Smoke Detector Spacing for High Ceiling Spaces

FINAL REPORT BY:

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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 higher ceilings. There is a need for clarification on how to apply smoke detection spacing requirements. To provide guidance, the Technical Committee needs additional information on the impact of ceiling height and detector spacing on smoke detection performance.

The Research Foundation initiated this project to review available literature and standards and perform a gap analysis related to the impact of ceiling height and detector spacing on smoke detection performance to inform the NFPA 72 Technical Committee.

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The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

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Keywords: smoke detection, NFPA 72, high ceilings, smoke detector spacing

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Executive Summary

NFPA 72, National Fire Alarm and Signaling Code, sets forth requirements for the application, installation, performance and inspection/testing/maintenance of fire alarm and emergency communications systems as well as their related components. As part of these requirements, NFPA 72 specifies location and spacing criteria for smoke detectors. Unlike the spacing reduction for heat detectors that is required based on ceiling height, NFPA 72 does not address spacing considerations for smoke detectors based on ceiling height. There is inconsistency in design and code enforcement for spacing requirements of smoke detectors when installed in areas with high ceilings, where high ceilings are defined as over 10 feet in height. Clarification is required in NFPA 72 on how to apply smoke detection spacing requirements for these high ceiling applications. To assist in justifying the code change (as applicable), the NFPA 72 technical committee needs additional information on the impact of ceiling height and detector spacing on smoke detection performance.

Detection devices perform an important function by providing warning for building occupants so that they are aware of a fire in time to allow for safe egress; however, a performance metric for a significant fire challenge or an acceptable response time is not clearly defined in NFPA 72. The 30 foot (9.1 meter) nominal spacing currently used for smoke detector spacing is defined by the NFPA 72 handbook as being "…adequate to achieve the life safety objectives implied by the building codes…", however the fire challenge(s) this protects is not explicitly defined. [1]

There is a body of research, including standard fire tests, non-standard fire tests, and computer modelling, which have studied smoke detector performance in high spaces (see Section 2.2); however, the central problem is that it is difficult to achieve consistency in identifying the smoke detector performance. Smoke detectors are tested in accordance to ANSI/UL 268 *Standard for Smoke Detectors for Fire Alarm Systems*, which specifies that sensitivity meet a minimum obscuration level measured using smoke generated from either a smoldering cotton lamp wick or an aerosol generator. [2] The sensitivity standard can compare one device to another, but it cannot provide guidance as to how the spacing in the built environment will affect the smoke detector performance.

Some countries have included maximum ceiling heights with respect to detector types, while others codify general approaches to high ceiling spaces. British Standards and Ireland Regulations include tables for numerous types of detectors. Codes from Australia, France, Germany, and the Netherlands, provide guidance to a certain height and require additional detection to be added at designated heights (see Section 2.1).

The content of this review of the impact of ceiling height and detector spacing on smoke detection performance will follow the proposed project tasks. The literature review gathered related information around the following focus areas.

- NFPA 72 requirements (including review of past editions of NFPA 72 and the technical basis for relevant smoke and heat detector spacing requirements for high ceiling applications) [Section 1]
- Requirements of other non-NFPA fire alarm codes/standards from around the world (i.e. fire alarm codes outside the United States, etc.) and the respective basis for smoke and heat detector spacing requirements for high ceiling applications [Section 2.1]
- Literature review on key research reports and studies [Section 2.2]
- Available literature on related fire dynamics modeling (computer modeling, detector entry modelling, detection modeling) and fire testing and data [Section 3]
- Available fire alarm manufacturer literature for spacing requirements for specific products and the associated justification as well as detector technology.

The outcomes of this review indicates that there is limited context and significant gaps in knowledge that preclude the formulation of scientifically justified prescriptive requirements regarding smoke detectors relative to ceiling height (see Section 4). Additional work is required to ensure that there is an appropriate scientific and engineering basis for future code requirements.

