Smoke Detector Performance For Level Ceilings With Deep Beams And Deep Beam Pocket Configurations

Research Project

An Analysis Using Computational Fluid Dynamics

SUMMARY DOCUMENT

THE FIRE PROTECTION RESEARCH FOUNDATION

FIRE RESEARCH

THE FIRE PROTECTION
RESEARCH FOUNDATION

ONE BATTERYMARCH PARK
QUINCY, MASSACHUSETTS, U.S.A. 02269
E-MAIL: Foundation@NFPA.org

Smoke Detector Performance for Level Ceilings With Deep Beams and Deep Beam Pocket Configurations
Research Project

An Analysis Using Computational Fluid Dynamics

SUMMARY DOCUMENT

Prepared by

Schirmer Engineering Corporation
(USA)

Daniel J. O'Connor, P.E.
Ervin Cui, Ph.D., P.E.
Matthew J. Klaus
Cheol H. Lee
Chen Su, P.E.
Zeqiang Sun

Vision Systems Ltd.
(Australia)

Ming He, MIEA
Yun Jiang, MIEA
John Vythoulkas
Tawfeeq Al-Farra

THE FIRE PROTECTION RESEARCH FOUNDATION

FIRE RESEARCH

THE FIRE PROTECTION
RESEARCH FOUNDATION

ONE BATTERYMARCH PARK
QUINCY, MASSACHUSETTS, U.S.A. 02269
E-MAIL: Foundation@NFPA.org

FOREWORD

In April of 2005, the Fire Protection Research Foundation's Detection and Alarm Research Council identified the need for a study to develop the technical justification for spacing rules for smoke detectors located on ceilings with deep beams and waffle-type construction.

The NFPA 72 rules on smoke detector spacing have been a major point of discussion and concern among the membership of the Initiating Devices Committee. The comprehensive review of smoke detection parameters for a wide variety of beam spacings, ceiling heights and room areas carried out in this study provides the technical information necessary to provide engineering and installation guidance and to resolve technical issues that will allow for more cost-effective and protection-effective smoke detector installations.

The project was initiated in July of 2005.

The Research Foundation expresses gratitude to: the report author, Daniel J. O'Connor, P.E., FSFPE; the Project Technical Panel: Bob Boyer, Jason Floyd, Bruce Fraser, Lynn Nielson, Lee Richardson, and Ralph Transue; and the project sponsors: Automatic Fire Alarm Association, GE Security, Honeywell, National Electrical Manufacturers Association, Siemens Building Technologies, and SimplexGrinnell for their support.

The content, opinions and conclusions contained in this report are solely those of the author.

Smoke Detector Performance for Level Ceilings With Deep Beams and Deep Beam Pocket Configurations
Research Project

Technical Panel

Bob Boyer, GE Security

Jason Floyd, National Institute of Standards and Technology

Bruce Fraser, SimplexGrinnell

Lynn Nielson, City of Henderson, NV

Lee Richardson, National Fire Protection Association

Ralph Transue, The RJA Group

Sponsors

Automatic Fire Alarm Association

GE Security

Honeywell Fire Group

National Electrical Manufacturers Association

Siemens Building Technologies

SimplexGrinnell

THE
FIRE PROTECTION
RESEARCH FOUNDATION

Smoke Detector Performance For Level Ceilings With Deep Beams And Deep Beam Pocket Configurations

An Analysis Using Computational Fluid Dynamics

SUMMARY DOCUMENT

Prepared by

Schirmer Engineering Corporation
(USA)

Daniel J. O'Connor, P.E.
Ervin Cui, Ph.D., P.E.
Matthew J. Klaus
Cheol H. Lee
Chen Su, P.E.
Zeqiang Sun

Vision Systems Ltd.
(Australia)

Ming He, MIEA
Yun Jiang, MIEA
John Vythoulkas
Tawfeeq Al-Farra

Summary Document 1805177-000

March 28, 2006

TABLE OF CONTENTS

INTRODUCTION

In accordance with the National Fire Alarm Code (NFPA 72), 2002 edition, the general guideline for spacing spot-type smoke detectors is 30 feet or 9.1 meters (NFPA 72, 5.7.3.2.3(A)). This guideline can be considered to represent a benchmark or baseline expectation for the performance of spot detectors on a smooth, level ceiling surface. NFPA 72, however, notes that ceiling shape, ceiling surface, and ceiling height are factors that can impact the response of detectors, and accordingly establishes prescriptive rules for spot-type smoke detectors when solid joist or beam construction or sloped ceiling configurations occur in a room or area protected by spot-type smoke detectors. These rules of NFPA 72 indicate that the guideline rule for 30 feet (9.1 meters) smooth ceiling spacing of spot-type detectors is to be modified based on the following criteria.

- Ceiling heights of 12 feet (3.66 m) or less and beam depths of one foot (300 mm) or less
  - Spacing in parallel direction – use smooth ceiling spacing
  - Spacing in perpendicular direction – reduce spacing to 1/2 smooth ceiling spacing
- Ceiling heights exceeding 12 feet (3.66 m) OR beam depths exceeding one foot (300 mm)
  - Locate spot detectors in every beam pocket

For ceiling heights less than 12 feet (3.66 meters) with relatively shallow beams of one foot (300 mm) or less, the guideline of 30 feet (9.1 meters) would require a reduction to 15 feet (4.55 meters) for spacings in the direction perpendicular to the beams or joists. Where ceiling height exceeds 12 feet (3.66 meters) or beams are relatively deep (>one foot or 300 mm), the spot-type smoke detector spacing is effectively the same as the spacing between beams in both directions.

The current NFPA 72 spacing rules for spot-smoke detectors have been a frequent source of questions and confusion for the design and code enforcement communities. Consider that a smooth level ceiling of a 90 foot x 90 foot (27.4 m x 27.4 m) room could reasonably be protected by a grid of nine spot smoke detectors as shown in Figure 1. By comparison, if the ceiling were of waffle concrete construction with structural deep beams (>12" or 300 mm) three feet on-center, the same room would strictly require 900 spot-type smoke detectors, each detector covering an area of 9 $ft.^2$ (0.84 m^2) as shown in Figure 2. Figures 3 and 4 illustrate actual situations of these types of ceilings. Without any technical analysis, engineering judgement suggests that installing 900 detectors with the deep beam pockets or waffles versus nine spot-type smoke detectors with a smooth ceiling configuration is not a cost effective detection solution or technically sound application of current smoke detection technologies.

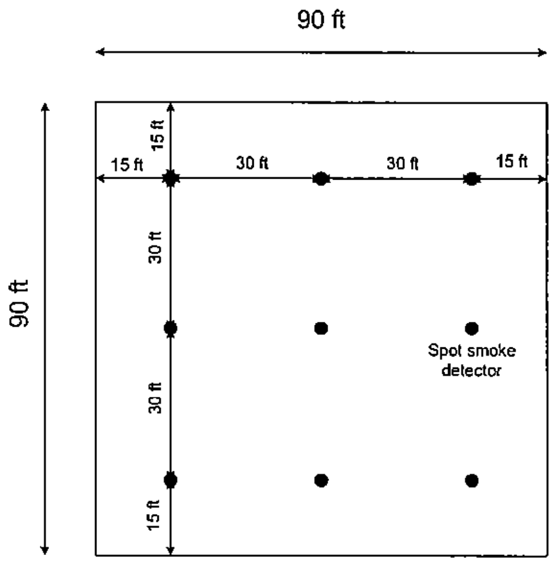


Figure 1

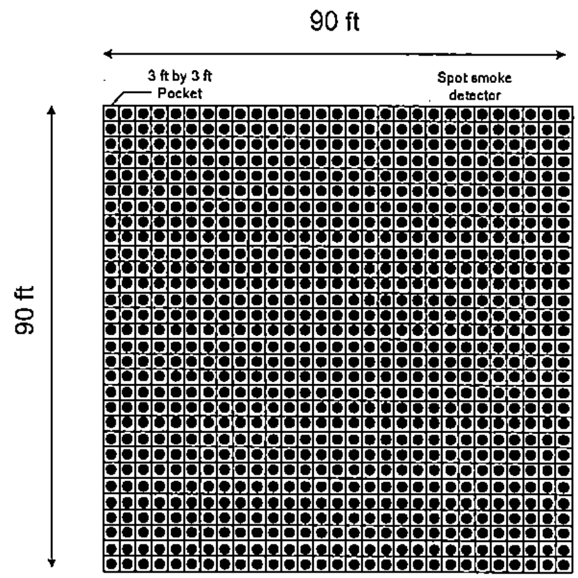


Figure 2

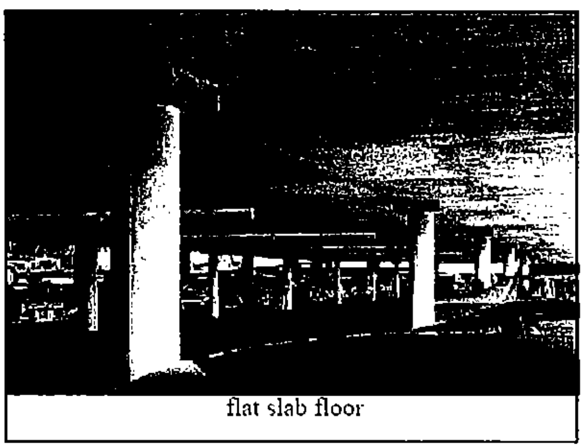


Figure 3

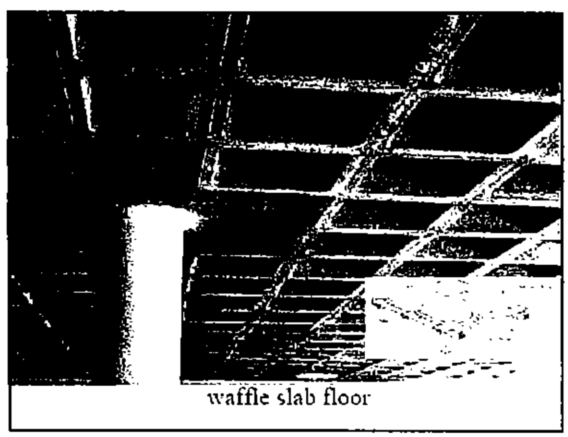


Figure 4

LITERATURE REVIEW

The current deep-beam rules in NFPA 72 were based on early Computational Fluid Dynamics (CFD) or field modeling work sponsored by the National Fire Protection Research Foundation (NFPRF) in 1993 and 1994. The methodology and results of the previous work performed at the Building & Fire Research Laboratory of the National Institute of Standards & Technology (NIST) is found in the following National Fire Protection Research Foundation documents.

- International Fire Detection Research Project, Field Modeling: Effects of Flat Beamed Ceilings on Detector and Sprinkler Response; Technical Report Year 1, October 1993.

- International Fire Detection Research Project, Field Modeling: Simulating the Effect of Sloped Beamed Ceiling on Detector and Sprinkler Response, Technical Report Year 2, October 1994.

The work at NIST sponsored by the NFPRF in 1993 and 1994 was significant in identifying the flow effects resulting from parallel channels, but was limited in scope due to the costs and computational time required for field modelling in the early 1990's. The 1993 work on level ceilings (Technical Report Year 1) was limited in several key respects.

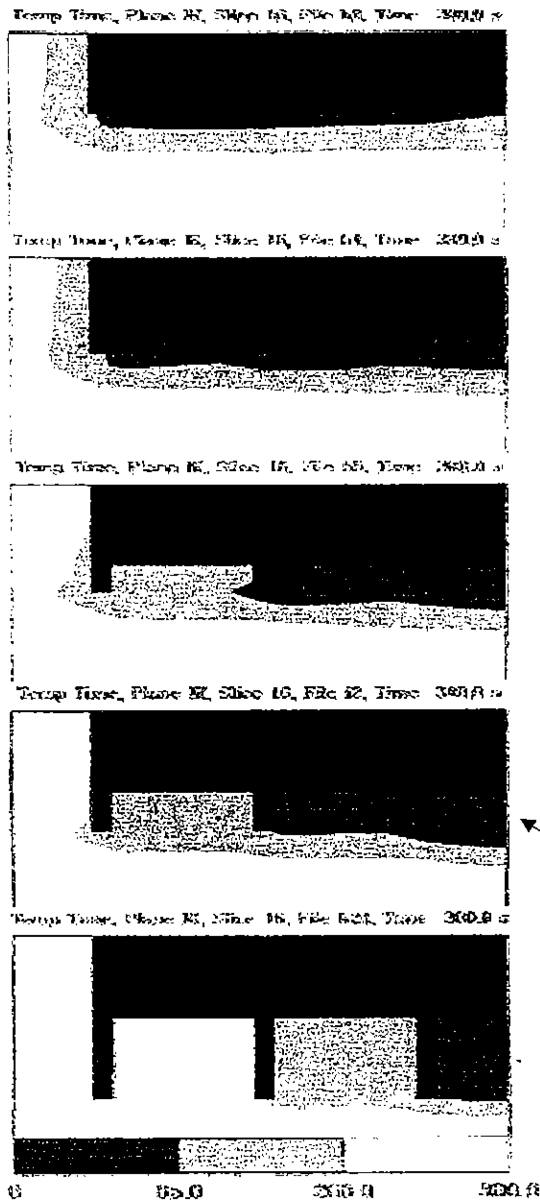
1. The distance between the fire source and the ceiling was maintained as a constant dimension of 8 feet (2.4 meters) in the majority of floor-to-ceiling scenarios using a height of 11 feet (3.35 meters). In those cases where ceiling height was extended beyond the range from 11 feet (3.35 meters) to 28 feet (8.53 meters), the beam depth was constant at one foot (.305 meters).

2. The criteria for detector activation was narrowly defined and did not consider any comparison to the baseline performance of smoke detectors spaced 30 feet (9.1 meters) apart on a smooth ceiling.

   Rather, the basis used for the determination of "successful" detector activation was directly related to threshold fire size of either a growing t-square 100 kW or 1.0 MW. For example, the CFD results presented in the 1993 Technical Report Year 1 identify the field conditions where the temperature rise (13°C) activation criteria for smoke detectors would be achieved before the fire reached either the threshold fire condition of 100 kW or 1.0MW. To illustrate the results for smoke detector response, Figure 19 is excerpted from the 1993 report and is reprinted on the following page.

   This method of evaluating smoke detector response uses performance-based design methodology, but it provides no comparison to the expectation of smoke detectors using the 30-foot NFPA 72 spacing guideline. Also, using distinct fire size thresholds did not allow for full understanding of how field conditions would change if examined five, ten, or thirty seconds later with the growing fires.

3. The model domain was limited to fire gas flows across four parallel channels typically with open boundaries (one series of simulations considered enclosed spaces) with no consideration for the constraining effects of corridor walls or beam pocket arrangements.



This Figure and text excerpted from Technical Report Year 1.

Figure 19: Shaded contour plot of smoke detector response volumes for various beam depths: 0.0 m (0 in), 0.10 m (4 in), 0.20 m (8 in), 0.30 m (12 in), 0.61 m (24 in)with 3.35 m (11 ft) ceiling height, 1.22 m (4 ft) beam spacingand medium fire. Dark and light grey denotes where a sensor activates before the fire reaches 100 kW and 1.0 MW respectively. White denotes where the sensor would not activate. Activation criteria: when the gas temperature rises 13°C above ambient.

FOCUS OF THIS STUDY

The primary focus of this study is to evaluate the appropriateness of the current NFPA 72 prescriptive provisions, using Computational Fluid Dynamics (CFD) simulations, and to determine which ceiling structure parameters, if altered, would cause significant differences in smoke detection performance as compared to a smooth level ceiling condition (the baseline). Currently, available modeling methods allow for this analysis to be conducted with greater efficiency for a wide variety of beamed ceiling configurations not previously studied, while taking advantage of current day computer processing capability.

Beam pockets are formed when a ceiling is split into a number of separate compartments by the presence of cross-beams or joists. The investigation seeks to answer several smoke detection performance questions relating to such ceiling construction:

- Is it necessary to install smoke detectors in every beam pocket?
- If not, what should be the appropriate detection point spacing? One every second, third, pockets?
- Would it suffice to put detectors on the undersides of beams? If so, at what spacing?
- How does ceiling height impact the performance?
- Which ceiling structure features have a significant effect on smoke detector performance?

This study is applicable to typical spot smoke detectors but does not consider the potential performance benefits of advanced or high sensitivity smoke detection technologies.

ACKNOWLEDGEMENTS

This study and CFD modeling effort was initiated through the collaborative efforts of Schirmer Engineering Corporation (USA) and Vision Systems Ltd. (Australia). The initial work of this study by the Vision/Schirmer team was presented to the Fire Detection and Alarm Research Council, an active subdivision of the Fire Protection Research Foundation. The Council believed that the work was in line with the Council's mission to advance the implementation of detection and alarm system technology through research and communication programs, closely tied to the needs of the National Fire Protection Association. Accordingly, the Foundation has provided funding to continue the study effort in order to better understand factors and performance of smoke detectors used with beamed and waffle ceiling configurations.

Along with the Foundation, this study has received the support of the Project Technical Panel appointed by the Foundation. The authors of this study wish to convey their thanks for the time and technical input of the following individuals:

Kathleen Almand, Executive Director
The Fire Protection Research Foundation

Project Technical Panel Members

Bob Boyer, Edwards Systems Technology, Inc.

Bruce Fraser, SimplexGrinnell

Jason Floyd, Hughes Associates, Inc.

Tom Hammerburg, Automatic Fire Alarm Association, Inc.

Lynn Nielson, Hendersen Nevada Fire Department

Ralph Transue, The RJA Group, Inc.

FIRE MODELING METHOD

The Fire Dynamics Simulator (FDS) developed by the National Institute of Standards and Testing (NIST) was used to generate the modeling domain and data for this study. A number of computer simulated situations were used to evaluate the detection performance of spot detectors in corridors, small rooms and large open spaces.

For this fire modeling effort, it was necessary to define the following:

1. Structure and dimensions of building enclosure.
2. Fire characteristics and associated parameters such as fire type and size.
3. Smoke detection point locations.

This modeling effort intends to determine the sensitivity of certain physical building parameters. Parameters deemed 'Sensitive' being those for which a change in value (such as beam pocket size) significantly affects detector performance.

Structure and Dimensions of Fire Compartment(s)

Table 1 below shows the building parameters used in the CFD in the fire models

Table 1 – Building Parameters

Structure Parameter	Specification
Corridor Enclosure Height	9ft, 12ft and 18ft (2.74m, 3.7m and 5.5m)
Small Room Enclosure Height	12ft, 18ft and 24ft (3.7m, 5.5m and 7.3m)
Large Open Area Enclosure Height	36ft and 50ft (11m and 16.5m)
Ceiling Type	Level
Beam Pocket Depths	flat ceiling, 1ft and 2ft (0m, 0.31m and 0.61m)
Beam Spacing (Pocket Width)	3ft, 6ft and 12ft (0.91m, 1.58m and 3.66m)
Beam Width for Corridor	6 in (0.15m)
Beam Width for Small Room	0.75ft (0.23m)
Beam Width for Large Open Space	1.5ft (0.46m)
Type of Beamed Ceiling	Flat (no beams, used as benchmark) Joists (beams in parallel) and pockets (perpendicular, crossed beams forming square or rectangle beam pockets)
Corridor Widths	5ft (1.52m), 12ft (3.66m)
Floor Area for Small Room	40ft by 35ft (12.2m by 10.7m)
Floor Area for Large Open Space	90ft by 80ft (27.4m by 24.4m)
Openings in Modeled Enclosure	No openings(1), corridor connecting internally to ambient
Air Handling Units in Modeled Enclosure	Not considered(2)

(1) Intent is to avoid large ventilation openings in modeling domain that would result in vent flow dynamics. Lack of openings found inconsequential to field conditions since detector responses occur prior to full room smoke layering development.

(2) Geiman's (2003) study of full scale Navy tests comparing smoke detector response of no ventilation scenarios and 12 air-changes scenarios concluded "the effect of ventilation is considered negligible for flaming fires".

Simulation Parameters

Table 2 summarizes the basic fire model parameters used for the CFD simulations.

Table 2 - Basic Fire Model Parameters

Fire Modeling Parameter	Description
Minimum Geometry Grid (fire plume region)	A 2m by 2m area around the fire source from floor to ceiling was divided into blocks of 1.5" (38mm) by 1.5" (38mm) by 1.5" (38mm).
Minimum Geometry Grid (under the ceiling)	A layer below the ceiling, twice the beam pocket depth, was divided into blocks of 1.5" (38mm) by 1.5" (38mm) by 1.5" (38mm). Corridors: 3ft (1m) deep from the ceiling Rooms: double of the beam depth
Minimum Geometry Grid (remainder of the enclosure)	The area outside those described above was divided into blocks of 6" (152mm) by 6" (152mm) by 6" (152mm)
Smoke Soot Yield	0.022 grams/gram fuel burned
Model Construction	Full plume region simulation and partial building structure representation of the corridor enclosure (see Figure 5)
Fire Types	Only flaming fire is considered Corridor: 100kW constant fire Rooms: 100kW (12ft ceiling), 200kW (18ft ceiling), 300kW (24ft ceiling), 400kW (36ft ceiling), 500kW (54ft ceiling) constant fire t-square medium growth fire
Fire Base Area	2ft by 2ft (0.61m by 0.61m)
Simulation Time	150 seconds
Fire Location	Mid way between detectors – the worst case scenario
Total Simulation Run	As required – based on boundary conditions and variables used in the sensitivity study.

For the purposes of the simulations, it was assumed that all compartments were enclosed still air environments. Figure 5 and 6 depict the corridor domain grid systems and thermocouple arrangements used for data gathering points. Figure 7 and 8 illustrate the grid and thermocouple arrangements for a typical enclosed room. Due to the relatively small fire sizes, it was also assumed that any materials inside the simulated area (furniture and wall linings for example) would have no effect on the results.

In accordance with the CFD modeling requirements, all objects within the simulated areas were approximated to rectangles with stair stepping to avoid vortices occurring at sharp corners. As shown in Table 2, a Minimum Geometry Grid was applied to partition the simulation area. For the small rooms, Figures 9, 10 and 11 illustrate in elevation view and ceiling plan view the location of measuring of sampling points used to track temperature, smoke density and velocity data.

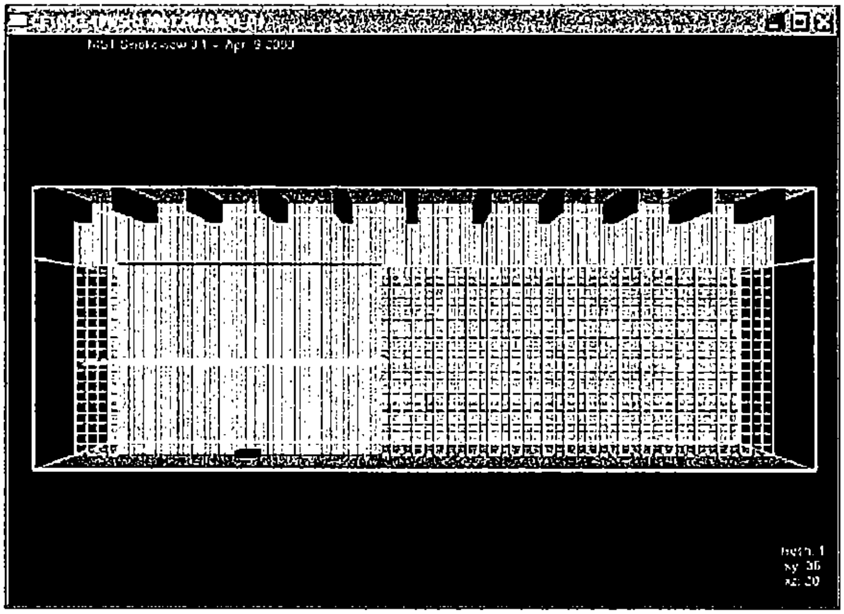


Figure 5 Corridor domain – grid system example

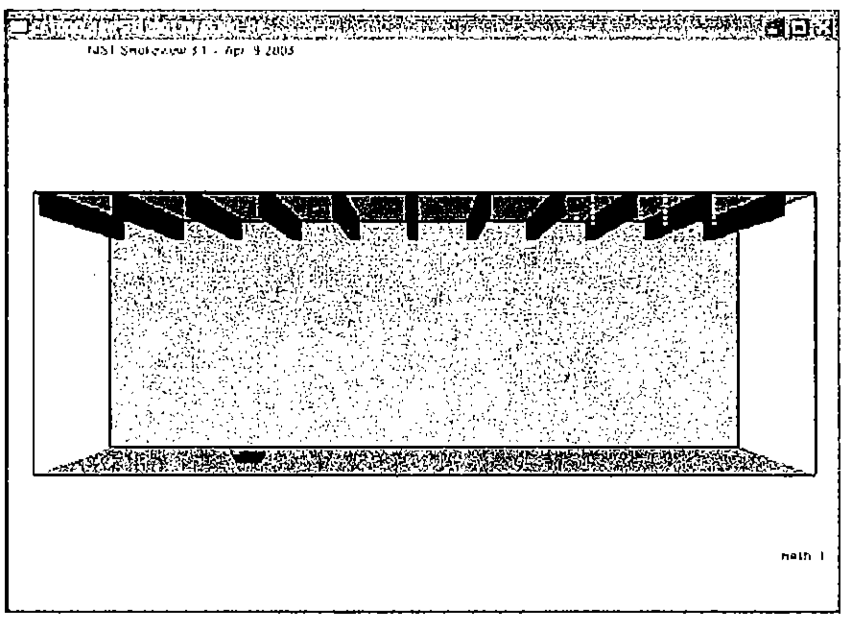


Figure 6 Corridor domain – thermocouples arrangement example

GRID SYSTEMS: The corridor simulation domain was divided into three grid systems. The first grid system includes the space around the fire plume and has a smaller cell size of 1.5" (38mm) cubes. The second grid system includes the space near the ceiling with the same cell size as the first grid system. The third and fourth grid systems include the rest of the simulation domain and with a larger cell size of 6" (152mm) cubes. Refer to Table 2 for grid systems in rooms.

