Smoke Detector Spacing for High Ceiling Spaces – Phase II

Final Report by:

Mishuk Datta, PE
Jensen Hughes
Baltimore, MD

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Foreword

*NFPA 72. National Fire Alarm and Signaling Code,* does not address spacing consideration for smoke detection based on ceiling heights. However, there is a table that allows for reduction of spacing for heat detection. There has been confusion in design and code enforcement on what to do when smoke detectors are installed on ceilings higher than 10 ft. A previous literature review and gap analysis study on smoke detectors in high ceiling spaces was published by the Research Foundation in 2017. The outcomes of this study indicated that there was limited context and significant knowledge gaps that preclude the formulation of scientifically justified prescriptive requirements regarding smoke detector spacing relative to ceiling height. The 2017 study outlined a path forward to better characterize smoke detector spacing in high ceilings, such as by establishing a performance metric for smoke detectors that can be applied to high ceilings.

Since the fire protection industry needed additional information on the impact of ceiling height and detector spacing on smoke detection performance, a Phase II study was initiated. This Phase II study aimed to develop guidance for the installation of smoke detectors on ceilings over 10 ft (3 m) that can be used as the technical basis for consideration of changes to applicable codes and standards. The project outcomes recommend providing prescriptive guidance up to 40 ft ceiling heights, and to encourage performance-based designs for ceiling heights exceeding 40 ft. For ceilings between 10 and 40 ft, equations to determine appropriate spacing based on the ceiling height has been proposed for spot type and beam type detectors.

The Fire Protection Research Foundation expresses gratitude to the report author Mishuk Datta, who is with Jensen Hughes located in Baltimore, MD. The Research Foundation appreciates the guidance provided by the Project Technical Panelists, the funding provided by the project sponsors, and all others that contributed to this research effort.

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About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.
Keywords: smoke detectors, spot-type, ionization detectors, photoelectric detectors, beam detectors, high ceilings, spacing, NFPA 72

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Project Manager: Victoria Hutchison and Jacqueline Wilmot, PE
Project Technical Panel

Robert Acosta, Arup (NY, USA)
Alhassan Kamel Taha Ahmed, WSP – Middle East (Riyad, Saudi Arabia)
Patrick Bakaj, NFPA (MA, USA)
Shane Clary, Bay Alarm (CA, USA)
Tom Cleary, NIST (MD, USA)
LJ Dallaire, Amazon Web Services (DC, USA)
Chad Duffy, NFPA (MA, USA)
Sebastian Festag, Hekatron (Sulzburg, Germany)
Mark Hopkins, TERP Consulting (MD, USA)
William Kuffner, WSP (Ottawa, Canada)
Gerry Landmesser, Microm Group (Ontario, Canada)
Fred Leber, AML-Encore (Ontario, Canada)
Shawn Mahoney, NFPA (MA, USA)
Dave Mills, UL Solutions (IL, USA)
Dan Michael, UL Solutions (alternative)
Lynn Nielson, City of Henderson (NV, USA)
Stephen Olenick, CSE (MD, USA)
Thorsten Schultze, University of Duisburg-Essen (Duisburg, Germany)
Jason Webb, Potter (MO, USA)
Project Sponsors

Automatic Fire Alarm Association (AFAA)
Canadian Fire Alarm Association (CFAA)
FireRay (FFE)
Honeywell
National Electrical Manufacturers Association (NEMA)
International Association of Fire Chief’s (IAFC) Fire and Life Safety Section (FLSS)
Siemens
Wagner

Sponsor Representatives

Automatic Fire Alarm Association (AFAA)
   — Dave Newhouse, Gentex
Canadian Fire Alarm Association (CFAA)
   — Suzanne Alfano, CFAA
FireRay (FFE)
   — Allen Brier and Abhishek Subramanian, FireRay
Honeywell
   — Scott Lang and Richard Roberts, Honeywell
National Electrical Manufacturers Association (NEMA)
   — Dave Newhouse, Gentex
International Association of Fire Chief’s (IAFC) Fire and Life Safety Section (FLSS)
   — Larry Cocco, City of Toronto
Siemens
   — Maria Marks and Wayne Aho, Siemens
Wagner
   — Frank Siedler and Chris Wesner, Wagner
FINAL REPORT

SMOKE DETECTOR SPACING IN HIGH CEILING SPACES – PHASE II

Fire Protection Research Foundation Project

PREPARED FOR

Fire Protection Research Foundation
1 Batterymarch Park
Quincy, MA 02169-7471

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PREPARED BY

Mishuk Datta, PE
3610 Commerce Drive, Suite 817
Baltimore, MD 21227

mdatta@jensenhughes.com
+1 443-258-9820

jensenhughes.com
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Executive Summary

Smoke Detector Spacing in High Ceiling Spaces – Phase II is a research project funded by the Fire Protection Research Foundation (FPRF). The goal of this project was to develop guidance for the installation of smoke detectors on level smooth ceilings over 10-ft (3m) that can be used as the technical basis for any changes to codes and standards. The scope of work comprised for total six tasks. Task 1, 2 and 3 comprised for literature review, development of taxonomy and gap analysis. Task 4 consisted of model verification and validation. Task 5 and 6 comprised of modeling and development of recommendations.

LITERATURE REVIEW

Jensen Hughes reviewed the current regulatory requirements of smoke detection in level smooth ceiling spaces, applicable to interior building spaces with ceiling heights more than 10 ft (3 m) in the US, Canada, UK, Germany, Netherlands, Belgium, Italy, Middle East, and Australia. The codes and standards that were reviewed include the following –

+ Fire Detection and Fire Alarm Systems for Buildings (BS 5839-1:2017), used in UK and Hong Kong
+ VdS-Richtlinien für automatische Brandmeldeanlagen Planung und Einbau (VdS 2095: 2022), used in Germany.
+ Automatic fire detection and fire alarm systems - Design, installation, and operation (UNI 9795, 2021 edition) used in Italy.

A nominal 30 ft (9.15 m) spacing between the spot type smoke detectors has been established as a primary requirement in all the codes and standards reviewed. In NFPA 72, a performance-based analysis is required for smoke detection design that is expected to be influenced by stratification and mechanical ventilation. The code is silent on a prescriptive ceiling height requirement for applying the performance-based approach. Apart from NFPA 72, all the other codes specify maximum level smooth ceiling height for the application of a prescriptive approach. Except UK and Canada, a maximum level smooth ceiling height of 39.36 ft (12 m) is specified in the codes for applying the nominal 30 ft spacing requirement. In the UK the limit is set to 34.4 ft (10.5 m). In Canada, the prescriptive approach of the nominal 30 ft spot type smoke detector spacing application is limited to a 11.8 ft (3.6 m) level smooth ceiling height. Beyond these prescriptive limits a performance-based approach is
necessitated. Even though the European and Australian codes do not directly provide a reference for the maximum ceiling height threshold, studies were found to provide justification for the nominal 30 ft spot type smoke detector spacing even in high ceiling spaces, such as 49 ft (15 m) and 72 ft (22.2 m) (Gott, et al. 1997). UL 268 and CAN/ULC S529, 2016 edition have been reviewed to obtain standardized fire test data and sensitivity thresholds.

Input data for the variables that would influence the spot type smoke detector performance were documented in numerous literatures (Heskestad 2016) (Newman, Yee and Su 2016) (Schifiliti, Custer and Meacham 2016) (Milke 2016). The identified variables are grouped into three broad categories.

1. Aerosol specific (fuel composition and combustion)
2. Transport specific (ambient temperature profile, ambient air flow, ceiling height and material and soot loss due to deposition and agglomeration)
3. Detector specific (detector location, sensitivity, and entry resistance)

Aerosol specific variables are related to fuel and combustion process. Rate of smoke production is dependent on soot yield and rate of combustion. Soot yields for a variety of fuels are listed (Khan, Tewarson and Chaos 2016). Rate of combustion of flaming fires are quantified based on the heat release rates they give off. Heat release rates of standardized t² fires can be obtained based on how fast 1MW is reached (National Fire Alarm and Signaling Code (NFPA 72) 2022). Ranges of heat release rates per unit area and heats of combustion for smoldering and flaming fires are reported (Rein 2016). The range of measured temperatures on smoldering surfaces is also available (Rein 2016).

Variables impacting smoke transport to the detector include the ceiling height, ambient temperature and air flow profile, convective heat transfer to the ceiling and soot loss due to deposition and agglomeration. Thermo-physical properties of typical ceiling materials are available in the literature and can be used to account for heat loss due to convection ( SFPE Handbook of Fire Protection Engineering 2016). Soot loss due to deposition and agglomeration has been studied extensively (Newman, Yee and Su 2016). Maximum and minimum smoke particle diameters necessary to calculate agglomeration are available in these papers (Newman, Yee and Su 2016).

Detector specific variables that influence detector performance are detector location, sensitivity, and aerodynamics characteristics. Characteristic lengths used to characterize entry resistance profile of typical smoke detectors are reported (Schifiliti, Custer and Meacham 2016).

The following gaps were identified based on the findings from literature review.

1. **Performance Criteria.** An established performance criterion to evaluate smoke detector performance for varying spacing and ceiling height is not available.
2. **Ambient temperature profile.** Impact of ambient temperature change with height on smoke detector performance needs to be evaluated.
3. **Smoke Detector Spacing.** Prescriptive guidance for smoke detector spacing in high ceiling spaces is not available.
4. **Ceiling height.** There is no ceiling height limit for use of nominal 30 ft spacing in NFPA 72, as the Canadian, European, and Australian codes have. Also, there are disagreements between Canadian (3.6 m), UK (10.5 m), European and Australian (12 m) requirements for smoke detection in high ceiling spaces.
5. **Soot Agglomeration Model**: A validation of the FDS soot deposition model is not currently available. The use of this model to calculate soot loss due to agglomeration, plume impingement and thermophoresis is to be decided.

**MODEL VALIDATION AND VERIFICATION**

Task 4 consisted of the model verification and validation work. Verification was used as a process to check the correctness of the stratification prediction. Validation was used to determine the appropriateness of the governing equations in the FDS model of the physical phenomena of detection. Validation involved comparing model results with experimental measurements. Test data needed for validation of the quantities were collected from the tests performed by Mealy et. al. used to develop smoke detector spacing requirements for complex beamed and sloped ceilings (Mealy, Floyd and Gottuk 2008). Differences were observed in ceiling jet temperatures, velocities, optical densities, and detector activation times. These differences could not be explained in terms of uncertainty in the measurements and are attributed to the assumptions and simplifications of the model.

Previous studies found that FDS overpredicted soot concentration because soot loss due to deposition during experiments were not accurately modeled in FDS (Mealy, Floyd and Gottuk 2008). In this validation the model was run with and without the soot deposition routine, which was not available during the previous studies. It was observed that the model constantly overpredicted the optical density at the plume centerline, even with the deposition routine. Additionally, model bias or overprediction increased with the ceiling height in all cases. Also, the optical density prediction did not change between soot deposition model runs and non-soot deposition model runs. This indicates that there are other parameters outside the soot deposition routines that are contributing to reducing smoke concentration in high ceiling areas. If deposition was the only/primary factor to influence the model prediction, the biases would have decreased with higher ceiling height as the temperature difference and deposition velocity decreased. One explanation is that with additional time and height of the plume, the mass extinction coefficient of the smoke changes. This transient characteristic of the mass extinction coefficient is not currently captured in FDS.

FDS model bias of optical density is a significant limitation in this study. The general trend observed was that FDS underpredicted the optical density in near field region and over predicted in the far field region. And so optical density would be higher than prediction in the low ceiling heights and lower than prediction as we increase the ceiling height. The other unknown is if optical density model bias would change with increasing fire size. It could be that with increase in fire size the optical density bias will be more uniform throughout. But we don't know that. Thermal predictions including prediction of stratification had bias close to 1, which is consistent with numerous previously performed validation for plume and ceiling jet temperatures.

**MODELING AND ANALYSIS**

To develop smoke detector design guidance for high ceiling spaces an equivalency approach was taken, where a 30 ft (9.1 m) spacing for spot type smoke detector and 60 ft spacing for projected beam detector was considered acceptable for a 10 ft (3 m) high ceiling space. Optical density and total obscuration predictions by FDS for selected smoke detector spacing and ceiling heights up to 60 ft (18 m) are then compared against the prediction made at device locations accepted for a 10 ft (3m) ceiling height scenario. Device locations predicting equal or higher quantities of smoke optical density were then considered as acceptable locations. A slow-growth t-squared fire scenario with growth rate factor of 0.00293 kW/s² was evaluated. For 10 ft (3 m) ceiling height, a threshold optical density of 0.215 m⁻¹ was achieved at 300 seconds (260 kW fire size).
Beam detector activation was considered at obscuration threshold of 90%. This corresponds to a uniform optical density of 0.055 m$^{-1}$ throughout the length of the beam, which for this study in 60 ft (18.3 m). Compared to the spot detector activation density, the threshold for beam detector is much lower and so it is expected to be activated in shorter time. For the 10 ft ceiling scenario, total obscuration threshold of 90% was achieved at 145 seconds (60 kW fire size).

Detection performance was found to reduce with ceiling height. To maintain the same detection time ceiling mounted spot type devices were required to reduce spacing with increase in ceiling height. The maximum spacing necessary to achieve detection time of 300 seconds or less for ceiling heights higher than 10 ft (3 m) and up to 40 ft (12 m) can be expressed using the following equation –

$$x = \frac{70 - y}{2}$$

Where, $x$ = spot type detector spacing (ft)
$Y$ = ceiling height (ft)

To maintain same detection time, beam detector spacing had to be reduced with ceiling height. The spacing needed to maintain 145 seconds detection time for ceiling heights higher than 20 ft up to 40 ft can be expressed using the following equation -

$$x = \frac{50 - y}{0.5}$$

Where, $x$ = beam spacing (ft)
$Y$ = ceiling height (ft)

Above 40 ft, the threshold optical density and obscuration could not be reached within the detection time derived from the 10 ft (3 m) ceiling height. However, the threshold optical density was eventually achieved for all the ceiling height scenarios even up to 60 ft within 510 seconds (750 kW). Beam detection threshold of 90% was achieved for all the ceiling heights within 415 seconds (500 kW).

Using the smoke detector spacing requirements prescribed and recommended in NFPA 72 (30 ft for spot type, 60 ft for beam) the threshold optical density and obscuration was eventually reached, but it took longer than 300 seconds or 145 seconds. For 60 ft ceiling height, using 30 ft spot type detector spacing threshold optical density was achieved at 510 s (760 kW fire size). 60 ft beam spacing achieved threshold obscuration within 315 seconds (290 kW). But in general, increase in ceiling height would allow smoke filling and reduced exposure of ceiling structural system to high plume temperature. Which is advantageous because this would increase available time to respond and evacuate occupants, and to protect the property. And so, an equivalent level of occupant protection and property protection may be achieved for higher ceiling spaces without reduction of spacing.

RECOMMENDATIONS

The following recommendations are established as based on the modeling performed,

+ Codes and standards specific to smoke detection system design must prescribe a goal or design objective that aligns with the goals and objectives found in the building, fire, and life safety codes.
Prescriptive code for smoke detection system should specify a design performance criterion that can be applied in device testing and listing application, modeling and performance-based design, and device installation and commissioning.

The enforceable part of the NFPA 72 should be revaluated to align with the manufacturer’s listing requirements and provide a consistent spacing guideline for the projected beam type smoke detectors.

Smoke detection design codes and standards should incorporate a quantifiable threshold to establish when a performance-based analysis is needed for smoke detector spacing determination. The study recommends a threshold of 30°F temperature difference (17°C temperature difference) or a ceiling height of 40 ft (12 m).

The study recommends following equation for spot type smoke detector spacing in ceilings higher than 10 ft (3 m) up to and including 40 ft (12 m).

\[ x = \frac{70 - y}{2} \]

Where, \( x \) = detector spacing (ft)
\( Y \) = ceiling height (ft)

The beam detector spacing is recommended to be reduced for ceiling height above 20 ft. (6 m) up to 40 ft (12 m) using the following equation -

\[ x = \frac{50 - y}{0.5} \]

Where, \( x \) = beam spacing (ft)
\( Y \) = ceiling height (ft)

Allowance should be provided for alternative smoke detector spacing if justified using performance-based analysis meeting the goals and objectives established by the codes and standards.

Continued improvement, testing and validation is needed to bring FDS model biases for optical density, detection time and obscuration quantities closer to 1.
1.0 High Ceiling Fire Risks

Below are a few typical applications for smoke detectors on high ceilings. In the very early days, most of these applications were handled with spot type smoke detectors (photoelectric and Ionization type). With today’s range of detection devices many of the below applications are handled with aspiration or beam detection due to possible difficulties and reaching detectors for annual service.

Typical High Ceiling Applications:

+ Atriums
+ Religious i.e., Churches
+ Shopping Centers
+ Power Stations
+ Electrical Rooms
+ Airports
+ Aircraft Hangers
+ Power Plants (Nuclear)
+ Warehouse
+ Battery Storage
+ Car Dealerships
+ Schools

To narrow down the type of buildings that have high ceiling spaces and would require smoke detection, model building codes were reviewed. The two codes that are mostly used in the US for occupant and property protection are the International Building Code (IBC) and NFPA 101 Life Safety Code.

Based on these codes, smoke detection is only required in a few building types and occupancies. For most occupancies, the model building codes rely on sprinklers and manual fire alarms as means of fire detection. Occupancies required by the codes to have smoke detection and that are susceptible to have high ceilings include special amusement buildings, detention centers, repair garages, and storages for highly toxic compressed gases, organic peroxides, oxidizers, high-piled combustibles, and energy storage systems (Life Safety Code (NFPA 101) 2021) (International Building Code 2021).

Other occupancies require smoke detection in limited areas where high ceiling spaces are not prevalent. These include occupancies like day care, health care and residential occupancies where manual detection is compromised due to occupant’s inability to self-preservation. In many other instances automatic detection would be required by the code as an alternative to sprinkler protection (International Building Code 2021) (Life Safety Code (NFPA 101) 2021).

