sup>[3]</sup>. Such inconsistencies occur particularly under complex combustion and environmental (ventilation) conditions.

---

<sup>1</sup> Dr. Yun Jiang, Senior Applications Engineer, Xtralis (yjjiang@xtralis.com)

ASD systems are increasingly being deployed in the protection of commercial and residential buildings. These systems actively draw samples from the protected area and, as such it is both logical and has been demonstrated that predictions of their response using CFD are significantly more accurate than with point type detectors. During the past 2 decades, ASD systems have been used in many challenging applications, such as large open spaces (LOS), high velocity environments (Cleanroom) and very early warning (VEW) detection required environment (IT&C). More recently, the high accuracy in quantified detection performance has seen an increasing use of ASD in performance-based design (PBD) solutions implemented by many fire consultants and engineers.

Computer fire modelling is becoming a powerful and useful tool in fire safety engineering designs, especially in PBDs where qualitative and quantitative performances are prerequisite. Great progress has been achieved recently on using computer models, especially CFD models to predict the performances of fire detection systems. Most significantly, FDS version 5 now integrates sub-models for various detection technologies, such as point, beam-projected and ASD type smoke detectors<sup>[4]</sup>. Researchers suggest that a higher accuracy prediction for point detectors activation performance can be expected by modelling real-time flow entry behaviours of such detectors<sup>[5]</sup>. However, accuracy in smoke detection remains relative poor from those sub-models compared to predictions for other, more fundamental phenomena, such as temperature and flow velocity, etc. Therefore, more validations for a wider range of detectors and fire scenarios by laboratory and in-situ tests are required to improve the models and achieve a higher grade of confidence.

Firegrid is a multi-million pound, multi-participator fire research project supported by the UK government. Firegrid aims to use various formats of data from sensor networks combined with grid and high performance computing in order to deliver real-time modelling data to an Artificial Intelligent (AI) based command station to provide prediction of fire development and structural response to fires. As such the project provided a great opportunity to test detection technologies under various full-scale fire test conditions. Furthermore, due to the richness of data gathering, CFD modelling results can be validated against experimental test data using a number of variables such as temperature, radiative flux, flow velocity, deflection, gas concentration as well as smoke level.

## **RESEARCH OBJECTIVE AND APPROACH**

In line with the general objective of Firegrid, to provide fire detection data to the grid for real-time modelling and prediction, Xtralis set its own objectives for the full-scale tests as follows:

- Obtain actual performance of ASD and conventional fire detectors from those real fire scenarios;
- Conduct FDS modelling of fire development and detection performance;
- Validate the prediction of smoke detection from various modelled and criteria with the experiments.

To achieve the above objectives, the following approach was adopted in the research:

- Use a high sensitivity ASD system to accurately monitor and record smoke levels adjacent to point detectors, during alarm activation of detection technologies;
- Validate the simulated ASD detection performance by the test data;
- Evaluate the alarm prediction accuracy of various computer modelling methods for point type detectors by both actual point detector and the ASD (reference) readings.

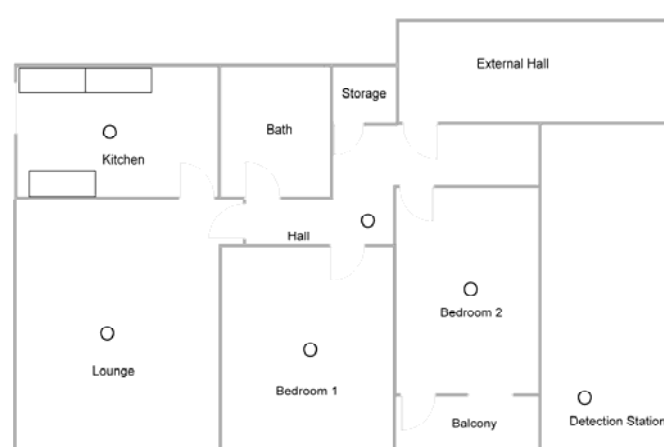
## FULL-SCALE IN-SITU TESTS

Two sets of full-scale fire tests were conducted in a high-rise apartment in Dalmarnock, Glasgow (July 2006) and in a test rig built in Building Research Establishment (BRE), London, (Oct 2008) respectively.

### 1. DALMARNOCK APARTMENT TESTS

#### Test Rooms

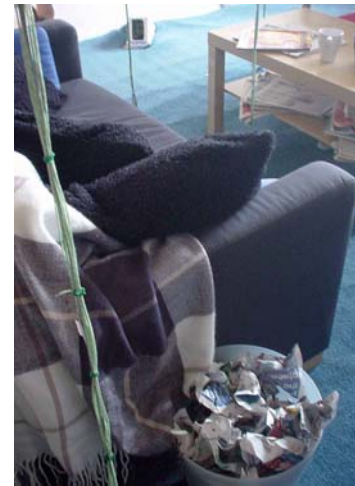
The tests were conducted in two sets of apartments, in Level Four and Six of high rise blocks, having identical layouts. Each of the apartments consisted of a lounge, a kitchen, two bedrooms and a bathroom, as shown in Figure 1. The fire started from the Lounge, which has dimensions of 6.4 x 4.0 x 2.7 metres (m) and was the only furnished room, as illustrated in Figure 2.