THERMALCOUPLES ARRANGEMENT: Along the centerline of the corridor, the thermocouples are placed at the center of each beam pocket, and at the bottom of each beam. As shown in the graphic, the yellow dots represent the positions of the thermal couples. Series of vertical thermocouples were placed at the beam pockets that are 15ft (4.6m), 18ft (5.5m), and 21ft (6.4m) from the fire. Additional series of vertical thermocouples located near the sidewall were added to the simulation for the purpose of comparison. The orange/yellow dots in Figure 8 represent those thermocouples located underside the beams. Details of thermocouple locations (detection points) for room scenarios are shown in Figures 9, 10 and 11.

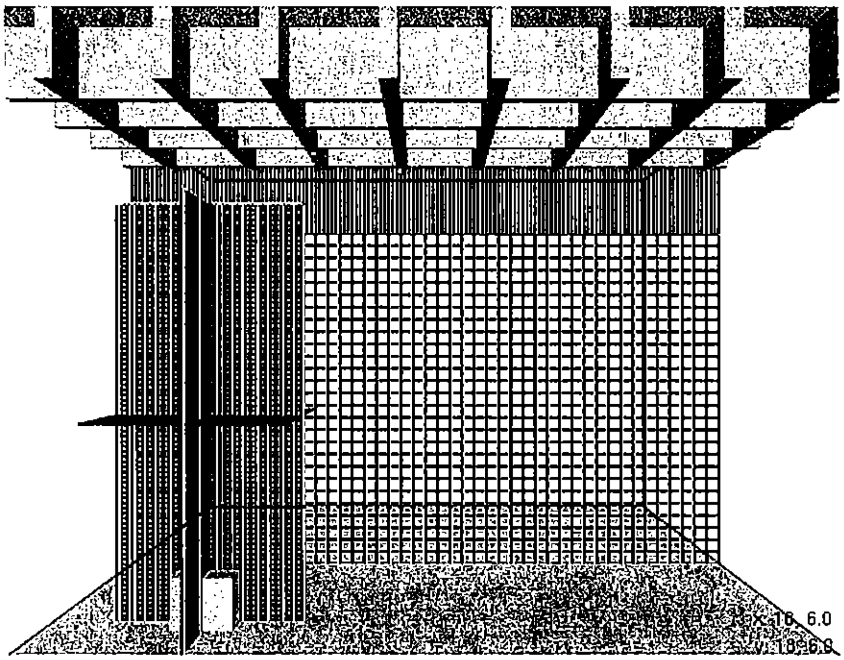


Figure 7 Example of CFD grid systems for rooms

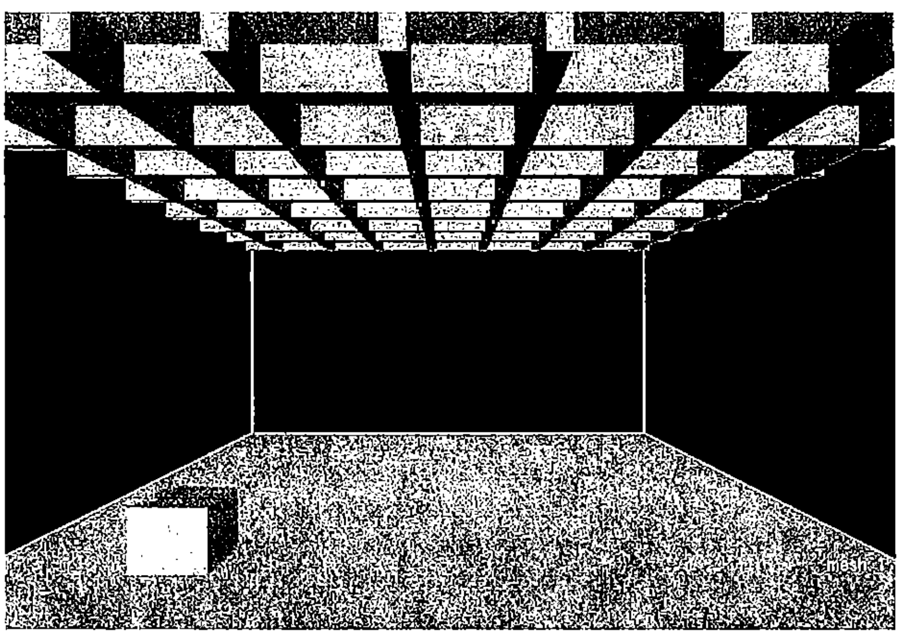
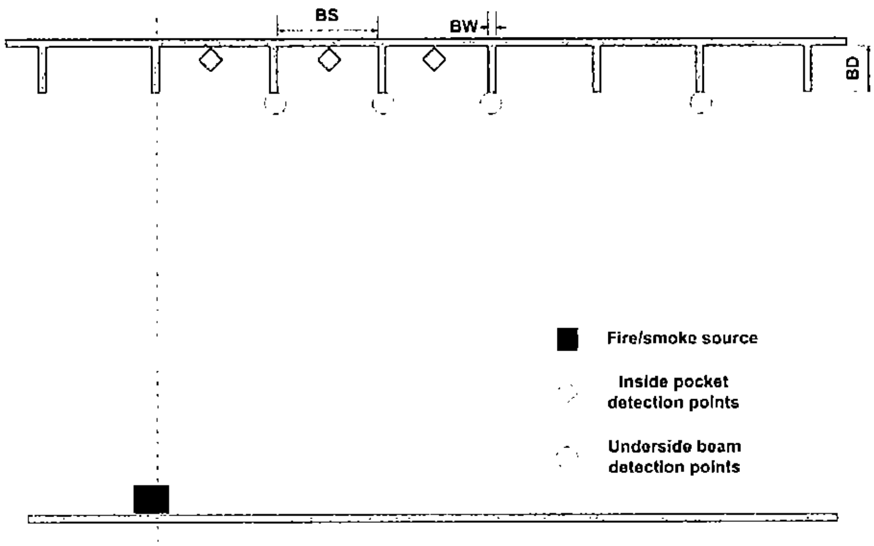
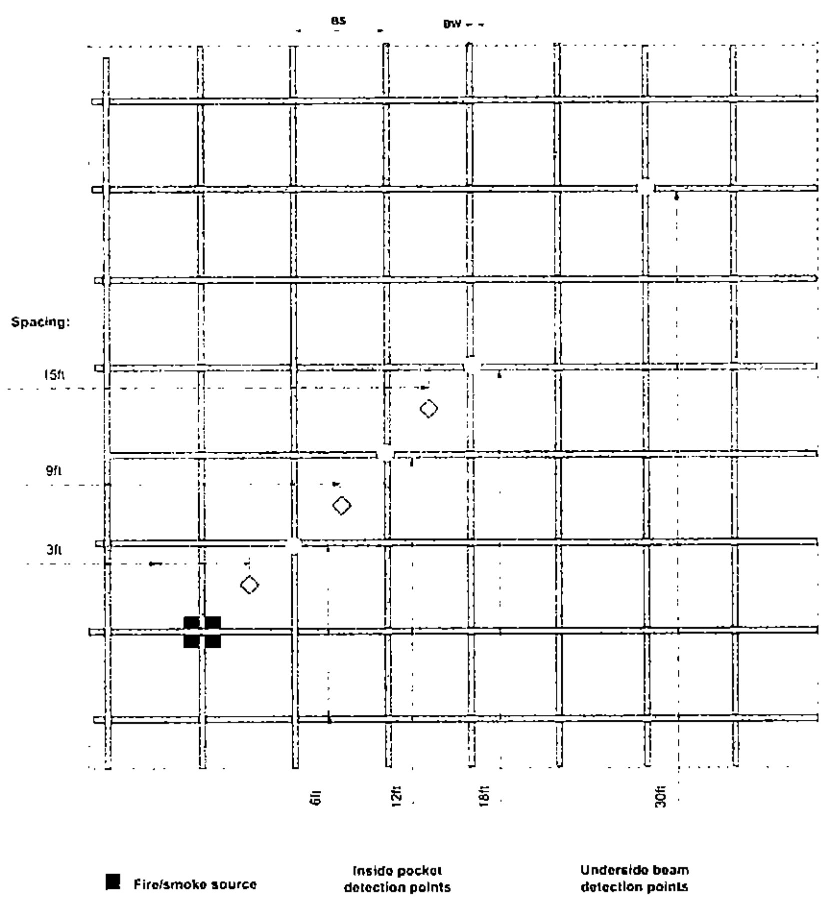


Figure 8 Example of a CFD simulation domain for rooms

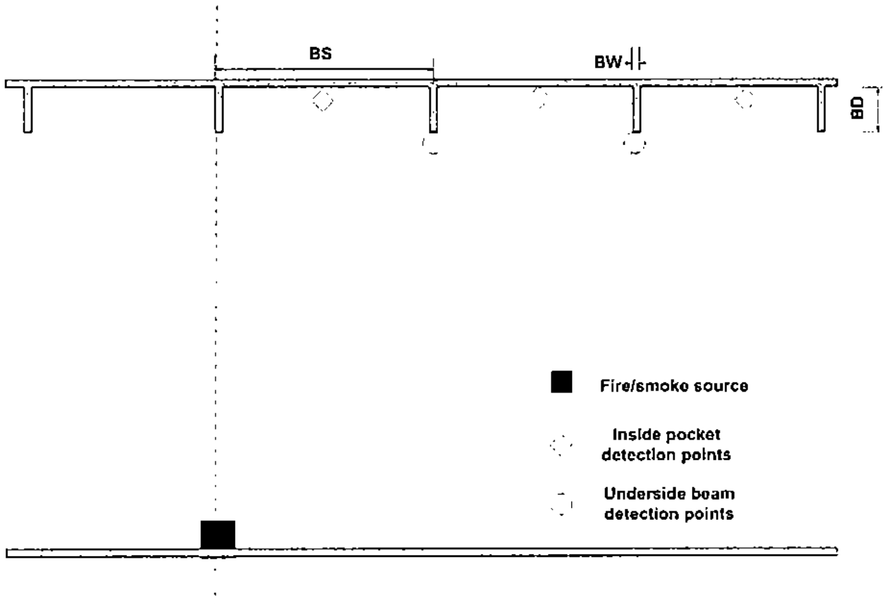


(a) Elevation view of one of the small room simulations.

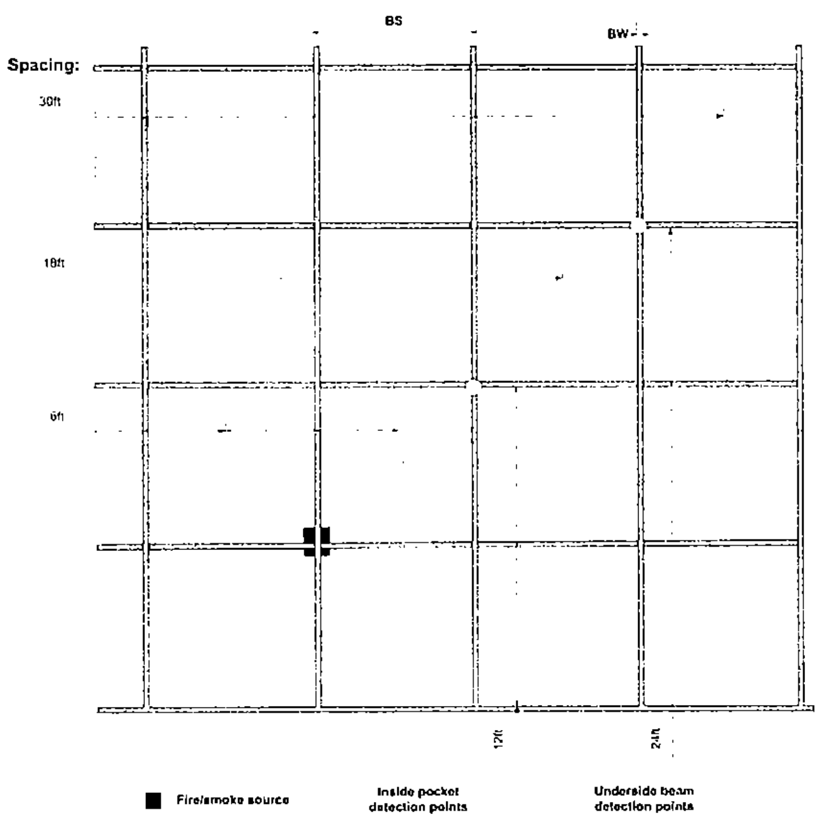


(b) Top view of one of the small room simulations.

Figures 9a and 9b   Small room layout (quadrant) with 3ft by 3ft beam pockets



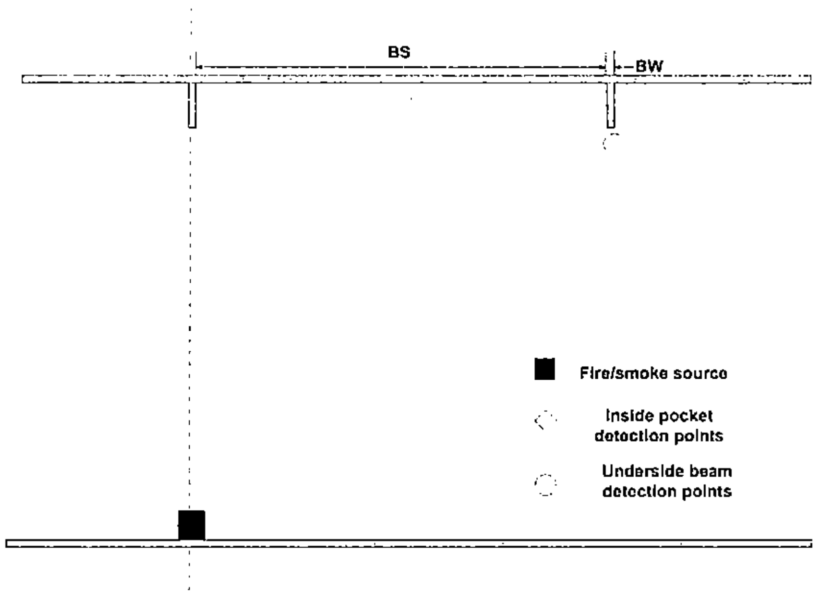
(a) Elevation view of one of the small room simulations.



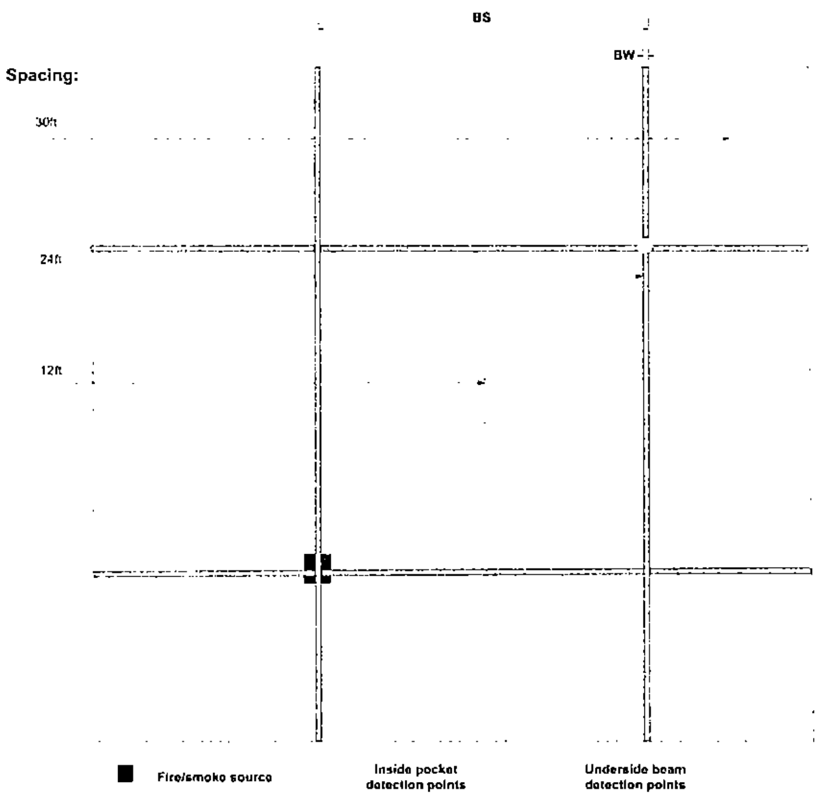
5.

(b) Top view of one of the small room simulations.

Figures 10a and 10b Small room layout (quadrant) with 6ft by 6ft beam pockets



(a) Elevation view of one of the small room simulations.



(b) Top view of one of the small room simulations.

Figures 11a and 11b Small room layout (quadrant) with 12ft by 12ft beam pockets

SMOKE DETECTION PERFORMANCE METRICS

Smoke Detector Alarm Thresholds

Predicting precise smoke detector activation times is not a focus of this analysis, rather the intent is to examine the field conditions at various smoked detector locations and evaluate the likelihood that field conditions at postulated smoke detector locations will result in an alarm condition. If there is sufficient optical density, temperature rise or velocity at the smoke detector location then it is reasonable to conclude that the smoke detector would likely alarm. In this analysis the key criteria for evaluating the field conditions are the thresholds that are selected to indicate conditions likely for smoke detector alarm.

Recent work by Geiman (2003) further refined by Geiman and Gottuk (2003) represents the best known review of the thresholds for estimating spot-type smoke detector alarm response. These two works present a review of numerous test series and the variety of threshold parameters suggested over the years for estimating smoke detection response. The evaluations of various thresholds demonstrate a significant variability in field conditions at the time of alarm depending on detector type, fire type (smouldering or flaming) and nominal detector sensitivity. However, the work of Geiman and Gottuk points to a number of significant findings that is useful to identifying smoke detector alarm thresholds for the purpose of this study. A detailed review of the Geiman and Gottuk alarm-threshold work is found in the full report.

Based on the technical review and analysis of various smoke detector alarm thresholds as detailed in the work of Geiman (2003) and Geiman & Gottuk (2003, 2005), the following approach to thresholds is considered appropriate:

1. As the focus of this analysis is not to determine precise smoke alarm times, but rather to review the trends in the data, no single point threshold values are used as a definitive predictor of smoke alarm.

2. For this study, neither the nominal smoke detector sensitivities, nor the maximum U. L. black smoke limit of 0.14 OD/m are considered appropriate thresholds for flaming fires. To review the trends and understand the nature of the difference between ionization and photoelectric detector response, the change of optical density at postulated detector locations are compared to a range of values described as the "80% OD Alarm Threshold" by Geiman & Gottuk. The "optical density alarm thresholds" represent the smoke optical density levels at which a certain percentage (e.g. 20%) of detectors would have alarmed in the examined database of detector responses. The detector responses were based on UL-listed smoke detectors in full scale fire test conditions. The values considered appropriate for this analysis is the 80% average alarm threshold from the following table (Geiman & Gottuk).

OD Alarm Threshold	Fire Type	Ionization Detectors	Photoelectric Detectors
20%	Flaming Fires	0.007 ± 0.004 OD/m	0.31 ± 0.016 OD/m
50%	Flaming Fires	0.021 ± 0.005 OD/m	0.063 ± 0.029 OD/m
80%	Flaming Fires	0.072 ± 0.027 OD/m	0.106 ± 0.039 OD/m

This average value and associated range of values, assure that the high percentage of smoke detector responses will be captured. Also, it is important to note the 80% alarm threshold values include data for mid-1970's detector technology. Thus, the

80% alarm values are expected to capture more than 80% of predictions given the effectiveness of today's more advanced detector technologies.

3. A secondary indicator of smoke alarm will compare the temperature rise at postulated smoke detector locations to the thresholds of 4°C and 13°C. The 4°C threshold is representative of a conservative threshold for ionization detection and the 13°C threshold is representative of a typical photoelectric detector. See Figure 12 below.

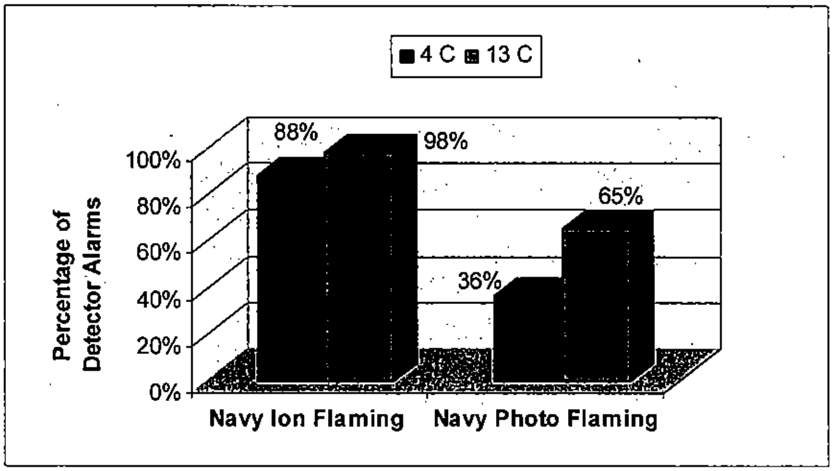


Figure 12. This graph is based on the data found in Geiman (2003) as Figure 7. Percentage of detectors that alarmed at a temperature rise less than or equal to each temperature alarm threshold for Navy tests with flaming fires. (Source: Geiman thesis page 72)

4. In those cases where optical density values are in the range of values indicating an expectation of smoke detector alarm, then the velocity field is reviewed where necessary to confirm that velocities are in the range of expectation for smoke detector alarm (0.13 m/s ± 0.07).

Detection Performance Analysis – Baseline

Two metrics are used in this study to evaluate the performance and expectation for smoke alarm at any of the postulated smoke detector locations.

1. For all ceiling heights examined, a baseline response for a smooth ceiling condition with smoke detectors located on a 30-foot grid is determined. This configuration is illustrated by Figures 13 and 14. The baseline detector performance is determined for each ceiling height scenario. Figure 15 illustrates the changing response of the baseline with increasing ceiling height when the same fire size is applied.

2. In this study, primarily small flaming fires (100 kW for corridor and rooms with low ceiling height, increased accordingly as ceiling height is increased) are used for analysis. The 100 kW fire provides a reference to earlier field model analysis performed in 1993 (NFPRF Technical Report Year 1) and represents a flaming fire that, although relatively small, is representative of a threat that is expected to be detectable and alarmed in the presence of commonly available spot detectors. In several corridor scenarios with higher ceiling heights fire sizes are increased to 300 kW to allow for energy and smoke transport sufficient to reach smoke detector alarm threshold ranges. In room scenarios with higher ceiling heights fire sizes are increased to 200, 300, and 600 kW to allow for energy and smoke transport sufficient to reach smoke detector alarm threshold ranges.

   It is important to ascertain if the temperature, smoke optical density and/or gas velocity reaches a level or threshold range that provides an expectation for alarm. It is possible that as parameters are changed (for example, increasing ceiling height) that the baseline detector and postulated detector's response falls below a range of values where alarm is expected. For this reason, threshold values are compared to both the baseline response and response of postulated detector locations.

The smooth ceiling model with detector points placed at the NFPA 72-recommended spacing of 30ft is used as a baseline, against which the detector performances for all other detector locations, detector types and ceiling structures are compared. Baseline detectors are compared to postulated detector locations using the worst case spacing scenario where a fire occurs at the furthest possible distance away from a detector. For the corridor scenarios the fire is considered midway between two detectors. For room scenarios the fire is considered centered between four detectors.