To resolve the gaps found a research plan has been formulated, which provides a path forward to better characterize the smoke detection spacing in high ceiling spaces (see Section 5). One of the imperatives for establishing the smoke detectors in high spaces is establishing the performance metric for smoke detectors along with other stakeholders, which can be applied towards higher ceilings. This would involve identifying either (a.) a generic set of design fires (i.e. range of combustibles, range of fire-growth rates, etc.) through which detector performance can be assessed, or (b.) developing a time by which smoke detectors need to respond to provide a tenable environment for occupants.

1 Review of Relevant NFPA 72 Requirements

NFPA 72 is a standard that has been in development for more than a century, with the first versions of the standard (NFPA 71-D) written in 1899. [1] The current version of the code was issued in 2016 and represents the longtime development and synthesis of research that has come together to develop prescriptive requirements for fire alarms. The NFPA 72 Handbook describes that the code requirements are "…intended to provide the minimum criteria sufficient to fulfill generally accepted response expectations. However, the Code does not quantify those response expectations." [1] As a result, this research was conducted to develop a method through which equivalent performance can be determined by investigating the historical basis of the requirements as well as reviewing relevant literature.

1.1 NFPA 72 Heat Detection Requirements

While the focus of this literature review is on smoke detectors, heat detectors are relevant to the discussion as there is currently guidance for heat detector spacing relative to ceiling height. To assist in the understanding of what would be necessary to implement a similar requirement for smoke detectors, it is useful to understand the historical context and basis for heat detectors relative to the prescriptive code.

To determine the spacing of heat detectors, full-scale tests are performed where the heat detectors are arranged in a square pattern. The basis for this approach takes into account that it is not known where a fire will begin, so the test considers a fire in the center of a square grid. It should be noted that the ceiling height used during these tests is 15' - 9" (4.8 meters), with no airflow, and the test sprinklers having an activation temperature of 160°F (71.1°C). The 1,138 BTU/sec (1,200 kW) ethanol/methanol fire is ignited and the greatest heat detector spacing which activates before a sprinkler activates is the listed spacing of the heat detector. [1]

This standard test is used to assign a heat detector with a relative indication of its thermal response, with a number of variables being considered during this test (i.e. fire size, fire growth rate, ambient temperature, ceiling height, and RTI). The test typically provides activation within ~2 minutes 10 seconds. [1]