**Figure 1:** Floor Plan of the Test Apartment



(a) Settings in Lounge



(b) Pilot Source

**Figure 2: Room of Fire Origin and Pilot Source**

### Fire Source and Test Conditions

Two fire tests: named controlled (ventilation) and un-controlled, were performed in the two apartments, with identical configurations in the fire source room (Lounge) and ignition condition. The un-controlled fire test results are presented in this paper to represent more realistic fire condition.

Ignition of the fire was from a plastic waste paper bin filled with crumpled newspaper and 500ml of heptane. A blanket was draped on one arm of the sofa to help flame spreading to the sofa, as shown in Figure 2 (b).

During the un-controlled fire test, all doors were kept open, except the Bath, Storage, and the door connecting Bedroom2 and Balcony. All windows were closed except those in Kitchen (ajar) and in Bedroom2 (open with fly screen).

### Fire Detectors

An ASD and three point type detectors, ionisation, optical-smoke and heat detectors, were installed in each major room of the apartment. Their locations are indicated in Figure 1 in as Detection Stations (DS). Each DS contained three point type detectors and one sampling hole of the ASD system. A total of five ASD detectors, one sampling hole per detector, were used to monitor absolute smoke levels (without dilution) at each DS.

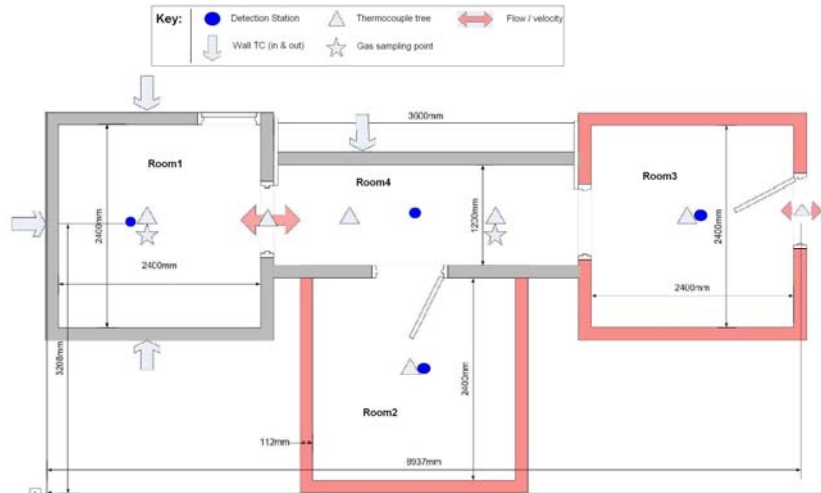
The Alert and Fire alarm thresholds of the ASD system were set to 0.05 and 0.20%OBS/m. The Fire alarm threshold of the point type smoke detectors (ionisation and optical) was set to 2.1%OBS/m. The Fire alarm threshold of the heat detectors was set to 58°C.

## 2. BRE TESTS

### Test Rig

The test rig in BRE's Burn Hall consists of three rooms of identical size, 2.4 x 2.4 x 2.4 m. One corridor, with dimensions of 3.6 x 1.2 x 2.4 m, in the middle connects all of the rooms, shown in Figure 3. All doors are the same size as 2.0 x 0.8 m.

Rooms 1 & 4 composed of identical wall materials (double plaster boards with 100mm Rockwool in middle) and ceiling materials (Supalux-inside and plaster board-outside sandwiching with 100mm Rockwool). Rooms 2 & 4 comprised single plaster board on timber studs for walls and ceiling. The floor in all rooms is made of concrete. Sampling locations of partial measured variables are marked in Figure 3 as well.



**Figure 3:** Floor Plan of the Test Rig in BRE

### Fire Source and Test Conditions

Various fire scenarios were tested in the test rig, including: smouldering timber stick, smouldering cotton braid/wick, overheated PVC wire, medium-size propane gas burner combustion, and finally a full load fire using a sofa as the main fuel load. This paper presents results from the big fire test only. This fire was piloted from the smouldering of cotton braid which after 2-3 minutes ignited a match (to provide a definitive point of ignition). The match ignited 4 small pieces of fibre boards (approx. 80 x 25 x 12 mm) soaked in industrial methylated spirits to spread the flame to the sofa. The configuration of the fire room (Room1) and the piloted source are pictured in Figure 4. During the test, all doors were kept open except the external door to Room1 which was for access during the setup only.



(a) Settings in Room1



(b) Pilot Source

**Figure 4:** Room of Fire Origin and Pilot Source

## Fire Detectors

The same types of detectors as those used in the Dalmarnock apartment test were adopted in this test. Detection Stations (DS) were placed under ceiling in the middle of each room, as indicated in Figure 3.

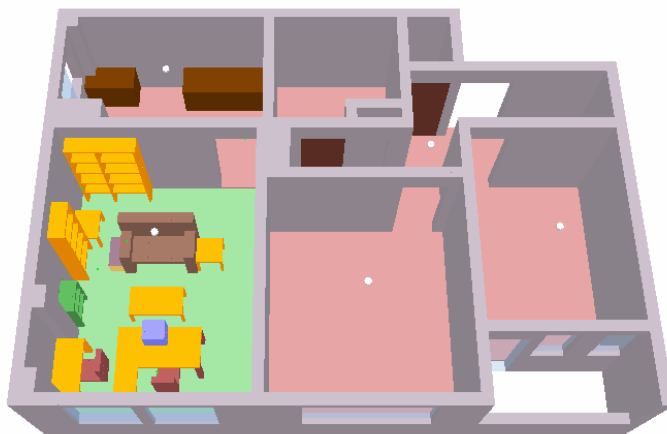
Sensitivities of the smoke detectors, including the ASD and the point type smoke detectors, were set as those in the Dalmarnock experiment. The Fire alarm threshold of the heat detectors were changed to 61°C.