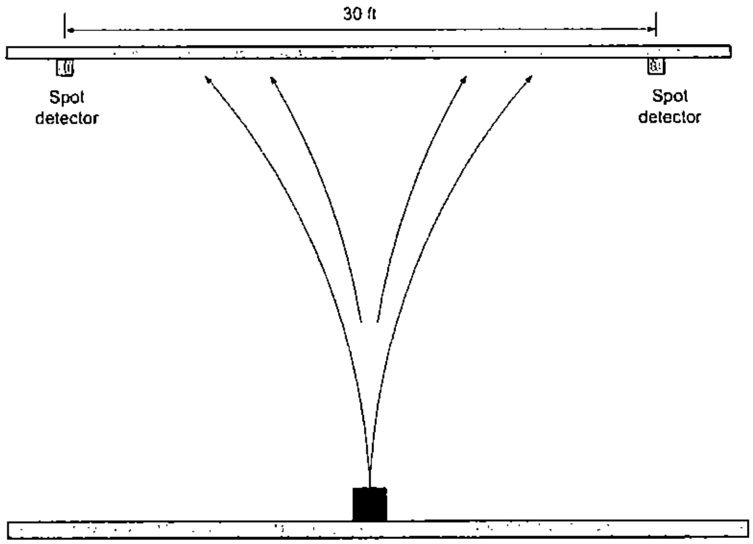


Figure 13 **Schematic of the flat ceiling, NFPA guideline for smoke detector spacing on a level smooth ceiling. This is the baseline situation.**

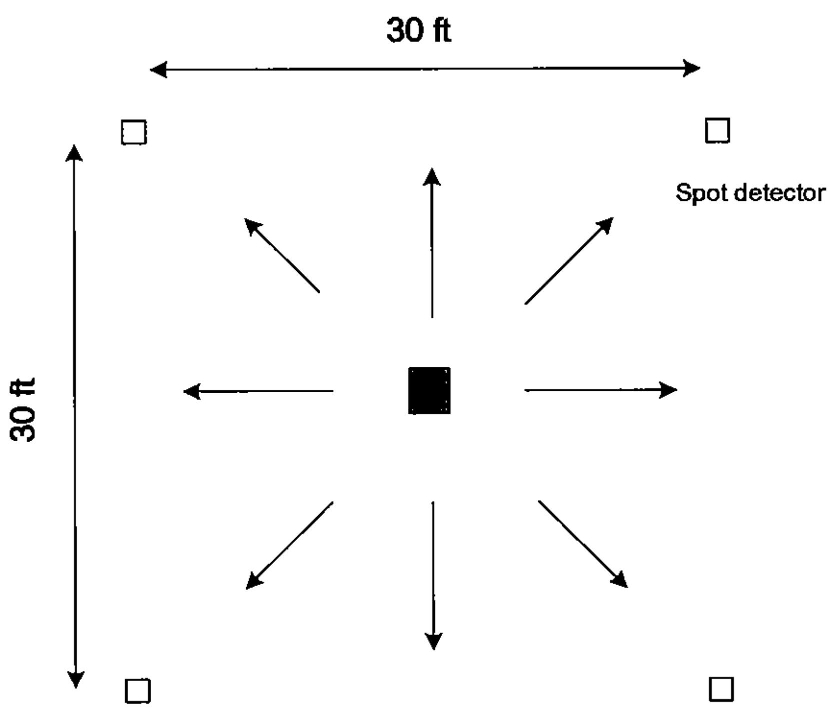


Figure 14 **Ceiling plan view of baseline smooth ceiling smoke detector spacing**

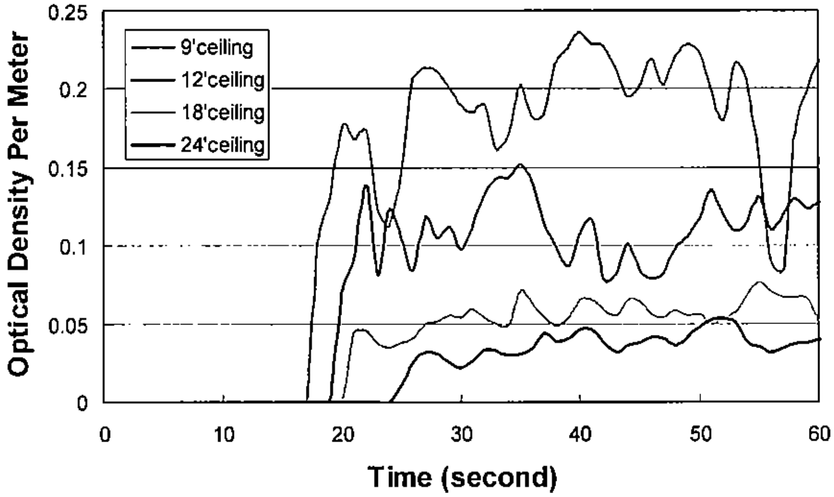


Figure 15 Changing response of the baseline with increasing ceiling height when the same fire size is applied

CORRIDOR SMOKE DETECTORS - RESULTS AND OBSERVATIONS

This section presents the data for various temperature and optical density measuring points that serve as postulated smoke detector locations. The data is presented in the graphs for temperature and optical density. Also, each graph provides the baseline or benchmark response of detectors on a smooth ceiling using the 30-foot spacing guideline of NFPA 72.

Generic Case Nomenclature for Corridor Scenarios

xFxxCLxxWxxHxxBDxxWxxSxxPxx_Xx

For example, each descriptor in the case description would be read as noted in the following example:

xFxx	Fire size.	CF100 - Fire of 100 kW, Constant
CLxx	Corridor Length in feet.	CL48 – 48 feet long corridor
Wxx	Corridor Width in feet.	W05 – 5 feet wide corridor
Hxx	Corridor Height in feet.	H09 – 9 feet high corridor
BDxx	Beam Depth in inches.	BD12 – 12 inches deep beam
Wxx	Beam Width in inches.	W06 – 6 inches wide beam
Sxx	Beam Spacing in feet.	S03 – Beams spaced in 3 feet
Pxx	Beam pocket in feet.	P00 – No beam pockets
_Xx	X: Fuel Type, x: Serial number	W: wood, P: plastics, S: Smoke cartridge

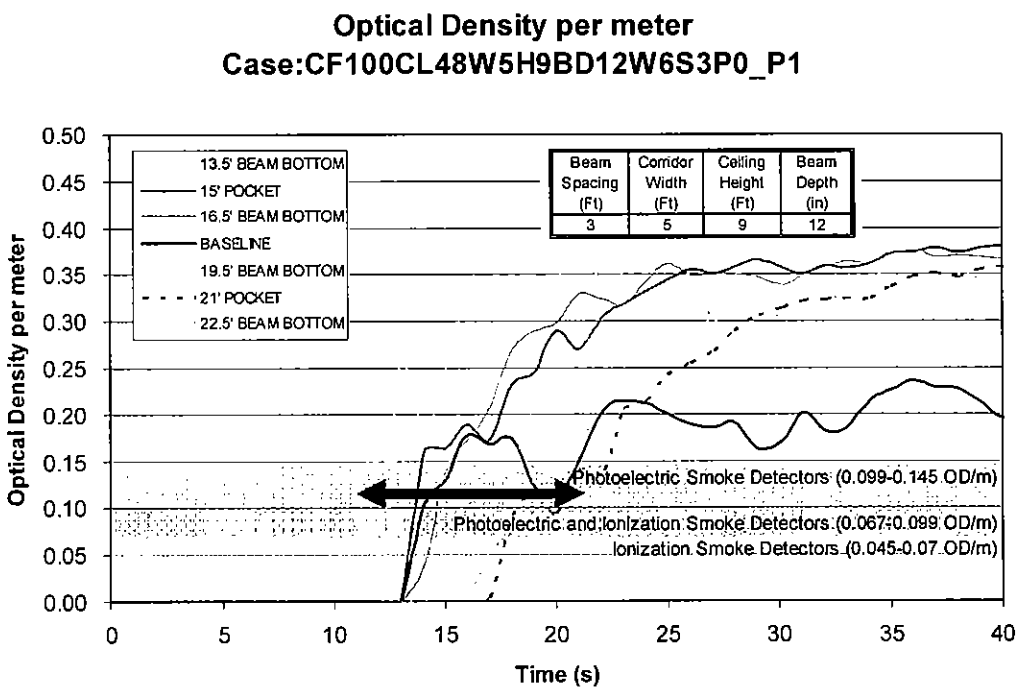
The analysis of the corridor data is broken into several distinct groups of graphs.

1. 18 Scenarios – Comparison of detector locations to temperature and optical density condition versus time for
   a. Corridor widths of 5, 12, 18 feet, and
   b. Beam depth of 0, 12, 24 inches, with
   c. Ceiling heights of 9, 12, and 18 feet
2. Graphs illustrating the Comparisons of Optical Density with Increasing Ceiling Height for
   a. 5 foot wide corridors with 24-inch beams
   b. 12 foot wide corridors with 24-inch beams
3. Graphs illustrating the Comparison of Optical Density with Increasing Beam Depth for
   a. 5 foot wide corridors with 18 foot ceiling height
   b. 12 foot wide corridors with 18 foot ceiling height
   c. 30 foot wide corridors with 18 foot ceiling height
4. Summary Comparison Graph
   a. Optical Density Comparison for Scenarios 1 – 9 at 30 seconds and 60 seconds
   b. Optical Density Comparison for Scenarios 1 – 18 at 30 seconds and 60 seconds

Detail description of each scenario is in Appendix B.

Time Shift Comparisons

In the graphs that follow in this report there is observed a time difference between the response of the benchmark detector and the postulated spot smoke detector locations for both the corridor and room scenarios. This time difference is generally evaluated at the time that the optical density at the detectors first reaches a measurement of 0.11 OD/m. Depending on the parameters of any given scenario the postulated detectors may achieve the optical density measurement of 0.11 OD/m either several seconds before or after the benchmark detector achieves an optical density measurement of 0.11 OD/m. This comparison is important as it provides a relative sense of whether the postulated detectors are operating in a time frame (approximately ± 60 sec) comparable to the benchmark detector or if the postulate detectors performance is significant minutes slower or faster to respond than the benchmark detector. The graphic below illustrates this time shifts for various detector locations as taken from one of the evaluated scenarios.



Corridor Scenario Examples

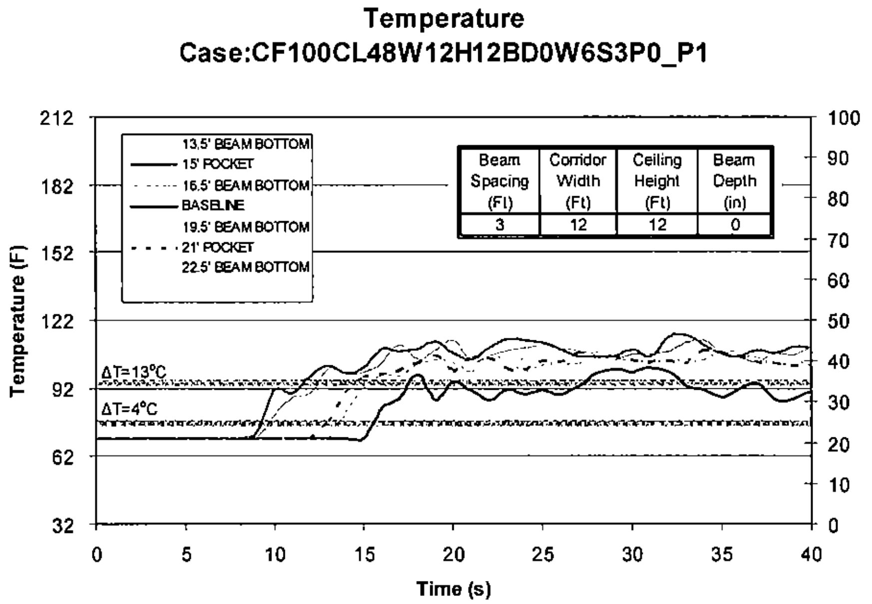
The full Final Report details the results of 27 corridor scenarios. For the purpose of illustration the results for a corridor with a 12 ft ceiling height, 12 ft. corridor width and beams located every 3 ft., varying in depth from 0 -24 inches are included on pages 21 - 23. These are Scenario's # 13, 14 and 15 from the full Final Report. A summary of the results for the initial 18 corridor scenarios follows the data presented for Scenario's # 13, 14 and 15.

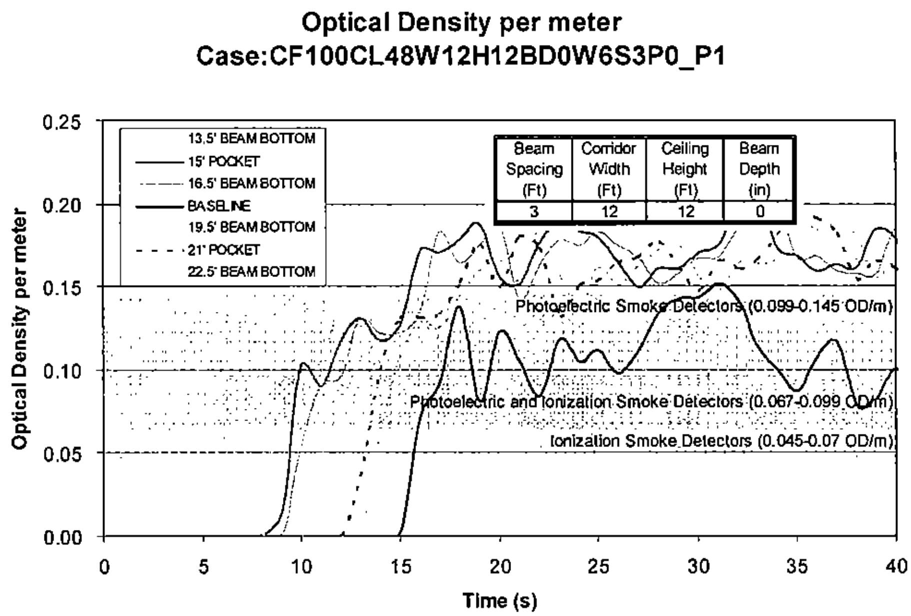
Additional Corridor Scenarios

The initial 18 corridor scenarios reviewed included in this report and the full Final Report illustrated the impact of the confining geometry of a corridor has on the development of optical density and temperatures at postulated detector locations with beams interrupting the ceiling every 3 feet. The effect is beneficial in terms of reaching levels of optical density or temperatures that provide an expectation of spot smoke detector operation although the effect does diminish as the corridor width increases. Also, as ceiling height increases it is observed that the baseline detector may not reach optical density or temperature levels that are sufficiently high; therefore, reducing expectations for alarm of the baseline spot detector. The expectation for the alarm of postulated locations of spot detectors is also reduced at increasing ceiling heights although to lesser degree due, again, to the benefits of the confining corridor geometry.

To further test the impact of corridor and beam geometry several additional scenarios were identified as useful to understanding the impact of changes in spacing between beams, the impact of very wide corridors such that the beams would effectively act as long parallel channels in a small room, the impact of increasing the fire size for high ceiling spaces to account for the larger fire needed to achieve baseline detector activation, and testing the impact of deeper beams (48 in.) in a high corridor space (24 ft.) These additional corridor scenarios are found only in the full Final Report.

Corridor Scenario #13



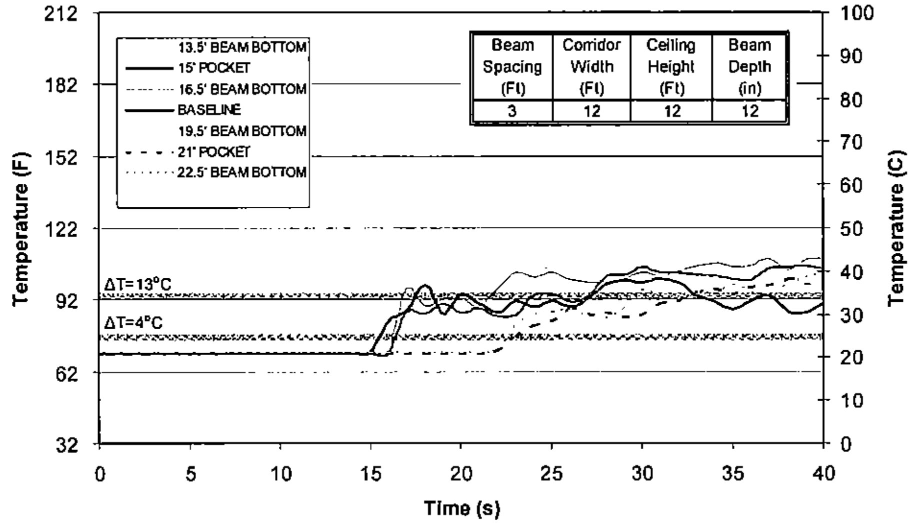


Observation: For this flat ceiling corridor scenario, temperature rise is well above the comparison thresholds of 13°C and 4°C. Similarly, the optical density is well above the comparison range and very rapid smoke detector activation is expected. The corridor geometry confines the smoke plume and ceiling jets resulting in reduced air entrainment and therefore, high temperature and smoke optical density. Time shift differences in the table below are all positive values indicating slightly faster response than the benchmark in all cases.

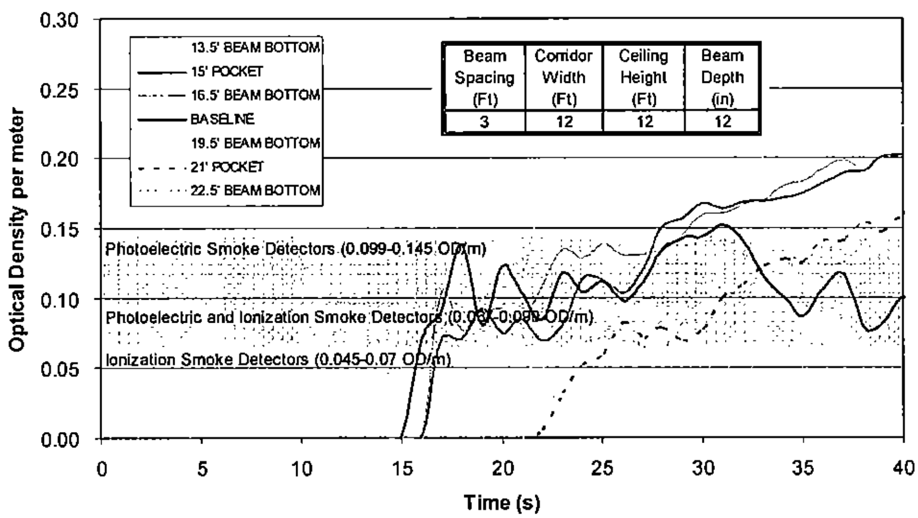
Scenario	Ceiling height (ft)	Beam Depth (in)	Corridor Width (ft)	Beam spacing (ft)	Baseline - Detectors at 30 ft spacing	15 feet			21 feet		
					Activation Criteria	Under Beam 13.5 ft	In Pocket 15 ft	Under Beam 16.5 ft	Under Beam 19.5 ft	In Pocket 21 ft	Under Beam 22.5 ft
CF100CL48W 12H12BD0W6 S3P0_P1	12	0	12	3	0.11 OD/m	6	5	7	4	3	2
					13 °C	7	5	6	4	3	2

Corridor Scenario #14

Temperature
Case:CF100CL48W12H12BD12W6S3P0_P1



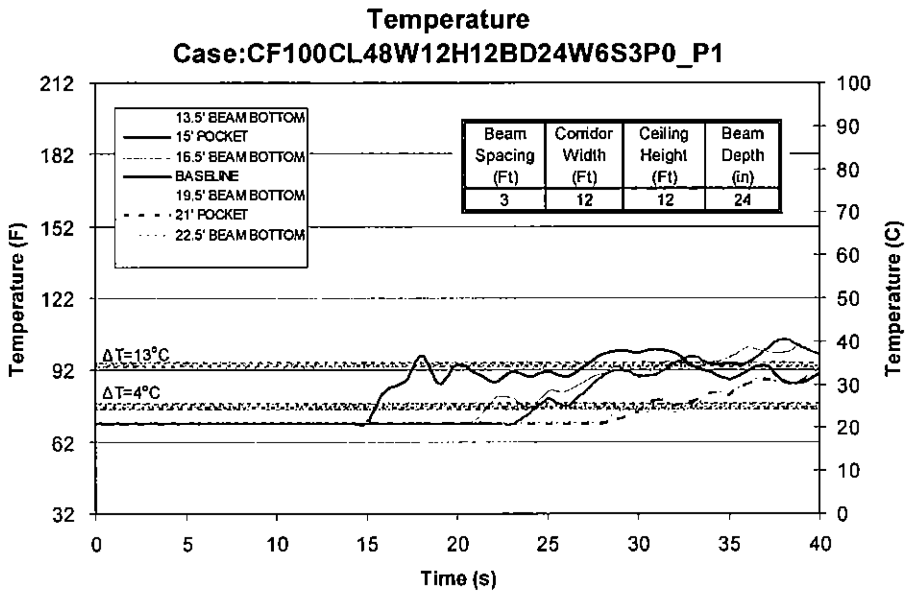
Optical Density per meter
Case:CF100CL48W12H12BD12W6S3P0_P1

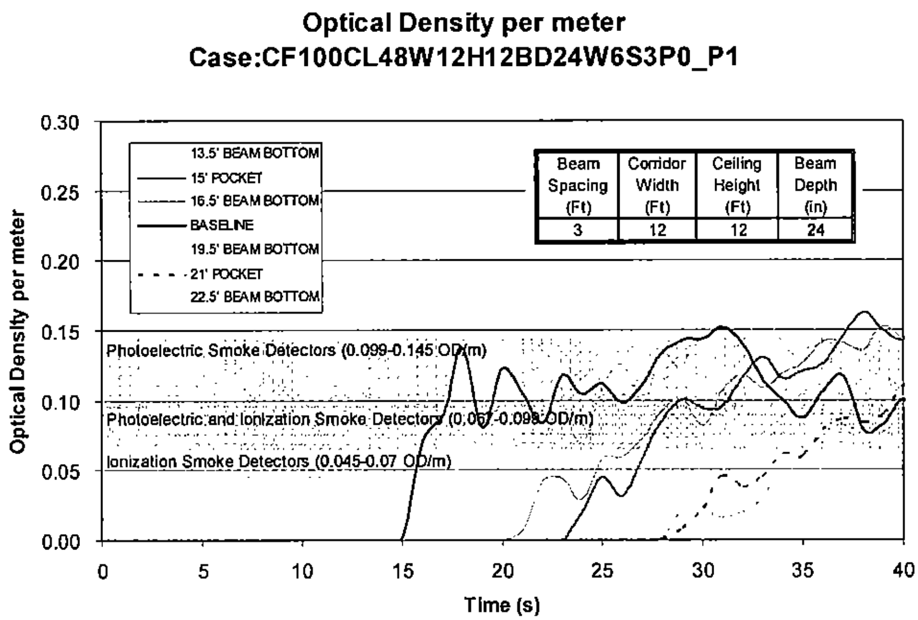


Observation: In this scenario 12 inch deep beams interrupt the ceiling surface every 3 feet. Temperature rise exceeds the threshold of 13°C and 4°C during an early time frame and all locations exceed that of the baseline detector. Optical density exceeds that of the baseline for detector locations. Detector locations within pocket or on the bottom of the beam experience comparable optical density. Time shift differences in the table below show 14 seconds or less difference in relative response to the 0.11 OD/m optical density level. Postulated detectors are slightly slower than the benchmark to reach to the 0.11 OD/m optical density level.

Scenario	Ceiling height (ft)	Beam Depth (in)	Corridor Width (ft)	Beam spacing (ft)	Baseline - Detectors at 30 ft spacing	15 feet			21 feet		
					Activation Criteria	Under Beam 13.5 ft	In Pocket 15 ft	Under Beam 16.5 ft	Under Beam 19.5 ft	In Pocket 21 ft	Under Beam 22.5 ft
CF100CL48W 12H12BD12W 6S3P0_P1	12	12	12	3	0.11 OD/m	2	-7	-5	-9	-14	-12
					13 °C	0	2	-7	-10	-15	-13

Corridor Scenario #15

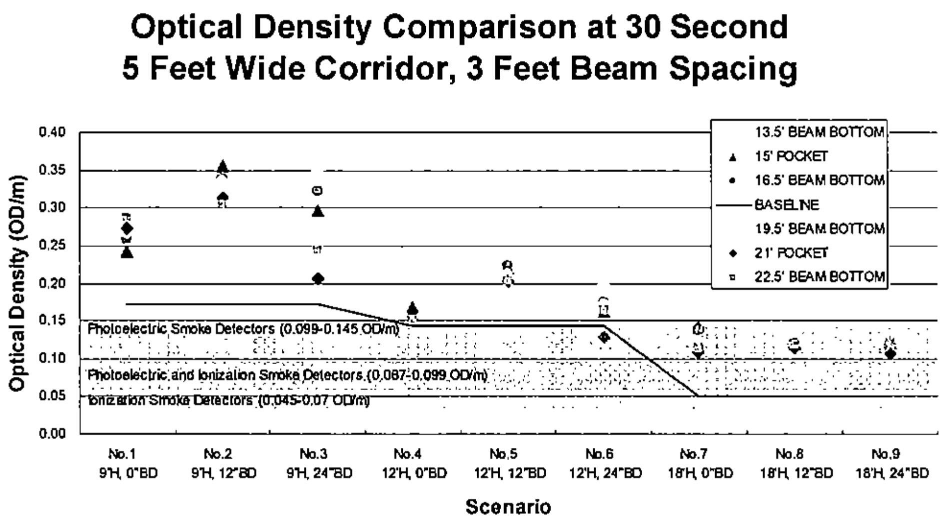


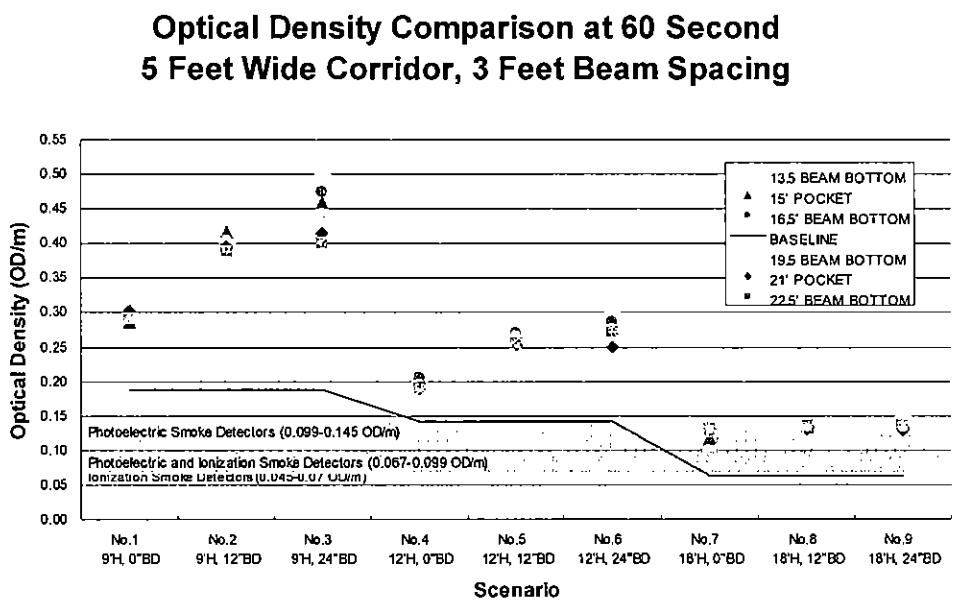


Observation: In this scenario 24 inch deep beams interrupt the ceiling surface every 3 feet. With the corridor width at 12 ft, the baseline results shift in time occurring approximately 8 to 24 seconds before that shown for the observed corridor detector locations. Yet, the temperature rise and optical density value indicating an expectation of detector activation is exceeded for all noted smoke detector locations. Time shift differences in the table below show 24 seconds or less difference in relative response to the 0.11 OD/m optical density level. Postulated detectors are slower than the benchmark to reach to the 0.11 OD/m optical density level.