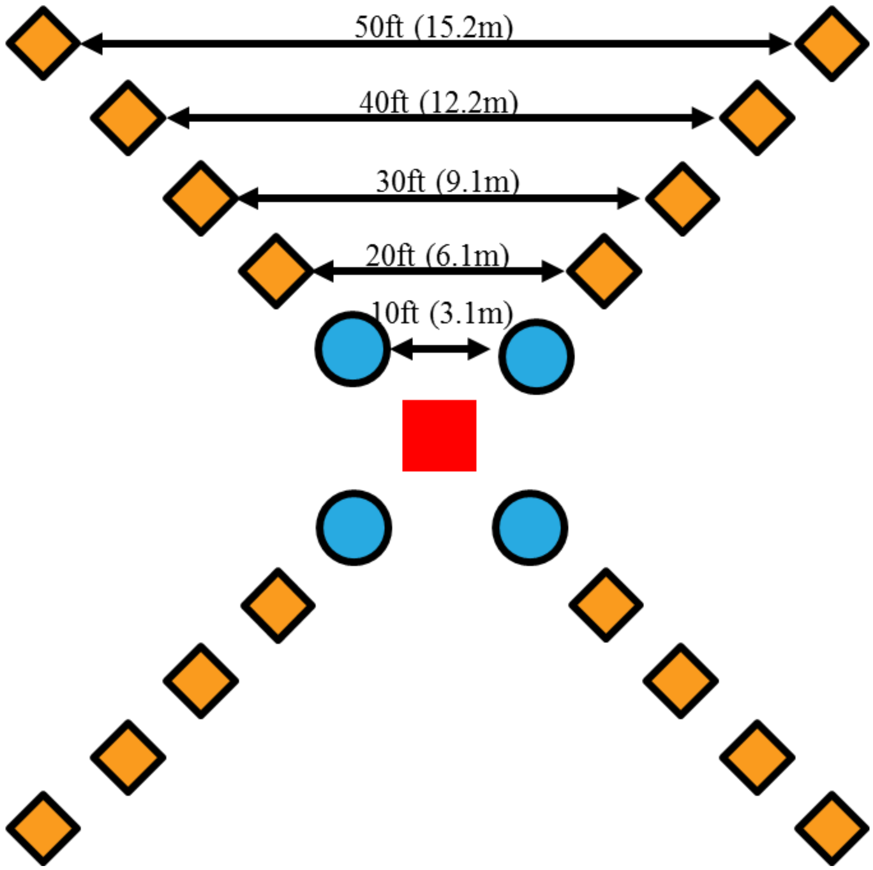

Figure 1: Heat Detector testing arrangement. The blue circles represent sprinklers whereas the orange diamonds represent the heat detectors. An 1138 BTU/sec (1,200 kW) ethanol/methanol fire is ignited. The greatest detector spacing that produces an alarm before a sprinkler actuates is the listed spacing for the detector. [1]

For ceiling heights higher than 10 ft. (3 m) the detector spacing is required to be reduced. As the ceiling height increases, the plume rises, mixing with additional cooler air, affecting its buoyancy and temperature and therefore the time when the heat detector would activate. To achieve roughly equivalent times to the testing, conducted at a ceiling height of 15’-9” (4.8 meters), a multiplier is prescribed to reduce the listed spacing of a given detector (see Table 1).

The basis for these multipliers was determined through experiments conducted by Heskestad and Delichatsios under National Bureau of Science grant Number NBS-GCR-77-95). [3] The research was reviewed by the NFPA 72 committee, but was considered too technical for inclusion in the prescriptive requirements. A working group from the Fire Detection Institute was formed to process the data and the table was included in the prescriptive requirements in 1982 [4].

Table 1: NFPA 72 Heat Detector Spacing Reduction Based on Ceiling Height [5]

Ceiling Height Greater Than		Ceiling Height Less Than Or Equal To		Multiply Listed Spacing By
(ft.)	(m)	(ft.)	(m)	
0	0	10	3	1
10	3	12	3.7	0.91
12	3.7	14	4.3	0.84
14	4.3	16	4.9	0.77
16	4.9	18	5.5	0.71
18	5.5	20	6.1	0.64
20	6.1	22	6.7	0.58
22	6.7	24	7.3	0.52
24	7.3	26	7.9	0.46
26	7.9	28	8.5	0.4
28	8.5	30	9.1	0.34

1.2 NFPA 72 Smoke Detection Requirements

The current code requirements for smoke detector spacing state that the maximum distance between detectors is a nominal 30 feet, and the distance between detectors must not exceed half of the nominal spacing measured from the wall or any partitions within the top portion of the ceiling height. The code also requires that at any location on the ceiling be within a maximum distance of 0.7 times the nominal spacing; however, there is no mention of ceiling height. [5] There is anecdotal evidence that the 30 feet spacing was decided upon by the NFPA 72 committee as this was the extent of lab space of the Factory Mutual Research Center where some of the testing was conducted. [4] The lack of a performance metric whereby the spacing requirement was determined is the principal gap from this research effort.

While there is no quantification of reduction of nominal spacing for high ceiling applications, NFPA 72 does require the effect of stratification below the ceiling to be considered. Additionally, the appendix to chapter 17 suggests mounting additional detectors below the height of the ceiling and considering use of beam type or aspirating type detectors at different levels. Furthermore, the commentary in the handbook suggests that when installing detectors at an elevation below the ceiling, the spread of smoke as a result of the ceiling jet may not be practical. Thus selection of the type of detection should consider alternatives to spot type detectors and spacing between detectors should be no less than 0.4 times the detector height above the floor (accounting for plume divergence). [1]

NFPA 72 provides additional guidance for ceilings, which are sloped or contain deep beams, joists, or other obstructions; however, for the purposes of this literature review the focus will be on smooth ceilings.

The primary variables considered in the NFPA 72 smoke detector spacing requirements are smoke flows, ceiling jets, ambient airflows and the heat release rate of a potential fire. Any of these factors could/ influence smoke detector performance and the ceiling height can have a strong impact on these variables as well. Increasing the ceiling height while maintaining the same spacing would predictably lead to a longer detection time.