## FDS MODELLING SETTINGS

The FDS versions 4.0.7 and 5.2.0 were utilised to conduct the computer modelling of each test. Settings of the models for the two tests are described below.

### 1. SIMULATION SETTINGS FOR DALMARNOCH TEST

Multiple meshes were introduced in the simulation. In the fire room (Lounge), the grid resolution was 0.05 x 0.05 x 0.05 m. In the rest of the apartment, 0.1 x 0.1 x 0.1 m resolution was applied. Illustration of the domain is shown in Figure 5.



**Figure 5:** Simulation Domain and Meshes

The combustion behaviours of the sofa in the Lounge was defined in the simulations by two methods: 1) a generic HRR profile from a NIST sofa burning test<sup>[6]</sup>, and 2) a HRR profile based on the average values of a Round-Robin simulation for the tests<sup>[7]</sup>. These HRR curves are illustrated in Figure 6.

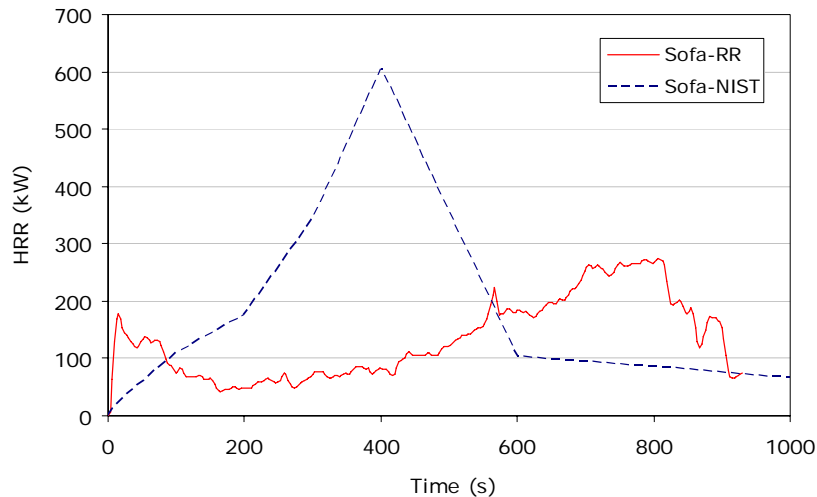


Figure 6: HRR Curves Adopted in the Simulations

## 2. SIMULATION SETTINGS FOR BRE TEST

A higher grid resolution, 0.05 x 0.05 x 0.05 m, was applied for the fire room (Room1) and the corridor (Room4), and 0.1 x 0.1 x 0.1 m resolution was applied to the other rooms. Figure 7 illustrated the simulation domain.

From a free burning test before the formal test, it was established that the HRR profile from the sofa burning is similar to a  $T^2$  slow growth trend with a peak value of 400kW. As such, a  $T^2$  slow growth profile was specified to the sofa in the simulation preceded by a 3-minute incipient stage (30W constant fire).

One particular feature in the test was the positioning of an additional light in the left hand bottom corner of Room1. This 500W halogen lamp was needed for the cameras, and influenced the flow pattern and smoke movement during the incipient stage. This lamp was simulated as a convective heat source with estimated 300W output.

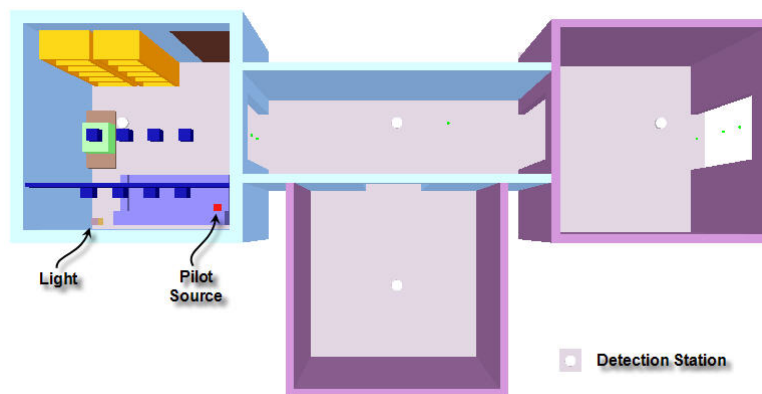


Figure 7: Simulation Domain

## SMOKE DETECTION SIMULATED IN FDS

### 1. ASD DETECTOR

As described by the author previously<sup>[8]</sup>, smoke density in an ASD central detection unit is a function of smoke densities and flow rates at each sampling hole of the

detector as well as transport times from the sampling holes to the central unit. While the smoke density distribution can be simulated by FDS, the other parameters (flow rate and transport time) need to be calculated separately. Most usually, this is done by using special pipe network computing software developed by one of the major ASD manufacturers. For this paper, the parameters of the ASD system were calculated by ASPIRE2, a software developed by Xtralis.