The most widely used application of smoke detection is in performance-based design where buildings may require alternative means to meet the intent of the code. This option can be applied to any building type, but the most common use involves application of smoke detection to reduce Required Safe Egress Time (RSET) in
buildings with very large occupant load or very long travel distances or in general where prescriptive requirements for means of egress are not met.

Smoke detection is also used to initiate fire protection systems. The most prevalent use is in buildings with atrium where automatic detection is provided to initiate smoke exhaust systems. Other systems include initiating notification, actuating suppression, closing doors, releasing locks, equipment shutdown or initiating hazardous exhaust ventilation.

The fire risks vary by occupancy types. Likelihood and consequences of fire in an occupied indoor stadium is very different from a scarcely occupied warehouse. In occupied areas, lack of detection could delay evacuation and the consequence could be catastrophic, but due to the presence of occupants the likelihood of a fire to remain undetected is remote. On the other hand, in a warehouse the likelihood of a fire to remain undetected may be high but the life safety consequences are minor; however, property loss can be high.

The risks also vary by construction type. A building constructed of fire resistance rated construction would have a significantly different tolerance for consequence than combustible construction.

Automatic detection reduces the fire risk by reducing detection time. Reduction in detection time allows more time to evacuate, relocate, respond, suppress fire, or exhaust smoke. All these actions contribute to minimizing consequence and in turn reducing the overall risk.
2.0 Literature Review

Jensen Hughes reviewed the current regulatory requirements of smoke detection in level smooth ceiling spaces, applicable to interior building spaces with ceiling height more than 10 ft (3 m) in the US, Canada, UK, Germany, Netherlands, Belgium, Italy, Middle East, and Australia. The following codes and standards that were reviewed -

+ National Fire Alarm and Signaling Code (NFPA 72 2021 edition) used in US and Middle East,
+ Standard for Installation of Fire Alarm Systems (CAN/ULC S524: 2019) used in Canada,
+ Fire Detection and Fire Alarm Systems for Buildings (BS 5839-1:2017) used in UK and Hong Kong,
+ VdS-Richtlinien für automatische Brandmeldeanlagen Planung und Einbau (VdS 2095: 2022) used in Germany,
+ Alarm Systems for Fire, Intrusion and Hold Up – Part 2: Requirements for Fire Alarm Systems English translation of DIN VDE 0833-2 (VDE 0833-2:2017) used in Germany,
+ Fire Safety of Buildings – Fire Detection Installation – System and Quality Requirement Guidelines for Detector Siting (NEN 2535, 2017 edition) used in Netherlands,
+ Automatic fire detection and fire alarm systems - Design, installation, and operation (UNI 9795, 2021 edition) used in Italy,

The codes and standards referenced in the Phase I report (Accosta and Martin 2017) were analyzed and compared to the most recent versions of these codes and standards that Jensen Hughes was able to obtain. The most recent version of certain codes/standards specifically, the DBI 232 (Sulzburg, Germany) and R7 (France) that were reviewed in the Phase I report were not able to be obtained. The 2017 report analyzed the ceiling height limitation for spot type, air sampling type and projected beam type smoke detectors. In this phase, the scope has been limited to spot type smoke detectors only.

2.1 NATIONAL FIRE ALARM AND SIGNALING CODE (NFPA 72), 2022 ED.

Requirements specific to spot type smoke detector application in level smooth ceilings are discussed herein. Technical terms used throughout this report are used as per the definitions in NFPA 72.

2.1.1 Environmental Limits [NFPA 72 section 17.7.1.8]

NFPA 72 prohibits smoke detectors if any of the ambient temperature is below 32°F (0°C) or above 100°F (38°C). The temperature requirements from NFPA 72 section 17.7.1.8 do not apply if the detector is "specifically designed and listed" for other conditions. Smoke detectors are commonly listed for temperatures up to 120°F (48.9°C).
2.1.2 Consideration for Stratification [NFPA 72 section 17.7.1.11]

NFPA 72 section 17.7.1.11 requires that the effect of stratification below the ceiling is considered where necessary. The guidelines in Annex B are permitted to be used for this purpose. The code does not specifically address when such considerations are necessary.

2.1.3 Consideration for ITM (Inspection, Testing and Maintenance) [NFPA 72 section 17.4.3]

Initiating devices are required to be installed in a manner that provides accessibility for periodic inspection, testing, and maintenance. Smoke detectors installed in high ceiling spaces are required to be accessible so that these can be inspected, tested, and maintained.

2.1.4 Requirements for smooth level ceilings [NFPA 72 section 17.7.4.2.3]

The distance between smoke detectors must not exceed a nominal spacing of 30 ft (9.1 m) and there must be detectors within one-half the nominal spacing, measured at right angles from all walls or partitions extending upward to within the top 15 percent of the ceiling height. All points on the ceiling are required to have a detector within a distance equal to or less than 0.7 times the nominal 30 ft (9.1 m) spacing (0.75).

2.1.5 Requirements for Beam and Solid Joist Constructions [NFPA 72 section 17.7.4.2.4]

For ceilings with beam depths of less than 10 percent of the ceiling height, smooth ceiling spacing is permitted. Spot-type smoke detectors are permitted to be located on ceilings or on the bottom of beams. The designer is permitted to use smooth ceiling spacing under level ceilings where beams and joists extend down from the ceiling surface less than 10 percent of the floor-to-ceiling height, regardless of the beam or joist spacing. Since the thickness of the ceiling jet is generally taken to be equal to the upper 10 percent of the floor-to-ceiling height, beams and joists extending down a depth of less than this thickness is not expected to have a significant effect on the response time of the smoke detector. The farthest a detector can be from the fire is 0.7 times the 30 ft (9.1 m) spacing. Therefore, detectors can be located on either the ceiling or the bottom of the beam. Similarly for beam pockets formed by intersecting beams, including waffle or pan-type ceilings, if the beam depths are less than 10 percent of the ceiling height, smooth ceiling spacing is permitted. For corridors 15 ft (4.6 m) in width or less having ceiling beams or solid joists perpendicular to the corridor length, smooth ceiling spacing is permitted. For rooms of 900 ft² (84 m²) or less, the use of smooth ceiling spacing is permitted.

2.1.6 Allowance for Performance-based Design [NFPA 72 section 17.3 and 17.7.1.3]

Although the 30 ft (9.1 m) spacing criterion is a requirement, NFPA 72 section 17.7.1.3 permits designers to use any other spacing they deem appropriate as a performance-based alternative. NFPA 72 Annex B contains methodologies on how to perform performance-based analysis to design smoke detection system.

2.1.7 Projected Beam Type Smoke Detector Requirements [NFPA 72 sections 17.7.4.7]

Projected beam type smoke detector installation is required to follow the manufacturer’s instructions for spacing and placement. NFPA 72 requires that each beam is considered as a row of spot type smoke detectors. In Annex A, 60 ft spacing between the beams is recommended for smooth level ceiling application.
2.2 UL 268 AND CAN/ULC S529:2016, STANDARD FOR SMOKE DETECTORS FOR FIRE ALARM SYSTEMS

Full-scale room fire tests are conducted during the listing evaluation of a smoke detector. The fire test room has a ceiling height of 10 ft (3.0 m). In accordance with UL 268 and CAN/ULC S529 smoke detectors are required to render an alarm when subjected to fires that ultimately produce smoke profiles as specified in Table 1.

Table 1. Smoke Detector Sensitivity Criteria

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Smoke Profile</th>
<th>Timeline</th>
<th>Device Response Time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper fire</td>
<td>Optical density of first peak between 0.45 m⁻¹ and 0.66 m⁻¹, followed by minimum 0.058 m⁻¹, second peak of maximum 0.2 m⁻¹.</td>
<td>First peak between 1 and 3 minutes, second peak between 20 and 40 seconds after first peak</td>
<td>4</td>
</tr>
<tr>
<td>Wood fire</td>
<td>Minimum 0.058, maximum 0.27.</td>
<td>4 minutes</td>
<td>4</td>
</tr>
</tbody>
</table>
| Flaming Polyurethane fire | Light transmission between 50% and 60%                | Between 5 minutes and 9 minutes                                         | Before obscuration limit of 15.47%/m is measured | 2.3 BS 5939-1 (2017 ED.)

The UK and Hong Kong use BS 5939-1, the British Standard for Fire detection and fire alarm systems for buildings, Part 1: Code of practice for design, installation, commissioning, and maintenance of systems in non-domestic premises. The 2013 edition was reviewed in the Phase I report (Accosta and Martin 2017), while the 2017 edition was reviewed for the current report. The code states that the generally applicable maximum ceiling height is 10.5 m (34.5 ft). However, portions of the ceiling can be considered adequately protected if the ceiling height for those portions is not greater than 12.5 m (41 ft) and they collectively do not exceed 10% of the ceiling area within the protected area. The spacing between detectors is limited to 7.5 m (25 ft). There were no differences noted between the 2013 and 2017 editions.

2.4 VDS 2095 (2022 ED.)

Two German standards were reviewed with the first being VdS 2095, the Guidelines for Automatic Fire Alarm Systems. The 2010 edition was reviewed in the Phase I report and compared to the 2022 edition. The ceiling height limitation provided by the code is 12 m (39.4 ft). The detector spacing is given in terms of area of coverage per detector, and states that the floor area of the room to be monitored is a maximum of 80 m² (861.1 ft²) when the floor to ceiling height is up to 12 m (39.4 ft). The floor area of the room to be monitored is above 80
Smoke Detector Spacing in High Ceiling Spaces – Phase II

m² (861.1 ft²) when the floor to ceiling height is less than 6 m (19.7 ft). There were no differences noted between the previously reviewed and current version of VdS 2095.

2.5 DIN VDE 0833-2 (2017 ED.)

The second German standard that was reviewed was DIN VDE 0833-2, which is the Alarm systems for fire, intrusion and hold up – Part 2: Requirements for fire alarm systems. The 2009 edition was reviewed in the Phase I report and the 2017 edition was reviewed for the current report. The maximum ceiling height is 12 m (39.4 ft) with a maximum coverage of up to 80 m² (861.1 ft²). The maximum area of coverage can be increased to 120 m² (1,291.7 ft²) for room heights between 12 and 16 m (39.4 and 52.5 ft) depending on occupancy and ambient conditions. There were no differences noted between the 2009 and 2017 editions of DIN VDE 0833-2.

2.6 NEN 2535 (2017 ED.)

The Netherlands uses NEN 2535, the Fire safety of buildings – fire detection installations – system and quality requirements and guidelines for detector siting. The 2010 edition was previously reviewed, and the 2017 version was reviewed for this current report. The ceiling height is limited to 12 m (39.4 ft) but can be extended to a maximum height of 12 to 16 m (39.4 to 52.5 ft) if demonstrated with a test fire. Additionally, the maximum monitoring area per detector of 80 m² (861.1 ft²) must not be exceeded. There were no changes noted between the 2010 and 2017 editions.

2.7 AS 1670.1 (2018 ED.)

Australia uses AS 1670.1, Fire detection, warning, control, and intercom systems – system design, installation, and commissioning. The 2015 edition was previously reviewed and was compared to the 2018 edition for the current report. The maximum ceiling height for use of point type smoke detectors is 12 m (39.4 ft). For level surfaces, detectors must be arranged so that the distance from any point on the level surface of the protected area to the nearest detector does not exceed 7 m (23 ft) and shall not exceed 10 m (32.8 ft) between detectors. There were no changes noted between the 2015 and 2018 editions.

There were additional standards that were reviewed that were not reviewed in the 2017 report, including NBN S 21-100-1, UNI 9795, ULC 524.

2.8 NBN S 21-100-1 (2020 ED.)

Belgium uses NBN S 21-100-1, Fire detection and fire alarm systems – Part 1: Rules for risk analysis and needs evaluation, study and design, installation, placing in service, control, use, monitoring and maintenance. The 2020 edition was reviewed, which prescribed a maximum allowable ceiling height of 12 m (39.4 ft). The maximum permitted area per detector is 80 m² (861.1 ft²), with the maximum distance between two detectors of 14 m (45.9 ft), and the maximum distance between a wall or vertical separation and any detector of 7 m (23 ft).

2.9 UNI 9795 (2021 ED.)

Italy uses UNI 9795, Fixed automatic fire detection and alarm signaling systems, and the 2021 edition was reviewed. The maximum ceiling height provided by the code is 12 m (39.4 ft) and the coverage radius cannot exceed 6.5 m (21.3 ft).
2.10 CAN/ULC S524 (2019 ED.)

Canada uses ULC S524, the Standard for Installation of Fire Alarm Systems. The 2019 edition states that the maximum permissible ceiling height is 3.6 m (11.8 ft). The detector coverage area is based on 9.1 m (25.9 ft) spacing and shall not exceed 83 m² (893.4 ft²). It should be noted that spacing is not required to be reduced for ceiling height but may be affected by beam construction. When ceilings are higher than 3.6 m (11.8 ft), spot type smoke detector spacing is required to be determined using performance-based analysis based on fire type, growth rate, engineering judgement and manufacturer’s published installation instructions. A proposal to allow detectors to be mounted on ceilings up to 10.5 meters has passed ballot for ULC S524.
Table 2. Summary of Ceiling Height and Spacing Limitations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>USA, Middle East</td>
<td>NFPA 72</td>
<td>2016</td>
<td>2022</td>
<td>No prescriptive requirements</td>
<td>In the absence of performance-based design, distance shall not exceed 30 ft (9.1 m)</td>
<td>None</td>
</tr>
<tr>
<td>UK, Hong Kong</td>
<td>BS 5839-1</td>
<td>2013</td>
<td>2017</td>
<td>10.5 m (34.5 ft)</td>
<td>Radius of 7.5 m (24.6 ft)</td>
<td>None</td>
</tr>
<tr>
<td>Germany</td>
<td>VdS 2095</td>
<td>2010</td>
<td>2022</td>
<td>12 m (39.4 ft)</td>
<td>80 m² (861.1 ft²)</td>
<td>None</td>
</tr>
<tr>
<td>Germany</td>
<td>DIN VDE 0833-2</td>
<td>2009</td>
<td>2017</td>
<td>12 m (39.4 ft)</td>
<td>80 m² (861.1 ft²)</td>
<td>None</td>
</tr>
<tr>
<td>Netherlands</td>
<td>NEN 2535</td>
<td>2010</td>
<td>2017</td>
<td>12 m (39.4 ft)</td>
<td>80 m² (861.1 ft²)</td>
<td>None</td>
</tr>
<tr>
<td>Australia</td>
<td>AS 1670.1</td>
<td>2015</td>
<td>2018</td>
<td>12 m (39.4 ft)</td>
<td>10 m (32.8 ft) between detectors</td>
<td>None</td>
</tr>
<tr>
<td>Belgium</td>
<td>NBN S 21-100-1</td>
<td>N/A</td>
<td>2020</td>
<td>12 m (39.4 ft)</td>
<td>80 m² (861.1 ft²), 14 m (45.9 ft) between detectors, 7 m (23 ft) between walls or vertical separation</td>
<td>N/A</td>
</tr>
<tr>
<td>Italy</td>
<td>UNI 9795</td>
<td>N/A</td>
<td>2021</td>
<td>12 m (39.4 ft)</td>
<td>Radius of 6.5 m (21.3 ft)</td>
<td>N/A</td>
</tr>
<tr>
<td>Canada</td>
<td>ULC 524</td>
<td>N/A</td>
<td>2019</td>
<td>3.6 m (11.8 ft)</td>
<td>Radius of 6.4 m (21.3 ft)</td>
<td>N/A</td>
</tr>
</tbody>
</table>
2.11 TECHNICAL SUBSTANTIATION FOR MAXIMUM CEILING HEIGHT

The European codes and standards reference EN 54-7 for technical justification of the smoke detector spacing requirements, but this standard does not reference to detailed test data in the context of ceiling height. The research performed by Gott et al. in high bay hangar facilities may support the ceiling height and spacing that are listed in these codes and standards. Experiments were performed in two hangars, with ceiling heights of 49 ft (15 m) and 72 ft (22 m). The report stated that spot-type smoke detectors can detect fires, even when located at these increased heights (Gott, et al. 1997). These experiments seem to provide a basis for 40 ft (12 m) ceiling height limitation observed in the European and Australian codes and standards. The study also stated that the smoke detector spacing can be increased as far as 40 ft (12.2 m) with no significant reduction in response time, further supporting the coverage areas and spacing prescribed in these standards.

Fire sizes used in the tests performed by Gott et. al. ranged from 100 kW to 33MW. JP-5 and JP-8 fuels were used in these experiments that produce comparatively much sootier smoke than many other normally available fuels. Many of the smoke detection applications in commercial buildings will not see these types of fuels.

It is not reasonable to conclude that the maximum ceiling heights found in the European and Australian codes are justified. The studies performed evaluating smoke detector performance in high ceiling applications are very limited.
3.0 Features Affecting Smoke Detection

Available data from the sources identified through the literature review and Phase I Report were reviewed. Characteristics and parameters important to smoke detector spacing in high ceiling locations is provided in this section.

3.1 Detector Response Timeline

The following variables in the fire event timeline can be used to evaluate success of smoke detector response (Newman, Yee and Su 2016):

1. The time at which a specific hazard created by the fire occurs to people, buildings or contents, \( t_H \);
2. The fire growth time to reach a detectable level of fire product(s) at the detector location, \( t_f \);
3. The detector response time once \( t_f \) has occurred, \( t_D \); and
4. The "effective" response time once the fire has been detected, \( t_E \). Effective response time is defined by the time when the intended responses by the occupants, emergency responders, or the fire protection systems established by the occupant emergency plan can be performed. The relationship between these times can be expressed as (Newman, Yee and Su 2016) (Schifiliti, Custer and Meacham 2016):

\[ t_r = t_H - (t_f + t_D + t_E) \]

where \( t_r \) = residual time, which must be greater than or equal to zero.