2 Review of Relevant Literature

2.1 Overview of Global Codes & Standards

Some international standards do contain requirements for maximum ceiling height in which smoke detectors can be applied. Chaggar compared smoke detector limitations in high ceiling spaces in codes from different countries to show that height limitations for particular types of detectors are required by some codes. [6]

Particularly, the UK provides a table recommending limits of ceiling height in BS5839 Part 1 (see Table 2). The standard recommends certain maximum ceiling heights that heat, smoke, and combustion gas detectors should be mounted on. The table also provides ceiling height limits for cases in which parts of the ceiling exceed the previous limits, given that the higher sections do not account for over 10% of the total ceiling area. [7]

Table 2: BS 5839-1: Limits of Ceiling Height [7]

Detector Type	**Generally Applicable Maximum Ceiling Height**	**For Sloped Ceilings - 10% of Ceiling Height No Greater Than:**
Heat Detectors		
Class A1	9.0m (29.5ft)	10.5m (34.4ft)
Other Classes	7.5m (24.6ft)	10.5m (34.4ft)
Point Smoke Detectors	10.5m (34.4ft)	12.5m (41.0ft)
Carbon Monoxide Detectors	10.5m (34.4ft)	12.5m (41.0ft)
Optical Beam Smoke Detectors		
Normal Sensitivity	25.0m (82.0ft)	28.0m (91.9ft)
Enhanced Sensitivity	40.0m (131.2ft)	43.0m (141.0ft)
Aspirating Detection System		
General Limit	10.5m (34.4ft)	12.5m (41.0ft)
Class C with at least 5 holes	15.0m (49.2ft)	18.0m (59.0ft)
Class C with at least 15 holes	25.0m (82.0ft)	28.0m (91.9ft)
Class B with at least 15 holes	40.0m (131.2ft)	43.0m (141.0ft)

Ireland also provides a table, nearly identical to that of the UK, in IS3218 that details what types of detectors are permitted to be used based on the ceiling height. [8] The restrictions in this table account for the increase in time to activate a detector as the ceiling height increases. Refer to Table 3 for maximum ceiling height limitations based on detector type from various global codes and standards.

The fire alarm installation codes from Canada specify a reduction in heat detector spacing as a function of ceiling height (3m (9.8 ft.) to 9m (29.5 ft.)) in a similar manner to NFPA 72. Although CAN/ULC-S524-06 does not require spot type smoke detector spacing to be reduced for ceiling height, the code requires on ceilings exceeding 3.6m (11.8ft), spacing shall be based on expected fire type, growth rate, engineering judgment and manufacturer’s recommendations. [9]

The review of international codes included BS 5839-1, VdS 2095, DIN VDE 0833-2, NEN 2535, R7, DBI 232, NFPA 72, AS 1670.1. [10] [11] [12] [7] [13] [8] [5] [14] The search for ceiling height limitations in other codes yielded results, with the ceiling height limitations in the codes are based upon the recommendations from the experts in the technical panels for the codes and standards listed. While recent testing on beam detector performance is starting to be included in the codes and standards, no direct link between testing and research papers and reports and the ceiling height limitations included in the code was discovered in this literature study.