Scenario	Ceiling height (ft)	Beam Depth (in)	Corridor Width (ft)	Beam spacing (ft)	Baseline - Detectors at 30 ft spacing	15 feet			21 feet		
					Activation Criteria	Under Beam 13.5 ft	In Pocket 15 ft	Under Beam 16.5 ft	Under Beam 19.5 ft	In Pocket 21 ft	Under Beam 22.5 ft
CF100CL48W 12H12BD24W 6S3P0_P1	12	24	12	3	0.11 OD/m	-8	-14	-15	-18	-23	-24
					13 °C	-3	-15	-14	-18	-23	-24

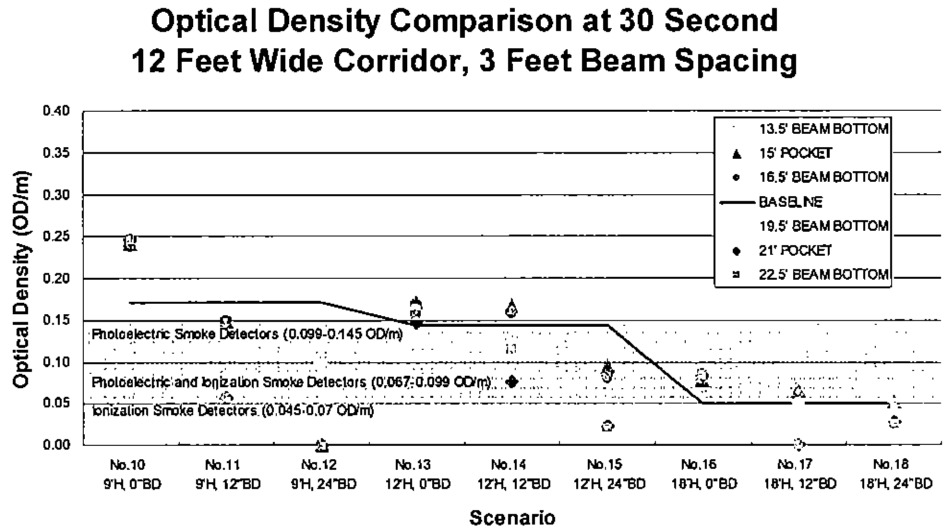
Summary Comparison for Scenarios 1 to 9

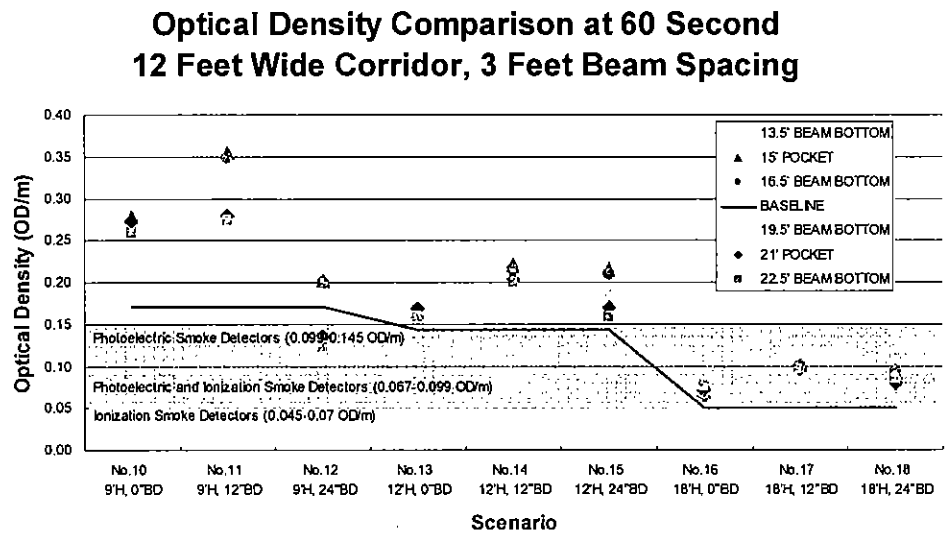




Observation: For a 5 ft wide corridor, the optical density at all locations along corridor reaches into the blue range and exceeds the baseline in 30 seconds. The comparison graph for the 60 second time frame illustrates trends resulting as steady state conditions are reached. At 60 seconds for any given ceiling height grouping the general trend is that optical density values tend to increase as beam depth increases. This is attributable to a reservoir effect that allows soot concentration to build in the deep beam pockets. As ceiling height groupings of data are reviewed left to right (from 9 ft to 18 ft) the trend is that optical density values are reducing in value due to the additional entrainment into the plume that results with increasing ceiling height. In all cases shown it is evident that at 60 seconds all postulate detector locations would be expected to alarm and exceed value for the baseline case.

Summary Comparison for Scenarios 10 to 18





Observation: For a 12 ft wide corridor, the optical density at all locations along corridor reaches into the green range and exceeds the base line in most cases in 60 seconds. Some turbulence impacts are observed at early time frame (30 seconds). Also Optical density value shows more entrainment and dilution results in these wider corridor scenarios as compared to the 5 ft wide corridor scenarios.

Graphics of Corridor Flow Phenomenon

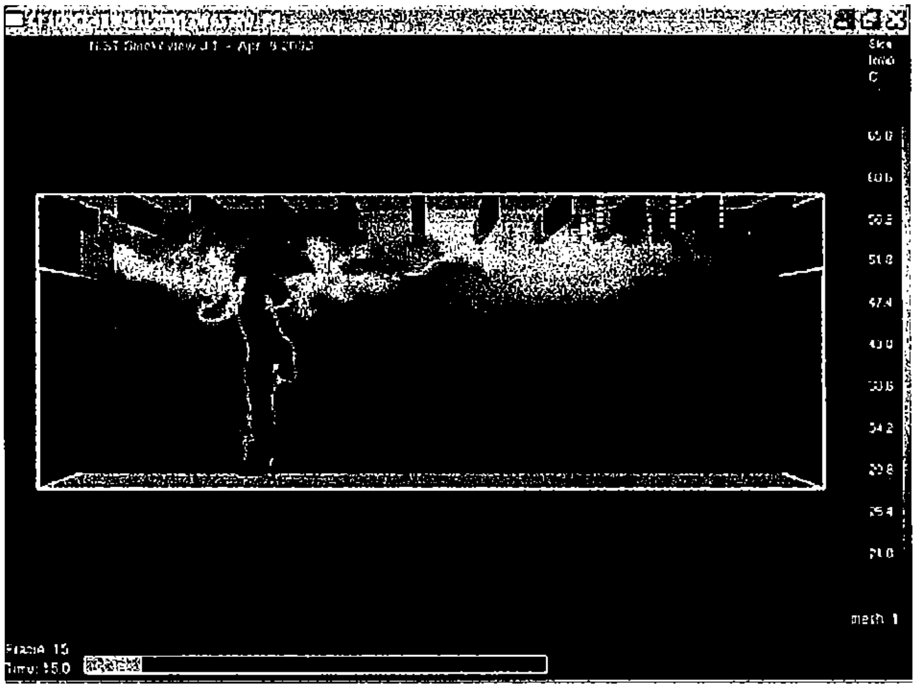


Figure 16 Temperature Distribution at 15 Seconds (ambient temperature 20°C in blue)

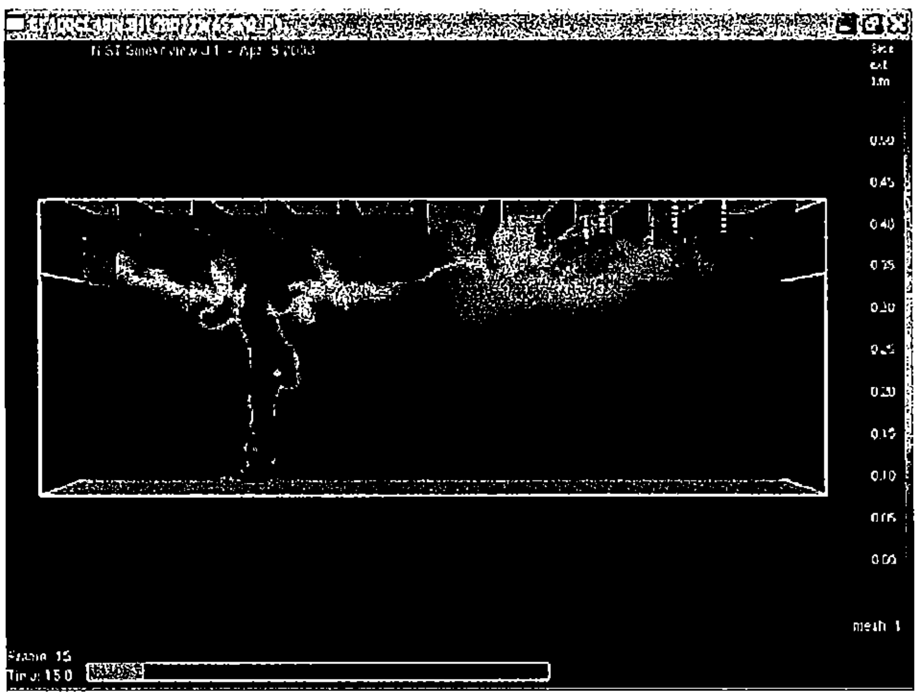


Figure 17 Extinction Coefficient Distribution at 15 Seconds (clean air in blue)

The two graphics above show the temperature and extinction coefficient (indication of OD) distributions at 15 second for Scenario 5. At this time, the flow of ceiling jet is just reaching the thermal couples that are 15' from the fire. It is also observed that the ceiling jet appears to slightly jump through the third and fourth beam pockets.

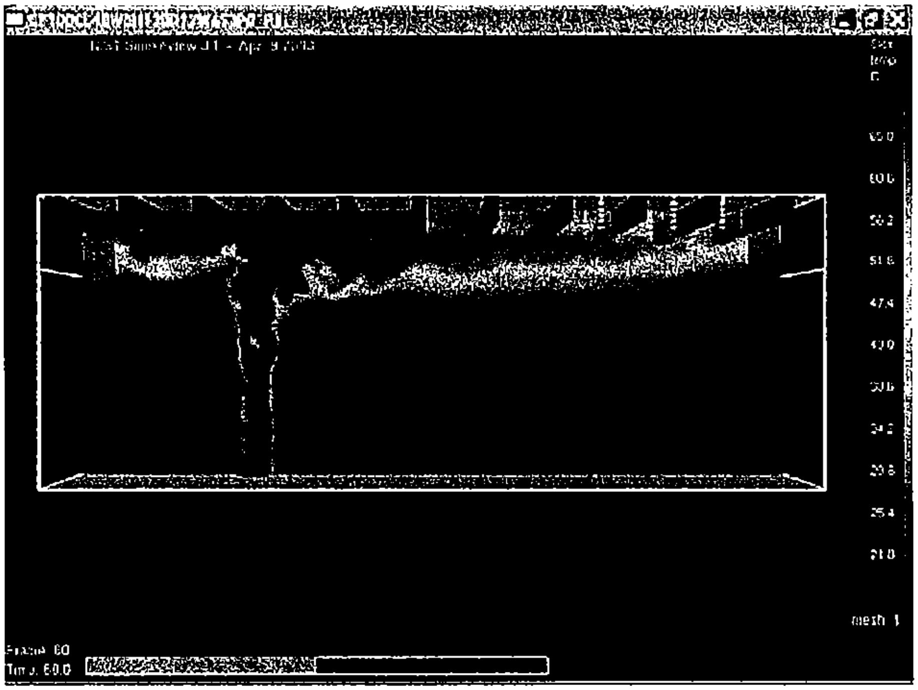


Figure 18 Temperature Distribution at 60 Seconds

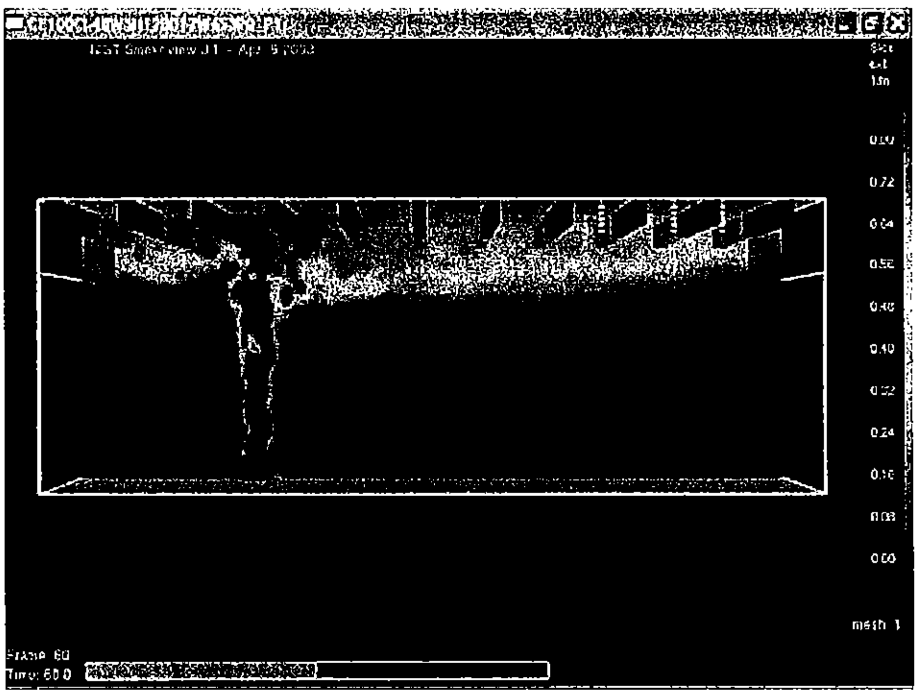


Figure 19 Extinction Coefficient Distribution at 60 Seconds

The above graphics shows the temperature and extinction coefficient distributions at 60 second for Scenario 5. At this time, the flow of ceiling jet has reached the end of the corridor. At the area approximate 15' from the fire, the smoke near the bottoms of the beams is slightly hotter and denser than that inside the beam pockets.

Smoke Detector Placement in Corridors

The several pages that follow illustrate the typical conditions of temperature and optical density that is developed at approximately 60 seconds after the fire initiation at a distance of 15 feet and 16.5 feet from the fire plume centerline. In all cases, temperature and optical density became fairly well mixed conditions at the noted timeframes with no visible dead air spaces.

Additional illustrations are also provided that show velocities for a wide variety of ceiling heights, beam depths and corridor widths that easily achieve or exceed velocities necessary to overcome detector entry resistance and provide confirmation that field conditions at the postulated detector locations would result in smoke detector alarm.

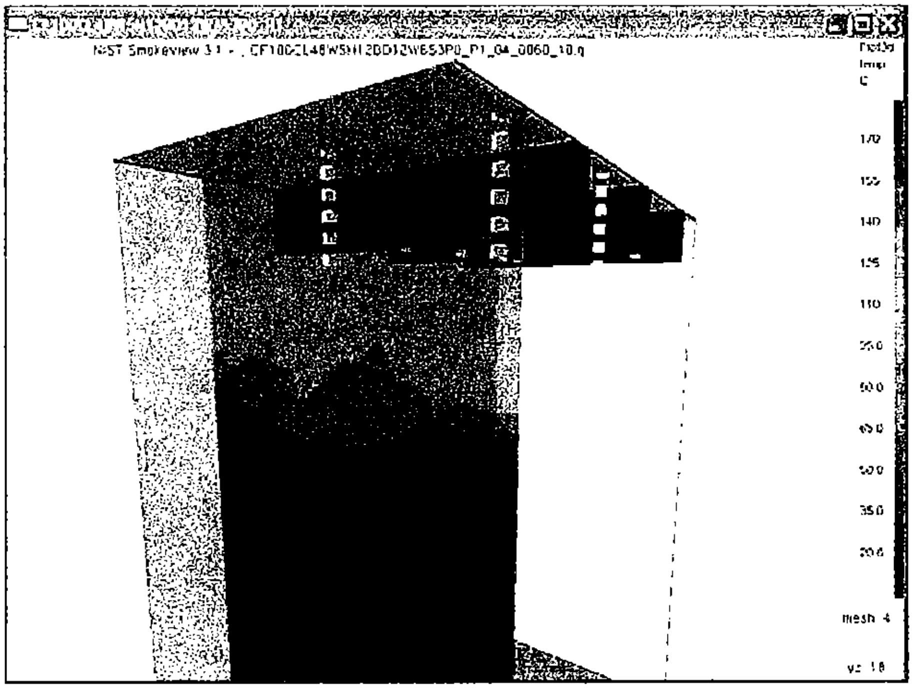


Figure 20 Traversal Temperature Distribution at 60 Seconds at 15' from the Fire

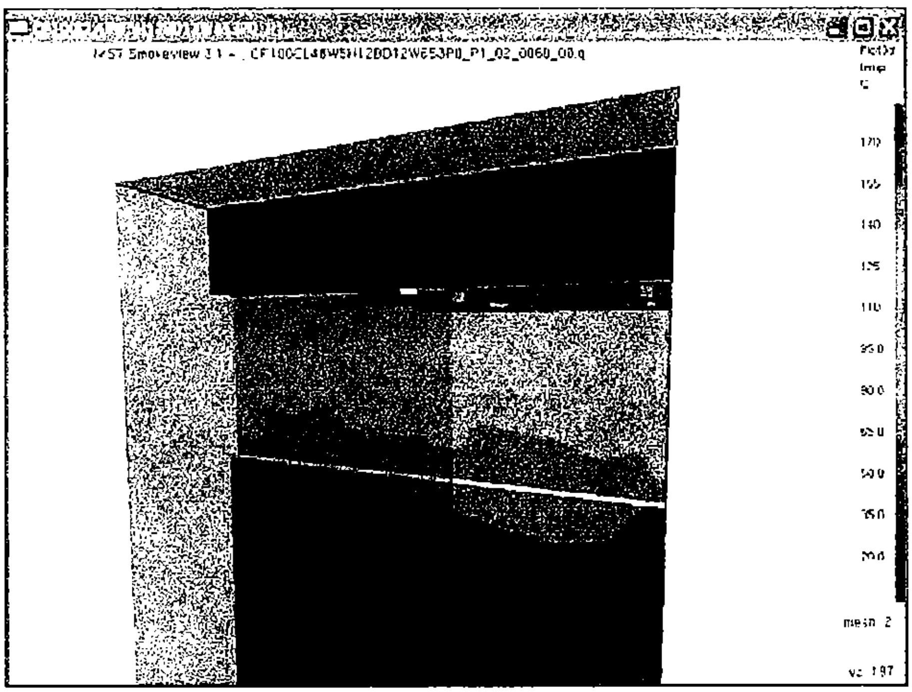


Figure 21 Traversal Temperature Distribution at 60 Seconds at 16.5' from the Fire

The graphics above show the traversal temperature distribution at 15' and 16.5' from fire, at 60 seconds. The results show that the spaces inside the beam pocket and near the bottom of the beam have comparable temperature gradient. No stagnant zone is observed near the sidewall or at the corners.

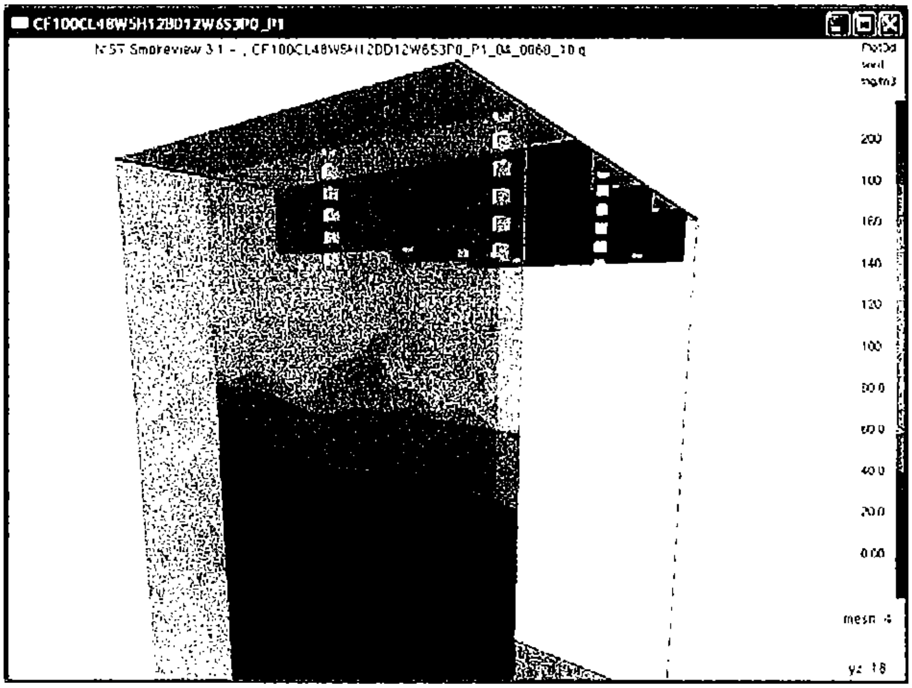


Figure 22 Traversal Soot Density Distribution at 60 Seconds at 15' from the Fire

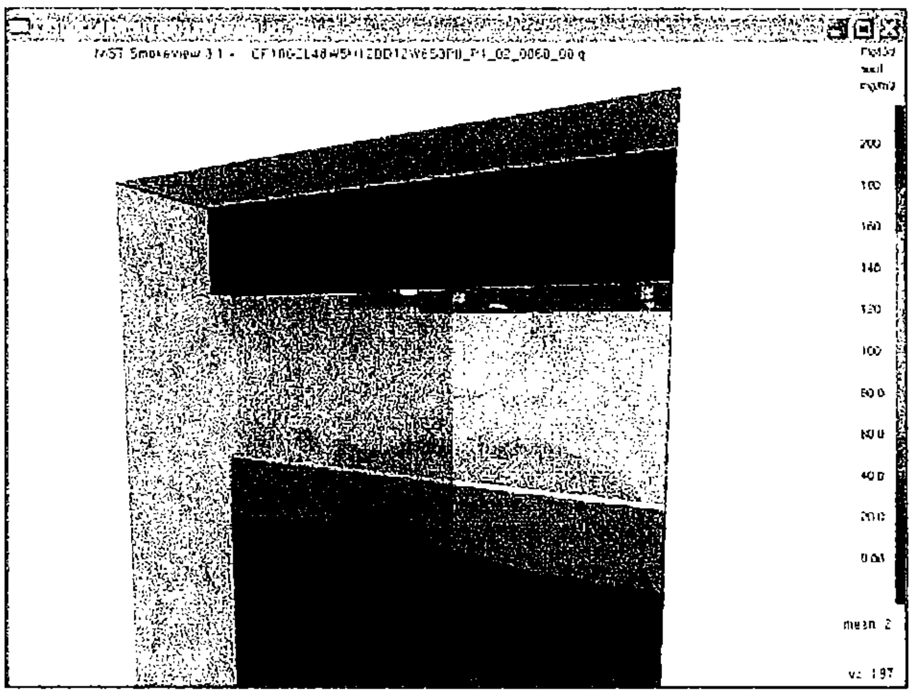


Figure 23 Traversal Soot Density Distribution at 60 Seconds at 16.5' from the Fire

The graphics above show the traversal soot density distribution at 15' and 16.5' from fire, at 60 seconds. Similar to the previous temperature distributions, the results show that the spaces inside the beam pocket and near the bottom of the beam have comparable soot density gradient. Compared to the temperature distribution, soot density shows more variation inside the pocket but no obvious stagnant zone is observed near the sidewall or at the corners. Under the beam in the center of the corridor and at the sidewall there is observed a slightly higher density area.