In general, the response of a smoke detector can be treated as a first-order system coupled with a time lag (Newman, Yee and Su 2016), i.e.,

\[ \frac{dC_s}{dt} = \frac{1}{\tau} [C_o(t - t_l) - C_s(t)] \]

where \( C_o \) is the instantaneous smoke concentration as measured by the detector at time \( t \). \( C_o \) is the "true" reference concentration (outside the detector) at time \( t \). \( \tau \) is the time constant for the specific sensor used in the detector. \( t_l \) is the delay in smoke transport to the sensor such as through filters.

It is important to note that this equation is marginally helpful since it requires experimental testing with the specific detector for several of the values used. It is not very practical and is of very limited use.

3.2 Fuel Composition and Soot Yield

In fires, smoke is generated because of gasification, and decomposition of materials involved in the fire and burning of the species in the gas phase with air in the form of a diffusion flame. The generation rate of soot is directly proportional to the mass of fuel burned, the proportionality constant being defined as the soot yield of the product. The average data for the yields of \( \text{CO, CO}_2 \), mixture of gaseous hydrocarbons, and smoke for well-ventilated fires are listed (Khan, Tewarson and Chaos 2016). Note that these are for small cone-type fire samples. As noted in several literatures (Mealy, Floyd and Gottuk 2008) (Pitts and Mulholland 2000), at larger scale, the same fuels can have different yields. Heat of combustion is defined by the amount of heat given off per unit mass of fuel burned. Heat energy output per unit of time is the heat release rate. The buoyancy of the smoke plume generated is dependent on the heat of combustion and convective heat release rate.
3.3 FIRE GROWTH

Research has shown that most fires grow exponentially and can be expressed by what is termed the “power law fire growth model” (R. Schifiliti 1986).

\[ Q = t^P \]

\( Q \) = Heat Release Rate (kW)
\( t \) = Time (s)
\( P \) = exponent

The exponent, \( p \), is specific to the assumed growth curve for the design fire. Because \( p \) is most often assumed to be 2, this relation is commonly known as the t-squared (t\(^2\)) fire.

For detection, growth phase of the fire is of primary importance. Based on how long it takes to reach 1,055 kW of heat release rate, standard fire growth rates are determined.

### Table 3. Standard flaming fire growth rates

<table>
<thead>
<tr>
<th></th>
<th>Time to reach 1.055 MW (s)</th>
<th>Growth Rate (kW/s(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-fast</td>
<td>75</td>
<td>0.1876</td>
</tr>
<tr>
<td>Fast</td>
<td>150</td>
<td>0.0469</td>
</tr>
<tr>
<td>Medium</td>
<td>300</td>
<td>0.0117</td>
</tr>
<tr>
<td>Slow</td>
<td>600</td>
<td>0.0029</td>
</tr>
</tbody>
</table>

3.4 TRANSPORT CONSIDERATIONS

Performance variables impacted by higher ceiling heights are primarily concerned with changes to the aerosol characteristics that occur with time and distance from the source and transport time. Changes in the aerosol largely relate to the particle size and concentration and result from the processes of sedimentation, agglomeration, coagulation, and dilution away from the fire. Transport time is a function of the characteristics of the travel path from the source to the detector, which include ceiling height and configuration and buoyancy effects such as layering and thermal inversions.

3.4.1 Transport Lag

The transport lag is composed of the time for a smoke plume to reach the ceiling (plume transport lag) and the time for the ceiling jet to reach the detector (ceiling jet transport lag). Correlations for the plume and ceiling jet transport lag are available in the literature for both steady and t\(^2\) fires (Roux and Mahoney 2022). Because virtually all fires have a growth period before reaching a steady phase, the transport lag correlations for steady fires have little relevance to fire detection. It is important to note that t\(^2\) may be significant for use in applications with very tall ceilings but in many applications, detection may likely occur during the incipient period before the fire is in a t\(^2\) profile. Even the shortest plume transport lag for t\(^2\) fires, associated with the fast t\(^2\) fire, have been
found to be greater than that for a modest-size steady fire. A comparison of the plume and ceiling jet transport lag for a modest-size steady fire and $t^2$ fires is presented in Figure 1 and Figure 2.

**Figure 1. Plume Transport Lag (Milke 2016)**

**Figure 2. Transport Lag to reach detectors for 5 m and 30 m ceiling heights (Milke 2016)**
3.4.2 Plume Height and Stratification

A high energy-output flaming fire produces a fire plume that propels smoke and hot air upward. The larger the fire, the higher the plume extends and the greater the air velocity within the plume.

The height at which stratification occurs depends on both the size of the fire and the ambient temperature and temperature gradient of the space. Stratification is most likely to occur when the fire is small relative to the ceiling height, and the floor-to-ceiling temperature difference is relatively high. No study has been performed to evaluate the aspect ratio for where this is an issue for detection. This is probably a starting point for further work. The calculation guidelines in NFPA 72 Annex B show that very small flaming fires (<10 kW, which is less than a small wastebasket fire) can drive smoke to relatively high ceilings unless the temperature gradient between the floor and the ceiling becomes quite large. HVAC systems often form a layer of cool air near the floor, while upper zones near the ceiling are not tempered by HVAC equipment and thus, hotter. This can create conditions with a similar or greater effect than naturally occurring stratification.

NFPA 72 Annex B has empirical equation to directly calculate the maximum height to which the smoke or heat will rise. Figure 3 shows the maximum plume height for given fires calculated based on that equation. In Y-axis, the differences in ambient temperatures on the floor and the ceiling are shown assuming a linear temperature gradient. X-axis shows the heights that plume can reach. Where maximum plume height, as calculated or determined graphically, is greater than the installed height of detectors, smoke or heat from a rising fire plume is predicted to reach the detectors. Where the compared values of maximum plume height and the installed height of detectors are comparable heights, the prediction that smoke or heat will reach the detectors might not be a reliable expectation (Roux and Mahoney 2022).

![Figure 3. Temperature Change and Maximum Height of Smoke Rise for Given Fire Sizes (Roux and Mahoney 2022).](image-url)
3.4.3 Heat Transfer from Ceiling Jet

Convection is the dominant mode of heat transfer for the case of weak plumes impinging on ceilings. This heat-transfer regime is important for the prediction of activation times for detection devices. The maximum convective heat flux to a ceiling occurs when the ceiling surface is at or near ambient temperature before there has been any significant heating of the ceiling material. Correlations to calculate heat flux at the ceiling surface in the plume impingement region and ceiling jet region are available (Alpert 2016). Convective heat transfer to the solid surfaces depends on the heat loss through the conduction process within the surface material and is a function of material specific heat, density, and conductivity and radiation (function of emissivity). The type of backing of the surface is also a contributing factor to the heat loss and should be evaluated considering whether the material is exposed or insulated.

3.4.4 Smoke Dilution

Smoke dilution refers to a reduction in the quantity of smoke available for detection at the location of the detector. This dilution can occur either through natural convection (entrainment in the plume or the ceiling jet) or by effects of a heating or ventilation system. In the early stages of fire development, when smoke production rate is small and the plume is weak, smoke can easily be drawn out of the room and away from area smoke detectors. Air flow effects become larger as the required fire size at detection, gets smaller (National Fire Alarm and Signaling Code (NFPA 72) 2022).

3.4.5 Soot Loss

Soot transport can be compared to gaseous species transportation. That is, the soot particles are small enough that their settling velocity is small compared to the fire-driven flows of the gas containing the soot. Near surfaces, however, other mechanisms can affect the soot, which results in its deposition onto surfaces. The removal of soot via deposition impacts the time for smoke detectors to activate.

3.5 DETECTOR CHARACTERISTICS

Once smoke reaches the detector, factors related to the aerodynamic characteristics of the detector and the type of sensor become important. The aerodynamics of the detector relate to the ease with which smoke can pass through the detector housing and enter the sensor measurement chamber. Different sensing technologies (e.g., ionization or photoelectric or dual wavelength photoelectric, etc.) respond differently, depending on the characteristics of the transported aerosol. Within the family of photoelectric devices, there are variations depending on the wavelengths of light and the scattering angles employed. Also, algorithms used to sample and weight the sensor's response are introduced by the manufacturer and affect the detector's response.

3.5.1 Detector Sensitivity

Smoke detectors are tested using various smoke sources that have different characteristics (e.g., color, particle size, number of particles, particle shape). Unless otherwise specified, NFPA 72, the manufacturers, and the listing agencies report and use the percent obscuration produced using a specific type of gray smoke exposed to a detector in a specific test chamber (smoke box) under specific conditions (UL 268, Smoke Detectors for Fire Alarm Systems 2016). Actual detector response will vary when the characteristics of the smoke reaching the detector are different from the smoke used in testing and reporting detector sensitivity.
3.5.2 Entry Resistance

In addition to smoke characteristics and the detector’s operating mechanism, the ability to get the smoke into the chamber affects the response of the unit. For spot-type photoelectric-and ionization-type smoke detectors, entry resistance is caused by bug screens, chamber design, and the detector’s aerodynamic characteristics.
4.0 Gap Analysis

4.1 GAPS IDENTIFIED IN PHASE I

Seven knowledge gaps were identified in the Phase I report (Accosta and Martin 2017). These were available data, smoke detector sensitivity, smoke entry characteristics, temperature gradient, ceiling surface, airflows, and performance metric. The current study acknowledges these gaps and addresses them with the available information.

Lack of consolidated data was attributed as a gap in Phase I. This study attempts to bridge that gap by providing a consolidated taxonomy (Section Error! Reference source not found.) and database. Information on smoke detector sensitivity and entry characteristics and methods to quantify these parameters are discussed in 3.5.1 and 3.5.2. The gaps on temperature gradient, ceiling surfaces, airflows and performance metric are addressed below. Additionally, discussion is added on how a workable detector spacing requirement for high ceiling and a maximum ceiling height threshold can be developed.

4.2 PERFORMANCE CRITERIA

An acceptable performance criterion to evaluate smoke detector performance for varying spacing and ceiling height was not available. The performance criterion to evaluate smoke detector performance on high ceilings should be the same as for standard ceiling. That is, affording occupants enough time to escape prior to untenable conditions.

The selected approach was to define an acceptable performance criterion based on code compliant detector spacing in a 10 ft (3 m) high level smooth ceiling. Detector response time for a $t^2$ flaming fire growth (slow) for a certain fuel characteristic can be determined and established as performance criteria matrix. Based on the results, detector response time and a critical fire size initiating detector response could be considered for high ceiling analysis.

4.3 AMBIENT TEMPERATURE PROFILES

NFPA 72 provides a prescriptive limit in ambient temperatures where smoke detector could be installed, which is 32°F (0°C) and 100°F (37.8°C). The temperature requirements from NFPA 72 section 17.7.1.8 do not apply if the detector is "specifically designed and listed" for other conditions. Smoke detectors are commonly listed for temperatures up to 120°F (48.9°C). Aspirating and beam type smoke detectors typically have wider application temperatures. This requirement and listing of the detectors prevent use of spot type smoke detector if the temperature at the ceiling is expected to exceed 120°F (48.9°C). A reasonable assumption for temperatures in the occupied areas can be established as 68°F (20°C). But for unoccupied spaces, that assumption may not be true. So, theoretically, a temperature difference of 32-degrees for occupied spaces and 68-degrees for unoccupied spaces can be considered as worst-case bounding conditions. An ambient temperature profile with a linear gradient of temperature rises from 68°F (20°C) on the floor up to 120°F (48.9°C) at the ceiling can be used as a worst-case scenario for occupied spaces. For unoccupied spaces, a credible worst-case scenario could be 40°F on the floor and 100°F on the ceiling.

The ambient temperature profiles should include both linear and step temperature gradient. In step temperature gradient, the heat loss from the plume is a function of both height and the temperature difference from the...
ambient. So, it’s imperative that scenarios consider varying elevations for the step change. Recommended heights are ¼, ½, and ¾ of the ceiling height for each variation.

4.4 SMOKE DETECTOR SPACING

NFPA 72 and other codes provide prescriptive guidance for smoke detector spacing. In NFPA 72 the prescriptive spacing is allowed until stratification is a concern. NFPA 72 Annex B and NFPA 92 has recommendations when stratification becomes a factor. NFPA 72 Annex B contains methodology for performance-based evaluation. Methods described in Annex B require understanding of fire dynamics and CFD tools to evaluate smoke detector performance.

NFPA 92 has prescriptive requirement for beam detector spacing (NFPA 92, Standard for Smoke Control Systems 2018). The spacing is determined using the following equation –

\[ d_p = K_d z \]

Where, \( d_p \) = plume diameter and spacing between beams (ft or m)

\( K_d = 0.25 \)

\( Z = \) distance above the base of the fire (ft or m)

The use of this equation is very limited. This equation is based upon the premise of detection of the plume region of the fire and does not consider the ceiling jet transport to the beam location. This equation yields very conservative beam detector spacing especially in low ceiling spaces.

4.5 MAXIMUM CEILING HEIGHT

NFPA 72 does not provide a maximum ceiling height threshold for smoke detector prescriptive code application as do the other codes. It requires all detectors to be installed at locations that can be accessed or necessary access provisions must be ensured by means of portable ladder or similar means to get to the detector. This task was not intended to evaluate safety for building occupants and service technicians using tall extension ladders or other means to access, test, inspect and maintain smoke detectors. As heat detector spacing requirements are established for up to 30 ft (9.15 m) ceiling height, the code acknowledges that access to up to 30 ft (9.15 m) height is safe and acceptable.

NFPA 72 also requires that when stratification is a concern a performance-based approach is employed. This requirement indirectly refers to a maximum ceiling height condition beyond which prescriptive spacing criteria is no longer allowable.

4.6 SOOT DEPOSITION

Loss of soot from the ceiling jet due to deposition and corresponding deviation of model prediction from true optical density measurements are well documented (Mealy, Floyd and Gottuk 2008). A thorough review of the model verification and validation was performed and discussed in section 8.0. After reviewing the results, FDS soot deposition routine was found to be limited in terms of providing better model predictions. And it was not used in this analysis. Rather an average model bias factor was calculated and used to conservatively bound the effect of soot loss in the transport of smoke to the detector location and ensure adjustment for the maximum expected soot drop out.
5.0 Model Establishment

All modeling in this project was performed using Fire Dynamics Simulator (FDS) v 6.7.9. FDS is a computational fluid dynamics model developed by the NIST for the purpose of fire modeling (McGrattan, Hostikka, et al., Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation 2022) (McGrattan, Hostikka, et al., Fire Dynamics Simulator Technical Reference Guide Volume 1: Mathematical Model 2022). In the context of the effort of smoke detector performance evaluation in high ceiling application, the salient features of FDS are:

5.1 COMPUTATIONAL DOMAIN

FDS computational domain can be partitioned into one or more rectilinear grids. This feature allows one to reduce the number of grid cells in regions of lesser importance. Grids containing smaller cells can be located around the fire and at the ceilings while grids containing larger grid cells can be used to define regions whose sole purpose is providing ambient air for entrainment into the fire plume or ceiling jet.

5.2 COMBUSTION MODEL AND SPECIES TRACKING

A multiple-parameter mixture fraction can be used for species tracking along with a single-step or two-step combustion model. Since all the fire scenarios expected to be modeled will be well ventilated, the single step combustion model will be used. This model does not predict soot formation, but rather imposes a fixed soot yield based on the amount of fuel that has combusted. The user, therefore, is responsible for providing this yield as an input quantity.

5.3 TURBULENCE MODEL

Large eddy simulation (LES) is used to resolve sub grid scale turbulence. LES presumes that the computational grid can resolve the critical flow structures (eddies) for a given simulation and that smaller structures are simply modeled using a sub grid model that does not require additional conservation equations. For the scenarios expected to be modeled, the key flow features to resolve are entrainment into the fire plume and the ceiling jet. Grid size for the dense grids to achieve ~ 8 cells within D*, characteristic dimension of the fire is expected to provide necessary resolution for the eddies.

5.4 BOUNDARY CONDITIONS

A 1D, multi-layer, multi-component, reacting surfaces model can be used for surface heat transfer. A FDS user can define several thermal boundary conditions for an FDS simulation including a fixed temperature wall, an adiabatic wall, or defined material properties for a time dependent temperature solution. In general, ceilings of buildings are expected to be insulated in some fashion. While the specific ceiling construction and materials will differ, plume temperatures of the small design fires of interest for detection are not very large. Thus, heat transfer to surfaces is expected to be small and any set of material properties that nominally represent an insulated surface should suffice.

5.5 SOOT LOSS

FDS allows users to track soot as aerosol and can remove soot from a ceiling jet by deposition on to the surface. FDS determines the total aerosol deposition velocity to surfaces by assuming the deposition phenomena are independent, computing a deposition velocity for each mechanism (Thermophoresis,
Gravitational settling, Diffusive and turbulent deposition) and then summing them (McGrattan, Hostikka, et al., Fire Dynamics Simulator Technical Reference Guide Volume 1: Mathematical Model 2022). Then the aerosol is removed from the ceiling jet and deposited onto the surface by imposing the following boundary condition

\[
\dot{m}' = \rho Y u
\]

Where, \( m' \) = Soot mass flux (kg/m²-s)
\( \rho Y \) = Volume fraction of soot
\( u \) = Deposition velocity

5.6  MODELING DETECTOR ACTIVATION

5.6.1  Spot Type Detection

FDS allows users to select a detection sub-model based on detection type and sensitivity. The detection sub-model is the lag time correlations with the inner chamber activation obscuration. In this analysis, detector activation is modeled based on gas phase optical density device measurement at the detector location. A threshold optical density was used that corresponds to the detector activation.

5.6.2  Projected Beam Detection

FDS allows users to set up projected beam devices that can track total smoke obscuration over the beam length. The device can predict detector response time based on a specified threshold obscuration per unit length.

5.7  AMBIENT TEMPERATURE GRADIENT CONDITION

FDS allows users to set up a temperature gradient in the domain. This allows users to evaluate smoke stratification in spaces where ambient temperature is expected to change with height.