Table 3: Summary of Requirements for Smoke Detector Ceiling Height Limitations

Country	Document	Year	Ceiling Height Limitation			Notes
			Point Type	Aspirator Type	Beam Type	
UK [7]	BS 5839-1	2013	Refer to Table 2			Other requirements for property protection are also stipulated
Germany [6]	VdS 2095	2010	12 m (39 ft.)	12 m (39 ft.)	16 m (52.5ft)	Ceiling heights exceeding 12 m (39 ft.) required a second level of detectors. Beams and aspirator type detection preferred when proved with fire test.
Germany [13]	DIN VDE 0833-2	2009	12 m (39 ft.)	20 m (65.6 ft.)	16 m (52.5ft)	Point detectors for ceilings heights of 12-16m (39 - 52.5 ft.) or use of beam detectors for ceiling heights of 16-29m (52.5- 95.1 ft.) requires fire test. Ceiling heights exceeding 20 m (65.6 ft.) require multiple layers of detectors.
Netherlands [15]	NEN2525+ C1	2010	12m (39 ft.)	45 m (147 ft.)	Single layer: 12m (39 ft.) Second layer: 25m (82 ft.)	Beam detectors at ceiling heights of 12-25 m (39–82 ft.) require a second layer detection. Point detectors for ceiling heights 12-16 m (39-52 ft.) requires a successful fire test demonstration. Aspirating detectors always requires a successful fire test demonstration.
France [6] [16] [17]	R7	2014	12 m (39 ft.)	12 m (39 ft.)	12 m (39 ft.)	For ceiling heights exceeding 12 m (39 ft.), 2 layers of detection may be needed pending the results of a risk analysis.
Denmark [6] [18] [19]	DBI 232	2016	-	11 m (36 ft.)	11 m (36 ft.)	For ceiling heights exceeding 11 m (36 ft.) multiple layers of detectors are required with not more than 11 m between the protection layers.
USA [5]	NFPA 72	2016	No prescriptive limitation; however, must account for stratification.			Limited by the lack of test data at other heights
Australia [14]	AS 1670.1	2015	12.0 m (39 ft.)	12.0 m (39 ft.)	12.0 m (39 ft.)	Higher ceiling heights require engineering analysis
Middle East	NFPA 72	Refer to above line for USA.				
Hong Kong [20]	BS 5839-1	2002	12.5 m (41 ft.)	12.5 m (41 ft.)	-	If the ceiling height exceeded 12.5m then other types of detector (e.g. beam detector) should be installed according to BS 5839 requirements.
European Union [21]	CEN/TS 54-14	2004	11 m (36 ft.)	-	25 m (82 ft.)	Beam detectors at ceiling heights of 12-25 m (39–82 ft.) require a second layer detection.

2.2 Overview of Key Literature

To determine the impact of ceiling height and detector spacing on smoke detector performance a review of relevant literature reveals that there are studies that characterize heat and smoke detector performance. The literature is broken down into two main categories, heat detectors and smoke detectors. Within those detection types there are three main types of study: fire testing, modeling (i.e. both empirical calculations and field models), and performance based design reports. To characterize smoke detection performance in high ceiling spaces, the variables contributing to detection performance are outlined in the following sections.

The sub sections below each represent a summary of select key pieces of literature.

2.2.1 Review of Heskestad and Delichatsios Literature - Detection Spacing for Flaming Fires

The work done by Heskestad and Delichatsios at the Fire Detection Institute formed the basis for the ceiling height requirements for heat and smoke detectors included in NFPA 72, as mentioned in Section 1.1. [3] To make these correlations between the ceiling height and the detector spacing, rigorous fire testing and analysis were conducted. The research focuses on heat detection, but also includes smoke detection.

The researchers sought to find a generalized correlation between the variables of the environment (i.e. temperature, velocity, and optical density) and the fire conditions (i.e. combustible material, fire-growth rate, and ceiling height). The test regiment included three flaming wood cribs (with different growth-rates) at three different ceiling heights (i.e. 8ft, 15ft, 29ft). The testing had instruments measuring temperature, velocity, and optical density at radial distances of 10ft, 20ft, and 40ft. The detectors that were used were:

- Ionization smoke detector
- Photoelectric smoke detector
- Heat detector, fixed temperature (135 °F)
- Heat detector, rate-of-rise
- Heat detector, rate-anticipation

A second test regiment sought to determine the effects of the combustible material, and the combustion mode. This test regiment only used an 8ft ceiling. The types of combustible materials used were the wood crib, foamed polyurethane, cotton fabric, and polyvinyl chloride. Both flaming and smoldering fires were tested.

From this analysis an empirical relationship was developed between time, temperature, and velocity based upon the fire size, fire growth rate (i.e. critical time), and ceiling height. Through discussions with the Fire Detection Institute, three fire growth rates were selected (i.e. 150 sec., 300 sec., 600 sec.), and a threshold fire size of 1000 BTU/sec (1,055 kW) were selected based on the range of critical fire sizes and fire growth rates in a typical occupancy.