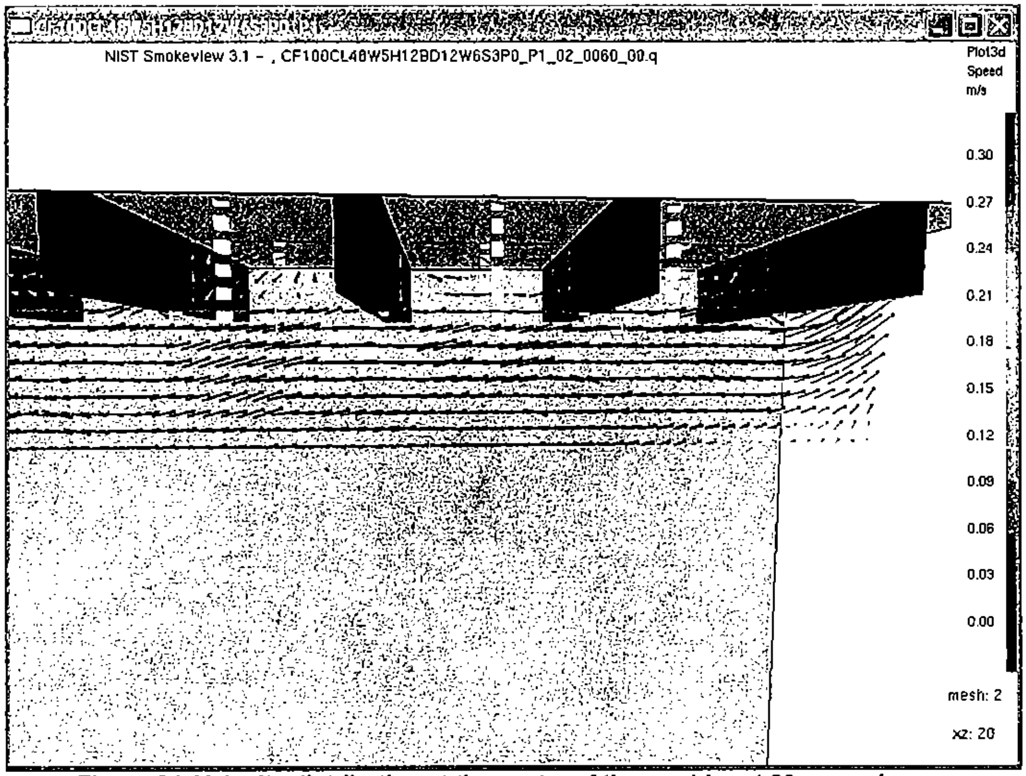


Figure 24 Velocity distribution at the center of the corridor at 60 seconds (Ceiling Height 12', Corridor Width 5', Beam Depth 12")

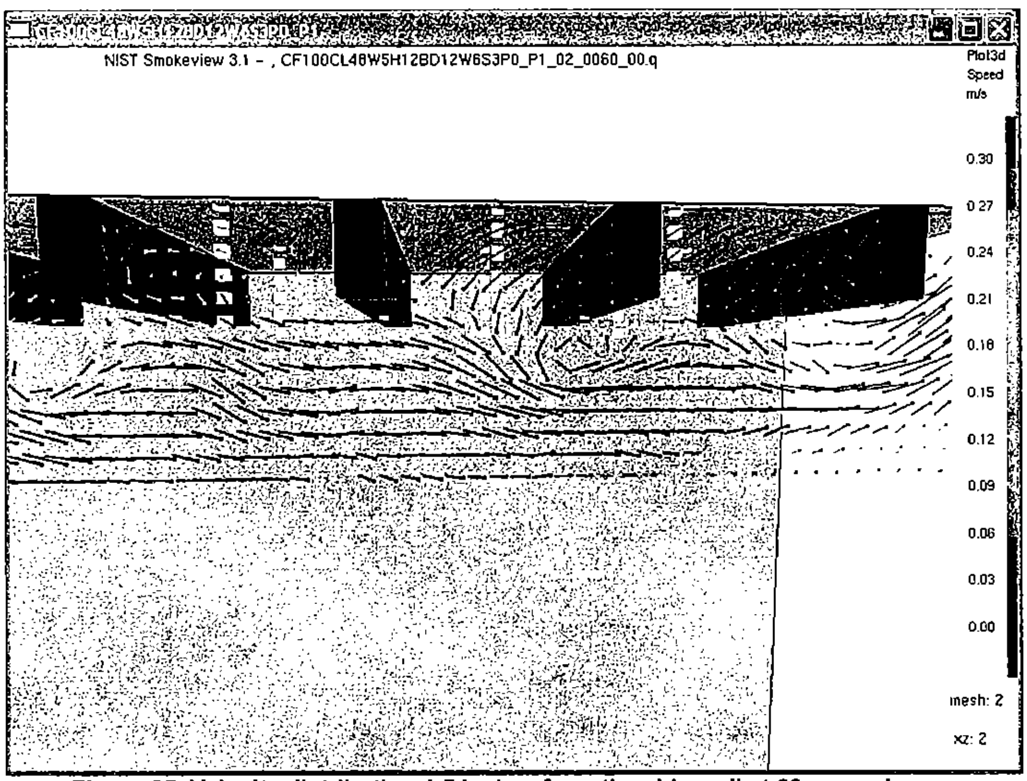


Figure 25 Velocity distribution 1.5 inches from the side wall at 60 seconds (Ceiling Height 12', Corridor Width 5', Beam Depth 12")

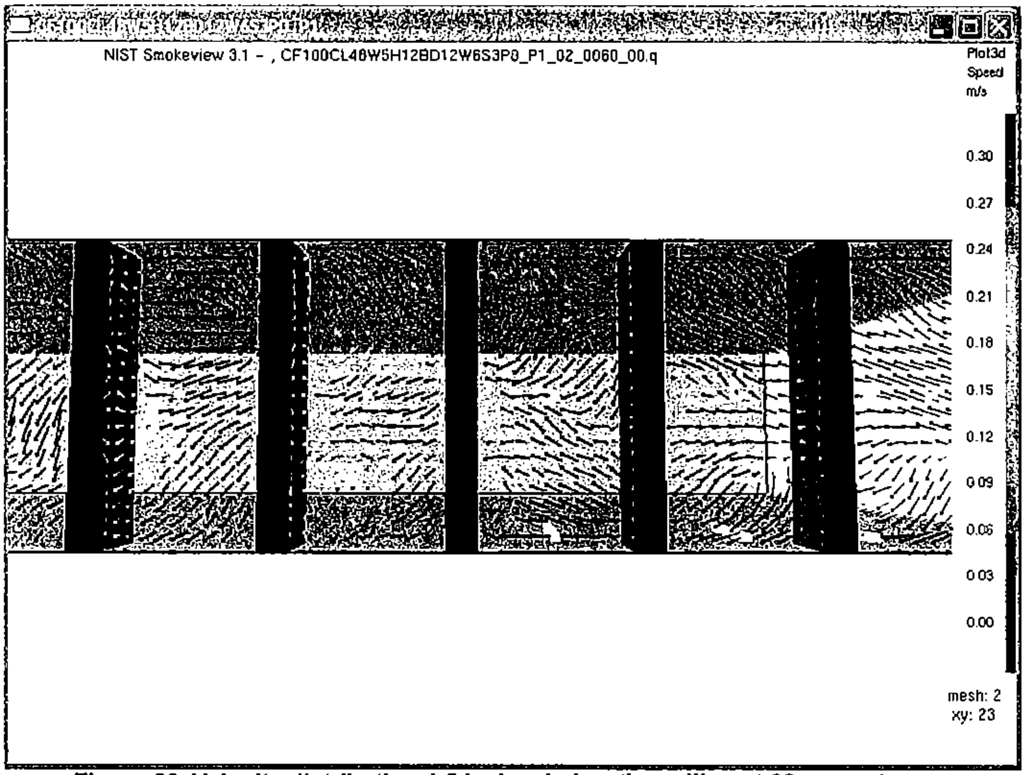


Figure 26 Velocity distribution 1.5 inches below the ceiling at 60 seconds (Ceiling Height 12', Corridor Width 5', Beam Depth 12")

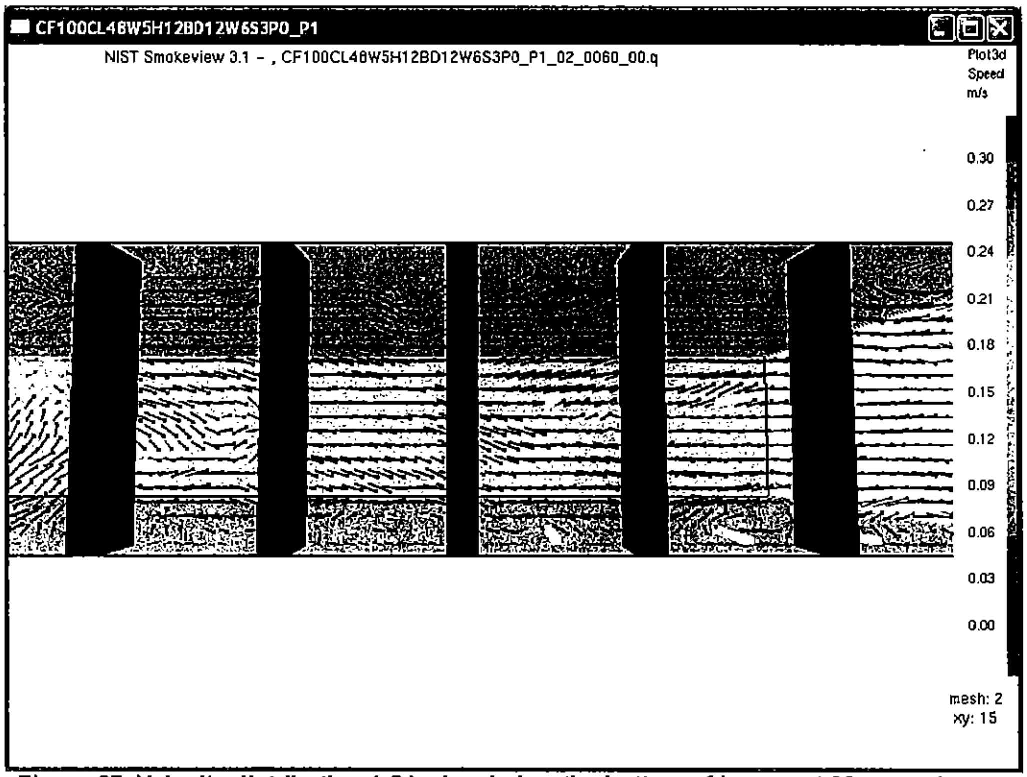


Figure 27 Velocity distribution 1.5 inches below the bottom of beams at 60 seconds (Ceiling Height 12', Corridor Width 5', Beam Depth 12")

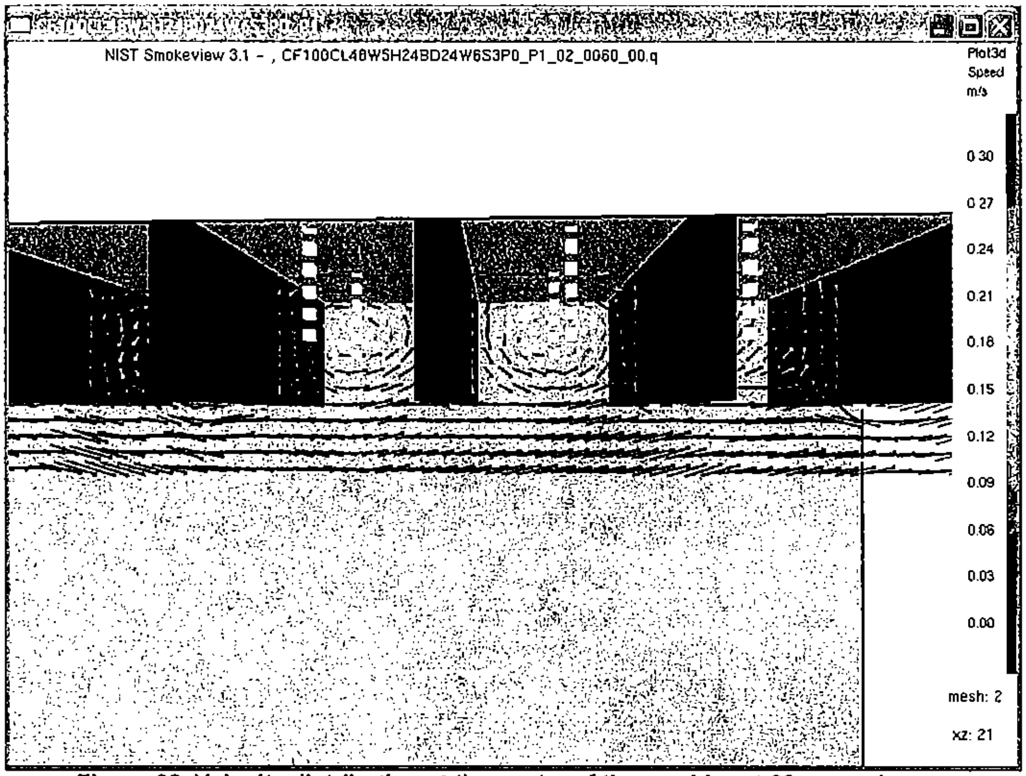


Figure 28 Velocity distribution at the center of the corridor at 60 seconds (Ceiling Height 24', Corridor Width 5', Beam Depth 24")

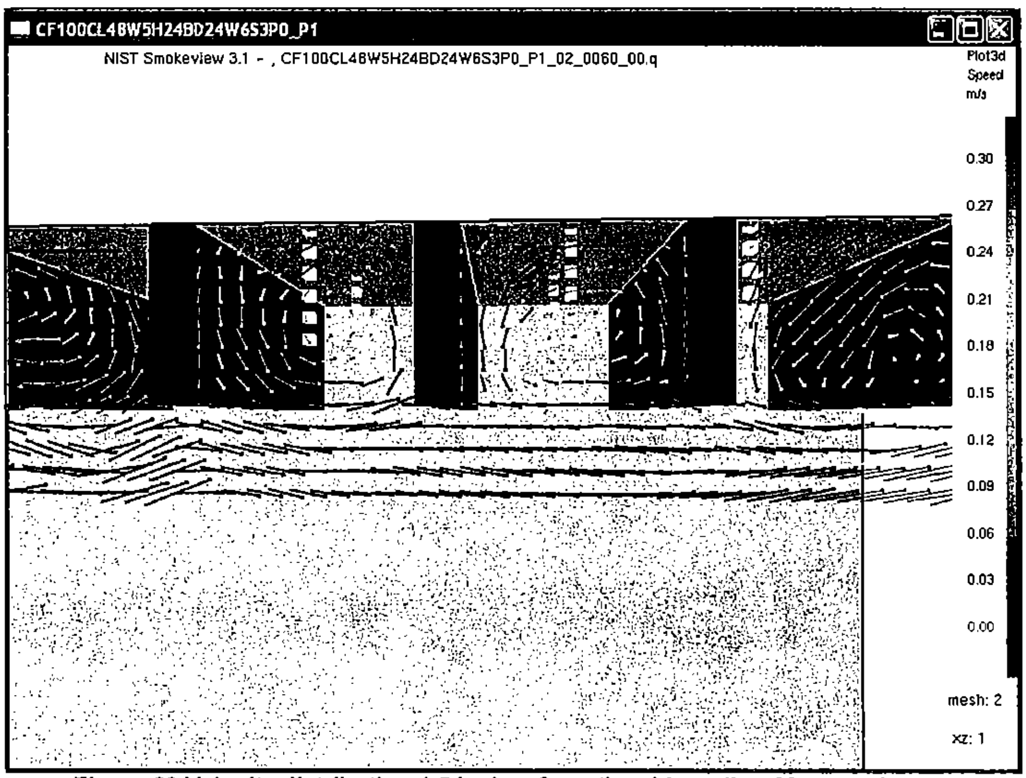


Figure 29 Velocity distribution 1.5 inches from the side wall at 60 seconds (Ceiling Height 24', Corridor Width 5', Beam Depth 24")

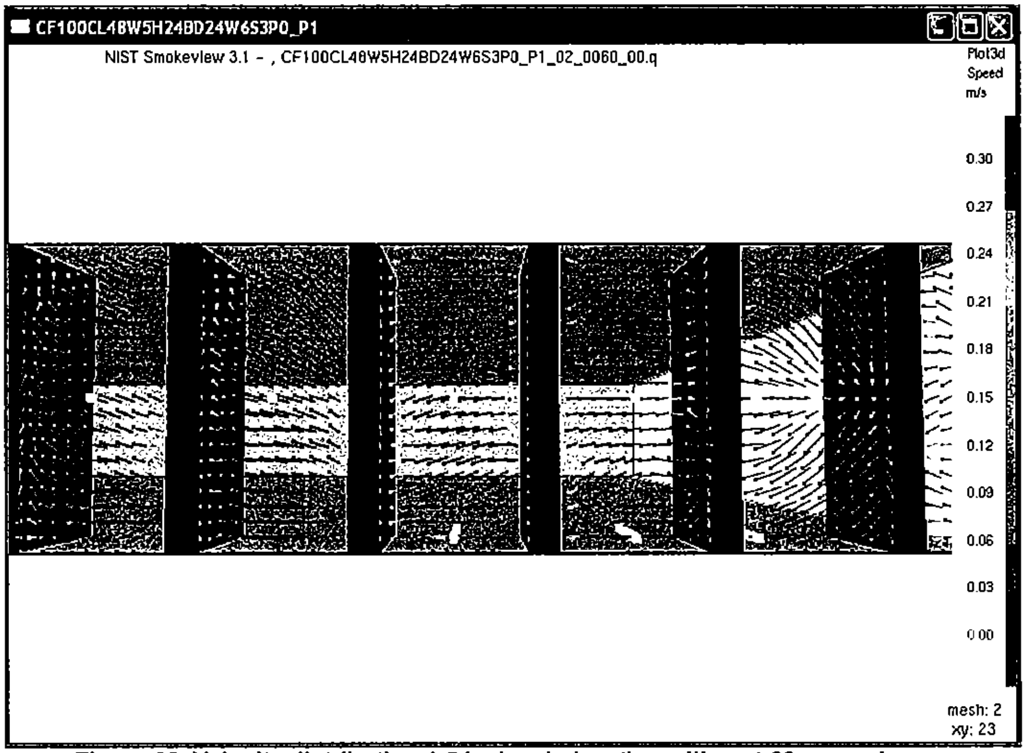


Figure 30 Velocity distribution 1.5 inches below the ceiling at 60 seconds (Ceiling Height 24', Corridor Width 5', Beam Depth 24")

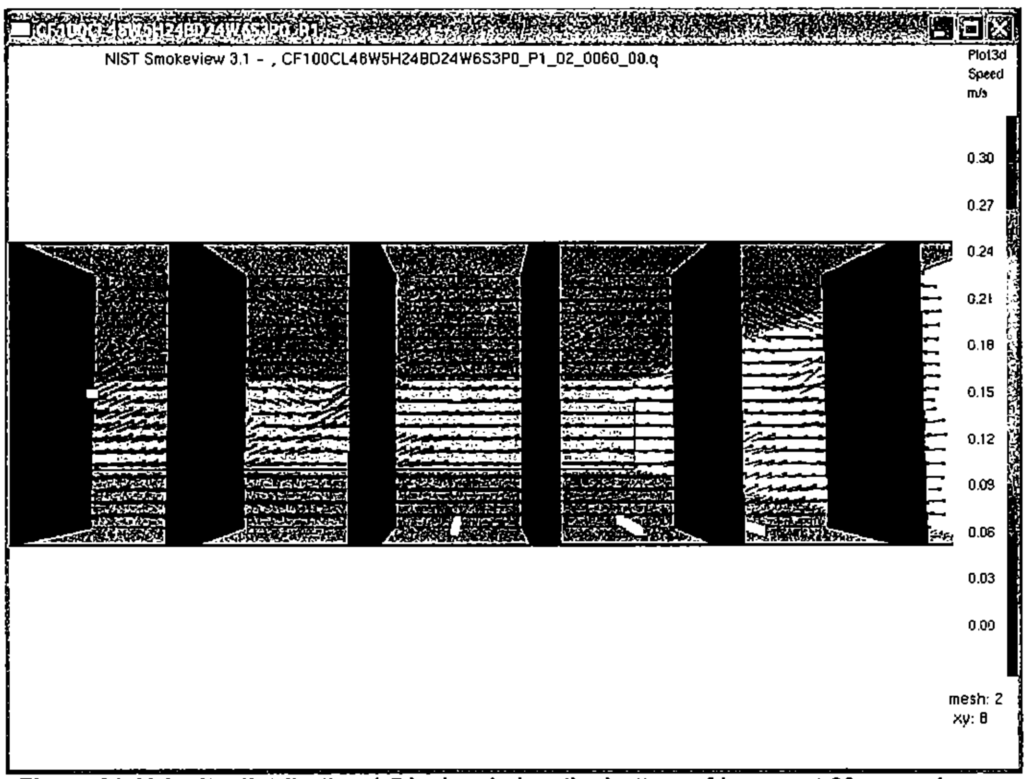


Figure 31 Velocity distribution 1.5 inches below the bottom of beams at 60 seconds (Ceiling Height 24', Corridor Width 5', Beam Depth 24")

Figure 32 Velocity distribution at the center of the corridor at 60 seconds (Ceiling Height 9', Corridor Width 5', Beam Depth 12")

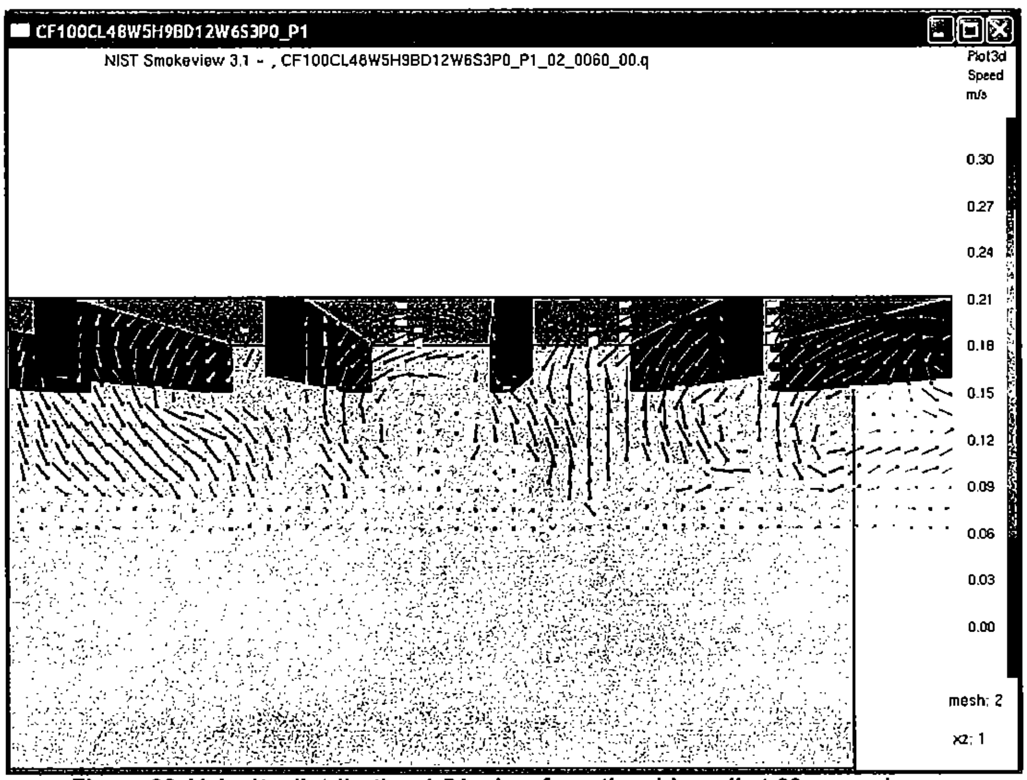


Figure 33 Velocity distribution 1.5 inches from the side wall at 60 seconds (Ceiling Height 9', Corridor Width 5', Beam Depth 12")

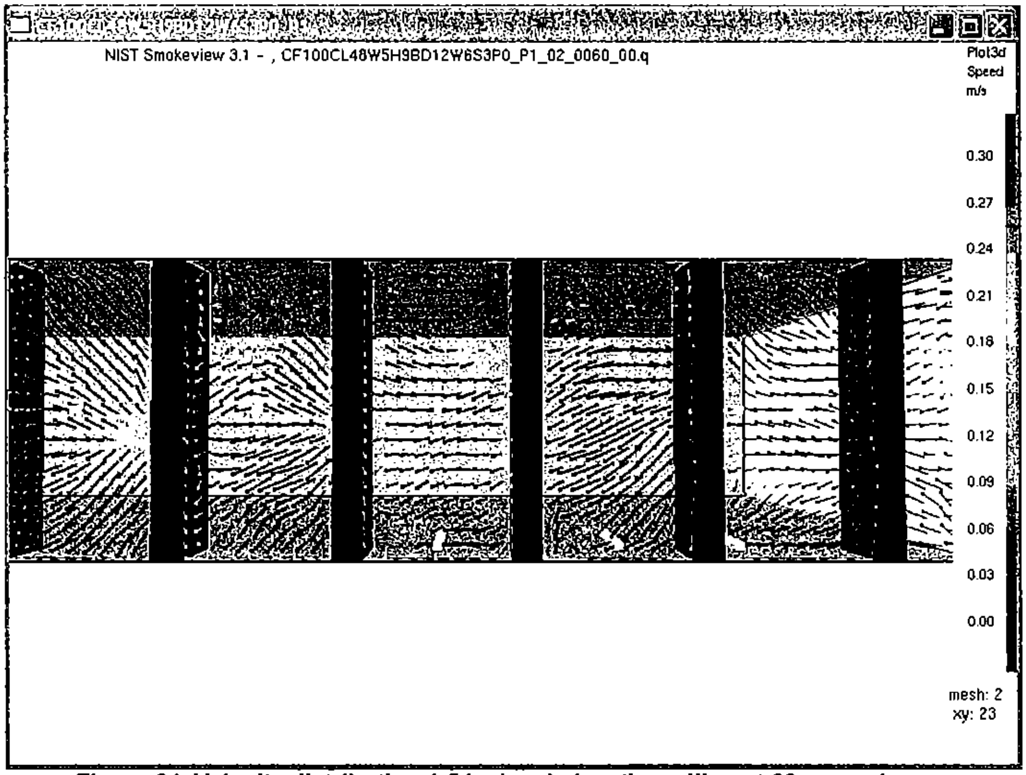


Figure 34 Velocity distribution 1.5 inches below the ceiling at 60 seconds (Ceiling Height 9', Corridor Width 5', Beam Depth 12")

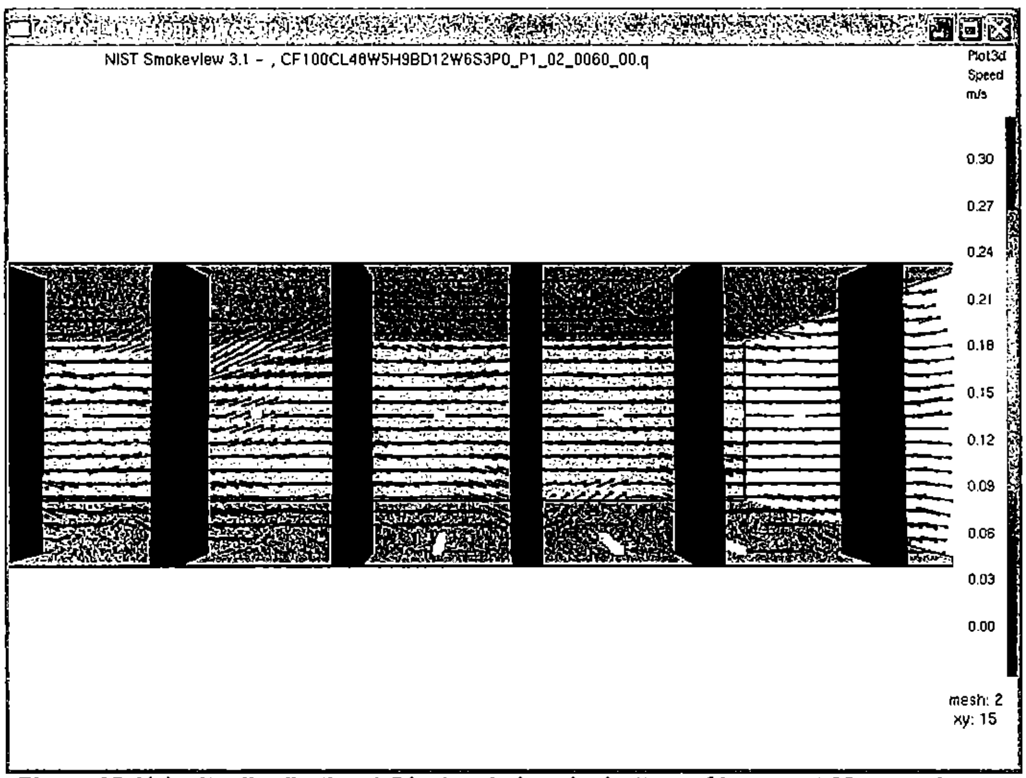


Figure 35 Velocity distribution 1.5 inches below the bottom of beams at 60 seconds (Ceiling Height 9', Corridor Width 5', Beam Depth 12")

CORRIDOR SCENARIOS – CONCLUSIONS & NFPA 72 RECOMMENDATION

Corridor geometry is a significant factor in evaluating the performance of smoke detectors. This is to be expected, understanding that the ceiling jet is confined by the nearby walls without opportunity for entrainment of air. This is in contrast to the case of a ceiling jet spreading out radially below unconfirmed smooth ceiling (the baseline) surface. The channeling or confinement effect was identified as a significant factor by Delichatsios (1981), who provided an empirical correlation for gas temperature at detector (heat) location. For this study, temperature rise is examined. Also, relying on the work of Geiman and Gottuk, smoke optical density measurements are reviewed to reveal whether or not smoke density reaches sufficient levels to expect smoke detector alarm.