Our current basis for establishing temperature gradients in buildings of interest is based upon International Mechanical Code (IMC) requirements for habitable spaces and NFPA 72 requirements for smoke detectors. Besides the temperature estimates established in this report, we seek information from the technical panel that can provide real thermal situations in buildings.
6.0 Model Validation

Although there are various definitions of model validation, the one contained in ASTM E1355 is generally well agreed upon in the fire protection community. It is the process of determining how well the mathematical model predicts the actual physical phenomena of interest. Validation typically involves three steps -

1. Comparing model predictions with experimental measurements,
2. Quantifying the differences considering uncertainties in both the measurements and the model inputs, and
3. Deciding if the model is appropriate for the given application.

To say that FDS is “validated” means that we have quantified the model uncertainty for the smoke detector response prediction in high ceiling application and decided that the model is appropriate for such prediction. Model uncertainty entails formulation of the mean and standard deviation of a statistical distribution within which the true value lies. The objective is to characterize the performance of the model in predicting a given quantity of interest (e.g., the smoke detector response time) with two parameters; one that expresses the tendency for the model to under or over-predict the true value of the quantity (bias) and one that expresses the degree of scatter about the true value (standard deviation). It is assumed that the model predictions are normally distributed about the true values multiplied by a bias factor.

A model that predicts the true value has a bias of 1, and a standard deviation of 0. For a certain quantity, bias larger than 1 means the model over predicts the quantity. Bias smaller than 1 means, the quantity is underpredicted. Standard deviation defines the scattering of the predicted values. Assuming a normal distribution, the values within one standard deviation of the bias account for about 68% of the predicted data set.

Table 4 lists the summary statistics for the different quantities examined relatable to smoke detector application (McGrattan, Hostikka, et al., Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation 2022) as reported in the 2022 version of the FDS Validation Guide. This is, for each quantity of interest, the table lists the biases and relative standard deviation of the predicted values.

**Table 4. Summary of model uncertainties for quantities of interest reported in FDS Validation Guide**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Standard Deviation</th>
<th>Model Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Release Rate</td>
<td>0.52</td>
<td>0.92</td>
</tr>
<tr>
<td>Smoke Concentration</td>
<td>0.94</td>
<td>2.68</td>
</tr>
<tr>
<td>Entrainment</td>
<td>0.06</td>
<td>1.15</td>
</tr>
<tr>
<td>Plume Temperature</td>
<td>0.23</td>
<td>1.06</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.08</td>
<td>1.02</td>
</tr>
<tr>
<td>Hot Gas Layer Temperature</td>
<td>0.1</td>
<td>1.02</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value 1</td>
<td>Value 2</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Hot Gas Layer Temperature (No Ventilation)</td>
<td>0.1</td>
<td>1.09</td>
</tr>
<tr>
<td>Ceiling Jet Temperature</td>
<td>0.12</td>
<td>1.03</td>
</tr>
<tr>
<td>Soot Deposition</td>
<td>0.49</td>
<td>1.08</td>
</tr>
<tr>
<td>Smoke Obscuration</td>
<td>0.14</td>
<td>1.05</td>
</tr>
<tr>
<td>Smoke Detector Activation Time</td>
<td>0.27</td>
<td>0.61</td>
</tr>
</tbody>
</table>

The model validation study intended to achieve the following objectives:

- FDS validation of optical density measurements at detection locations and detector response time using the latest soot deposition mechanism in FDS v6. Model predictions were compared against available experimental data from tests performed for smooth ceilings up to 18 ft (5.5 m) high.

- Evaluation of the direct smoke concentration threshold method discussed in section 5.6, using the soot coagulation and deposition routines. Experimental detector response time and optical density measurements available from tests performed for smooth ceilings up to 5.5 m (18 ft) were used for comparison.

- FDS validation of smoke plume rise for a high ceiling with a linear ambient temperature gradient condition. Available empirical equations were used for comparison.
7.0 Validation Scenarios

A total of twelve (12) scenarios were evaluated. Nine scenarios with ceiling heights of 9 ft (2.7 m), 12 ft (3.7 m), and 18 ft (5.5 m) were run to validate temperature, velocity, optical density, and detector activation time. Each of these ceiling height scenarios was run with three different soot deposition sub-models that are described in detail below. Results were compared against the results collected from the experimental data set. Three additional scenarios were run for stratification evaluation with a ceiling height of 60 ft (18 m) to verify plume rise, with linear temperature gradients of 1°C/m, 2°C/m, and 3°C/m.

Table 5. Validation Scenario Matrix

<table>
<thead>
<tr>
<th>Scenario No</th>
<th>Ceiling Height (m)</th>
<th>Deposition Sub-model</th>
<th>Ambient Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.7</td>
<td>None</td>
<td>30°C</td>
</tr>
<tr>
<td>2</td>
<td>2.7</td>
<td>Single mean soot diameter</td>
<td>30°C</td>
</tr>
<tr>
<td>3</td>
<td>2.7</td>
<td>Two bins of soot diameter</td>
<td>30°C</td>
</tr>
<tr>
<td>4</td>
<td>3.7</td>
<td>None</td>
<td>30°C</td>
</tr>
<tr>
<td>5</td>
<td>3.7</td>
<td>Single mean soot diameter</td>
<td>30°C</td>
</tr>
<tr>
<td>6</td>
<td>3.7</td>
<td>Two bins of soot diameter</td>
<td>30°C</td>
</tr>
<tr>
<td>7</td>
<td>5.5</td>
<td>None</td>
<td>30°C</td>
</tr>
<tr>
<td>8</td>
<td>5.5</td>
<td>Single mean soot diameter</td>
<td>30°C</td>
</tr>
<tr>
<td>9</td>
<td>5.5</td>
<td>Two bins of soot diameter</td>
<td>30°C</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>None</td>
<td>20°C with 1°C/m gradient</td>
</tr>
<tr>
<td>11</td>
<td>18</td>
<td>None</td>
<td>20°C with 2°C/m gradient</td>
</tr>
<tr>
<td>12</td>
<td>18</td>
<td>None</td>
<td>20°C with 3°C/m gradient</td>
</tr>
</tbody>
</table>

7.1 FIRE DEFINITION

Propylene with a 4.8% soot yield and heat of combustion of 45,800kJ/kg was used. All fires were 100 KW steady state.
7.2 MATERIAL PROPERTIES

Ceilings were assigned properties of gypsum wallboard (density 1440 kg/m\(^3\), specific heat 0.48 W/m-K, and conductivity 0.84 kJ/kg). Floors were assigned the thermal properties of concrete.

7.3 PRESSURE BOUNDARY CONDITIONS

Only the floor and ceiling surfaces were no-flow boundaries. All side boundaries of the computational domain were open boundaries. This prevented the formation of smoke layers.

7.4 AMBIENT TEMPERATURE

Scenarios 1-9 had an ambient temperature of 30°C (86°F) throughout. Scenarios 10 – 12 with 18 m ceiling height had linear temperature gradient conditions with 1°C/m, 2°C/m, and 3°C/m respectively; the temperature at the bottom of the domain was 20°C (68°F).

7.5 COMPUTATIONAL GRID

The multi-block feature of FDS was used for all simulations. Experience has shown that for well-ventilated fire plumes that grid sizes on the order of

\[
\Delta x = 0.125 \left( \frac{\dot{Q}}{\rho_a T_a c_p \sqrt{g}} \right)^{2/5}
\]

result in an adequate resolution of the fire plume and ceiling jet. Given the 100-kW fire size, a grid size of 0.05 m (2 in.) was targeted around the fire and in the vicinity of the ceiling. Outside the plume and ceiling jet region grid sizes were limited by available computational resources and time. A grid study was performed to verify that the selected grid sizes yielded converged results (Floyd and McDermott, Modeling Soot Deposition Using Large Eddy Simulation with a Mixture Fraction 2010). The grid study used a 10 ft high 100 kW flat ceiling case. This case was run using fine/coarse mesh sizes of 1.2 in./2.4 in. (0.03 m/0.06 m), 1.6 in./3.2 in. (0.04 m/0.08 m), and 2.0 in./4 in. (0.05 m/0.10 m). The grid study determined that a 2.0 in. (0.05 m) fine grid and 4.0 in. (0.1 m) coarse grid was adequate, and conditions were not substantially different amongst the various grid sizes.

7.6 SOOT DEPOSITION

In scenarios 2, 5 and 8 a mean soot diameter of 0.4 micron and a thermophoretic diameter of 35 nm was used (Mensch and Cleary 2019). The following chemical equation was used to specify the combustion reaction and soot yield.

\[
4.33(3.76N_2 + O_2) + C_3H_6 = 16.29N_2 + 2.83CO_2 + 2.99H_2O + 0.18C_{0.9}H_{0.1}
\]

In scenarios 3, 6 and 9, a thermophoretic diameter of 35 nm was used. Soot diameter was specified using a range of minimum 0.2 micron and a maximum of 2 micron and two bins of soot diameters to be generated. The following chemical formula was used to specify the combustion reaction and soot yield.

\[
C_3H_6 + 4.33(3.76N_2 + O_2) = 16.29N_2 + 2.83CO_2 + 2.99H_2O + 0.09C_{0.9}H_{0.1}(Soot 1) + 0.09C_{0.9}H_{0.1}(Soot 2)
\]
8.0 Model Validation Results

Model validation has been performed using the methodology described in FDS Validation Guide.

8.1 DESCRIPTION OF EXPERIMENTS

A brief description of the experiments that were used for model validation is provided here. Only enough detail is included here to provide a general understanding.

An adjustable ceiling test apparatus was designed for experimental validation to evaluate smoke detector spacing requirements (Mealy, Floyd and Gottuk 2008). The apparatus was constructed using primarily gypsum wall board (GWB) and steel stud. Exposure fires located beneath the apparatus were positioned at the approximate center of the ceiling structure. To characterize the conditions along the ceiling optical density meters were installed. Two different smoke detection technologies were also installed throughout the apparatus.

Six tests were conducted beneath a smooth, unconfined ceiling configuration (i.e., no walls present). A photograph of this ceiling configuration is provided in Figure 4.
A 0.31 m (1 ft) square sand burner was used during all experimental testing. The burner was constructed in general accordance with the requirements of Annex A of ISO 9705. As shown in Figure 5, the burner used in experimental testing was laterally centered beneath the ceiling.
The fuel source used in all tests was chemically pure propylene. A fuel mass flow rate of 2.2 g/s was used for the 100 kW fire tests along with an effective heat of combustion of 45.8 MJ/kg (SFPE Handbook of Fire Protection Engineering 2016). A photograph of the 100-kW exposure fire used in testing is provided in Figure 6. As shown in Figure 6, a baffle was used to mitigate the effects of air currents in the lab on the structure of the flame. The baffle was constructed from 0.6 m x 1.2 m (2 ft x 4 ft) sections of GWB that were elevated 0.05 m (2 in.) above the floor and was installed around the perimeter of the source fire.

![Figure 6. Photograph of the 100 kW Exposure Fire Used in Testing (Mealy, Floyd and Gottuk 2008)](image)

8.2 CEILING JET TEMPERATURES

Temperatures throughout the corridor apparatus were collected using 24 Ga, Type K, bare-bead thermocouples. The standard uncertainty for Type K thermocouples is 2.2 °C per manufacturer. Given the fire size and expected ceiling temperatures directly over the fire, errors due to radiation should be on the order of the standard uncertainty and will decrease as one moves further away from the fire. Ceiling level thermocouples were installed directly above the fire source as well as at distances of 0.9 m (3 ft), 2.7 m (9 ft), 4.6 m (15 ft), and 6.4 m (21 ft) from the fire source. All thermocouples were installed such that the measurement bead was offset approximately 19 mm (0.75 in.) from the ceiling surface. Furthermore, all thermocouple locations were selected to characterize temperatures at locations proximate to detector clusters. Thermocouple locations are provided in Figure 7. Measured and predicted temperatures for each ceiling height and deposition scenario are shown in Figure 8 through Figure 16 for Scenarios 1 through 9. All the predicted temperatures are averaged over 5 seconds.
Figure 7. Instrumentation Locations for Ceiling Apparatus Testing. Thermocouples are circled in red, optical density meters shown as circle-to-square figures (blue), and velocity probes as rectangles (green) (Mealy, Floyd and Gottuk 2008)
Figure 8. Measured and predicted temperatures for 9 ft (2.7 m) ceiling and no deposition (Scenario 1).
Figure 9. Measured and predicted temperatures for 9 ft ceiling, single mean soot diameter scenario (Scenario 2).
Figure 10. Measured and predicted temperatures for 9 ft ceiling two bins of soot diameter scenario (Scenario 3).
Figure 11. Measured and predicted temperatures for 12 ft ceiling no deposition scenario (Scenario 4).
Figure 12. Measured and predicted temperatures for 12 ft ceiling single mean soot diameter scenario (Scenario 5).
Figure 13. Measured and predicted temperatures for 12 ft ceiling two bins of soot diameter scenario (Scenario 6).
Figure 14. Measured and predicted temperatures for 18 ft no deposition scenario (Scenario 7).
Figure 15. Measured and predicted temperatures for 18 ft single mean soot diameter scenario (Scenario 8).
Figure 16. Measured and predicted temperatures for 18 ft ceiling with two bins of soot diameters scenario (Scenario 9).
The ceiling jet temperature initially rises more quickly in the model versus in the experiments. This is attributed to the time for the burner and baffle etc. to warm up, whereas in the model it ramps up to 100 kW instantly. Predicted temperature rise over measured temperature rise for non-deposition Scenarios 1, 4 and 7 are shown in Figure 17. The temperatures are averaged over a 60 second period between 30 and 90 seconds. The experimental relative standard deviation was calculated to be 0.07 (denoted by black dashed lines in Figure 17). The model relative standard deviation was calculated as 0.14 (denoted by red dashed lines in Figure 17). Model bias factor was calculated as 1.24 (denoted by red solid line in Figure 17). This is higher than the model bias factor reported in the FDS Validation Guide, which is 1.03 (McGrattan, Hostikka, et al., Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation 2022). Even though the uncertainties were not calculated for the deposition scenarios, the biases are expected to be the same as the non-deposition scenario based on the predicted temperatures shown in Figure 8 through Figure 16.

![Figure 17. Ceiling jet temperature rise predictions for non-deposition Scenarios 1, 4 and 7 (Black solid line – experimental true value, black dashed line – experimental relative standard deviation, red solid line – model bias factor, red dashed line – model relative standard deviation).](image)

### 8.3 CEILING JET VELOCITIES

Velocity measurements were collected at two locations using Applied Technologies Sonic Anemometer/Thermometer Model SPA5/2Y. The velocity probes were located 4.6 m (15 ft) and 6.4 m (21 ft) from the fire source. The probes measured velocity components in both the longitudinal and lateral directions;
velocities reported are the magnitude of the total vector. They were installed such that velocities were measured approximately 19 mm (0.75 in.) from the ceiling of the corridor. The velocity probes used were capable of measuring velocities ranging from 0 - 10 m/s with a resolution of 0.01 m/s. The accuracy of these devices, as provided by the manufacturer, was +/-0.03 m/s.

Measured and predicted velocity magnitudes are shown in Figure 18 through Figure 20 for Scenarios 1 through 9. All measured and predicted magnitudes are averaged over 5 seconds.
Figure 18. Measured and predicted velocities for 9 ft ceiling scenarios (Scenario 1, 2 and 3).
Figure 19. Measured and predicted velocities for 12 ft ceiling scenarios (Scenario 4, 5 and 6).
Figure 20. Measured and predicted velocities for 18 ft ceiling scenarios (Scenario 7, 8 and 9).
Comparisons of predicted velocities and measured velocities for non-deposition scenarios are shown in Figure 21 for Scenarios 1, 4 and 7. For each scenario an average velocity for 60 seconds between 30 and 90 seconds was used. The experimental relative standard deviation denoted with black dashed lines, was calculated as 0.05. Model relative standard deviation denoted in red dashed lines was calculated as 0.1. Model bias factor shown with red line is calculated as 1.74. Reported bias factor in FDS Validation Guide for velocity prediction is 1.02 (McGrattan, Hostikka, et al., Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation 2022).

The model bias for the velocity is much higher in this study compared to those in the validation guide. There are a lot of points in the validation guide from more than 10 experiments that consistently come up with the bias of 1.02. It’s probably because of the velocities in 2008 experiments are usually 1.0 m/s or less, and there are fewer points in the NIST guide for those lower velocities.

![Figure 21. Summary of comparisons of predicted and measured velocities for non-deposition scenarios. (Black solid line – experimental true value, black dashed line – experimental relative standard deviation, red solid line – model bias factor, red dashed line – model relative standard deviation).](image)

8.4 OPTICAL DENSITY

Smoke measurements were collected using white light optical density meters (ODM). These instruments were installed proximate to each detector cluster at distances of 0.9 m (3 ft), 2.7 m (9 ft), 4.6 m (15 ft), and 6.4 m (21 ft) from the fire source on one side of the ceiling and only proximate to the detector cluster located 4.6 m (15 ft) from the fire source on the other end of the ceiling. Optical density meters were constructed in general
accordance with the specifications of UL 268. The optical density meters used were comprised of a 6V General Electric sealed beam light source and a Huygen Model 856 RRV photovoltaic cell. The ODM’s installed on the ceiling were wired in parallel and powered using a Kenwood Model PD18-30AD regulated DC power supply. Each light source on the ceiling was powered with 3.5V being transmitted through approximately 15.2 m (50 ft) of 18/2 copper strand power wire. The path length for all ceiling mounted ODMs was 1.52 m (5 ft). The optical density meters used in the test were calibrated using Melles Griot neutral density filters. The optical filters were used to expose each photocell to a known quantity of light. The transmittance values used to calibrate the photocells were 93.3, 79.4, 50.1, 31.6, 10, and 1 percent. All devices measured within 3 percent of the known filter value for the 93.3, 79.4, and 50.1 filters and within 10 percent of the known filter value for the 31.6, 10, and 1 filter.