The key outcome of this research is the calculation of appropriate heat detector spacing as related to ceiling height. Figure 2 and Figure 3 show the heat detector spacing for a critical time of 600 seconds (i.e. a low to medium growth fire) and 150 seconds (i.e. a fast growth fire). The figures show empirical derivation of the heat detector spacing based upon a set of equations derived from the experimental results.

The color of the line represents detector spacing at a normal ceiling height, where, “50ft” refers to a 50ft x 50ft spacing. Green lines represent a detector spacing of 50 feet at a normal ceiling height, blue represents detectors at 20-foot spacing, and orange represents detectors at 10-foot spacing. The line type refers to the temperature rating of the heat detector. The solid line represents the 128^0F rating, the dotted line represents the 145^0F rating, and the dashed line represents the 165^0F rating. To compare this research to the NFPA 72 reduction codified multiplier, the bold line indicates the values that would be required by NFPA 72 given the initial spacing.

Figure 2 & Figure 3 show that the trends between detector spacing and ceiling height for heat detectors are comparable with the experimental values. The results do not give an indication as to the time the detectors activate, only whether they activate. Slow growth-rate fires (Figure 2) results in more variability in terms of the spacing. Fast growth-rate fires (Figure 3) show that the radial spacing is more dependent on the ceiling height.

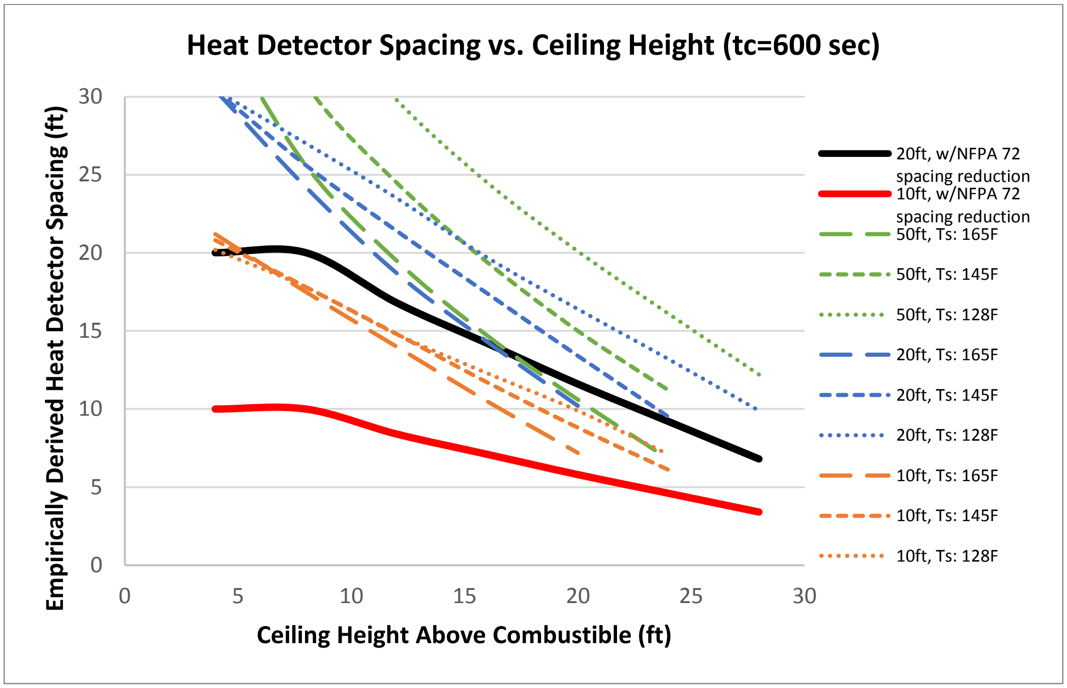

Figure 2: Comparison of the ceiling height above combustibles as required in NFPA 72 and in the Heskestad and Delichatsios paper for a critical time of 600 seconds. [3] [5]