FDS version 5 now supports calculation of accumulation of smoke from multiple sampling holes in an ASD system once the flow and transport time for each individual sampling hole is provided. However, the data presented in this paper for the Dalmarnock test was performed using FDS version 4. As such the calculation was calculated manually. For validation, the same manual calculations were also done on the simulations generated using FDS5 and compared with the results obtained using the new automatic accumulation code in FDS5 - identical results were obtained.

## 2. POINT TYPE SMOKE DETECTORS

Three methodologies for predicting the point detector's response were adopted:

- 1) using built-in smoke detector sub-models from FDS,
- 2) applying averaged optical densities from statistics, and
- 3) by multiple criteria.

Two types of smoke detection sub-models, Cleary and Heskestad models, have been built in FDS to simulate the response of point type smoke detectors<sup>[4]</sup>. The behaviour of smoke entering into the detection chamber was simulated by various numbers of parameters. In Heskestad's model, a single parameter model, dwell time was expressed by time for smoke travelling over a characteristic length  $L$ . In Cleary's multi-parameter model, the smoke entry lag time is expressed as sum of dwell time and mixing time, which are computed by two parameters respectively. NIST developed a test facility, FE/DE to determine those required parameters for point type smoke detectors<sup>[9]</sup>. However, without enough validation results, applicability and suitability of those parameters in real fire scenarios are still unclear since environmental conditions surrounding the detectors may be quite different from the standard test. Furthermore, such parameters are still unavailable for most of today's point type smoke detectors, even for widely used ones such as those used in the Firegrid tests. Therefore, the default parameters for the Cleary model suggested by the FDS manual were adopted in the current simulation. As for the Heskestad model, characterised length values as 1.8m for the ionisation detector and 15m for the optical detector, recommended from SFPE handbook<sup>[10]</sup>, were used.

The second method is to use an average optical density (OD), rather than the detectors' nominal sensitivity, to achieve a higher certainty in detection. As recommended by Geiman and Gottuk<sup>[1]</sup>, optical density of  $0.11 \text{ OD/m} \pm 0.04$  as the primary indicator of a smoke alarm can result in 80% certainty from various research tests (i.e. 80% of detectors tested have responded by this OD). This method has been used in number of studies, including fire modelling conducted for a Fire Protection Research Foundation (NFPRF) Detector Performance In Waffle Ceilings research project<sup>[11]</sup>. To assess the ionisation and photoelectrical detectors used in the current study individually, values suggested by the author for this two types of detectors were adopted as: ionisation detector,  $0.072 \text{ OD/m}$ ; photoelectrical detector,  $0.11 \text{ OD/m}$ . While the value for photoelectrical detectors is applicable for both flaming

and smouldering fires, the value of 0.072 OD/m is just for flaming fires. However, since the fire was flaming in both tests before either type or detector operated it is reasonable to use the latter figure for the ionisation detector.

The third method in determining the alarm status of the point type detectors is by satisfying certain criteria, including optical density, temperature rise and gas velocity at the postulated smoke detector locations. Thresholds of those criteria were given as below:

- a) The optical density was decided by the detector’s nominal sensitivity.
- b) Temperature rise ( $\Delta T$ ) was 4 °C for ionisation detectors and 13 °C for photoelectric detector (representing conservative thresholds).
- c) Velocities should be above 0.13 m/s  $\pm$  0.06.

## **RESULTS AND DISCUSSION**

### **1. RESPONSE TIMES OF THE DETECTORS FROM THE TESTS**

The detectors’ response times from the two tests are shown in Table 1 and Table 2. Since an incipient stage burning was included in Test2, ASD’s dual stage response times, at Alert and Fire alarms, were given in the tables.

**Table 1 Detectors’ Response Times from Test1**

Location	Alarm Response Time (s)				
	ASD		Ionisation	Optical	Heat
	Alert Alarm	Fire Alarm	Fire Alarm	Fire Alarm	Fire Alarm
Lounge	9	9	16	25	40
Kitchen	14	17	30	57	230
Hall (Corridor)	23	23	84	83	109
Bedroom1	42	42	98	100	307
Bedroom2	227	227	234	234	328

**Table 2 Detectors’ Response Times from Test2**

Location	Alarm Response Time (s)				
	ASD		Ionisation	Optical	Heat
	Alert alarm	Fire alarm	Fire alarm	Fire alarm	Fire alarm
Room1	78	98	200	226	440
Room2	117	252	273	313	863
Room3	100	239	247	248	813
Room4	71	79	230	261	702

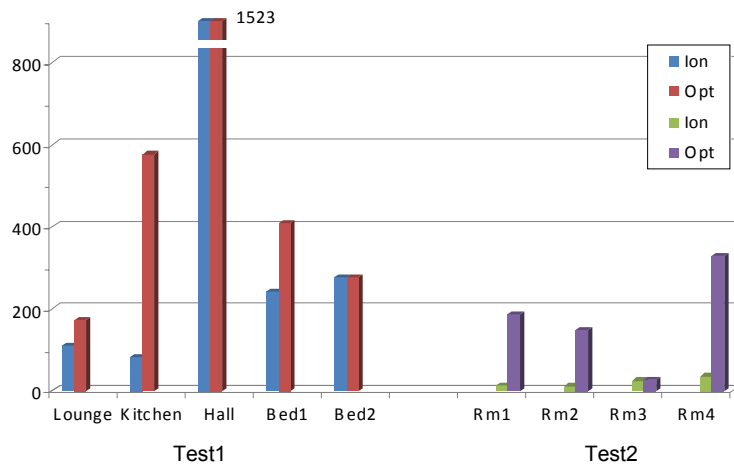
In the two tests, ASD had earlier response to smoke than the point detectors, in all locations. When an incipient stage is presented, an ASD system can provide very early warning (VEW) fire detection to small amounts of smoke generated from a smouldering burning, as shown from the 2<sup>nd</sup> test. ASD’s early detection feature is attributed to a combination of its high sensitivity and stable and reliable performance from its “active sampling” technique. The advantages of very early warning (VEW) are clearly reduced where there is no incipient stage in the development of the fire such as in Test1 when a significant flaming fire was set at the beginning of the test.