Measured and predicted optical densities are shown in Figure 22 through Figure 30. All data has been averaged over 5 seconds.
Figure 22. Measured and predicted optical densities for 9 ft ceiling with no deposition scenarios.
Figure 23. Measured and predicted optical densities for 9 ft ceiling with single mean soot diameter scenario.
Figure 24. Measured and predicted optical densities for 9 ft ceiling with two bins of soot diameters.
Figure 25. Measured and predicted optical densities for 12 ft ceiling with no soot deposition.
Figure 26. Measured and predicted optical densities for 12 ft ceiling with single mean soot diameter scenarios.
Figure 27. Measured and predicted optical densities for 12 ft ceiling with two bins of soot diameters.
Figure 28. Measured and predicted optical densities for 18 ft ceiling with no soot deposition.
Figure 29. Measured and predicted optical densities for 18 ft ceiling with single mean soot diameter.
Figure 30. Measured and predicted optical densities for 18 ft ceiling with two bins of soot diameters.
Predicted optical densities for non-soot deposition model, deposition model with single bin and two bins of soot diameters are compared over measured optical densities in Figure 31, Figure 32, and Figure 33 respectively. For each scenario an average velocity of 60 seconds between 30 and 90 seconds has been used. The experimental standard deviation based on the optical density measurement uncertainty and propagated input uncertainty associated with the heat release rate was calculated to be 0.06. This standard deviation is indicated with black dashed lines. The model relative standard deviation is calculated to be 0.59 (red dashed lines). The calculated model bias factor (red solid line) is 1.43 for no soot deposition, 1.42 for single bin soot diameter and 1.45 for two bins of soot diameter. The model bias factor for smoke concentration prediction reported in FDS Validation Guide was 2.68. Model bias for smoke obscuration predictions was reported as 1.05 (McGrattan, Hostikka, et al., Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation 2022).

Figure 31. Optical density predictions for non-soot deposition models. (Black solid line – experimental true value, black dashed line – experimental relative standard deviation 0.06, red solid line – model bias factor 1.43, red dashed line – model relative standard deviation 0.59).
Figure 32 Optical density predictions with single bin of soot diameter. *(Black solid line – experimental true value, black dashed line – experimental relative standard deviation 0.06, red solid line – model bias factor 1.42, red dashed line – model relative standard deviation 0.59).*
Figure 33 Optical density predictions with two bins of soot diameter. (Black solid line – experimental true value, black dashed line – experimental relative standard deviation 0.06, red solid line – model bias factor 1.45, red dashed line – model relative standard deviation 0.59).

Figure 31, Figure 32, and Figure 33 show that optical densities were underpredicted for a 9 ft (2.7 m) ceiling, and over predicted for an 18 ft (5.5 m) ceiling. The 12 ft (3.7 m) ceiling scenario gave the best predictions of optical densities but were generally underpredicted. This is in contrary to the original belief that FDS over predicted smoke concentration due to its non-accounting of soot deposition. If soot deposition was the primary contributor of overprediction then the trend would have been opposite (i.e., higher optical densities in the lower ceiling and lower optical densities in higher ceilings as thermophoretic deposition velocity decreases with temperature difference between the plume and the ceiling). It is hypothesized that the variability of the mass extinction coefficient could be the cause of the biases observed. Smoke aging could lead to changes in mass extinction coefficient of smoke that otherwise in FDS is a constant parameter in the obscuration calculation (8,700 m$^2$/kg) (McGrattan, et al. 2022).

The optical density model bias must be better understood before further conclusions can be drawn, particularly about smoke detection activation. For 9 ft (2.7 m) ceilings the model overpredicts at the centerline and then begins to underpredict as the prediction moved further from the centerline. The thought would be that the deposition model is overdoing it, but this is consistent with or without the deposition model. The experimental data appears to remain constant no matter the distance from the centerline, while the model decreases. The question is whether smoke dilution is expected along the ceiling jet. If dilution is expected, the explanation about a change in the mass extinction coefficient in the experiment that is not captured by the model might make sense. If dilution is not expected, the experiment is probably "correct" as is with a constant mass extinction coefficient and something else is amiss with the optical density measurements or with the model results.
Meanwhile, for the 12 ft (3.7 m) ceilings, the model overpredicts at the centerline, but then predicts decently at the outward locations. And then at 18 ft (5.5 m) ceilings, it overpredicts the whole way. The single bin soot diameter deposition model seems to help a little in the 18 ft (5.5 m) cases, but not a whole lot. The trends described are regardless of the soot deposition model use. So, while there may be small improvements with the soot deposition model, it is not greatly fixing any problems.

If Figure 31 is divided into 3 figures for the 3 ceilings heights, differing results can be observed. Figure 34 shows the model predictions for 9 ft (2.7 m) ceiling height scenario. Calculated model bias was 0.77 confirming the under prediction. Figure 35 is showing the model predictions for 12 ft (3.7 m) ceiling height scenario. Calculated model bias for 12 ft (3.7 m) ceiling height scenario is 0.92. Figure 36 is showing the model predictions of optical density for 18 ft (5.5 m) ceiling height. Calculated model bias for 18 ft (5.5 m) is 2.68. Regardless, all 3 models are overpredicting the optical density at the centerline. But as the device location progress away from the centerline, the result seems to depend on the ceiling height. For 9 feet (2.7 m), it progresses to underpredicting. For the 12 ft (3.7 m) ceiling, it progresses to basically correctly predicting (within error of course), and for the 18-foot (5.5 m) ceiling, it still overpredicts. Whether this is something in the model, or something else, that is still to be determined.

Figure 34 Optical density predictions for non-soot deposition 9 ft (2.7 m) ceiling height model. (Black solid line – experimental true value, black dashed line – experimental relative standard deviation 0.06, red solid line – model bias factor 0.77, red dashed line – model relative standard deviation 0.23).
Figure 35 Optical density predictions for non-soot deposition 12 ft (3.7 m) ceiling height model. (Black solid line – experimental true value, black dashed line – experimental relative standard deviation 0.06, red solid line – model bias factor 0.92, red dashed line – model relative standard deviation 0.14).
Figure 36 Optical density predictions for non-soot deposition 18 ft (5.5 m) ceiling height model. (Black solid line – experimental true value, black dashed line – experimental relative standard deviation 0.06, red solid line – model bias factor 2.68, red dashed line – model relative standard deviation 0.34).

Figure 37 through Figure 39 show the predicted aerosol deposition velocities on 9 ft (2.7 m), 12 ft (3.7 m), and 18 ft (5.5 m) ceiling surfaces from scenarios 2 and 3, scenario 5, and scenarios 8 and 9, respectively. The deposition velocity boundary output from scenario 6 was not collected. With increase in ceiling height deposition velocity was seen to reduce. Deposition velocity increased with number of mean soot diameters used in the model. Deposition velocity was maximum at the plume impingement region and reduced radially as the jet moved away from the plume centerline. Highest velocities were observed on 9 ft (2.7 m) high ceiling surface at 0.7e-3 m/s for single mean diameter and 0.8e-3 m/s for two mean diameter scenarios. The velocity reduced to 0.1e-3 m/s for single mean diameter and 0.2e-3 m/s for two mean diameter on 18 ft (5.5 m) high ceiling.
Figure 37. Instantaneous deposition velocities at 9 ft (2.7 m) ceiling. Top: Single mean soot diameter (Scenario 2), bottom: two bins of soot diameters (Scenario 3).
Figure 38. Instantaneous deposition velocity at 12 ft (3.7 m) ceiling and single mean soot diameter (Scenario 5).
Figure 39. Instantaneous deposition velocities at 18 ft ceiling. Top: single mean soot diameter (Scenario 8), bottom: two bins of soot diameters (Scenario 9).

Figure 40 through Figure 42 show the predicted aerosol mass deposition at 9 ft (Scenario 2 and 3), 12 ft (Scenario 5), and 18 ft (Scenario 7 and 8) ceiling heights. Mass deposition output for Scenario 6 was not collected.
**Figure 40.** Predicted soot deposited mass (kg/m²) at 9 ft ceiling (top: single mean soot diameter, bottom: two bins of soot diameters).
Figure 41. Predicted soot deposited mass (kg/m$^2$) at 12 ft ceiling (single mean soot diameter).
Figure 42. Predicted soot deposited mass (kg/m²) at 18 ft ceiling (top: single mean soot diameter, bottom: two bins of soot diameters).
8.5 SMOKE DETECTOR ACTIVATION TIMES

Two different detection technologies (i.e., ionization and photoelectric) from two different manufacturers were installed as shown in Figure 43. Detector clusters installed on the ceiling were located at distances of 0.9 m (3 ft), 2.7 m (9 ft), 4.6 m (15 ft), and 6.4 m (21 ft) from the fire source in both directions.

![Figure 43. Detector locations on ceiling apparatus. Manufacturer A photoelectric are blue circles, Manufacturer B photoelectric are filled orange circles, Manufacturer B ionization are orange triangles. (Mealy, Floyd and Gottuk 2008)](image)

Photoelectric detectors from the same manufacturer (Mfg. A) were installed at all locations along the length of the ceiling. Photoelectric detectors from Manufacturer B were installed on the right-hand side (RHS) and ionization detectors from Manufacturer B were installed on the left-hand side (LHS).

The photoelectric detectors provided by both Manufacturers A and B were set to an alarm threshold of 8.0 percent obscuration per meter (2.5 %/ft or 0.036 m⁻¹) and the ionization smoke detectors provided by Manufacturer B ionization detectors were set to alarm at a threshold of 3.9 percent obscuration per meter (1.2 %/ft or 0.017 m⁻¹). The Manufacturer B devices were connected to a standard fire alarm control unit. Detector activation was monitored using normally open I/O modules provided by Manufacturer B for the respective devices. These normally open relays were hard-wired directly to the data acquisition system which recorded a step change in voltage for each individual detector alarm. Detector outputs for Manufacturer A devices were collected using an independent data logger and post-processing routine. This system allowed post-test evaluation of alarms at any user-selected sensitivity setting. Each photo device from Manufacturer A was calibrated by the manufacturer to be within + 0.23 percent obscuration per meter (0.07 %/ft) at 9.5 %/m (3 %/ft).

FDS can model smoke detector activation in two ways. The method used assumes that activation occurs when the optical density near the detector rises above a given threshold. Essentially this method treats the smoke detector exactly like a projected beam detector with a relatively higher optical density threshold value. Figure 44
compares the measured versus predicted smoke detector activation times using a threshold optical density approach. The smoke detectors were set with an activation optical density of 0.14 OD/m (Geiman and Gottuk 2003). The predicted optical density measurements were averaged using a 1 second running average prior to evaluating activation threshold.

![Figure 44. Smoke detector activation time predictions using optical density threshold of 0.14 OD/m. (Black solid line – experimental true value, black dashed line – experimental relative standard deviation, red solid line – model bias factor, brown dashed line – model relative standard deviation).](image)

The experimental relative standard deviation calculated based on uncertainty associated with photoelectric smoke detector chamber obscuration measurement, and propagated input uncertainty of heat release rate is 0.06 (black dashed lines). The model relative standard deviation is calculated as 0.8 (red dashed lines). The model bias factor is calculated as 0.51 (red solid line). The model bias factor reported in FDS Validation Guide is 0.61 (McGrattan, Hostikka, et al., Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation 2022).

Figure 44 shows that, there were far less activation of smoke detectors on 12 and 18 ft ceilings than 9 ft. This contrasts with the experiments, where all detectors at all the ceiling heights activated within 64 seconds. The model shifts from underpredicting to overpredicting the activation times as the detector moves away from the plume.
8.6 PLUME RISE

NFPA 72 Annex B.4.6.3.2 provides guidance on calculating plume rise in linear temperature gradient spaces. To determine whether the rising smoke or heat from an axisymmetric fire plume will stratify below detectors, the following equation can be applied where the ambient temperature increases linearly with increasing elevation:

\[
Z_m = 5.54 Q_c^{1/2} \left( \frac{\Delta T_0}{dZ} \right)^{3/8}
\]

Where:
- \(Z_m\) = maximum height of smoke rise above the fire surface (m)
- \(\Delta T_0\) = difference between the ambient temperature at the location of detectors and the ambient temperature at the level of fire surface (°C)
- \(Q_c\) = convective portion of the heat release rate (kW).

Three cases are considered where the air is stably stratified with temperature gradients, \(dT/dz\), of 1, 2 and 3 K/m. The expected equilibrium heights given by the empirical expression are 16.02 m, 12.36 m, and 10.61 m. The convective portion of the heat release rate is estimated as 70 percent of a 100-kW heat release rate.

Figure 45 displays snapshots of the simulations and Figure 46 displays the comparison of FDS simulations with the empirical correlation. In the simulations, the plume height was taken as the location of the peak optical density of the smoke, 4.6 m (15 ft) away from the plume centerline. Using a 15-degree angle of plume cone, the plume diameter at 16 m height is 4.3 m. So, 4.6 m was thought to be far enough that will not be impacted by the plume, unless the plume stratifies and start moving laterally. The grid is composed of 0.1 m cubes. The temperature is linearly stratified.
Figure 45. Snapshots of simulations of plume rise. The domain is 18 m high and 12 m wide. Top left: $dT/dz = 1°C/m$, top right: $dT/dz = 2°C/m$, bottom: $dT/dz = 3°C/m$. 
The model bias factor calculated for plume height was 0.98. The experiment standard deviation was 0.07. The model relative standard deviation was 0.07 (Figure 46). There were no tests performed to validate these model results.
9.0 **Model Uncertainty Statistics**

The FDS model uncertainty calculation is based upon the assumption that the model predictions are normally distributed about the true (but unknown) values multiplied by a bias factor. The bias factors and the model relative standard deviations of the quantities discussed in Section 8.0 are calculated based on comparisons of model predictions with past experiments and are corrected to account for uncertainties associated with the experimental measurements.

Table 6 lists the bias factors and relative standard deviation of the predicted values for optical density, detector activation time and plume height. It also lists the total number of experimental data sets on which these statistics are based, as well as the total number of point-to-point comparisons.

**Table 6. Summary statistics for all quantities of interest**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Section</th>
<th>Datasets</th>
<th>Points</th>
<th>Experimental Relative Standard Deviation</th>
<th>Model Relative Standard Deviation</th>
<th>Bias Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Density</td>
<td>8.4</td>
<td>6</td>
<td>36</td>
<td>0.06</td>
<td>0.59</td>
<td>1.43</td>
</tr>
<tr>
<td>Detector Activation Time</td>
<td>8.5</td>
<td>6</td>
<td>67</td>
<td>0.06</td>
<td>0.8</td>
<td>0.51</td>
</tr>
<tr>
<td>Plume Rise</td>
<td>8.6</td>
<td>3</td>
<td>6</td>
<td>0.07</td>
<td>0.07</td>
<td>0.98</td>
</tr>
</tbody>
</table>

To understand the results, let’s consider the uncertainty associated with the optical density prediction. The bias factor $\delta$ calculated in this validation is 1.43. The relative standard deviation, $\sigma_M$ is 0.59. Let’s assume, at a certain ceiling height and horizontal distance from plume centerline FDS predicted optical density, $M$ is 0.06 OD/m. Then the mean ‘true’ value, $\mu$ and standard deviation of the distribution $\sigma$ can be calculated as follows,

$$\mu = \frac{M}{\delta} = \frac{0.06}{1.43} = 0.042 \text{ OD/m}; \quad \sigma = \sigma_M \frac{M}{\delta} = 0.59 \times \frac{0.06}{1.43} = 0.0248 \text{ OD/m}$$

The probability that the ‘true’ optical density is less than a critical optical density value, can be expressed via a complimentary error function. Using the same example, if we consider a critical optical density $OD_C$ of 0.01 OD/m, the probably that the true optical density is less than the critical optical density is calculated as follows:

$$P(OD < OD_C) = \frac{1}{2} \text{erfc} \left( \frac{\mu - OD_C}{\sigma \sqrt{2}} \right) = \frac{1}{2} \text{erfc} \left( \frac{0.042 - 0.01}{0.0248 \sqrt{2}} \right) = 0.065$$

This means that there is a 6.5% chance that the true optical density would be less than the critical optical density of 0.01 OD/m, at the location where the model prediction of optical density is 0.06 OD/m.
The histograms in Figure 47 are created to display the distribution of the quantity \( \ln(M/E) \), where \( M \) is the Model prediction and \( E \) is the Experimental measurement. The premise of uncertainty calculation assumes that \( \ln(M/E) \) is normally distributed as shown on the bottom figures of Figure 47, calculated based on the average and standard deviation of all the compared \( \ln(M/E) \) values.

When computing the relative error between measured and predicted values, the optical density bias factor may have been skewed by large number of datapoints where \( \ln(M/E) \) exceeded 0.6. All such overpredictions occurred in the 18 ft (5.5 m) ceiling height scenario. The calculated optical density bias factor may not be
representative of the overall model bias, especially for large measured optical densities that were prone to underprediction [$\ln(M/E) < 0$], mostly observed on 9 ft and 12 ft ceiling scenarios, outside of the plume region.

Similarly, the detector activation time bias factor may be skewed by data points that resulted in $\ln(M/E)$ smaller than -1.4. These significant underpredictions were observed for detectors that were within 9 ft of the plume centerline. The calculated bias factor might not be representative of the overall model bias, especially for data points that resulted in $\ln(M/E)$ higher than 0.6. Such predictions were observed for detectors located more than 15 ft away from the plume centerline.

This validation has unfortunately opened more questions and unknowns. The differences in the model and experiment for the important variables needs to be better understood. In this case, it seems like the original concerns of stratification can be captured by the model, but other issues have arisen.
10.0 Performance-Based Analysis Approach

A performance-based approach was utilized to evaluate smoke detector spacing in ceiling heights taller than 10 ft. The performance-based approach consisted of two phases. In the first phase, goals were identified to meet the scope of the project. The goals were then translated into stakeholder’s objectives that were subsequently developed into design objectives. A set of performance-criteria were then developed to meet the design objectives. Fire scenarios and design fires were then created to evaluate the design performance.