The scenarios examined to date confirm the following for corridors for 100 kW - 300 kW flaming fires.

1. **Linear Spacing of Smoke Detection:**

   The smooth ceiling 30-foot spacing guideline of NFPA 72, with permitted increases for narrow space geometry, allows smoke detectors to extend to approximately 41 feet on-center along a corridor. The data observed in this analysis indicates that for ceilings up to 24 feet in height, the deep-beam configurations do not negatively affect expected performance. This means that for these conditions, spot smoke detectors can be effectively used in corridors with deep beams with spacing of 30 to 41 feet, as is permitted for smooth ceilings.

2. **Increasing Corridor Width:**

   The width of corridors reviewed in this study ranged from 5 feet to 30 feet. For 100 kW fire in corridors 30 feet wide, the optical density measurements tend towards the low end of the specified spot detector alarm range, with measurements comparable to the baseline detector measurements. Therefore, as corridor width increases, the fire size threshold needed for activation of the baseline spot smoke detector must increase. In this study, increasing the fire size to 300 kW in a 30-foot wide corridor shows that the optical density values are significantly increased beyond that observed for the baseline detector, and well into and beyond the expected range of values for alarm. This result demonstrates that for relatively wide corridor spaces with deep beams forming parallel channels, that the corridor and reservoir effect will contribute to increased optical density and temperature levels sufficient to alarm spot smoke detectors (with spacing of 30 to 41 feet, as is permitted for smooth ceilings.)

3. **Increasing Ceiling Heights:**

   As ceiling height increases, the fire size threshold needed for activation of the baseline spot smoke detector must increase. With an increased fire size, the smoke detectors on a beam ceiling in a corridor will be comparable to the performance result for the baseline detector at the same ceiling height. A comparable performance is generally judged to be when the conditions of optical density at postulated detector locations occur in a time frame that is approximately ± 60 seconds of those same measurements being achieved by the baseline detector. Table 3 is a summary comparison of the time difference between postulated detectors and the baseline determined when optical density reaches 0.11 OD/m.

Table 3: Performance Comparison – Corridor with Constant Fires (100kW)

Scenario	Ceiling height (ft)	Corridor Width (ft)	Beam Depth (in)	Beam Spacing (ft)	30 ft spacing	40 ft spacing
					In Pocket	In Pocket
CF01CL48W05H09BD00W06S03P00_P1	9	5	0	3	7	4
CF01CL48W05H09BD12W06S03P00_P1	9	5	12	3	1	-4
CF01CL48W05H09BD24W06S03P00_P1	9	5	24	3	-3	-2
CF01CL48W05H12BD00W06S03P00_P1	12	5	0	3	9	7
CF01CL48W05H12BD12W06S03P00_P1	12	5	12	3	3	0
CF01CL48W05H12BD24W06S03P00_P1	12	5	24	3	-1	-6
CF01CL48W05H18BD00W06S03P00_P1	18	5	0	3	NOTE A	NOTE A
CF01CL48W05H18BD12W06S03P00_P1	18	5	12	3	NOTE A	NOTE A
CF01CL48W05H18BD24W06S03P00_P1	18	5	24	3	NOTE A	NOTE A
CF01CL48W12H09BD00W06S03P00_P1	9	12	0	3	5	2
CF01CL48W12H09BD12W06S03P00_P1	9	12	12	3	-10	-23
CF01CL48W12H09BD24W06S03P00_P1	9	12	24	3	-19	-31
CF01CL48W12H12BD00W06S03P00_P1	12	12	0	3	5	3
CF01CL48W12H12BD12W06S03P00_P1	12	12	12	3	-7	-14
CF01CL48W12H12BD24W06S03P00_P1	12	12	24	3	-14	-23
CF01CL48W12H18BD00W06S03P00_P1	18	12	0	3	NOTE B	NOTE B
CF01CL48W12H18BD12W06S03P00_P1	18	12	12	3	NOTE B	NOTE B
CF01CL48W12H18BD24W06S03P00_P1	18	12	24	3	NOTE B	NOTE B

NOTE A. Detectors located at 30 or 40 ft. spacing along corridor reach upper range of optical density measurements for which detection alarm/actuation would be expected within 10-25 seconds after fire initiation. The baseline detector never reaches the upper range.

NOTE B. Detectors located at 30 or 40 ft. spacing along corridor reach mid to low range of optical density measurements for which detection alarm/actuation would be expected within 15-35 seconds after fire initiation. Optical density levels are comparable or higher than that of the baseline.

4. Placement Under Beams or on Ceiling Between Beams:

Based on all the corridor data evaluated, there is no significant difference in temperature rise or optical density conditions for smoke detectors mounted on the bottom beam or in the beam pocket at approximately equal distances from the fire. Where deep beams interrupt the ceiling surface in a corridor, mounting the detector on the ceiling between beams or the bottom of the beam is acceptable, either location providing comparable response to alarm.

5. Sidewall Mount or Center of Corridor:

The concern of NFPA 72 for keeping smoke detector locations 12 inches below or away from a ceiling-wall corner is unsubstantiated. No stagnant zone or locations are observed that would preclude smoke detector alarm. Temperature and smoke optical density are relatively uniform and well-mixed throughout the volume of the beam pocket within seconds after the initial ceiling jet passes. It is noted that while the modeling results show no stagnant zones, it is not suggested that spot detectors can be installed in close proximity or contact to the wall or ceiling surface. Such close mounting may impact the airflow characteristics into and around the detector housing which could have a negative impact on smoke flow into the detector sensing chambers. Such airflow effects have not been evaluated by the modeling conducted in this study.

6. Recommendation for NFPA 72:

Based on the findings of this study it is recommended to add the following new text and Annex text to NFPA 72, 5.7.3.2.4(B) addressing the installation of spot smoke detectors in corridors with beam or solid joist ceilings.

(New #)* *Corridors with beams or solid joist ceilings*

(a) Corridors 4.5 m (15 ft.) in width or less having deep ceiling beams or joists perpendicular to the corridor length shall be permitted to use the spacing permitted for smooth ceilings including those requirements permitted for irregular areas of Section 5.6.5.1.2.

(b)Spot type smoke detectors shall be permitted to be located on the ceiling or on the bottom of beams.

A.5.7.3.2.4.(B)(New #) Corridor geometry is a significant factor that contributes to the development of velocity, temperature and smoke obscuration conditions at smoke detectors located along a corridor. This is based on the fact that the ceiling jet is confined or constrained by the nearby walls without opportunity for entrainment of air. For corridors of approximately 4.5 m (15 ft.) in width and for fires of approximately 100 kW or greater the performance of smoke detectors in corridors with beams has been shown to be comparable to spot smoke detector spacing on an unconfined smooth ceiling surface.

Editorial Note: At the time of presentation of a preliminary report to the NFPA 72 Initiating Devices Committee, several additional 30-foot wide corridor scenarios had not been modeled. Since that time the 30-foot corridor scenarios have been modeled and the data indicates it would be appropriate to modify the above recommended code text to allow the provisions to apply for corridors up to 30 feet in width.

ROOM SMOKE DETECTORS – RESULTS AND OBSERVATIONS

The room geometry evaluated in this section of the report varies significantly in size and ceiling height. When a beamed ceiling is present, the beam pocket physical layout and parameters change as well. Each of these factors can affect smoke transport and the character of the smoke optical density, temperature and flow velocity. These characteristics of the smoke are evaluated to determine the impact on the detection performance when different detector spacing or placement is considered.

In order to compare the performance of postulated detector locations subject to the influence of beam pockets for room-type enclosures a baseline detector performance is used. The smooth ceiling model with detector points placed at the NFPA 72-recommended spacing of 30 feet is used as the baseline, against which the detector performances for all other detector locations, detector types and ceiling structures are compared. Baseline detectors are compared to postulated detector locations using the worst case spacing scenario where a fire occurs at the furthest possible distance away from a detector. For the room scenarios evaluated the fire is considered centered between four detectors.

Detector Activation Thresholds

The selection of detector smoke alarm criteria is discussed in detail in the section of this report titled "Smoke Detection Performance Metrics." The following is a summary of the smoke thresholds used in the analysis of the room simulations.

To review the trends and understand the nature of the difference between ionization and photoelectric detector response, the change of optical density at postulated detector locations are compared to a range of values described as the "80% OD Alarm Threshold" by Geiman & Gottuk. This review of optical density condition is considered the primary indicator of smoke alarm. The "80% OD Alarm Threshold" values are as follows:

- Spot Detector (Ionization type) = 0.072 ± 0.027 OD/m (0.045 to 0.099 OD/m).
- Spot Detector (Photoelectric type) = 0.106 ± 0.039 OD/m (0.067 to 0.145 OD/m).

To simplify and aid in the comparison, the following two levels are graphically utilized in the presentation of data:

- 0.11 OD/m for photoelectric type detectors.
- 0.08 OD/m for ionization type spot detectors.

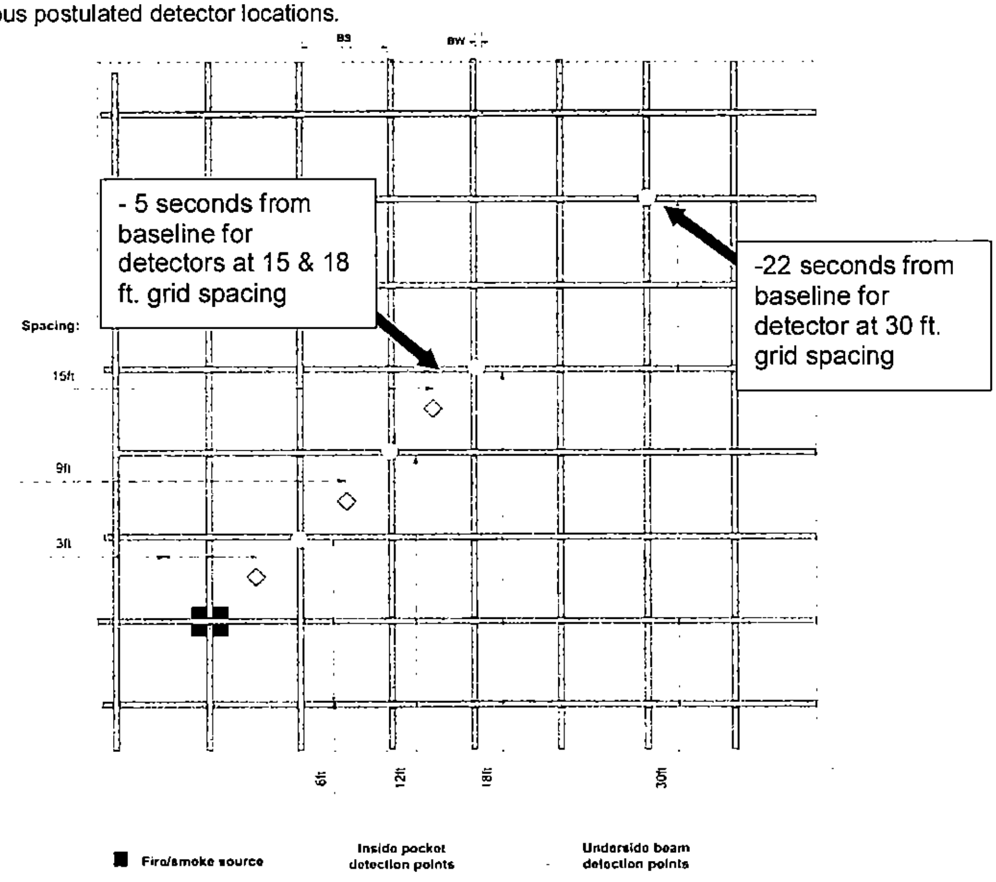
Temperature (i.e. temperature rise of 4 °C and 13 °C to cover different fire types) and velocity (0.15 m/s) in the location of interest will be analyzed so a smoke alarm prediction can be verified.

Performance Comparison Method

In order to quantitatively assess the NFPA 72 requirement for a spot-type detector in every beam pocket under certain room and beam pocket conditions, it is essential to consider the development of the smoke plume and its dispersion as it ascends and along the ceiling. The size and depth of the beam pockets, as well as the room's physical parameters such as the ceiling height will affect the smoke movement to varying extents. This will in turn have an impact on the detection performance when detectors are installed at different spacing and locations.

The baseline detection performance is a performance requirement implied or specified by NFPA 72 as prescriptive provisions. The following comparison method aims at developing a systematic and consistent approach so the detection performance can be compared when other factors are changed. Once a quantitative result is achieved, a decision can be made on whether a spot-type detector is really needed in every single pocket or whether every second or third pocket would suffice.

- For each scenario the baseline performance is established using NFPA 72 30-ft. guideline spacing for a flat ceiling with the same ceiling height;
- The detection performance of postulated detector locations using the same smoke alarm thresholds (smoke density, temperature rise and velocity) are compared to those for the baseline;
- In the graphs that follow in this report there is observed a time difference between the response of the benchmark detector and the postulated spot smoke detector locations for both the room scenarios. This time difference is generally evaluated at the time that the optical density at the detectors first reaches a measurement of 0.11 OD/m. Depending on the parameters of any given scenario the postulated detectors may achieve the optical density measurement of 0.11 OD/m either several seconds before or after the benchmark detector achieves an optical density measurement of 0.11 OD/m. This comparison is important as it provides a relative sense of whether the postulated detectors are operating in a time frame (approximately ± 60 sec) comparable to the benchmark detector or if the postulate detectors performance is significant minutes slower or faster to respond than the benchmark detector.;
- In addition to the graphical data presented each scenario has associated a table that reports the time shift differences for the postulated detectors as compared to the baseline. These tables include the time shift value for a detector postulated to be located using NFPA 72 30-ft. guideline spacing (the detector is 21 feet from the plume centerline) although the ceiling is beamed ceiling. This comparison is important as it provides a comparison of the performance of a detector spaced on a 30-foot grid in a room with beamed ceilings. The meaning of the data is as illustrated by the following graphic, which notes the time shift differences for the various postulated detector locations.



Effect of Different Constant Fire Sizes on the Baseline

Shown in Figure 36 are optical densities at NFPA spacing (30 ft) under a 24 ft high flat ceiling. The fire sizes are constant fires of 300, 500 and 700 kW.

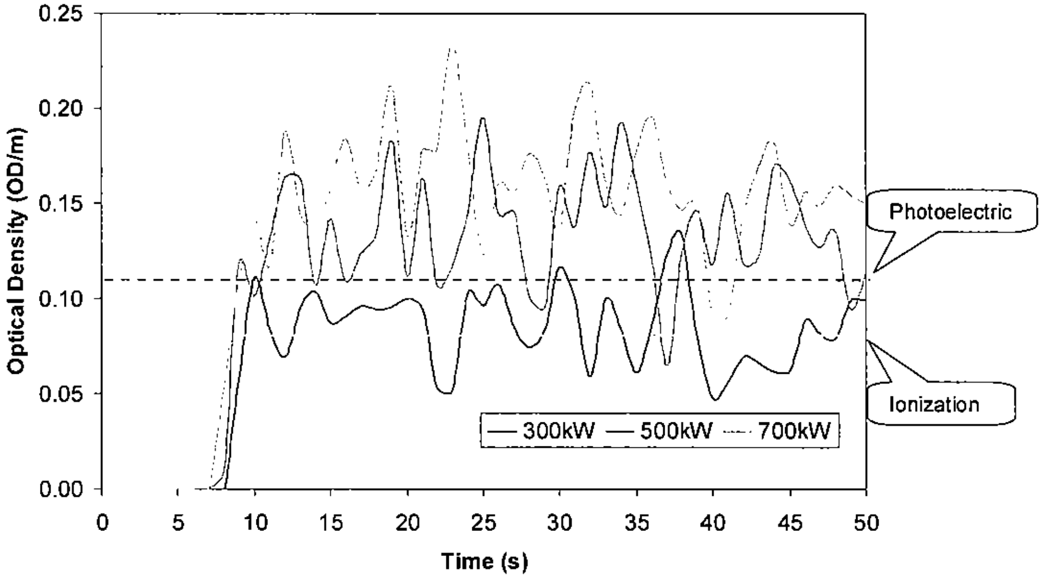


Figure 36 **Comparison of OD from various constant fire sizes at NFPA 30 ft spacing**

It is obvious that the peak and average ODs increase as the constant fire size increases. The OD curves start appear to be dropping from around 25 to 40 seconds, however, this is a reflection of the pulsing nature of the fire.

Room Scenario Examples

The full Final Report details the results of 33 small and large room scenarios. For the purpose of illustration the graphical results for a room with a 18 ft. ceiling height, 24 inch deep beam pockets and beam pockets ranging in size from 3 ft x 3ft pockets to 12 ft. x 12 ft. pockets are included in the following three pages. These are Scenario's # 2-5b, 2-6b and 2-7b from the full Final Report , which were modeled using a 200kW fire due to ceiling height considerations.

Small Rooms - Constant Fires

The pages that follow include the graphs and tables which show the relative performance of postulated spot detector locations in pockets or underside the beams for a small room with constant fire scenarios.

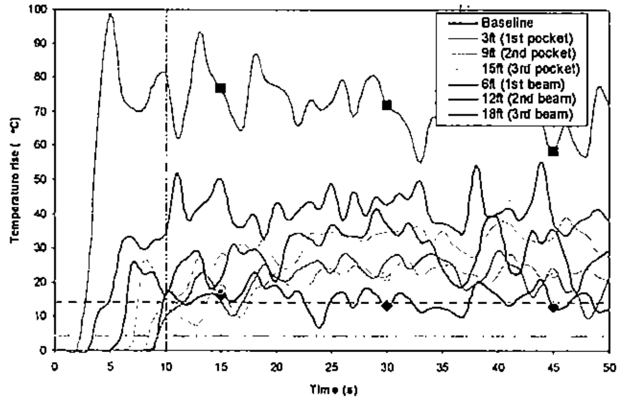
The small room data analysis is divided into several distinct groups of graphs.

1. 28 scenarios – Comparison of detector locations to temperature and optical density condition versus time for
    a. Pocket size 3x3, 6x6, 12x12 ft, and
    b. Beam depth of 0 (as baseline), 12, 24 inches, with
    c. Ceiling heights of 12, 18, and 24 ft
2. Graphs illustrating the Comparisons of Optical Density with various fire sizes for
    a. 24 ft high flat ceiling
3. Graphs illustrating the Comparison of Velocity with Increasing Pocket Size for
    a. 3x3 ft pocket size with 12 ft ceiling height and 12 inches beam depth;
    b. 6x6 ft pocket size with 12 ft ceiling height and 12 inches beam depth;
    c. 12x12 ft pocket size with 12 ft ceiling height and 12 inches beam depth
4. Graphs illustrating the OD and Temperature distributions in the pocket for
    a. 3x3 ft pocket size with 18 ft ceiling height and 24 inches beam depth;
    b. 6x6 ft pocket size with 18 ft ceiling height and 24 inches beam depth;
    c. 12x12 ft pocket size with 18 ft ceiling height and 24 inches beam depth.

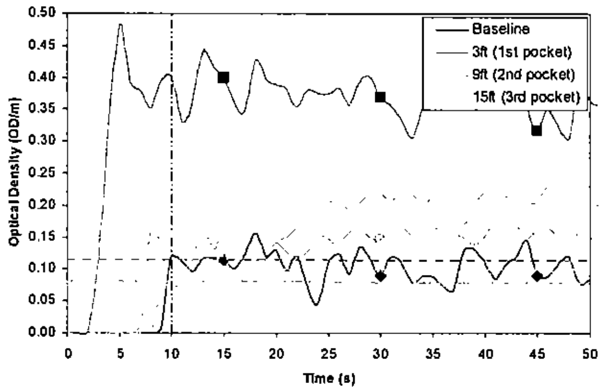
A detailed description of each scenario is in Appendix B.

In the tables below, CH is "Ceiling Height", BD is "Beam Depth", PS is "Pocket Size".

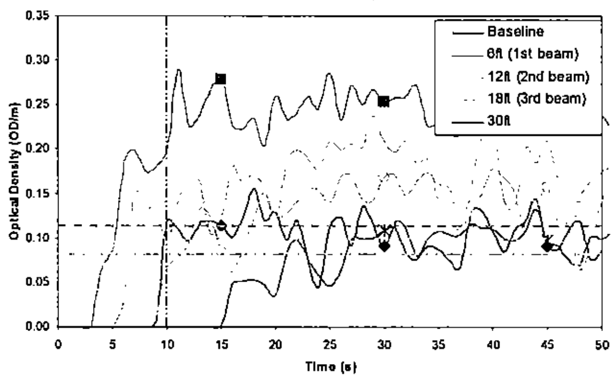
Small Room Scenario #2-5b CF02RL40W35H18BD24W09S03P03_P1



(a) Temperature rise



(b) OD in the beam pockets

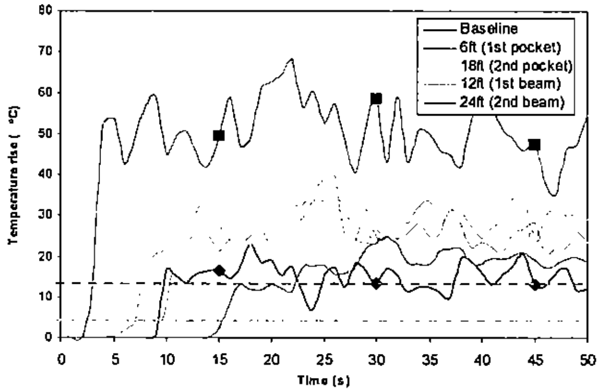


(c) OD under the beams

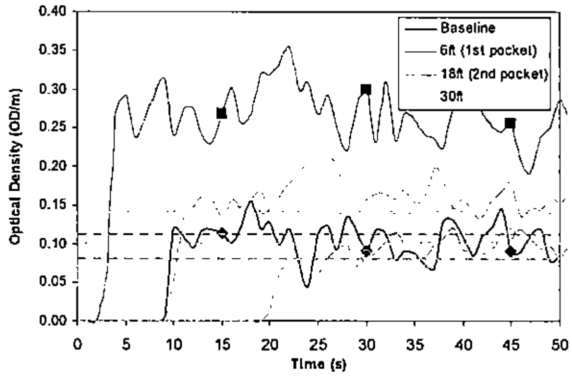
Observation: The temperature rise at each point is above 13 °C, but only those points in the 1st and 2nd pockets and under the 1st and 2nd beams are earlier than the baseline. Similarly ODs at the above mentioned points reach 0.11 OD/m earlier than the baseline.