It’s interesting to note that in Test2, the ASD detector in the corridor (Room4) raised an alarm earlier than that in the fire room (Room1). This unexpected result can be attributed to the 500W lamp installed in the corner of the fire room. Built-up of convective flows in the room caused by hot air rising from this lamp meant that smoke rising from the smouldering cotton braid drifted out of the fire room through

the open door during the incipient burning stage – away from the sampling hole in the middle of Room1. When the fire developed into a flaming fire, the convective airflows in the room became dominated by the fire rather than the lamp, and as such, the situation was totally different by the time the fire was bigger enough to trigger the conventional smoke detectors. Hence as one might expect, the detectors in the fire room responded to the fire quicker than those in the corridor.

**2. ACTUAL SMOKE LEVELS AT POINT DETECTORS RESPONDED**

Figure 8 shows smoke levels (in percentage) recorded by the ASD detectors at detection times, appropriate transport times applied for corrections, of those point type smoke detectors. The nominal sensitivities of the point detectors are 2.1%/m.



**Figure 8:** Percentage of Monitored Smoke Levels to the Nominal Sensitivity

In Test1, the ranges of smoke levels recorded for the ionisation and optical detectors are from 81.0% to 1523.8% and from 171.0% to 1523.8% of the nominal sensitivity. In Test2, the ranges are from 11.9% to 35.7% and from 27.6% to 328.6% for the ionisation and optical detectors respectively. Generally higher smoke levels were recorded for the both types of detectors in Test1, where a fire developed quickly and complicated geometry conditions were presented.

The ionisation detectors response appears significantly different in the two test fires when assessed against the smoke density measured using the ASD. In contrast the optical detectors seem to show a more consistent response. This is not particularly surprising because the ASD system used in the comparison incorporates optical laser technology to determine the smoke density. While the optical points used incorporate a similar optical (but LED based) technology, the ionisation detectors incorporate a fundamentally different detection technology. Clearly the ionisation detectors were relatively more responsive to the products of combustion produced in the early phases of Test2 than in Test1. What is worth noting is that the nominal sensitivities used are essentially related to optical density, not to an ionisation reference. As such it is not unexpected that the ionisation detectors may respond much faster than is predicted by a measurement of optical density – particularly where a flaming fire is in progress. In some research this tendency to generate alarms much lower than its nominal sensitivity has been described as the “selective detection feature of ionisation detectors”. Recent research<sup>[12]</sup>, recorded smoke levels

at ionisation detectors (with sensitivities between 2.5 to 5 %/ft) activated are below than 1%/ft.

The optical detectors respond at smoke levels much higher than their nominal sensitivity in the two tests consistently. The one exception to this observation is the detector in Room3 in Test2. Response of this detector is questionable since its alarm time is earlier than the one in Room4 which is closer to the fire room. Excluding the result from Detector 3 in Test2, the mean values of the recorded smoke levels at alarm for the optical detectors in the two fires are 5.8 and 2.2 times of the nominal sensitivity respectively. These results match with other researches<sup>[2][12]</sup>.

### 3. SIMULATED DETECTORS' PERFORMANCES

#### The ASD Detector

From the simulations for Test1, higher smoke density was obtained from simulations conducted using FDS5 compared with using FDS4, and the discrepancy increased as the fire developed. However, simulated ASD detection performances from these two versions are quite close since the high sensitivity ASD detectors are capable of responding to very low smoke density occurring during the early stage of the combustion, when the discrepancies between FDS4 and 5 were small. Therefore, for Test1, this paper presents results from simulations by version 4. Results obtained from the two HRR setting methods, from the NIST sofa burning and the RR simulations, were presented in Table 3 along with the actual response times measured during the tests.

**Table 3: Simulated ASD Response Times – Test1**

Detector Location	FDS Simulated Response Time (s)				Tested Resonse Time (s)
	NIST	Percentage of Tested (%)	RR	Percentage of Tested (%)	
Lounge	9	100.0	10	111.1	9
Kitchen	18	105.9	19	111.8	17
Hall	21	91.3	22	95.7	23
Bedroom 1	35	83.3	41	97.6	42
Bedroom 2	46	20.3	52	22.9	227

No significant difference exists between these two setting methods of the fire source even through the HRR profiles are different. Furthermore, the predicted response times were all within 20% of the times recorded during the test – with the one exception of Bedroom2. This is because the open windows in Bedroom2 were not included in the simulation. From video footage of the experiment it was observed that during the test, smoke spread into Bedroom2 was postponed by wind entering into the apartment through the external hall and a fly screen mounted on top of the Bedroom2 windows. When the smoke front overcame the resistance and eventually entered into Bedroom2, smoke density became quite high which resulted similar response times from the ASD and point type detectors, as shown in Table 1. Such wind effect was not simulated in the modelling and significant errors occurred in simulated response times not only for the ASD detector but also for the point detectors in the Bedroom2.