In the second phase, the candidate designs were developed. The designs were then evaluated for each fire scenario. If the results meet the performance criteria the design was then accepted and selected. Designs that did not meet the performance criteria were not considered.

In this project, the goals, and objectives were intended to align with the model building and fire codes intended for occupant and property protection. A code compliant design for 10 ft ceiling height was used to develop performance criteria.

The candidate designs consisted of detection devices placed every 10 in. (0.25 m) throughout the ceiling and every 3 ft (1 m) vertically. The device performances were evaluated for ceiling heights up to 60 ft (18 m) for every 5 ft (1.5 m) increment. The successful design was selected based upon smoke detector locations achieving the performance criteria. Figure 48 shows the overview of the process.

![Figure 48. Overview of the Performance-Based Design Process](image-url)
11.0 Performance Goals and Objectives

The goal of this research project was to develop guidance for the installation of smoke detectors on smooth level ceilings over 10-ft (3m) that can be used as the technical basis for any changes to codes and standards. In the US the primary standard regulating smoke detector placement, location and performance is NFPA 72 National Fire Alarm and Signaling Code. The purpose of NFPA 72 as stated in Chapter 1 of the standard is to define the means of signal initiation, transmission, the levels of performance, and the reliability of the various types of fire detection and their components (National Fire Alarm and Signaling Code (NFPA 72) 2022).

In chapter 17 of NFPA 72, the purpose of automatic initiating devices is discussed. The standard requires all automatic initiating devices to contribute to life safety, fire protection, and property conservation by providing a reliable means to signal other equipment arranged to monitor the initiating devices and to initiate a response to those signals. But the standard itself does not define the extent of life safety, fire protection and property conservation in a quantifiable manner and refers to the applicable building and fire codes. For example, NFPA 72 sections 17.4.5 and 17.5.3 refers to applicable building and fire codes for the type of coverage necessary for certain occupancies (National Fire Alarm and Signaling Code (NFPA 72) 2022).

To attain the goals and objectives of smoke detection application in high ceiling spaces, model building codes used in the US were consulted. International Building Code (IBC) section 101.2 states its intent as to 'establish minimum requirements consistent with nationally recognized good practice for providing a reasonable level of life safety and property protection from the hazards of fire, explosion, and dangerous conditions in new and existing building, and to provide a reasonable level of safety to fire fighters and emergency responders during emergency operations'.

Goals established by NFPA 101 Life Safety Code also revolves around providing an environment for the occupants that is reasonably safe from fire, protection of occupants who are not intimate with the initial fire development and improvement of the survivability of occupants intimate with the initial fire development (Life Safety Code (NFPA 101) 2021).

To attain these goals, NFPA 101 also prescribes two objectives. The first objective is to design, construct and maintain a structure to protect occupants for the time needed to evacuate, relocate, or defend in place. And secondly to maintain structural integrity for the time needed to evacuate, relocate, or defend in place. The concept of defend in place would require a separation from room of fire origin. Protection strategies such as compartmentation would be addressing that objective.

Based upon the goals and objectives established in the model building codes, the following two objectives were considered for this project –

1. Recommend smoke detector spacing for application in high ceiling to protect occupants for the time needed to evacuate or relocate to safety.
2. Recommend smoke detector spacing for application in high ceiling to maintain structural integrity for the time needed to evacuate or relocate occupants.

A third objective can be found in NFPA 101 which is to reasonably prevent or mitigate events involving hazardous materials to allow the time needed to evacuate, relocate, or defend in place occupants who are not intimate with the initial emergency incident. This objective speaks directly to the smoke detection requirements in spaces storing and using highly toxic compressed gases, organic peroxides, and oxidizers. To meet this objective, fire exposure to several different storage conditions and arrangements would have to be evaluated.
The scope of this analysis has been limited to achieving occupant protection and property protection. Fire exposure to hazardous materials is not evaluated.

As with the progression of the analysis, it was understood that achieving these objectives are very much dependent on external factors that are not influenced by fire detection. In case of occupant protection confinement of the space drives the tenability criteria and consequences. Rooms with high ceilings outperform low ceiling spaces in maintaining tenability and structural integrity. In a hypothetical case where rooms with the same floor area have different ceiling heights, the room with the lower ceiling height has worse consequences in terms of tenability conditions and structural failure. For the same fire scenario, the low ceiling would be exposed to higher plume temperatures due to the proximity to the fire. For non-rated construction and buildings without sprinkler protection failure sequence would be initiated in the low ceiling space much faster than it would in high ceiling spaces.

The other factor that impacts the occupant tenability is the containment of the space. Rooms with low ceilings and wall enclosures are susceptible to faster loss of tenability. And even though in the hypothetical rooms with the same floor area, detection in the low ceiling room would occur much faster than with the high ceiling; most often the failure would be driven by architectural building configuration, means of egress arrangement, and occupant loads. These factors would vary from building to building and there is no fit-for-all template to use or justify.

In the absence of building specific detail to work with, the option was to evaluate detection performance against an acceptable detection criterion that is known to have met the broader objectives set by the model building and fire codes. In that light, the objective for this exercise has been established as the following –

+ Recommend smoke detector spacing for high ceiling spaces that achieves the same performance as the prescriptive detection design for smoke detection on a 10 ft ceiling.
12.0 Performance Criteria

To meet the objective established in section 11.0, a performance criterion was established based on the NFPA 72 prescriptive requirements for smoke detector device location and placement. For flat ceilings, spot type devices are required to be spaced at 30 ft (9.1 m) maximum (National Fire Alarm and Signaling Code (NFPA 72) 2022).

For projected beam detection, a single beam is compared to a row of spot type devices. Spacing between rows of spot type devices are required to be used for beam spacing. However, this requirement is not in alignment with the recommendation in NFPA 72 Annex (not enforceable part of the standard) and manufacturer’s installation guides for most detectors available. The Annex and manufacturer’s guide allows the beams to be spaced up to 60 ft (National Fire Alarm and Signaling Code (NFPA 72) 2022).

12.1 THRESHOLD OF DETECTION FOR SPOT TYPE

Detection time was calculated based on optical density prediction using the model FDS (Fire Dynamics Simulator). In general, optical density is the defined by the amount of attenuated light over certain distance. When the light attenuation is divided by the distance, the optical density per unit distance is found. Optical density per unit distance as a measurement unit allows characterization of smoke without having to consider the distance of the light. In this report, where the term optical density is used it should be understood as the optical density per unit distance. The following equation is used to calculate the optical density based on light transmittance in smoke detector listing tests (UL 268, Smoke Detectors for Fire Alarm Systems 2016) –

\[ D = -\frac{1}{L} \log_{10} \left( \frac{I}{I_0} \right) \]

Where, \( D \) = Optical density (m\(^{-1}\))
\( L \) = distance of the light
\( I \) = Light transmittance through smoke
\( I_0 \) = Light transmittance without smoke

The calculation of optical density in FDS differs from method used to measure optical density in spot type smoke detector listing fire tests. In FDS optical density output is generated based on density of the smoke calculated at the grid cell where the device is located using the following equation (McGrattan, et al. 2022) –

\[ D = \frac{K}{2.3} \]

\[ K = K_m \rho Y_s \]

Where, \( D \) = Optical density (m\(^{-1}\))
\( K \) = Extinction Coefficient (m\(^{-1}\))
\( K_m \) = Mass specific extinction coefficient (constant value of 8,700 m\(^2\)/kg)
\( \rho Y_s \) = density of smoke particulate (kg/m\(^3\))

Mass specific extinction coefficient is a constant in this equation, and a value of 8,700 m\(^2\)/kg is used (McGrattan, et al. 2022).
Research performed by others indicated 0.15 OD/m have more than 80% success of being detected by all types of spot type devices (Geiman and Gottuk 2003). To consider FDS model bias, a bias factor of 1.43 established in section 9.0 was used. Including the bias factor, an optical density threshold of 0.215 m\(^{-1}\) was used to represent successful detection for spot type smoke detector.

The combination of a statistical number and a bias multiplier could lead to a wide range of values. In section 8.4, it is discussed how model biases changed with ceiling height and radial distance from the plume centerline. Ideally, the best approach would have been using different bias factors changing with ceiling height, radial distance, and increasing fire size. In absence of such level of precision, any constant optical density threshold value would lead to some error in the model prediction.

There is no significant merit in using 0.215 m\(^{-1}\) as spot type detector activation threshold. Use of a constant optical density threshold for spot type detector activation modeling is a simplified approach that does not consider smoke entry resistance to the detector chamber. The selected threshold is considered conservative enough to take entry resistance into account.

Available detection technologies listed based on UL268 sensitivity and fire tests would be activated at different optical densities for different fuel types that are not consistent with the threshold optical density used in this analysis (UL 268, Smoke Detectors for Fire Alarm Systems 2016).

### 12.2 Threshold of Detection for Beam Detector

NFPA 72 acknowledges some similarities between projected beam type detectors and spot type detectors and considers a beam equivalent to a row of spot type detectors. But this similarity cannot be translated into the same detection threshold for the two types. Spot type detectors are set off by presence of smoke inside the chamber. Presence of detectable optical density in just a single detector would set off the device. So, the performance threshold is much higher. The beam detectors evaluate the light attenuation over long distances. The presence of smoke may or may not cover the full length of the beam. And so, the performance threshold used for beam detectors require to be much lower.

The beam detectors evaluate presence of smoke based on light attenuation between the transmitter and the receiver. In general, obscuration is expressed using the following equation (UL 268, Smoke Detectors for Fire Alarm Systems 2016) –

\[
O = \left(1 - \frac{I}{I_o}\right) \times 100\%
\]

Where, O = Obscuration (%)
I = Light transmittance through smoke
I\(_o\) = Light transmittance without smoke

Based on equation discussed in section 12.1, reduction in light transmittance through uniform smoke of 0.215 m\(^{-1}\) (spot type detection threshold) over 60 ft (18.3 m) length can be calculated –

\[
\frac{I}{I_o} = \exp(-D \times L) = \exp(-0.215 \times 18.3) = 1.16e - 4
\]

And the obscuration of the beam through uniform optical density of 0.215 m\(^{-1}\) can be calculated based on the equation under section 12.2.
\[ O = (1 - 1.16e^{-4}) \cdot 100\% = 99.99\% \]

The light attenuation is affected by the length of beam passing through smoke. As the beam travels through smoke the intensity of the light reaching to the receiver is reduced. Longer beams passing through same smoke concentration and optical density would yield lower intensity or higher obscuration. And so, to detect the same smoke concentration longer beams will have to be more sensitive (lower in obscuration threshold) than shorter beams. To address this varying obscuration threshold, UL 268 uses obscuration per unit length, \( O_u \), for beam detector sensitivity criteria which is calculated using the following equation, where \( L \) is the length of the beam (UL 268, Smoke Detectors for Fire Alarm Systems 2016),

\[ O_u = \left[ 1 - \left( \frac{I}{I_o} \right)^\frac{1}{L} \right] \cdot 100 \]

In FDS, obscuration per unit length cannot be used as an output quantity. So, obscuration has been used instead and adjustment was made in the threshold to address the length of the beam used. For beam lengths longer than 44 ft (13.4 m), UL 268 uses an obscuration per unit of 1%/ft as detection threshold (UL 268, Smoke Detectors for Fire Alarm Systems 2016). If the length of the beam is changed the measured obscuration would change even if the obscuration per unit value remains constant. Table 7 shows how much light will be received back at the receiver and resulting obscuration levels for beam lengths of 44 ft (13.4 m), 60 ft (18.3 m), 100 ft (30.5 m), 200 ft (61 m), 230 ft (70.1 m), 300 ft (91.5 m), and 400 ft (122 m), when it passes through uniform concentration of 1%/ft obscuration per unit or UL 268 smoke concentration threshold for beam detector activation.

**Table 7. Light attenuation and obscuration for different beam lengths through uniform 1%/ft obscuration per unit smoke concentration**

<table>
<thead>
<tr>
<th>Length of beam in ft (m)</th>
<th>Light attenuation ((I/I_o))</th>
<th>Obscuration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 (13.4)</td>
<td>0.64</td>
<td>35.74</td>
</tr>
<tr>
<td>60 (18.3)</td>
<td>0.55</td>
<td>45.28</td>
</tr>
<tr>
<td>100 (30.5)</td>
<td>0.37</td>
<td>63.4</td>
</tr>
<tr>
<td>200 (61)</td>
<td>0.13</td>
<td>86.6</td>
</tr>
<tr>
<td>230 (70.1)</td>
<td>0.10</td>
<td>90.1</td>
</tr>
<tr>
<td>300 (91.5)</td>
<td>0.05</td>
<td>95.1</td>
</tr>
</tbody>
</table>
In this study, FDS obscuration prediction of 90% was used as beam detector activation threshold. From Table 7, 90% obscuration represents uniform smoke concentration detectable by a 230 ft long beam listed per UL 268. Obscuration higher than 90% was difficult to use as detection threshold. As the beam obscuration predictions exceeded 90%, a long tail of the curve followed where change between each percentage increment was very slow. This was being translated into very unusual results when plotted over varying ceiling heights and device placements.

The beam length used in this study was 60 ft (18.3 m). It is acknowledged that 90% obscuration threshold for detection is higher compared to detection threshold used in UL 268 for 60 ft (18.3 m) long beams (45.3%). The higher obscuration threshold addresses FDS bias for overprediction of smoke concentration (see section 9.0 for discussion on optical density model bias).

FDS uses the following equation to calculate obscuration –

\[ O = \left(1 - \exp\left(-K_m \sum \rho_{s,i} \Delta x_i \right)\right) \times 100\% \]

where \(i\) is a mesh cell along the path of the beam,
\(\rho_{s,i}\) is the soot density of the mesh cell (kg/m\(^3\)),
\(\Delta x_i\) is the distance within the mesh cell that is traversed by the beam (m)
\(K_m\) is the mass extinction coefficient (constant value of 8,700 m\(^2\)/kg).

### 12.3 DETECTION TIME PERFORMANCE CRITERIA

Acceptance test criteria in UL 268 requires smoke detector operation within 240 s and provides limits on optical density values. These tests are performed in enclosed test chamber. Optical density necessary for smoke detector activation is achieved by the containment of smoke within the test chamber. In this analysis, the ceilings are considered unconfined. Without the aid of any smoke containment the optical density values and the detection time criteria of UL 268 could not be used.

In absence of detection performance criteria in the code or testing standards, an equivalence method has been established to determine detection time performance criteria. For the 10 ft (3 m) ceiling scenario the spot type device outputs from four cardinal sides of the fire are averaged and plotted as shown in Figure 49. The details on this fire scenarios are discussed in section 13.0. The devices were located at the ceiling at a 21 ft (6.5 m) distance from the plume centerline corresponding to NFPA 72 compliant spacing of 30 ft (9.15 m) (i.e., 21 ft is half the distance of the diagonal spacing of detectors spaced in a 30 ft by 30 ft grid). The averaged output indicated that smoke optical density of 0.215 m\(^{-1}\) was achieved at 300 seconds.
Similarly, beam obscuration outputs were collected for the 10 ft (3 m) ceiling scenario. The modeled smoke obscuration levels from four cardinal sides were averaged and plotted over time, as shown in Figure 50. The beams are located 8 in. (0.2 m) below the ceiling, at 30 ft (9.25 m) distance from the plume centerline, corresponding to NFPA 72 Annex compliant 60 ft (18 m) spacing. The plot indicates that total obscuration of 90% was achieved in 145 seconds.
Figure 50. Averaged beam obscuration output plot for devices at the ceiling 30 ft (9.25 m) from plume centerline in 10 ft (3 m) ceiling scenario.

Table 8 shows the detection quantity thresholds used in the analysis along with the correction factors applied and the detection times attained from 10 ft ceiling height scenario to be used as performance criteria.

Table 8. Quantity threshold corresponding to detection and detection time performance criteria.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Selected Threshold</th>
<th>Correction Factor</th>
<th>Threshold used in the analysis</th>
<th>Detection time performance criteria (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Density (m(^{-1}))</td>
<td>0.15</td>
<td>1.43</td>
<td>0.215</td>
<td>300</td>
</tr>
<tr>
<td>Obscuration (%)</td>
<td>90</td>
<td>1</td>
<td>90</td>
<td>145</td>
</tr>
</tbody>
</table>
13.0 Fire Scenarios and Design Fire

13.1 FIRE DYNAMICS SIMULATOR MODEL

Fire Dynamics Simulator (FDS) version 6.7.9 was used for this analysis. FDS is a computational fluid dynamics (CFD) tool developed by the National Institute of Standards and Technology (NIST). Detailed technical information on the equations and assumptions that are used in the model are available in the literature published by NIST (McGrattan, Hostikka, et al., Fire Dynamics Simulator Technical Reference Guide Volume 1: Mathematical Model 2022).

To solve mass, species, and momentum transfer equations, FDS uses a rectilinear domain divided in grid cells. In this analysis a grid cell size of 8 in. (0.2 m) was used. The cell size was determined based on the following equation –

\[
\delta x = 0.25 \left( \frac{Q}{\rho \alpha c_p T_\alpha \sqrt{g}} \right)^{\frac{5}{2}}
\]

Where, \( \delta x \) = cell size (m)
\( Q \) = Heat release Rate (kW)
\( \rho \alpha \) = Density (1.204 kg/m\(^3\))
\( c_p \) = Specific Heat (1.005 kJ/kg-K)
\( T_\alpha \) = Ambient temperature (293 K)
\( g \) = gravitational acceleration (9.81 m/s\(^2\))

The analysis uses a time squared fire starting at 0 KW and growing up to 1,500 kW. In the equation above, 750 kW was used that yields a cell size of 0.214 m.

13.2 SCENARIOS

A total of ten (10) scenarios were evaluated, excluding the 10 ft (3 m) ceiling height scenario used to develop the performance criteria. The scenarios differ by the height of the ceiling used in each scenario. Ceiling heights from 15 ft (4.5 m) to 60 ft (18 m) were evaluated with 5 ft (1.5 m) increments. All scenarios consisted of a 67 ft (20.4 m) square floor where the fire was located and a 67 ft (20.4 m) square ceiling where the detectors were located. The ceilings were flat and level with no obstruction to cause impedance in ceiling jet flow. There were no walls that could affect the ceiling jet by containing or obstructing or as such affect the detector performance; this provided a conservative approach as confining walls could increase smoke concentrations.