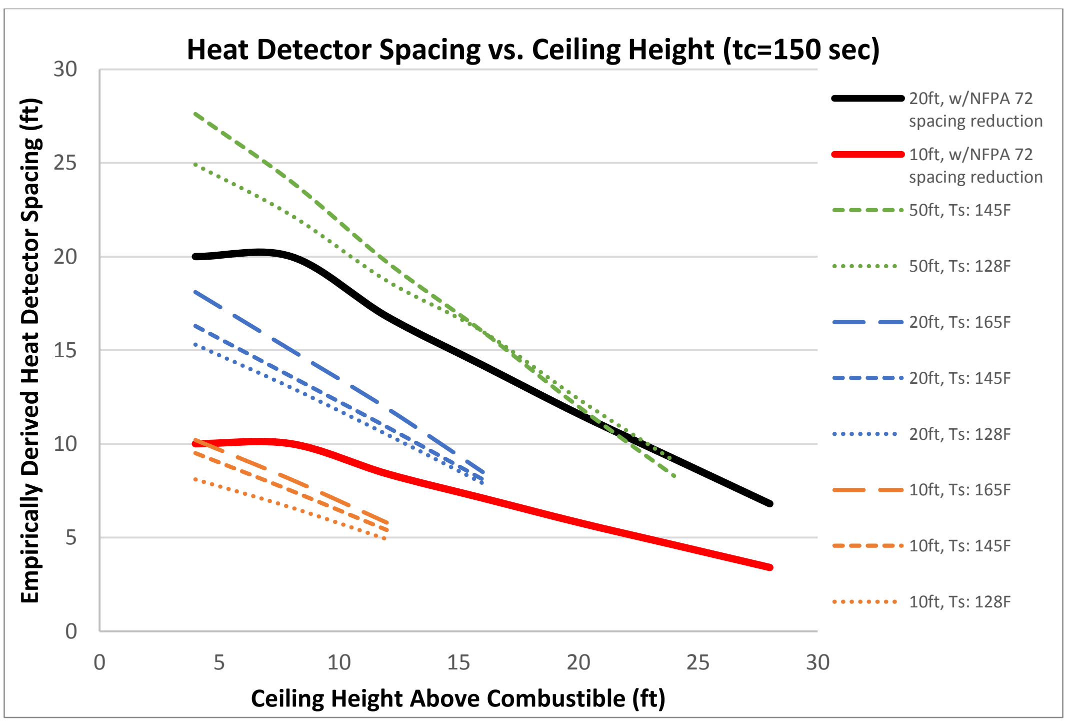

Figure 3: Comparison of the ceiling height above combustibles as required in NFPA 72 and in the Heskestad and Delichatsios paper for a critical time of 150 seconds. [3] [5]

Smoke Detector Spacing

The results of the experimental test demonstrated relatively consistent trends between temperature and smoke detector activation. The gas-temperature rise from a flaming fire is based primarily on the combustion material and mode of fire spread, in addition to ease of smoke entry at the detector. Detector spacing, as a function of ceiling height, is shown in Figure 4 for various values of temperature rise at response. The figure is the result of using the empirical and varying the detector spacing, ceiling height, and temperature rise at response.

The color of the line indicates the change in temperature of the smoke detector response used in the equations. The three green lines indicate the different fire scenarios (i.e. critical time of 150 seconds, 300 seconds, and 600 seconds) as we can see at lower changes in temperature (i.e. smoke detector response for different fires) the spacing given by the equations can be quite large at different ceiling heights. Comparing the data from the equations to the static value currently in NFPA 72 (i.e. red line) the smoke detector model for photoelectric detectors of natural fires (i.e. change in temperature of 80°F) fits best for a typical ten-foot ceiling. The graphs are limited to a 30-foot ceiling height as that is the limit of the experimental data.

While this relationship between ceiling height, smoke detector spacing, and change in temperature at detector is useful, further experimental testing should be conducted to determine whether there is a correlation.