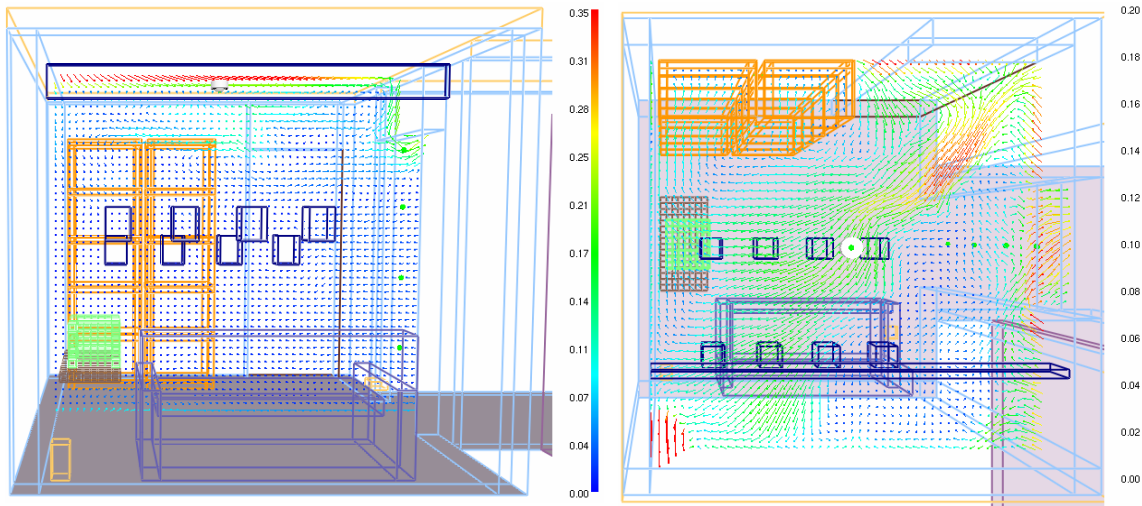
Predictions of the ASD detector response times in Test2 are given in Table 4 based on Alert alarm set at 0.05%/m and Fire alarm at 0.2%/m. Also included in the table are the comparisons to the time measured during the fire.

**Table 4:** Simulated ASD Response Times – Test2

Location	Room1		Room2		Room3		Room4	
Alarm Level	Alert	Fire	Alert	Fire	Alert	Fire	Alert	Fire
Response Time (s)	83	92	140	177	112	130	73	81
Response Time from Test (s)	78	98	117	252	100	239	71	79
Percentage of the tested (%)	106.4	93.9	119.7	70.2	112.0	54.4	102.8	102.5

As can be seen, the predictions, particularly during the incipient stage of the fire are reasonably accurate. The predictions of the Alert alarm times, corresponding to the first hints of smoke at the sampling locations, were dramatically affected by modelling of the flow pattern. In simulations which included the 500W lamp, the built-up of convective flow from the lamp was reasonably simulated in FDS, as illustrated in Figure 9. However, simulations performed prior to the live test were performed with the 500W lamp excluded and predicted that the ASD detector in Room1 would alarm first and that responses of the ASD detectors in other rooms would also be slower than the values presented in Table 4.

This clearly demonstrates the importance of considering and including all possible heat and ventilation sources in any simulations of incipient conditions as it is the natural (or residing) air flows which determine where smoke will travel and how early warning and very early warning detectors will respond.



(a) Elevation View – at Centreline  
 (b) Top View – at 2m High  
**Figure 9:** Simulated Flow Pattern (Velocity) in Fire Room Before Flaming

Considering the response predictions further into the fire (after the end of the incipient phase and some time after ignition) it is clear that the flows become dominated by the heat generated by the fire. However, the smoke generation model used in FDS is also a significant parameter in determining the accuracy of the response prediction. As shown in Figure 10, simulated smoke densities in all of the 4 rooms, expressed as obscuration levels, are much higher than those recorded during the test. (It's noted that the maximum value can be displayed by the ASD detector is

32%/m.) Such over-predicted smoke concentrations by FDS has been reported by other researchers<sup>[13]</sup>. There are two principle reasons for this over-prediction;

- 1) Firstly, in modelling of soot generation. Soot yield adopted in FDS simulations are usually obtained from small scale tests<sup>[14]</sup>. It is reported that as the fire size increases the soot yields decreases<sup>[15]</sup>. Difference between measured soot yields from tests and those reported in literatures ranged from a factor of 2 to 5<sup>[13]</sup>. Therefore much higher smoke density was predicted by FDS under large fire size conditions comparing to the test results.
- 2) Secondly, in modelling of soot transportation. Soot deposition on ceiling above the fire source in the test can significantly reduce amount of smoke transported to sampling locations. According to a test conducted under a 2.7m high ceiling, 39% of soot was removed from combustion of a 100kW propylene fire in the first 5 minutes, by depositing on the ceiling<sup>[13]</sup>.