13.3 AMBIENT CONDITIONS

Ambient temperature of 68°F (20°C) were used for the 10 ft (3 m) ceiling scenario. For all other scenarios, a temperature gradient of positive 1°F/ft (1.8°C/m) was used above 10 ft (3 m) to evaluate the effect of stratification. So, the temperature at the floor up to 10 ft (3 m) remained at 68°F (20°C) and started increasing gradually. At 15 ft (4.6 m) the temperature was 73°F (23°C), at 60 ft (18.3 m) the temperature was 118°F (48°C).

All scenarios were at 1 atm (101,325 Pa) ambient pressure. No other external air flow condition was considered. Figure 51 shows a visual output from the graphic software Smoke View showing the initial ambient temperature gradient for the 60 ft (18.3 m) ceiling scenario.
13.4 FIRE SIZE AND FUEL ASSUMPTIONS

In traditional performance-based analysis, fire sizes consider the likely smoke layer height above the highest occupied elevation and allows for use of smoke detection at 30 ft (9.14 m) spacing. Steady heat release rates or fast-growing fires are used. In this analysis, a more generic approach had to be considered. In absence of surrounding walls concept of smoke layer height does not apply.

For each scenario a 4 ft (1.2 m) square shaped fire was located at the center of the floor. The fire was considered to have an exponential growth rate of 0.00293kW/s², which means at the initial time step the heat release rate is 0 kW. By 600 seconds the fire reaches a heat release rate of 1,054 kW. In the fire protection industry this is known as a slow growing t-squared (t²) fire, opposed to medium or fast-growing fires that reach 1,054 kW by 300 and 150 seconds respectively.

The reasoning for using an unsteady fire was to consider a scenario that can incorporate the plume dynamics associated with a growing fire. In the incipient stage the fire size was small, and the plume did not have the buoyancy it needed to overcome the stratification. But as the fire grew so did the energy in the plume and the
associated hazards of tenability and structure failure. As the fire grew the detection performance was tracked for each device location.

Any $t$-squared growth rate could have been used in this analysis. The slow growth rate was used to observe the transition of the plume and predictable optical density and obscuration in matter of hundreds of seconds instead of within seconds for fast or medium growth rate fires.

A list of ordinary combustibles with soot yields, heat of combustion and convective heat release rate fraction is provided in Table 9, along with the fuel properties used in this analysis.

*Table 9. Common ordinary combustibles with soot yields, heat of combustion and convective heat fraction*

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Soot Yield</th>
<th>Heat of Combustion (kJ/kg)</th>
<th>Convective Heat Release Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon</td>
<td>0.075</td>
<td>27,100</td>
<td>0.601</td>
</tr>
<tr>
<td>PMMA</td>
<td>0.028</td>
<td>24,200</td>
<td>0.686</td>
</tr>
<tr>
<td>Polyurethane – GM27</td>
<td>0.198</td>
<td>16,400</td>
<td>0.463</td>
</tr>
<tr>
<td>Polyurethane – GM37</td>
<td>0.113</td>
<td>17,900</td>
<td>0.486</td>
</tr>
<tr>
<td>Red Oak</td>
<td>0.015</td>
<td>12,400</td>
<td>0.629</td>
</tr>
<tr>
<td><strong>Fuel used in this analysis</strong></td>
<td><strong>0.05</strong></td>
<td><strong>19,400</strong></td>
<td><strong>0.65</strong></td>
</tr>
</tbody>
</table>

For this analysis, a soot yield of 0.05 was used. A heat of combustion of 19,400 kJ/kg which is also an average based on bench scale testing of various combustibles, cellulosic and non-cellulosic plastic materials (SFPE Handbook of Fire Protection Engineering 2016). A sensitivity analysis was not performed. It was expected that change in fuel properties would impact the results in the same way for different ceiling heights. The heat release rate output from one of the scenarios is provided in Figure 52.
Figure 52. Heat release rate output
14.0 Smoke Detector Spacing Evaluation

In all the scenarios, spot smoke detector devices were modeled at the ceiling at every 10 in. (0.25 m) interval. Beam devices were modeled at every 10 in. interval horizontally 8 in. (0.2 m) below the ceiling. Additionally, the device arrays (both optical density and beam obscuration) were repeated every 3.28 ft (1 m) vertically throughout the computational domain.

The device outputs were written to a file every 5 seconds. The output quantities were time-averaged between printouts. This was done for efficient data management and to reduce noise or short-lived high fluctuations in the output quantity.

For each scenario, a smoke view output file was reviewed to confirm that the fire location, device locations and temperature gradients were correctly input. Smoke view output images in Figure 51, Figure 53 and Figure 54 are showing the initial temperature gradient, fire location, and device locations for the 60 ft (18.3 m) ceiling scenario.

![Figure 53. Plan view showing fire and device locations. Optical density devices are shown with green dots. Beam devices are shown with black line. Fire location shown in red.](image-url)
14.1 PERFORMANCE EVALUATION MILESTONES

To understand progression of detector performance at growing heat release rates multiple points in time were selected. As the heat release rate was growing over time, these selected points in time also correspond to different heat release rates. Selected times and corresponding heat release rates selected for spot type device evaluation are shown in Table 10.

Table 10. Selected points in time and heat release rates for spot type smoke detector evaluation.

<table>
<thead>
<tr>
<th>HRR (kW)</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>260</th>
<th>500</th>
<th>760</th>
<th>1000</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>185</td>
<td>230</td>
<td>260</td>
<td>300</td>
<td>415</td>
<td>510</td>
<td>585</td>
<td>720</td>
</tr>
</tbody>
</table>
Selected points in time and corresponding heat release rates for projected beam type detector evaluation are shown in Table 11. Ceiling mounted beam detectors in all scenarios reached detection threshold within 415 seconds. And so additional points in time were not considered.

Table 11. Selected points in time and heat release rates for projected beam type smoke detector evaluation

<table>
<thead>
<tr>
<th>HRR (kW)</th>
<th>60</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>145</td>
<td>185</td>
<td>230</td>
<td>260</td>
<td>290</td>
<td>415</td>
</tr>
</tbody>
</table>

14.2 CEILING MOUNTED SPOT TYPE DEVICE PERFORMANCE EVALUATION

For each scenario, the four-spot type smoke detector optical densities at each incremental radial distance were averaged. Table 12 shows the optical density averages for each increment between 5 m and 7 m between 230 and 300 seconds. The predicted optical densities exceeding 0.215 m$^{-1}$ are shown in red. From the table, radial progression of the ceiling jet with time can be observed. At 230 seconds none of the devices located or beyond 5 m (16.4 ft) saw detectable optical density. At 260 seconds, detectable density was seen at 5 m (16.4 ft). Within 40 seconds all the devices up to 6.75 m (22 ft) saw the detectable optical density.
### Table 12. Optical smoke density (1/m) between 5 m and 7 m from the plume centerline between 230 and 300 seconds for then10 ft ceiling scenario. Smoke values exceeding 0.25 m\(^{-1}\) in red.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>5.0 m</th>
<th>5.25 m</th>
<th>5.5 m</th>
<th>5.75 m</th>
<th>6.0 m</th>
<th>6.25 m</th>
<th>6.5 m</th>
<th>6.75 m</th>
<th>7.0 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>0.180</td>
<td>0.172</td>
<td>0.169</td>
<td>0.167</td>
<td>0.165</td>
<td>0.165</td>
<td>0.164</td>
<td>0.162</td>
<td>0.157</td>
</tr>
<tr>
<td>235</td>
<td>0.201</td>
<td>0.192</td>
<td>0.186</td>
<td>0.180</td>
<td>0.173</td>
<td>0.167</td>
<td>0.163</td>
<td>0.160</td>
<td>0.153</td>
</tr>
<tr>
<td>240</td>
<td>0.198</td>
<td>0.190</td>
<td>0.184</td>
<td>0.178</td>
<td>0.171</td>
<td>0.165</td>
<td>0.160</td>
<td>0.155</td>
<td>0.149</td>
</tr>
<tr>
<td>245</td>
<td>0.184</td>
<td>0.180</td>
<td>0.178</td>
<td>0.174</td>
<td>0.170</td>
<td>0.165</td>
<td>0.163</td>
<td>0.163</td>
<td>0.160</td>
</tr>
<tr>
<td>250</td>
<td>0.197</td>
<td>0.187</td>
<td>0.182</td>
<td>0.179</td>
<td>0.175</td>
<td>0.169</td>
<td>0.164</td>
<td>0.160</td>
<td>0.153</td>
</tr>
<tr>
<td>255</td>
<td>0.203</td>
<td>0.199</td>
<td>0.198</td>
<td>0.195</td>
<td>0.188</td>
<td>0.183</td>
<td>0.179</td>
<td>0.175</td>
<td>0.170</td>
</tr>
<tr>
<td>260</td>
<td>0.216</td>
<td>0.203</td>
<td>0.194</td>
<td>0.186</td>
<td>0.179</td>
<td>0.173</td>
<td>0.171</td>
<td>0.169</td>
<td>0.163</td>
</tr>
<tr>
<td>265</td>
<td>0.227</td>
<td>0.217</td>
<td>0.212</td>
<td>0.206</td>
<td>0.197</td>
<td>0.189</td>
<td>0.183</td>
<td>0.177</td>
<td>0.169</td>
</tr>
<tr>
<td>270</td>
<td>0.223</td>
<td>0.214</td>
<td>0.210</td>
<td>0.205</td>
<td>0.200</td>
<td>0.191</td>
<td>0.185</td>
<td>0.181</td>
<td>0.174</td>
</tr>
<tr>
<td>275</td>
<td>0.248</td>
<td>0.240</td>
<td>0.234</td>
<td>0.226</td>
<td>0.214</td>
<td>0.205</td>
<td>0.198</td>
<td>0.194</td>
<td>0.186</td>
</tr>
<tr>
<td>280</td>
<td>0.255</td>
<td>0.241</td>
<td>0.234</td>
<td>0.226</td>
<td>0.219</td>
<td>0.213</td>
<td>0.209</td>
<td>0.207</td>
<td>0.202</td>
</tr>
<tr>
<td>285</td>
<td>0.245</td>
<td>0.237</td>
<td>0.231</td>
<td>0.225</td>
<td>0.218</td>
<td>0.208</td>
<td>0.204</td>
<td>0.199</td>
<td>0.193</td>
</tr>
<tr>
<td>290</td>
<td>0.226</td>
<td>0.218</td>
<td>0.213</td>
<td>0.209</td>
<td>0.205</td>
<td>0.202</td>
<td>0.199</td>
<td>0.196</td>
<td>0.191</td>
</tr>
<tr>
<td>295</td>
<td>0.255</td>
<td>0.246</td>
<td>0.239</td>
<td>0.232</td>
<td>0.224</td>
<td>0.217</td>
<td>0.212</td>
<td>0.208</td>
<td>0.200</td>
</tr>
<tr>
<td>300</td>
<td>0.259</td>
<td>0.248</td>
<td>0.244</td>
<td>0.240</td>
<td>0.233</td>
<td>0.227</td>
<td>0.222</td>
<td>0.217</td>
<td>0.209</td>
</tr>
</tbody>
</table>

The rows highlighted in yellow are selected points in time (Table 10) where the device locations achieving the threshold optical density were collected. Using this methodology all the scenarios were evaluated for ceiling mounted device locations that achieved the threshold optical density.

The ceiling device radial distances from plume centerline were then translated into corresponding device spacing. Considering the device radial distance as the base of an Isosceles right triangle, the device spacing was the hypotenuse of the triangle. Table 13 shows the device spacings that provide successful detection at selected points in time and heat release rates.
Table 13. Optical device spacing meeting performance criteria at selected points in time / heat release rates.

<table>
<thead>
<tr>
<th>Ceiling Heights (ft)</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>260</th>
<th>500</th>
<th>760</th>
<th>1000</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points in Time (s)</td>
<td>185</td>
<td>230</td>
<td>260</td>
<td>300</td>
<td>415</td>
<td>510</td>
<td>585</td>
<td>720</td>
</tr>
<tr>
<td>10 ft</td>
<td>13</td>
<td>19</td>
<td>23</td>
<td>30</td>
<td>43</td>
<td>43</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>15 ft</td>
<td>9</td>
<td>14</td>
<td>17</td>
<td>24</td>
<td>37</td>
<td>43</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>20 ft</td>
<td>8</td>
<td>14</td>
<td>17</td>
<td>23</td>
<td>37</td>
<td>43</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>25 ft</td>
<td>8</td>
<td>14</td>
<td>17</td>
<td>23</td>
<td>37</td>
<td>43</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>30 ft</td>
<td>6</td>
<td>10</td>
<td>14</td>
<td>20</td>
<td>37</td>
<td>43</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>35 ft</td>
<td>0</td>
<td>8</td>
<td>10</td>
<td>17</td>
<td>35</td>
<td>43</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>40 ft</td>
<td>0</td>
<td>6</td>
<td>9</td>
<td>13</td>
<td>28</td>
<td>41</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>45 ft</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>8</td>
<td>15</td>
<td>35</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>50 ft</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>17</td>
<td>29</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>55 ft</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>28</td>
<td>34</td>
<td>43</td>
</tr>
<tr>
<td>60 ft</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>19</td>
<td>28</td>
<td>34</td>
<td>43</td>
</tr>
</tbody>
</table>

In Table 13, the shades of green are used to color the cells, to indicate the spacing modification that is necessary for each ceiling height to detect the fire at a smoke optical density threshold of 0.215 m⁻¹. The shade lightens as the spacing is reduced. Based on Table 13 the following key observations were noted.

1. In the early development of the fire, the smoke was detectable very close to the fire location, both vertically and horizontally. At 185 seconds when the heat release rate was 100kW, the fire was detectable at 13 ft (4 m) spacing in the 10 ft (3 m) ceiling space.

2. As the ceiling height increases, the ability to detect smoke reduces. At 100-kW, the fire was not detectable beyond a 30 ft (9.15 m) ceiling height. For a 30 ft (9.15 m) ceiling height the threshold smoke level was detectable only at 6 ft (1.8 m) spacing.
3. At later times when the fire size was larger, threshold smoke optical density was detectable at higher ceilings and with further detector spacing. For example, a 760-kW fire was detectable at 60 ft (18.3 m) ceiling, at 28 ft (8.5 m) radial distance from the plume centerline, and all the other ceiling scenarios.

Based on these findings, the following two options are explored as recommendations for spot type smoke detector spacing on ceilings higher than 10 ft.

14.2.1 Option 1: Reduced Spacing

Option 1 is using the same approach as how NFPA 72 developed the heat detector spacing reduction table used for ceilings higher than 10 ft. This method entails developing a spacing reduction factor to offset for the high ceiling conditions that impact plume and ceiling jet transport.

For the 10 ft (3 m) ceiling height scenario, using NFPA 72 compliant detection design of 30 ft (9.14 m) spacing, detection occurred at 300 seconds when the heat release rate was 260-kW. If all the successful device spacings (maximum for each ceiling height scenario) at 300 seconds or 260-kW are plotted against the ceiling heights, a straight-line curve can be drawn as shown in Figure 55. The fire scenarios were detectable in 45 ft (13.7 m) and 50 ft (15 m) ceiling heights by 300 seconds, but the spacing necessary to detect at these heights was less than 10 ft (3 m) and were not used as these are considered impractical.

![Figure 55. Successful maximum spot type detector spacing for ceiling heights between 10 and 40 ft that meet the threshold optical density of 0.215 m⁻¹ for a 260-kW fire.](image-url)
The equation of the straight-line curve fit is shown in Figure 55. By rounding up the gradient and the intercept, the following equation was derived –

\[ x = \frac{70 - y}{2} \]

Where, \( x \) = detector spacing (ft)  
\( Y \) = ceiling height (ft)

Using this equation, spot type detector spacing for ceiling heights higher than 10 ft up to and including 40 ft was derived and shown in Table 14.

Table 14. Reduced smoke detector spacing for high ceilings based on a 260-kW fire and a detection threshold of 0.215 m\(^{-1}\).

<table>
<thead>
<tr>
<th>Ceiling height (ft)</th>
<th>Spot type detector spacing (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>27.5</td>
</tr>
<tr>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>25</td>
<td>22.5</td>
</tr>
<tr>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>35</td>
<td>17.5</td>
</tr>
<tr>
<td>40</td>
<td>15</td>
</tr>
</tbody>
</table>

The spacing reduction would reduce time to detection in high ceiling spaces and would decrease likelihood of severe consequences that could jeopardize occupant and property protection. In 40 ft (12.2 m) ceiling height scenario, using 30 ft spacing yielded a detection time of 415 seconds. With a detector spacing of 15 ft (4.6 m) the fire was detected at 310 seconds. The reduction in spacing would save 105 seconds of detection time, that could be used to initiate early evacuation or emergency response.

14.2.2 Option 2: Increased Detection Time / Heat Release Rate Tolerance

The second option is based upon the questioning the premise of using a fixed heat release rate and detection time threshold as the basis to smoke detection design for high ceiling spaces. Section 11.0 touched on the goals and objectives of model building and fire codes. Qualitatively it was assessed that, heat release rate and detection time tolerance could be increased for high ceilings because of the increased distances to the structural
beams from fire location and additional volume that allows the smoke to fill before the tenability conditions are exceeded.

From Table 13, in 10 ft (3 m) ceiling height scenario a 30 ft (9.14 m) smoke detector spacing achieved detection at 300 seconds when the heat release rate was 260 kW. For ceiling heights higher than 10 ft (3 m) it took longer but did not exceed 500kW or 415 seconds to reach activation for ceiling heights up to 40 ft (12.2 m). Even for higher ceilings up to 60 ft (18.3 m) detection was achieved at 760 kW heat release rate or detection time of 510 seconds. The 30 ft (9.14 m) detector spacing allows increase in heat release rate and detection time with ceiling height increase, which is justifiable, because time for smoke filling and hot plume to reach the ceiling structure in high ceiling spaces would allow such tolerances.