Scenario	Description CH (ft), BD (in), PS (ft x ft)			Baseline - Detectors at 30 ft spacing (21 ft to plume center)	1st Pocket		2nd Pocket		3rd Pocket		30 ft Grid
				Activation Criteria	In Pocket	Under Beam	In Pocket	Under Beam	In Pocket	Under Beam	Under Beam
C02H18D24P03	18	24	3x3	0.11 OD/m	7	5	2	5	-5	-2	-22
				13 °C	7	5	4	2	-2	-4	-11

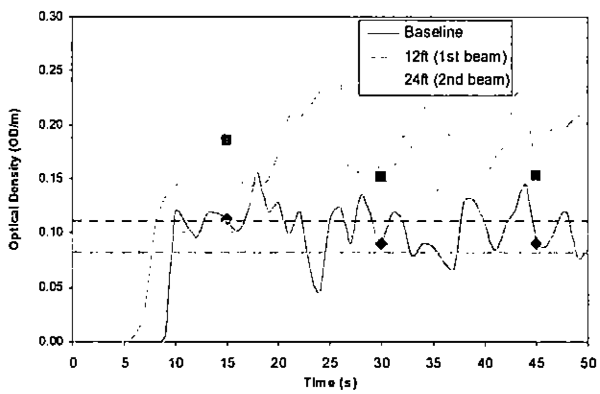
Small Room Scenario #2-6b CF02RL40W35H18BD24W09S06P06_P1



(a) Temperature rise



(b) OD in the beam pockets

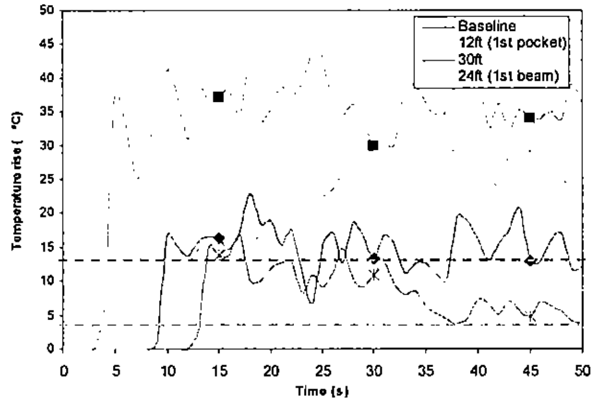


(c) OD under the beams

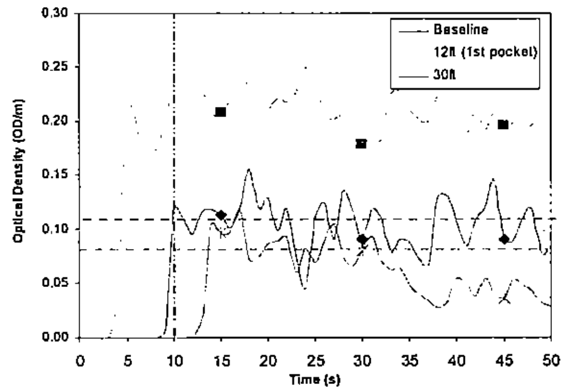
Observation: The temperature rise at each point is above 13 °C, but only those points in the 1st pocket and the 1st beam are earlier than the baseline. ODs at points in the 1st pocket and under the 1st beam reach 0.11 OD/m earlier than the baseline. OD at the point in the 2nd pocket is equivalent to the baseline.

Scenario	Description CH (ft), BD (in), PS (ft x ft)			Baseline - Detectors at 30 ft spacing (21 ft to plume center)	1st Pocket		2nd Pocket		3rd Pocket		30 ft Grid
				Activation Criteria	In Pocket	Under Beam	In Pocket	Under Beam	In Pocket	Under Beam	In Pocket
C02H18D24P06	18	24	6x6	0.11 OD/m	7	2	0	-12	NA	NA	-23
				13 °C	7	2	-1	-8	NA	NA	-18

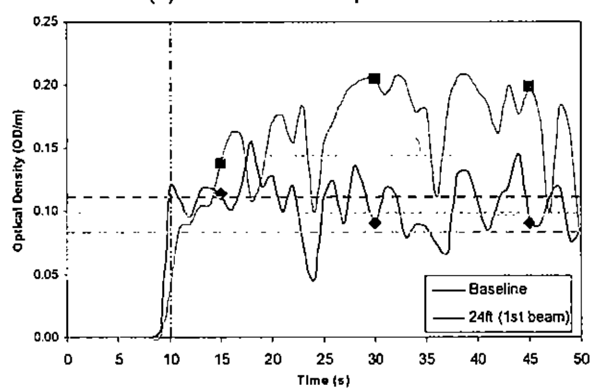
Small Room Scenario #2-7b CF02RL40W35H18BD24W09S12P12_P1



(a) Temperature rise



(b) OD in the beam pockets



(c) OD under the beams

Observation: The temperature rise at each point is above 13 °C, but only the point in the 1st pocket is earlier than the baseline. Similarly OD at the point in the 1st pocket reaches 0.11 OD/m earlier than the baseline.

Scenario	Description CH (ft), BD (in), PS (ft x ft)			Baseline - Detectors at 30 ft spacing (21 ft to plume center)	1st Pocket		2nd Pocket		3rd Pocket		30 ft Grid
				Activation Criteria	In Pocket	Under Beam	In Pocket	Under Beam	In Pocket	Under Beam	In Pocket
C02H18D24P12	18	24	12x12	0.11 OD/m	5	-4	NA	NA	NA	NA	-7
				13 °C	5	-1	NA	NA	NA	NA	-4

Velocity

The velocity at different locations, including the baseline, in the pockets and underside beams, are presented for selected scenarios in the small room with constant fire size.

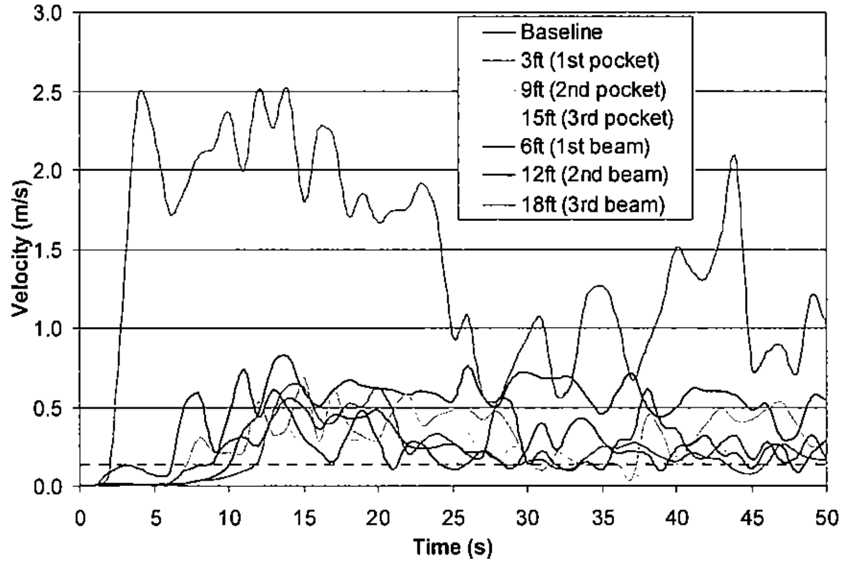


Figure 37 Scenario H12D12P03 results, velocity, 100 kW constant fire

Observation: Velocities at all investigated points exceed the predefined criteria of 0.15 m/s. However velocities only at the points in the 1st and 2nd pockets and underside the 1st and 2nd beams reach the critical level earlier than the baseline.

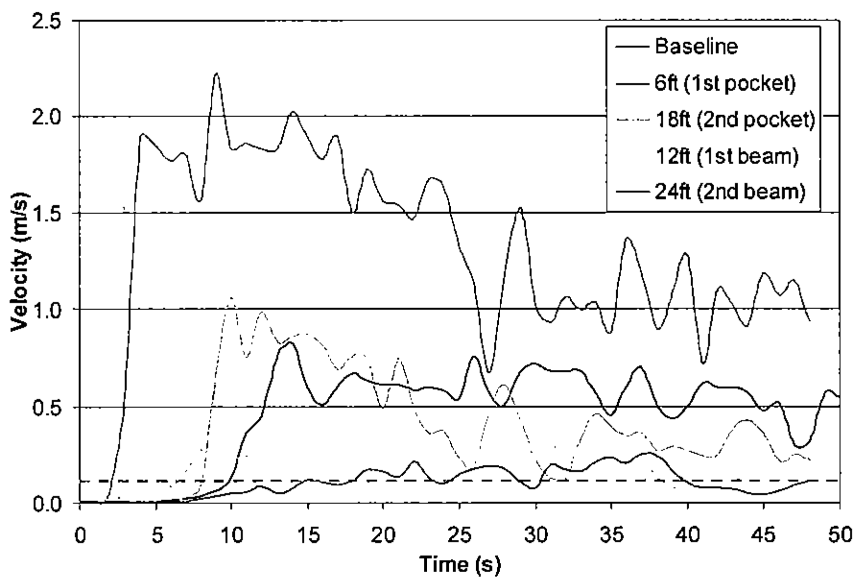


Figure 38 Scenario H12D12P06 results, velocity, 100 kW constant fire

Observation: Velocities at all investigated points exceed the critical value (0.15 m/s). However velocities only at the points in the 1st and 2nd pockets and underside the 1st beam reach the critical level earlier than the baseline.

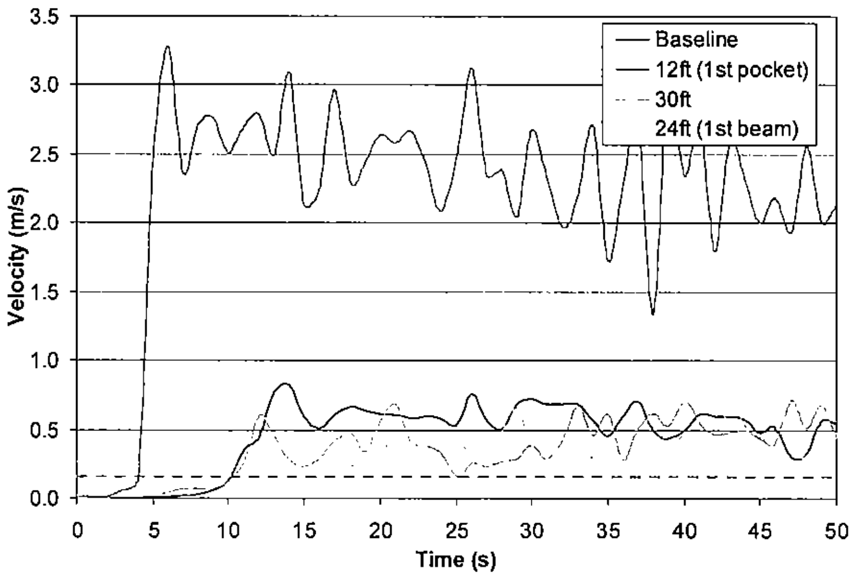


Figure 39 Scenario H12D12P12 results, velocity, 100 kW constant fire

Observation: Velocity at all investigated points exceed the critical value (0.15 m/s) and reach the critical level earlier than or equivalent to the baseline.

Performance Comparisons

Tables below summarize the time-shift differences for the small room and large room scenarios. In Tables 4 and 5 the values represent the time difference between the response of the benchmark detector and the postulated spot smoke detector locations for the room scenarios. This time difference is generally evaluated at the time that the optical density at the detectors first reaches a measurement of 0.11 OD/m. Depending on the parameters of any given scenario the postulated detectors may achieve the optical density measurement of 0.11 OD/m either several seconds before or after the benchmark detector achieves an optical density measurement of 0.11 OD/m. This comparison is important as it provides a relative sense of whether the postulated detectors are operating in a time frame (approximately ± 60 sec) comparable to the benchmark detector or if the postulate detectors performance is significant minutes slower or faster to respond than the benchmark detector.

Notes "A" and "B" are provided in the Tables to clarify those situations where the postulated detectors did not attain an optical density measurement of 0.11 OD/m (the selected value for comparison purposes), but did attain an optical density measurement that is in the range of detector activation (as selected for this study.) Note "C" describes one unique scenario for which an optical density measurement in the range of detector activation was not achieved. This result was attributable to modeling geometry used for the 12 ft. x 12 ft. scenarios (see Figures 11a and 11b.) In these 12 ft. x 12 ft. scenarios the detector located at the 30-ft. grid spacing position was not surrounded by deep beams on all sides and, therefore, was not subject to the reservoir effect otherwise created by surrounding beams.

Table 4: Performance Comparison – Room Part 1 (Small Room with Constant Fires), Values Noted are Time Differences in Seconds

Scenario	Ceiling height (ft)	Beam Depth (in)	Pocket Size (ft x ft)	1st Pocket		2nd Pocket		3rd Pocket		30 ft Grid - Detectors at 30 ft spacing (21 ft to plume center)
				In Pocket	Under Beam	In Pocket	Under Beam	In Pocket	Under Beam	IP = in pocket UB = under beam
C01H12D12P03	12	12	3x3	9	5	2	1	-3	-3	NOTE A
C01H12D12P06	12	12	6x6	8	5	2	-3	NA	NA	NOTE B
C01H12D12P12	12	12	12x12	6	-4	NA	NA	NA	NA	-7 IP
C01H12D24P03	12	24	3x3	8	5	3	1	-10	-11	NOTE A
C01H12D24P06	12	24	6x6	8	5	-19	-30	NA	NA	NOTE A
C01H12D24P12	12	24	12x12	5	-2	NA	NA	NA	NA	NOTE C
C02H18D12P03	18	12	3x3	8	4	5	4	0	0	-16 UB
C02H18D12P06	18	12	6x6	7	2	1	-5	NA	NA	-39 IP
C02H18D12P12	18	12	12x12	6	-1	NA	NA	NA	NA	-3 IP
C02H18D24P03	18	24	3x3	7	5	2	5	-5	-2	-22 UB
C02H18D24P06	18	24	6x6	7	2	0	-12	NA	NA	-23 IP
C02H18D24P12	18	24	12x12	5	-4	NA	NA	NA	NA	-7 IP
C03H24D12P03	24	12	3x3	7	6	4	4	0	1	-12 UB
C03H24D12P06	24	12	6x6	7	-3	-12	-15	NA	NA	-6 IP
C03H24D12P12	24	12	12x12	5	-5	NA	NA	NA	NA	-20 IP
C03H24D24P03	24	24	3x3	7	6	2	4	-3	-2	-20 UB
C03H24D24P06	24	24	6x6	7	-13	-12	-18	NA	NA	NOTE B
C03H24D24P12	24	24	12x12	5	-8	NA	NA	NA	NA	-13 IP

NOTE A. Detector positioned on 30 ft. grid spacing reaches lower range of optical density measurements for which detection alarm/actuation would be expected at approximately 30-45 seconds after fire initiation. In comparison the baseline detector shows higher optical density measurement than detector at the 30 ft. grid position.

NOTE B. Detector positioned on 30 ft. grid spacing reaches mid range of optical density measurements for which detection alarm/actuation would be expected at approximately 30-35 seconds after fire initiation. In comparison the baseline detector shows higher optical density measurement than detector at the 30 ft. grid position.

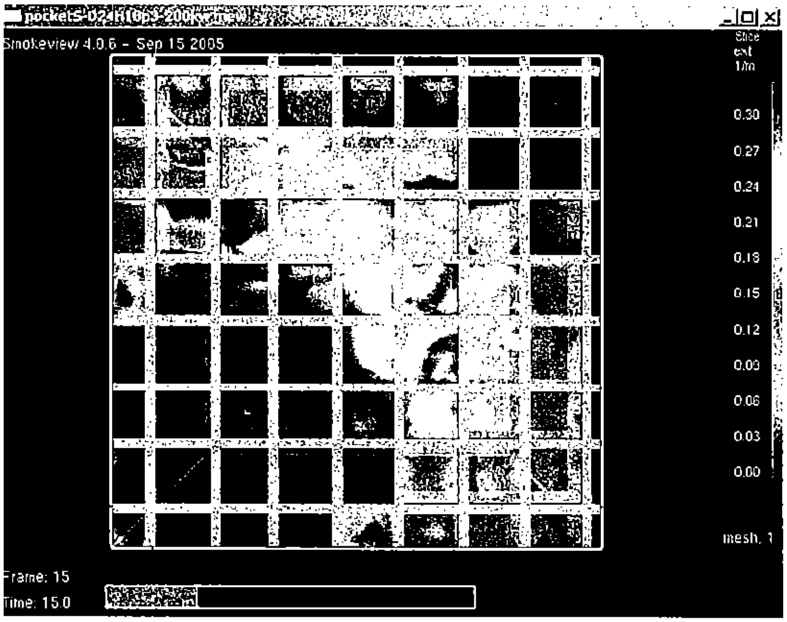
NOTE C. Detector positioned on 30 ft. grid spacing does not reach lower range of optical density measurements for which detection alarm/actuation would be expected. In the 12 ft. x 12 ft. scenarios the detector located at the 30-ft. grid spacing position was not surrounded by deep beams on all sides and, therefore, was not subject to the reservoir effect otherwise created by surrounding beams.

Table 5: Performance Comparison – Room Part 2 (Large Rooms with Constant Fires), Values Noted are Time Differences in Seconds

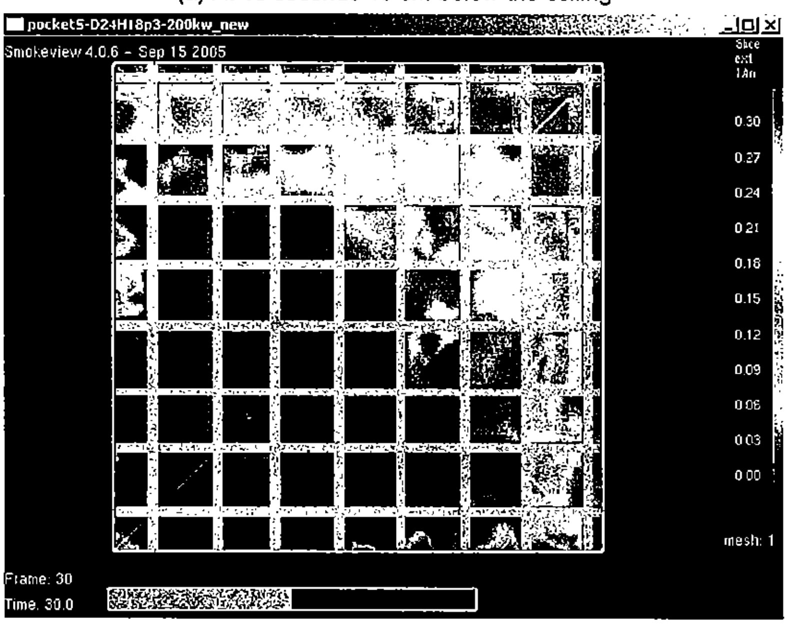
Scenario	Ceiling height (ft)	Beam Depth (in)	Pocket Size (ft x ft)	1st Pocket		2nd Pocket		3rd Pocket		30-ft Grid - Detectors at 30 ft spacing (21 ft to plume center)
				In Pocket	Under Beam	In Pocket	Under Beam	In Pocket	Under Beam	IP = in pocket UB = under beam
C06H36D12P03	36	12	3x3	13	10	13	9	10	8	-5 UB
C06H36D12P06	36	12	6x6	13	10	-4	-9	NA	NA	-10 IP
C06H36D12P12	36	12	12x12	12	10	NA	NA	NA	NA	-20 IP

Visual Observation of the Smoke Distribution

Smoke distributions in the beam pocket area are presented for various pocket sizes from different angles, in Figure 40 to Figure 42. Since the smoke propagating paths (from the fire source to the detection point) in the room geometries are not along the axes, it is not possible to show these paths in a slice image in FDS. Therefore several slice images are used to illustrate the smoke distribution in the pocket in elevation views from Figure 43 to Figure 46.