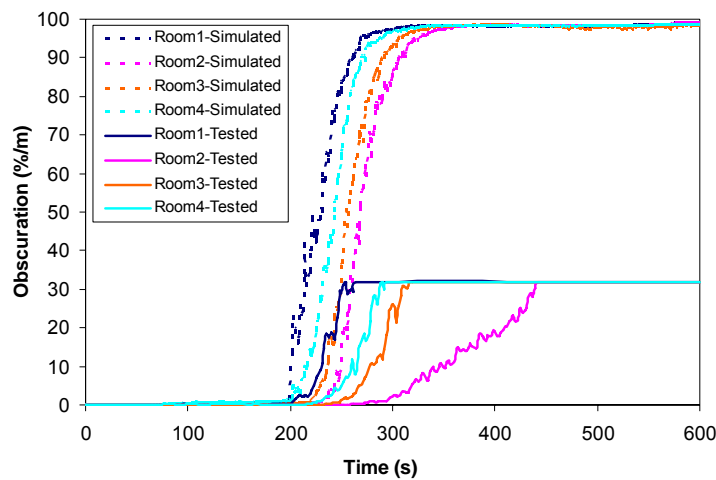


Figure 10: Smoke Obscuration from the Simulation and Test – Test2

### The Point Type Smoke Detectors

Predicted response times for the point type smoke detectors in Test 1&2 are shown in Table 5 and Table 6 respectively along with comparisons with the times recorded during the tests. The predicted response times for Test1 were generated by Cleary model with the default parameters, while those for Test2 were generated using 4 different methods (as indicated in the table).

Table 5: Simulated Response Times for the Point Detectors – Test1

Detector Location	Detector Type	FDS Simulated Response Time (s)				Tested Response Time (s)
		NIST	Percentage of Tested (%)	RR	Percentage of Tested (%)	
Lounge	Ionization	9	56.3	7	43.8	16
	Optical	9	36.0	7	28.0	25
Kitchen	Ionization	30	100.0	21	70.0	30
	Optical	31	54.4	20	35.1	57
Hall	Ionization	28	33.3	20	23.8	84
	Optical	28	33.7	20	24.1	83
Bedroom 1	Ionization	55	56.1	40	40.8	98
	Optical	54	54.0	39	39.0	100
Bedroom 2	Ionization	84	35.9	51	21.8	234
	Optical	84	35.9	51	21.8	234

Table 6: Simulated Response Times by Various Methods – Test2

		Room1		Room2		Room3		Room4	
		Ionisation	Optical	Ionisation	Optical	Ionisation	Optical	Ionisation	Optical
Cleary model	Response time (s)	204	204	246	244	231	229	207	206
	Percentage. of the tested (%)	102.0	90.3	90.1	78.0	93.5	92.3	90.0	78.9
Heskestad model	Response time (s)	199	201	235	246	226	233	203	210
	Percentage. of the tested (%)	99.5	88.9	86.1	78.6	91.5	94.0	88.3	80.5
Average OD method	Response time (s)	202	210	251	257	238	244	224	228
	Percentage. of the tested (%)	101.0	92.9	91.9	82.1	96.4	98.4	97.4	87.4
Multi-criteria	Response time (s)	201	214	251	269	238	253	219	243
	Percentage. of the tested (%)	100.5	94.7	91.9	85.9	96.4	102.0	95.2	93.1

From Table 5 it is clear that the FDS simulations over-predict the detector performance – i.e. that they will detect earlier than they actually do during the test. The simulated response times were 20 to 50% of the tested result in most cases. The predictions generated using the HRR profile created by the Round-Robin simulations, which has lower peak value and is believed closer to the real combustion condition compared to that from the NIST sofa burning profile, actually resulted in even early and more misleading predictions. The shorter response times from the RR simulation, 40.0% and 29.6% of the nominal sensitivity for the ionisation and optical detectors compared to 56.3% and 42.8% accordingly from the NIST simulation, may be caused by the 1<sup>st</sup> quick rising peak in the HRR curve. As per the discussion above with respect to the effect of over-predicted soot levels by FDS the soot generation at this peak (approximated 160kW) calculated by the simulation would be much higher than would actually occur in the real fire burning. Such uncertainty should be taken into consideration when complex geometry, boundary and combustion conditions are modelled.

In the relatively simple test condition (Test2), where most of detection stations located in the centerline of the open doors and were closer to the fire source, much higher accuracy of the predicted detection performance has been achieved for the point detectors. Generally, the predictions for the ionisation detectors are more accurate compared to the photoelectrical detector, due to a fact that flaming fire from the liquid fuels existed in early stage in both tests and that favors the ionisation detector.

The single parameter Heskestad model generated a similar accuracy as the multiple parameters Cleary model, by using the default and normal suggested values for the parameters. This matches with other’s observation<sup>[5]</sup>. However, comparing to Cleary model, Heskestad model produced a better trend to match that tested, i.e. slower responses from the optical detectors than the ionisation detectors at the same location. This indicates that Cleary model much more over-predicted detection performance for the optical detectors.

By applying the average OD method and the multi-criteria method, prediction of the response times for all the point type detectors has been improved. Among all the methods investigated in the current study, prediction by the multi-criteria method produces highest accuracy. The improvement between predictions by the multi-criteria method and the Cleary model can reach to 14% in Test2.

Generally, over-predicted soot density from FDS simulation has greater impact on prediction accuracy of detection performance of point type detectors due to their relatively lower sensitivity and passive detection feature. It's under certain level of risks to predict point type detector's performance based on their nominal sensitivities, even by FDS built-in detection models. Utilizing the average OD method or multi-criteria method can improve prediction certainty of the point type detectors, especially for the optical detectors.