This however assumes that the occupants are on the ground. If this is an atrium and occupants are egressing from upper floors the later detection could affect the occupants as they would be in the reservoir for a longer period. Secondly, at least the IBC acknowledges that one of the objectives of fire protection (in this case, detection) is to provide a reasonable level of safety to the fire department. The difference between larger fire sizes (500 or 760 kW) at detection vs. 260 kW could be meaningful to those that must ultimately manage and suppress the fire.

14.3 PROJECTED BEAM TYPE DEVICE PERFORMANCE EVALUATION

Like Table 13, Table 15 is developed using averaged obscuration predictions from FDS. The device spacings achieving 90% obscuration at the selected points in times/heat release rates are provided in Table 15.
Like the spot type smoke detector evaluation, beam spacing had to be reduced with ceiling height to detect fire within 145 seconds or 60 kW, which was the benchmark performance derived from the 10 ft (3 m) ceiling height scenario. The 60 ft (18.3 m) spacing was able to detect fire for all ceiling heights up to 60 ft (18.3 m) within 415 second detection time or 500 kW heat release rate.

For the 10 ft (3 m) ceiling scenario, a 60 ft (18 m) spacing provided a 90% obscuration detection time of 145 seconds when the fire reached 60 kW. A detection time of 145 seconds for ceiling heights higher than 10 ft can be maintained by adding more beams or reducing spacing horizontally. Figure 56 shows the successful maximum beam spacings to achieve 90% obscuration detection within 145 seconds (i.e., when the fire reaches 60 kW). A straight-line curve fit is drawn for successful maximum spacing up to 40 ft. Ceiling heights of 45 ft (13.7 m) and above took longer than 145 seconds to achieve detection.

### Table 15. Beam detection spacing meeting performance criteria at selected points in time / heat release rates.

<table>
<thead>
<tr>
<th>Ceiling heights (ft)</th>
<th>Heat release rate (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td>Points in time (s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>145</td>
</tr>
<tr>
<td>10 ft</td>
<td>61</td>
</tr>
<tr>
<td>15 ft</td>
<td>57</td>
</tr>
<tr>
<td>20 ft</td>
<td>57</td>
</tr>
<tr>
<td>25 ft</td>
<td>48</td>
</tr>
<tr>
<td>30 ft</td>
<td>26</td>
</tr>
<tr>
<td>35 ft</td>
<td>21</td>
</tr>
<tr>
<td>40 ft</td>
<td>20</td>
</tr>
<tr>
<td>45 ft</td>
<td>0</td>
</tr>
<tr>
<td>50 ft</td>
<td>0</td>
</tr>
<tr>
<td>55 ft</td>
<td>0</td>
</tr>
<tr>
<td>60 ft</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 56. Successful maximum beam detector spacing for ceiling heights between 10 and 40 ft that meet the threshold obscuration of 90% for a 60-kW fire.

The equation shown on Figure 56 can be simplified by rounding up the gradients and y-intercept. The following equation provides the beam detector spacing to maintain a 145 second detection time to a slow growth t-squared fire with a detection criterion of 90% obscuration.

\[ x = \frac{50 - y}{0.5} \]

Where, \( x \) = beam spacing (ft)
\( y \) = ceiling height (ft)

This equation can be applied for ceiling heights from 10 ft up to 40 ft. Table 16 shows the beam spacings derived for every 5 ft ceiling increments using the equations.
Table 16. Successful beam spacing based upon curve fit equation.

<table>
<thead>
<tr>
<th>Ceiling height (ft)</th>
<th>60 KW</th>
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14.4 BELOW CEILING BEAM DETECTION PERFORMANCE EVALUATION

For the fire scenarios analyzed, the stratification was a dynamic phenomenon. As the heat release rate grew, the elevation and intensity of stratification changed. Figure 57, Figure 58, Figure 59 and Figure 60 shows the progression of smoke layer stratification through time in 60 ft (18.3 m) ceiling height scenario. Smoke started stratifying at 40 ft (12.2 m) elevation at 200 seconds, when the heat release rate was 120 kW. By 300 seconds, it already started to recede from 40 ft (12.2 m) and started to stratify at 46 ft (14 m) elevation. Between 400 and 500 seconds, there seemed to have developed a cloud of stagnant smoke between 45 ft (13.7 m) and 55 ft (16.8 m) outside the plume region, right below the ceiling jet. It slowly dissolved into the air by around 600 seconds, when the heat release rate was 1,054 kW.
Figure 57. Smoke stratification at 40 ft (12.2 m) elevation at 200 seconds (heat release rate 120-kW)
Figure 58. Smoke stratification between 45 ft (13.7 m) and 50 ft (15.2 m) at 300 seconds (heat release rate 260-kW)
Figure 59. Stagnant smoke layer between 45 ft (13.7 m) and 55 ft (16.8 m) at 500 seconds (heat release rate 730 kW)
From the analysis, the success of having beam detectors at every 10 ft (3 m) vertical spacing was evaluated. Figure 61 shows the total obscuration predictions from beam detectors located at 30 ft (9m), 40 ft (12 m), 50 ft (15 m) and 8 in. (0.2 m) below the ceiling, at 60 ft (18.3 m) spacing. From Figure 61, the stratified smoke layer at 40 ft (12.2 m) elevation barely reached the 90% obscuration threshold needed for detection. The device at 50 ft (15.2 m) below the ceiling reached 90% obscuration threshold at the same as the device at the ceiling did. This indicates that, 10 ft (3 m) vertical spacing with 60 ft (18.3 m) spacing added no benefit. Either the obscuration was not enough, or obscuration threshold was reached at the same time as the detectors on the ceiling.
Detection chances can be slightly improved by reducing the spacing to 30 ft (9.15 m) and having beams every 10 ft (3 m) vertically. **Figure 62** shows the beam obscuration predictions from 60 ft (18 m) ceiling scenario for 30 ft (9.15 m) horizontal beam spacing located at 30 ft (9 m), 40 ft (12.2 m), 50 ft (15.2 m) and 8 in. (0.2 m) below the ceiling.

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**Figure 61.** Total obscuration predictions at 30 ft (9.14 m), 40 ft (12.2 m), 50 ft (15.2 m), and ceiling from 60 ft (18.3 m) ceiling scenario. Devices at 60 ft (18.3 m) horizontal spacing.
Figure 62. Beam obscuration prediction at 30 ft (9.1 m), 40 ft (12.2 m), 50 ft (15.2 m) and ceiling from 60 ft (18.3 m) ceiling scenario. Devices located at 30 ft (9.1 m) horizontal spacing.

From Figure 62, the beam located at 30 ft (9.15m) elevation clearly did not see any detectable amount of obscuration. And as such, for the scenario analyzed there is no benefit in having detectors more than 20 ft (6 m) below the ceiling.

Device at 40 ft (12.2 m) elevation achieved detectable threshold at 200 seconds, followed by the device at the ceiling which saw detectable threshold only 25 seconds after the device at 40 ft (12.2m) elevation. This indicates that providing additional layer of beam devices below the ceiling may yield somewhat limited benefit.

Rather reducing the spacing at the ceiling saved considerable amount of detection time. 60 ft (18.3m) beam spacing activated at 310 seconds (Figure 58), whereas 30 ft (9.14 m) spacing activated at 245 s (Figure 59), reducing detection time by 65 seconds.

The other option to detect stratified smoke layer is by having the transmitter and reflector/receiver at different elevation such that the beams are at angle to vertical and horizontal axis. This option was not explored under this study.
15.0 Critical Assumptions and Limitations

The following assumptions were used in this analysis. Limitation of each assumption is discussed below –

15.1 PERFORMANCE CRITERIA

15.1.1 Detection Time

The analysis uses a detection time of 300 seconds for spot type smoke detector and 145 seconds for beam detectors, that was derived from acceptable spacing in 10 ft (3 m) ceiling height scenario. This performance criteria fails to acknowledge that high ceiling spaces by the virtue of its reservoir effect and distance of structural systems from the fire location gains an advantage to achieving occupant safety and property protection goals better than a low ceiling space with all the similar attributes. And as such comparing and attaining performance criteria based upon detection in 10 ft (3 m) ceiling space may not be reasonable.

Even though the analysis uses NFPA 72 compliant detection design in 10 ft ceiling height as the acceptable performance, the study does not intend to prove or validate that such design will meet the occupant safety and property protection goal required by the building and fire codes.

15.1.2 Detection Threshold

The performance criteria for spot type devices uses an optical density prediction of 0.215 m⁻¹ at device location. This is a simplified approach that does not consider smoke entry resistance to the detector chamber. The selected threshold is considered conservative enough to take entry resistance into account.

The study acknowledges that there is variation in optical density due to color of smoke and fuel type. Available detection technologies listed based on UL268 sensitivity and fire tests would be activated at different optical densities for different fuel types that are not consistent with the threshold optical density used in this analysis. The analysis considers a conservative optical density threshold collected from published research that is attributed to 80% detection success rate over broad range of detector manufacturers (Geiman and Gottuk 2003).

Beam detection obscuration threshold of 90% is based upon a 60 ft beam length. The study acknowledges that there are beam detectors available in the market that are more sensitive and can operate over much longer beam lengths.

15.1.3 Model Bias

FDS model bias is a significant limitation in this study. The general trend observed was that FDS underpredicted the optical density in near field region and over predicted in the far field region. And so optical density would be higher than prediction in the low ceiling heights and lower than prediction as we increase the ceiling height. The other unknown is that we don't know how optical density model bias would change with increasing fire size. It could be that with increase in fire size the optical density bias will be more uniform throughout. But we don't know that.

A model bias factor of 1.43 has been considered in this study on the FDS prediction of optical density. The team acknowledges that previous study on this phase have found indication of inconsistent biases as the device is
moved further away from the fire. Further study is needed on FDS model development and improvement on smoke extinction coefficient calculation mechanism and reduce model bias in the far field regions.

Also, the model bias factor 1.43 was calculated based on experiments performed using steady state 100-kW fires. Certainty of FDS ability to predict optical density for chosen fire size/type is unknown.

15.2 FIRE SCENARIOS

15.2.1 Ceiling Heights

The analysis was limited to ceiling height up to 60 ft. Additional study or performance-based analysis must be performed for ceiling heights higher than 60 ft.

15.2.2 Ceiling Conditions

The analysis was limited to flat level ceiling with no features to contain or obstruct ceiling jet flows. The existing prescriptive requirements in NFPA 72 applicable to beams, slopes and other ceiling features could be used in high ceiling context. But this analysis did not study the usefulness, impacts, or limitations of those requirements in the context of high ceiling.

The analysis was limited to unconfined ceiling. Existing NFPA 72 requirements applicable to corridor smoke detection can still be used for high ceiling context. But this study did not explore the usefulness, impacts, or limitations of those requirements in the context of high ceiling.

15.2.3 Ambient Temperature

The analysis considered a linear temperature gradient condition with increase in temperature of 1°F/ft (1.8°C/m) in the direction towards the ceiling. The temperature at the floor up to the height of 10 ft (3 m) was modeled as 68°F (20°C). For buildings with a step temperature change or temperature gradient higher than 1°F/ft (1.8°C/m) may have a different stratification profile than that observed in this study, especially if a fire reaches steady state or has a different power growth factor than the one anticipated in this study.

15.2.4 Ambient Airflow

The ambient air velocity in the computational domain was 0 ft/s (0 m/s). Impact of mechanical or forced ventilation was not explored in this study. There is some guidance in NFPA 72 that can be used even for high ceiling context. But this study did not explore the usefulness, impact, or limitations of those guidance.

15.2.5 Detection type

The analysis was limited to spot type smoke detection and linear beam type smoke detection devices that do not actively move air to detect soot particles. The study did not address air-sampling type detection.

15.2.6 Detection Design

Spot type detection devices were placed at the ceiling at every 10 in. (0.25 m) interval. Beam detectors were placed 8 in. (0.2 m) below the ceiling at every 10 in. (0.25 m) interval. Additionally beam detector placements at every 10 ft (3 m) vertical intervals were analyzed. The analysis did not explore inclined beam detection (receiver and transmitter at different elevation). Further study should be performed to evaluate performance of such design.
16.0 Recommendations

The following recommendations have derived from this study.

16.1 GENERAL RECOMMENDATIONS

+ A goal must be established by the NFPA 72 specific to smoke-sensing devices that aligns with the goals and objectives of the building and fire code. The goal should be translatable to performance objectives and performance criteria that can be used to evaluate detection design.

+ A standard for smoke sensing detection performance criteria needs to be developed that is independent of the test standard used for listing of the devices. The performance criteria should be quantifiable and versatile so that it can be applied in device testing and listing application, modeling and performance-based design, and device installation and commissioning.

+ In current NFPA 72, there is a confusion about projected beam type smoke detection spacing. The prescriptive requirement is to consider each beam like a row of spot type detectors and to use the spacing requirements specified for spot type detectors. Using this requirement results beam spacing of 30 ft for level ceiling. There is a non-enforceable Annex section expanding on this requirement. The Annex allows beam spacing up to 60 ft. Available manufacturer’s cutsheets and technical manuals also uses 60 ft as the maximum beam spacing. The enforceable part of the code should be reevaluated to align with the manufacturer’s listing requirements and provide a consistent spacing guideline.

+ Continued development of FDS is recommended to bring optical density, detection time and obscuration prediction model biases closer to 1. Additional testing is necessary for validation and improvement of FDS. Consistency is needed between smoke concentration measurements and predictions in near field and far field regions. Testing and validation should also look at varying fire sizes and fuel types.

16.2 PRESCRIPTIVE GUIDANCE TO PERFORMANCE-BASED DESIGN

Currently, NFPA 72 requirement for stratification consideration does not include a prescriptive threshold. A prescriptive threshold is recommended to be included either by ambient temperature difference or by ceiling height. The study indicated that in general the plume can overcome temperature difference of 30°F (17°C) even for the smallest credible fire. Beyond 30°F (17°C) the plume requires more energy to overcome stratification. The recommendation is to change the code to require performance-based design when temperature difference between the floor and ceiling is expected to exceed 30°F (17°C).

The other option would be to specify a ceiling height threshold. Based on the temperature gradient used in this study, at 40 ft smoke is observed to stratify for smallest credible fire. So, the recommendation is to change the code to require performance-based design for ceiling heights exceeding 40 ft.

16.3 SPACING REDUCTION FOR HIGHER CEILINGS

16.3.1 Spot Type Device Spacing Recommendation

This recommendation acknowledges that even in high ceiling spaces reduced detection time could be useful and contributing factor to occupant and property protection. And as such following equation is proposed to regulate smoke detector spacing in ceilings higher than 10 ft (3 m) up to and including 40 ft (12 m).
\[ x = \frac{70 - y}{2} \]

Where, \( x \) = spot type detector spacing (ft)
\( Y \) = ceiling height (ft)

This equation allows a spacing of 30 ft (9.14 m) for 10 ft (3 m) ceiling height. With increase in ceiling height the spacing is reduced by 2.5 ft (0.76 m) for every 5 ft (1.5 m) increase. At 40 ft (12 m) ceiling height, the smoke detector spacing is proposed to be 15 ft (4.5 m). For ceiling heights higher than 40 ft (12 m), performance-based design should be performed as allowed by NFPA 72. Placing detectors at varied elevations below the ceiling as an alternative measure must be avoided.

### 16.3.2 Projected Beam Detector Spacing Recommendation

Like spot type detectors, the beam detector spacing is recommended to be reduced for ceiling heights between 20 ft (6 m) and 40 ft (12 m). The equation derived from the study is as follows -

\[ x = \frac{50 - y}{0.5} \]

Where, \( x \) = beam detector spacing (ft)
\( Y \) = ceiling height (ft)

This would allow 60 ft (18 m) beam spacing for ceiling height up to 20 ft (6 m). The spacing would reduce by 6.67 ft (2 m) for every 5 ft (1.5 m) increase in ceiling height. Spacing for 40 ft (12 m) ceiling height would be 20 ft (6 m) between the beams. For ceiling heights more than 40 ft (12 m), performance-based design is recommended.

### 16.3.3 Allowance for Performance-based Design

High ceiling spaces are found in large rooms that create a volume of air that contains smoke in the upper layer. There is a correlation between high ceilings with large rooms and the RSET where occupants are not expected to occupy the upper layer early in a fire scenario. Establishing this correlation could inform the size of fire that might be able to be compared to size of fire in a smaller room with a low ceiling that would give an equivalent RSET. This may lead to detector spacing that can be used for higher ceilings in larger rooms with an allowance for longer detection times (to account for transport times) and larger fires. A fire alarm designer should be allowed the option to modify the prescriptive spacing based on performance-based analysis.

### 16.4 ALTERNATIVE RECOMMENDATION CONSIDERING REDUCED RISK

This recommendation considers the advantages of high ceiling spaces over the low ceiling that allows additional time to smoke filling and lower plume temperature exposure to ceiling structure. The study indicated that using a 30 ft (9.15 m) spacing for spot type and 60 ft (18.3 m) for beam type, detection was achieved in higher ceilings within time and heat release rates that are considered reasonably safe for such spaces. The current NFPA 72 spacing requirements can be applied to high ceiling spaces. Even though the detection time would increase along with heat release rate for a growing fire before the fire is detected, such increase is far from overwhelming the occupant or property protection performance threshold.
This however assumes that the occupants are on the ground. If this is an atrium and occupants are egressing from upper floors the later detection could affect the occupants as they would be in the reservoir for a longer period. Secondly, at least the IBC acknowledges that one of the objectives of fire protection (in this case, detection) is to provide a reasonable level of safety to the fire service. The difference between larger fire sizes (500 or 760 kW) at detection vs. 260 kW could be meaningful to those that must ultimately manage and suppress the fire.
17.0 Acknowledgement

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