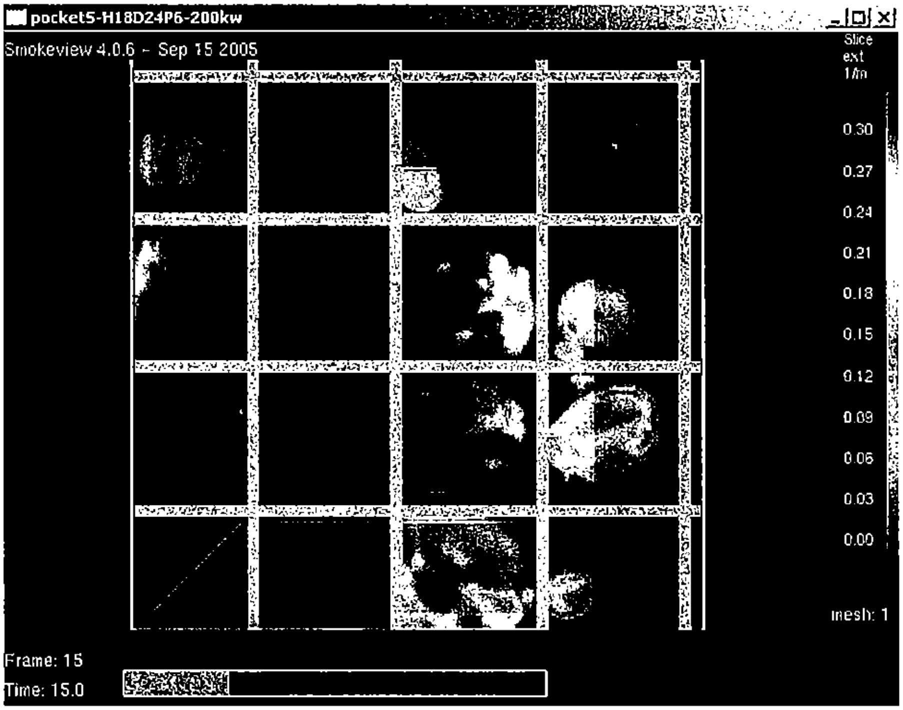


(a) At 15 seconds 10 cm below the ceiling

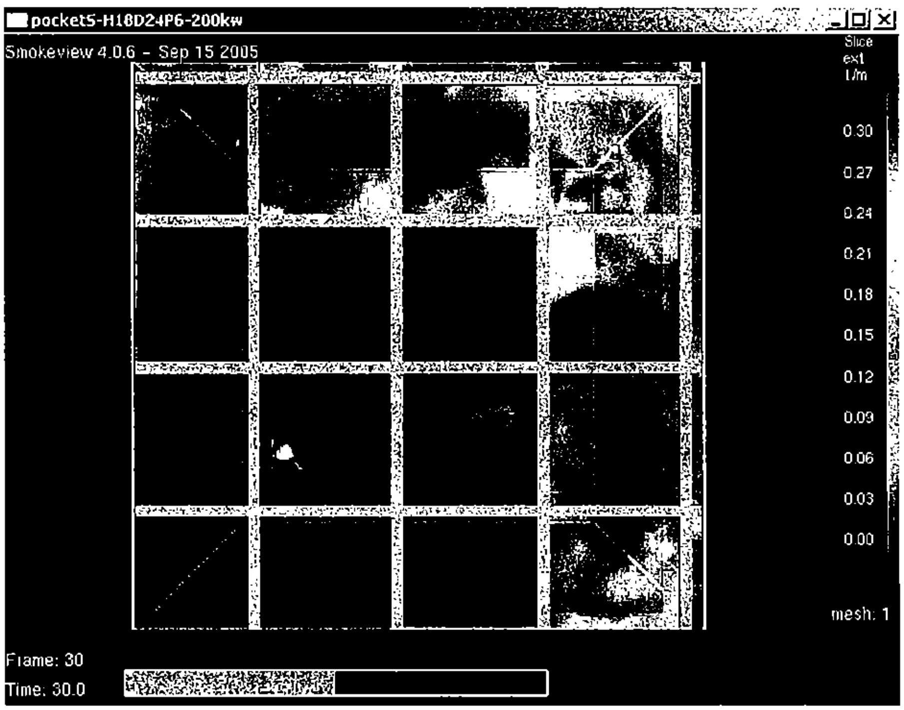


(b) At 30 seconds 10 cm below the ceiling

Figure 40 Top view of OD distribution, H18D24P3

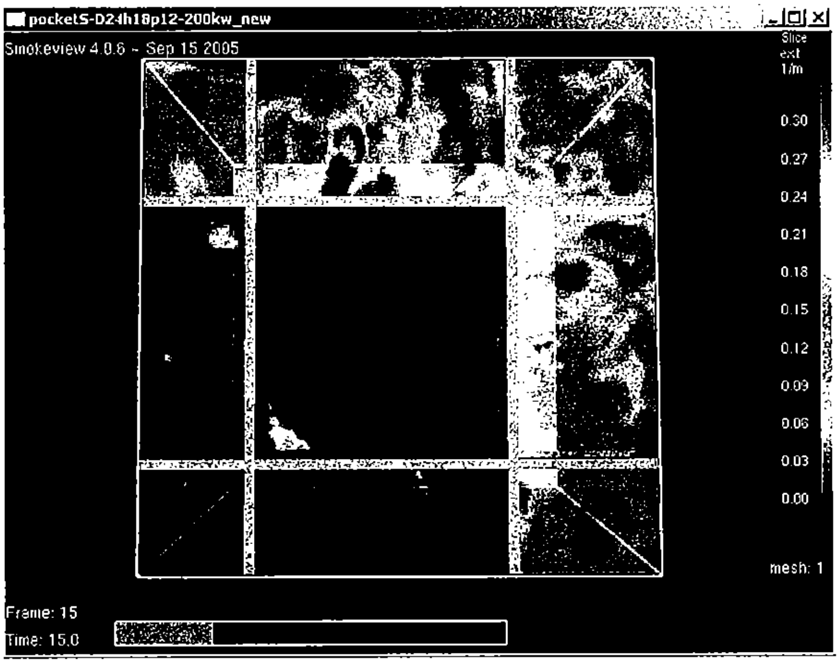


(a) At 15 seconds 10 cm below the ceiling

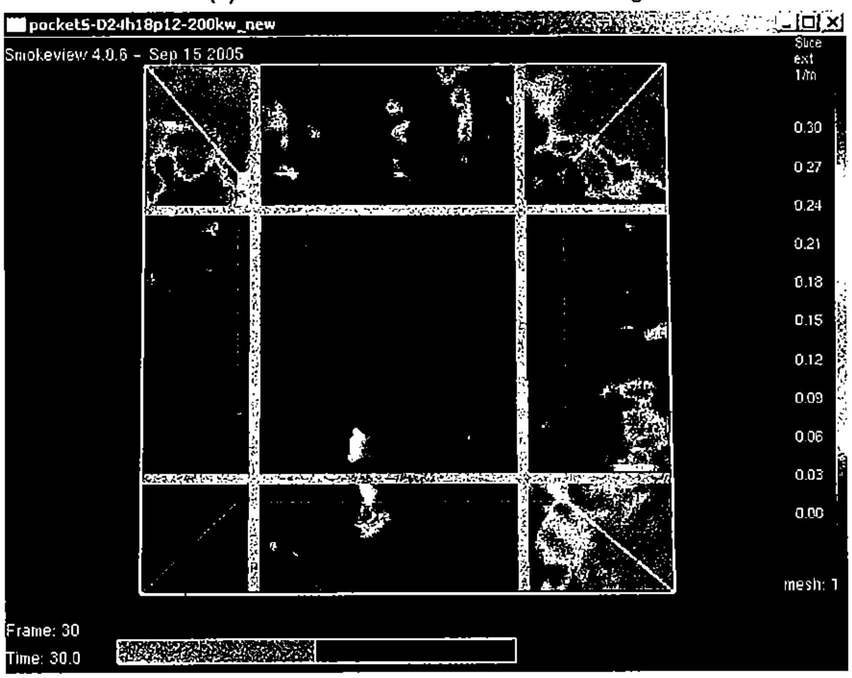


(b) At 30 seconds 10 cm below the ceiling

Figure 41 Top view of OD distribution, H18D24P6



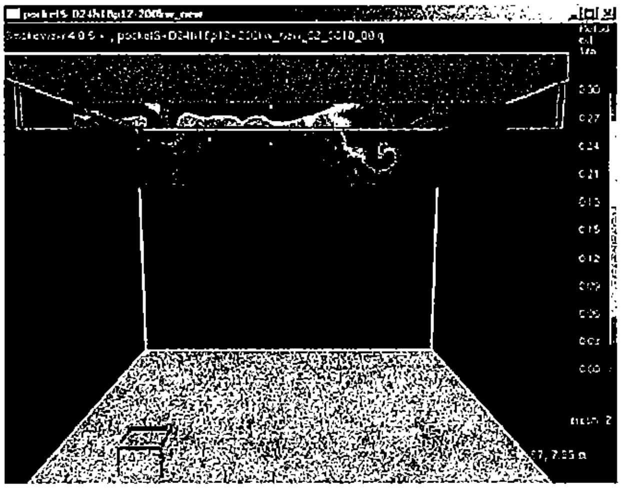
(a) At 15 seconds 10 cm below the ceiling



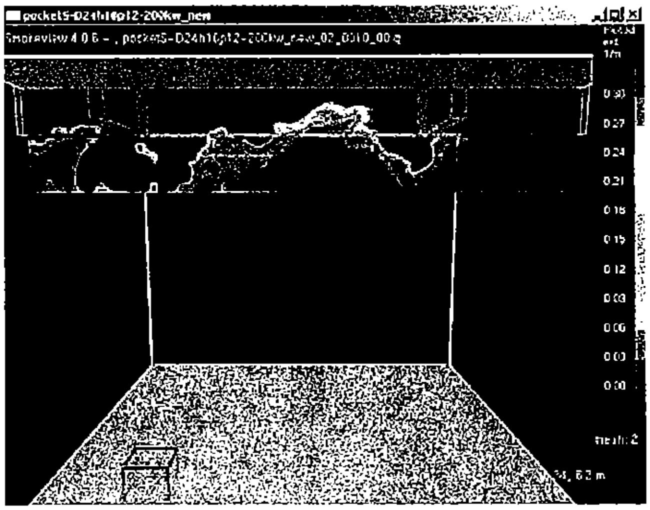
(b) At 30 seconds 10 cm below the ceiling

Figure 42 Top view of OD distribution, H18D24P12

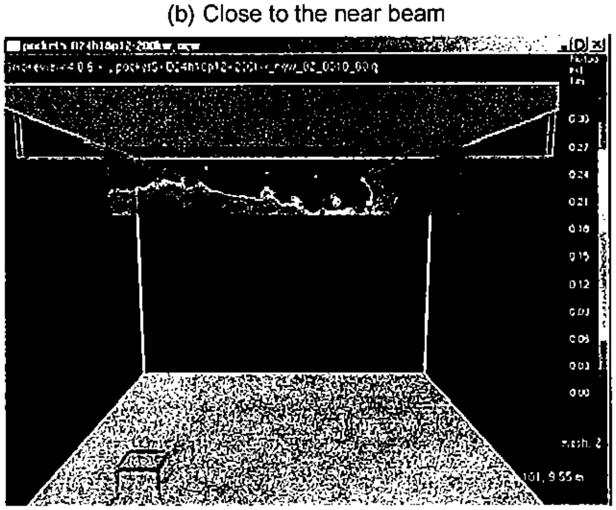
From Figure 40 to Figure 42, it is noticed that some small stagnant zones were found at the investigated height (10 cm below the ceiling). However these stagnant zones are transient and the areas fill with smoke seconds after pocket filling begins. Due to the rapid smoke filling there is no significant impact on the postulated detector performance.



(a) At the centerline of the pocket

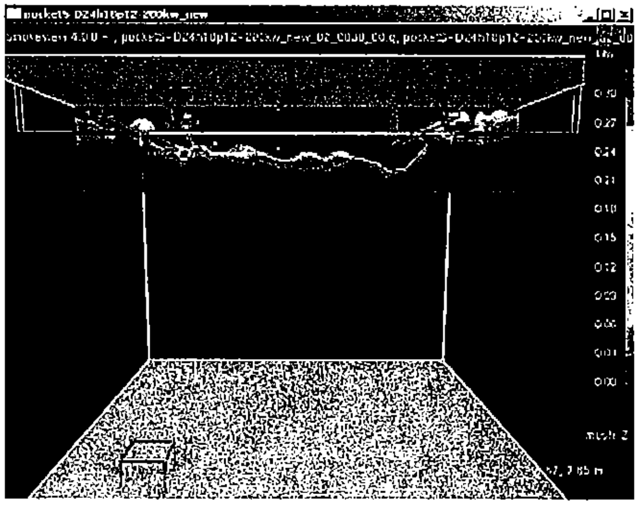


(b) Close to the near beam

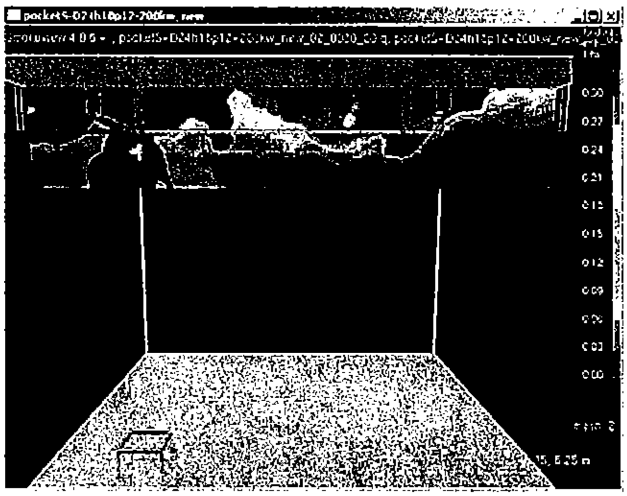


(b) Close to the far beam

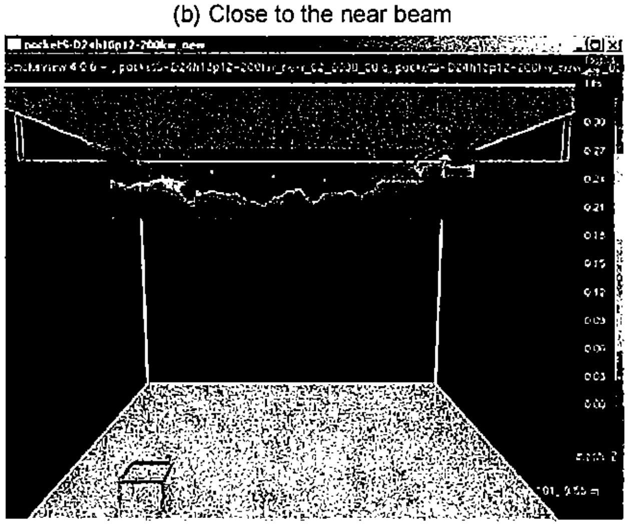
Figure 43 Elevation view of OD distribution at 10 seconds, H18D24P12



(a) At the centerline of the pocket

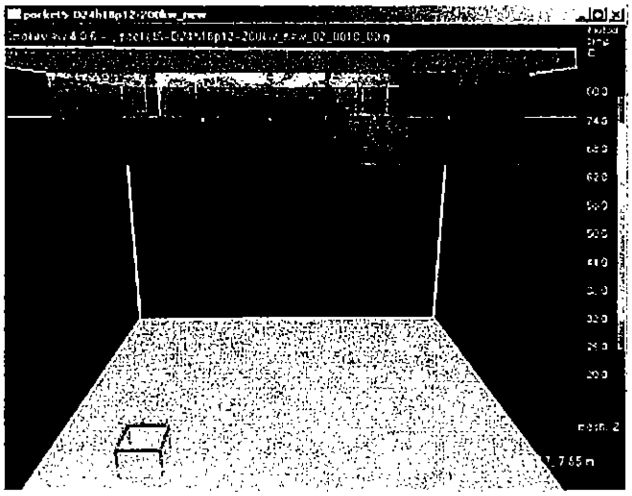


(b) Close to the near beam

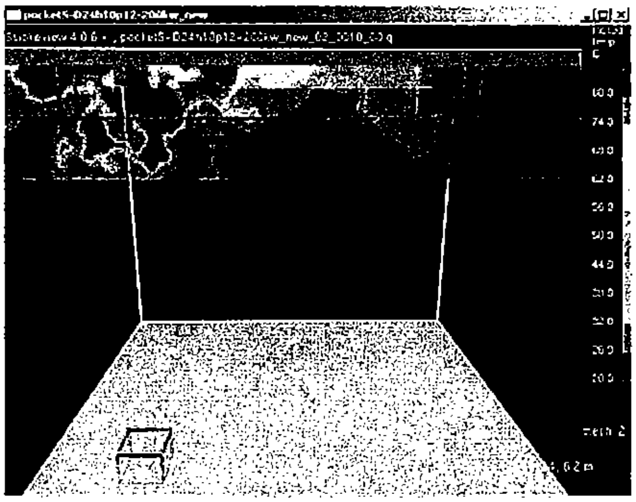


(c) Close to the far beam

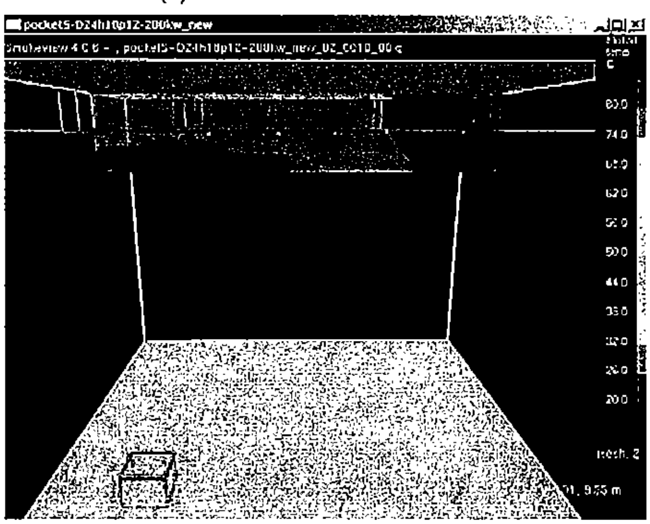
Figure 44 Elevation view of OD distribution at 30 seconds, H18D24P12



(a) At the centerline of the pocket

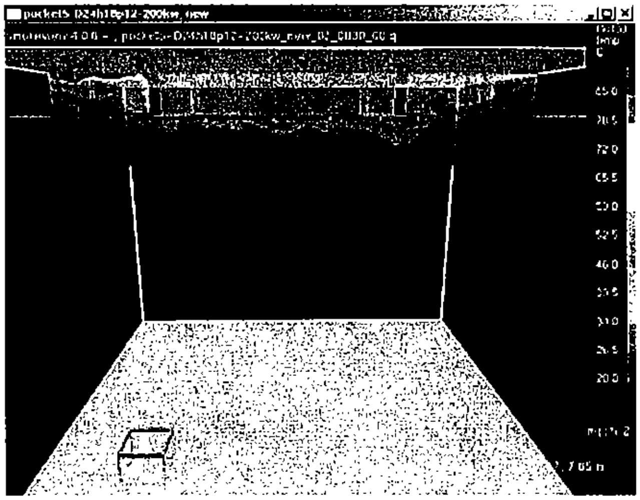


(b) Close to the near beam

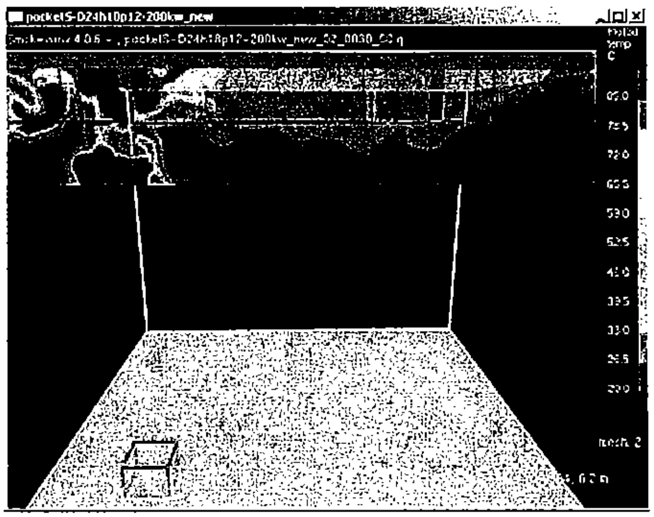


(c) Close to the far beam

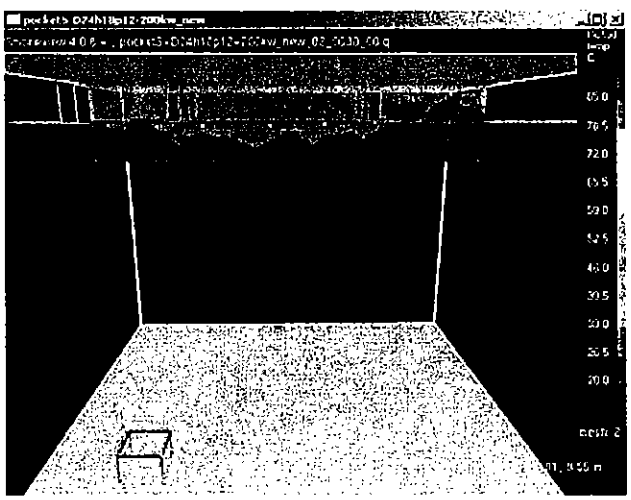
Figure 45 Elevation view of temperature distribution at 10 seconds, H18D24P12



(a) At the centerline of the pocket



(b) Close to the near beam



(c) Close to the far beam

Figure 46 - Elevation view of temperature distribution at 30 seconds, H18D24P12

From the elevation views, it is noted that there are some transient stagnant zones around the edge area of the pocket when smoke first spills around the beam. Close to the beams ((b) and (c)) there are no significant differences between the optical density at locations under the beams and at the ceiling height in the pocket. As the smoke propagates away from the fire source (from (a) to (c)), the distribution of temperature becomes well mixed and the difference between points under the beams and at the ceiling height in the pocket is insignificant.

ROOM SCENARIOS – CONCLUSIONS & NFPA 72 RECOMMENDATION

Beam pockets on a room ceiling have traditionally been viewed as an impediment to smoke transport, which seems to intuitively suggest a significant delay in the operation of ceiling spot smoke detectors. This is in contrast to the case of a ceiling jet spreading out radially below an unconfined smooth ceiling (the baseline) surface. In this study the "intuitive" delay traditionally anticipated is shown to be a false expectation. Review of the data and the visualized smoke flows show that the reservoir effect of the beam pocket geometry is beneficial to detector operation and accounts for spot smoke detector performance that is comparable to spot smoke detectors, located at 30-ft. spacing on a smooth ceiling.

The scenarios examined to date confirm the following for constant 100 kW - 300 kW flaming fires and fast growth t^2 fires.

1. Reservoir Effect

The geometry and reservoir effect is a significant factor that contributes to the development located on the ceiling in beam pocket areas or at the bottom of beams as smoke collected of velocity, temperature and smoke obscuration conditions at smoke detectors in the reservoir volume spills into adjacent pockets. The waffle or pan type ceilings created by deep beams or joists although retarding the initial flow of smoke results in increased optical density, temperature rise and gas velocities comparable to spot smoke detectors at 9.1m (30 ft.) spacing on an unconfined smooth ceiling surface.

2. NFPA 72 (2002 Ed.) Provisions for Spot Detectors in Every Beam Pocket

Where ceiling height exceeds 12 feet (3.66 meters) or beams are relatively deep (>one foot or 300 mm), the provisions of NFPA 72, 2002 and prior editions requires that spot-type smoke detectors be located in every beam pocket. The results of this study demonstrate that there is no technical basis for this requirement and that spot smoke detectors located on alternate spacing's will provide comparable or better performance than the baseline case (i.e. spot smoke detectors located 30-ft. apart on a smooth level ceiling.)

3. Spacing of Spot Smoke Detectors – Ceilings with Beam Pockets:

The data reviewed in this analysis indicates for ceilings up to 24 feet in height with 24-inch deep-beam pocket configurations, that the deep beams do not significantly delay spot smoke detector response. This means that for these conditions, spot smoke detectors can be effectively used in rooms with deep beams with a spacing of 30 feet, as is permitted for smooth ceilings.

4. Increasing Ceiling Heights:

As ceiling height increases, the fire size threshold needed for activation of the baseline spot smoke detector must increase. With an increased fire size, the smoke detectors on a beam-pocketed ceiling will be comparable to the performance result for the baseline detector at the same ceiling height. A comparable performance is generally judged to be when the conditions of optical density at postulated detector locations occur in a time frame that is approximately ± 60 seconds of those same measurements being achieved by the baseline detector. Tables 1 is a summary comparison of the time difference between postulated detectors and the baseline determined when optical density reaches 0.11 OD/m.

5. **Placement Under Beams or on Ceiling Between Beams:**

Based on all the beam dimensions evaluated (12, 24, 48 inches), there is no significant difference in temperature rise or optical density conditions for smoke detectors mounted on the bottom of the beam or in the beam pocket at approximately equal distances from the fire. Where deep beams interrupt the ceiling surface in a room, mounting the detector on the ceiling between beams or the bottom of the beam is acceptable, either location providing comparable response to alarm.

6. **Beam Sidewall Mount:**

The concern of NFPA 72 for keeping smoke detector locations 12 inches below or away from a ceiling-beam corner is unsubstantiated. No stagnant zone or locations are observed that would preclude smoke detector alarm. Temperature and smoke optical density are relatively uniform and well-mixed throughout the volume of the beam pocket within seconds after the initial ceiling jet passes. It is noted that while the modeling results show no stagnant zones, it is not suggested that spot detectors can be installed in close proximity or contact to the wall or ceiling surface. Such close mounting may impact the airflow characteristics into and around the detector housing which could have a negative impact on smoke flow into the detector sensing chambers. Such airflow effects have not been evaluated by the modeling conducted in this study.

7. **Recommendation for NFPA 72:**

Based on the findings of this study it is recommended to add the following new text to NFPA 72, 5.7.3.2.4(B) addressing the installation of spot smoke detectors on waffle or pan type ceilings.

(New #)* *Waffle or pan type ceilings with beams or solid joists no greater than 600 mm. (24 in.) deep and no greater than (12 ft.) center to center spacing.*

(a) Smoke detectors for waffle and pan ceilings shall be permitted to use the spacing permitted to use the smooth ceiling spacing including those requirements permitted for irregular areas of Section 5.6.5.1.2.

(b)Spot type smoke detectors shall be permitted to be located on the ceiling or on the bottom of beams.

A.5.7.3.2.4.(B)(New #) *The geometry and reservoir effect is a significant factor that contributes to the development of velocity, temperature and smoke obscuration conditions at smoke detectors located on the ceiling in beam pocket areas or at the bottom of beams as smoke collected in the reservoir volume spills into adjacent pockets. The waffle or pan type ceilings created by beams or solid joists although retarding the initial flow of smoke results in increased optical density, temperature rise and gas velocities comparable to unconfined smooth ceilings.*

REFERENCES

Brozovski, E., "A Preliminary Approach to Siting Smoke Detectors Based on Design Fire Size and Detector Aerosol Entry Lag Time, Master of Science Thesis, Worcester Polytechnic Institute, Worcester, MA, 1991.

Cholin, J.M., and Marrion, C., "Performance Metrics for Fire Detection," *Fire Protection Engineering*, pp. 21-30, No. 11, Summer 2001.

Forney, G.P., Bukowski, R.W., and Davis, W.D., National Institute of Standards and Technology, International Fire Detection Research Project, Field Modeling: Effects of Flat Beamed Ceilings on Detector and Sprinkler Response; Technical Report Year 1, National Fire Protection Research Foundation, October 1993.

Forney, G.P., Bukowski, R.W., and Davis, W.D., National Institute of Standards and Technology, International Fire Detection Research Project, Field Modeling: Simulating the Effect of Sloped Beamed Ceiling on Detector and Sprinkler Response, Technical Report Year 2, National Fire Protection Research Foundation, October 1994.

Geiman, J.A., and Gottuk, D.T., "Alarm Thresholds for Smoke Detector Modeling," *Fire Safety Science – Proceedings of the 7th International Symposium*, June 16-21, 2002, Worcester, MA, International Association for Fire Safety Science, Boston, MA, Evans, D.D., Editor, 2003, pp. 197 – 208.

Geiman, J.A., "Evaluation of Smoke Detector Response Estimation Methods", Master of Science Thesis, University of Maryland, College Park, MD, 2003.

Gottuk, D.T. and Geiman, J.A., "Estimating Smoke Detector Response", 2005 National Fire Protection Association Annual Meeting Presentation, Hughes Associates, Inc., 2005.

Gottuk, D.T., Harrison, M.A., Rose-Pehrsson, S.L., Owrutsky, J.C., Williams, F.W., and Farley, J.P., "Shipboard Evaluation of Fire Detection Technologies for Volume Sensor Development," Naval Research Laboratory, Memorandum Report, 6180-0282, 2003.

McGrattan, K.B., Fire Dynamics Simulator (Version 4) – Technical Reference Guide, NIST Special Publication 1018, September 2005.

McGrattan, K.B. and Forney, G.P., Fire Dynamics Simulator (Version 4) User's Guide, NIST Special Publication 1019, September 2005.

McGrattan, K.B. and Forney, G.P., User's Guide for Smokeview Version 4 – A Tool for Visualizing Fire Dynamics Simulation Data, NIST Special Publication 1017, August 2004.

NFPA 72, *National Fire Alarm Code*, National Fire Protection Association, Quincy, MA, 2002.

Schifiliti, R.P., Meacham, B.J., and Custer, R.L.P., "Design of Detection Systems," *SFPE Handbook of Fire Protection Engineering*, Chapter 4-1, 3rd Edition, DiNenno, P.J., Ed., National Fire Protection Association, Quincy, MA, 2002.

Su, J.Z., Crampton, G.P., Carpenter, D.W., McCartney, C., and Leroux, P., "KEMANO FIRE STUDIES – PART 1: Response of Residential Smoke Alarms," Research Report 108, National Research Council of Canada, Ottawa, Canada, April 2003.

UL 217, "Standard for Single and Multiple Station Smoke Alarms," Fifth Edition dated February 21, 1997 with revisions through October 12, 2001, Underwriters Laboratories Inc., Northbrook, IL, 2001.

UL 268, "Standard for Smoke Detectors for Fire Protective Signaling Systems," Fourth Edition dated December 30, 1996 with revisions through October 22, 2003, Underwriters Laboratories Inc., Northbrook, IL, 2003.