## **CONCLUSIONS**

The ASD system during the in-situ fire tests exhibited very early response compared to the normal sensitivity point detectors (ionisation and optical detectors). The ASD very early response capability was consistent across all fire scenarios from large HRR to incipient (smouldering) fires (with very low heat and smoke product generations).

The ASD system detection performance has been simulated successfully by FDS providing reasonable accuracy in prediction. Therefore when modelled ASD performance is to be applied into FSE designs, including PBD, relative higher degree of confidence is expected, compared to conventional detectors.

The performance of the tested point type detectors during the in-situ fire tests was unstable. Higher smoke levels than their nominal sensitivities, with a factor of 1.5 to 5, were required for the photoelectrical detector. Response of the ionisation detector is somehow hard to predict and depending on fuel type of combustion greatly, from 20% to 1500% of its nominal sensitivity. How accurately simulated the combustion profile will affect accuracy of performance prediction on point type smoke detectors. Higher soot densities simulated in FDS, especially in version 5, usually over-predict the performance of the point type smoke detectors.

Issues existing in modelling of soot generation and transportation, and in modelling of entry behaviors of point type detectors may introduce significant errors and uncertainty in fire detection in fire engineering designs by applying the detectors. Certain degree of conservative should be taken into design practices. Investigated average OD method and multi-criteria method can improve accuracy in prediction of detection performance for the point detectors.

Future analysis of full set of experimental data and study soot yields under various combustion conditions will increase understanding of fire behaviours and further improve FDS modelling on fire products and then fire detection.

## **REFERENCES**

- [1] Geiman, J.A. and Gottuk D.T., 2002, Alarm Thresholds for Smoke Detector Modelling, Fire Safety Science – Proceedings of the Seventh International Symposium
- [2] Geiman, J., Gottuk, D., and Milke, J., 2004, Evaluation of Smoke Detector Response Estimation Methods, 8th NFPA Fire Suppression & Detection Symposium
- [3] Geiman, J.A., 2003, Evaluation of Smoke Detector Response Estimation Methods, Thesis of Master degree, University of Maryland

- [4] McGrattan, K.B., Klein, B., Hostikka, S., et. al, Forney, G.P., 2007, Fire Dynamics Simulator (Version 5) User's Guide, NIST Special Publication 1019-5, National Institute of Standards and Technology, Gaithersburg, MD
- [5] Roby, R.J., Olenick, S.M., Zhang, W., et. al, 2007, A Smoke Detector Algorithm for Large Eddy Simulation Modelling, NIST GCR 07-911, National Institute of Standards and Technology, Gaithersburg, MD
- [6] NIST, Fire Experiment Results, National Institute of Standards and Technology, <http://www.fire.nist.gov/fire/fires/fires3.html>
- [7] G. Rein et. al, 2007, Round-Robin Study of Fire Modelling Blind-Predictions using the Dalmarnock Fire Experiments, 5th International Seminar on Fire and Explosion Hazards, Edinburgh, April 2007
- [8] He, M., and Jiang, Y., 2005, Use of FDS to Assess the Effectiveness of an Air Sampling-Type Detector for Large Open Space Protection, Journal of Fire Protection Engineering, The Society of Fire Protection Engineers
- [9] Cleary, T., Chernovsky, A., Grosshandler, W., et. al, 1999, Particulate Entry Lag in Spot-Type Smoke Detectors, 6<sup>th</sup> International Association for Fire Safety Science, Poitiers, France
- [10] Schifiliti, R.P., Meacham, B.J., and Custer, R.L.P., 2002, Design of Detection Systems, The SFPE Handbook of Fire Protection Engineering (3<sup>rd</sup> ed), National Fire Protection Association, Quincy, MA
- [11] O'Connor, D., Cui, E., Klaus, M., et. al, 2006, Smoke Detector Performance for level Ceilings with Deep Beams and Deep Beam Pocket Configurations, An Analysis Using Computational Fluid Dynamics, The Fire Protection Research Foundation, Quincy, MA
- [12] Mowrer, F.M., Milke, J.A., Gandhi, P., 2008, Validation of a Smoke Detection Performance Prediction Methodology, Volume 3. Evaluation of Smoke Detector Performance, The Fire Protection Research Foundation, Quincy, MA
- [13] Gottuk, D., Mealy, C., and Floyd, J., 2008, Smoke Transport and FDS Validation, 9<sup>th</sup> International Association for Fire Safety Science, Karlsruhe, Germany
- [14] Tewarson, A., 2002, Generation of Heat and Chemical Compounds in Fire, The SFPE Handbook of Fire Protection Engineering (3<sup>rd</sup> ed), National Fire Protection Association, Quincy, MA
- [15] Pitts, W.M. and Mulholland, G.W., 2000, Improved Real-fire Measurements Having Meaningful Uncertainty Limits, NISTIR 6588, National Institute of standards and Technology, Gaithersburg, MD

## **ACKNOWLEDGEMENT**

This paper is based on work undertaken as part of the FireGrid Project ([www.Firegrid.org](http://www.Firegrid.org)) which is co-funded by the Technology Strategy Board's Collaborative Research and Development programme, following an open Competition. Xtralis is a key sponsor of this project.