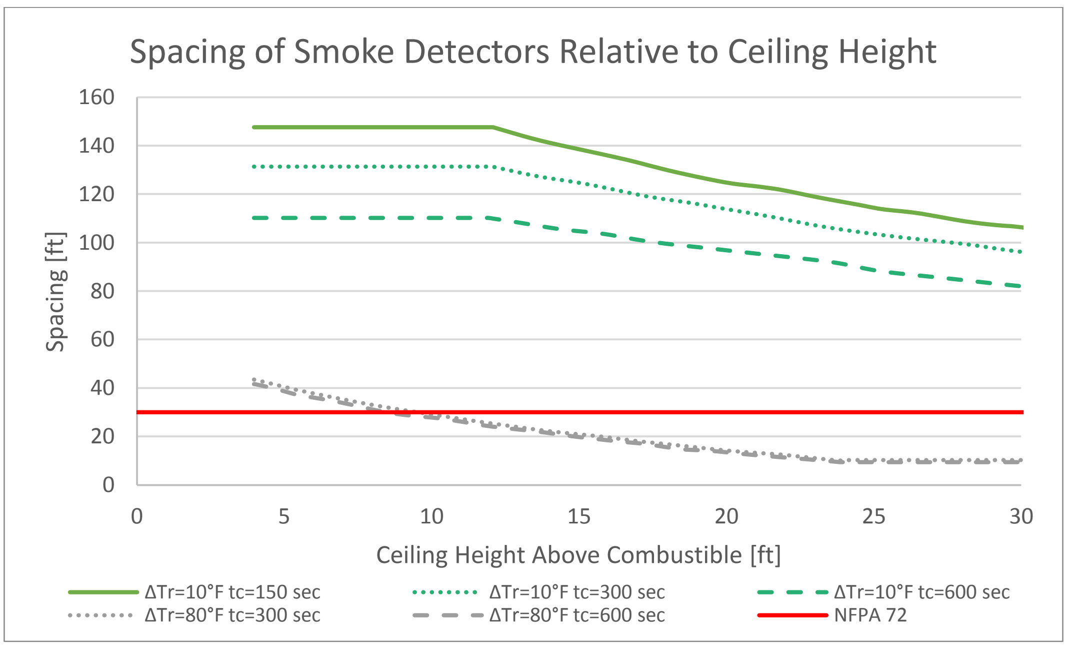

Figure 4: Smoke detector spacing v. ceiling height for temperature rise at response and critical fire times. The different colors indicate different temperature rise characteristics and the different curves represent different critical times (i.e. growth rates with t_c= 150, 300, 600) [3]. For reference the spacing currently codified in NFPA 72 is indicated by a red line. [5]

2.2.2 Review of Andersson and Blomqvist Literature - Smoke Detection in Buildings with High Ceilings

Andersson and Blomqvist performed several tests to evaluate smoke detector performance in buildings with high ceilings. [22] The premise of the tests performed here was to evaluate the performance of smoke detectors in buildings with high ceilings based on location of the detector and smoke production of the provided fire.

<u>Method</u>
In order to measure smoke production, cone calorimeter testing was used. Package material and electrical equipment fires were chosen for testing. Smoke production was proved to be larger per gram during testing under non-flaming conditions.

To test the detector sensitivity and performance, the EN54 Standard room was used, and detectors were tested using smoke produced from fires involving storage materials/electrical products as well as from a smoke generator. CFD simulations were run with different arrangements of ventilation systems and different placements of detectors relative to the ceiling height. During experiments, detectors were placed in layers, one being at the ceiling height and a second 1.5 m (4.9 ft.) below the ceiling. From the full-scale tests, it was concluded that detectors placed further from the ceiling, specifically at about 1.5 m (4.9 ft.) below the ceiling height, provided warning more quickly than those located closer to the ceiling, with the same spacing. Also, a higher amount of heat flux applied to the fuel package produced a higher possibility of detection. The experiments demonstrated that the way in which smoke moves throughout a space due to airflow patterns caused by ventilation systems, heating sources and temperature gradients in the room, were found to have a larger impact on detection capabilities than other variables and are grounds for future studies.

<u>CFD Modelling of Experiment</u>
CFD models and simulations of the full-scale tests were created for further confirmation; however, simulations were not able to accurately reflect the experiments. Likely, this is due to over-simplifications or inaccuracy of details to do with the smoke source. Since the temperature gradient necessary for smoke to be unable to reach a 7 m (23.0 ft.) high ceiling was determined to be substantial, it is implied that forces such as local air flow patterns dilute the smoke plume as well.

2.2.3 Review of Kuffner Literature - Method of Determining Smoke Detector Spacing in High Ceiling Applications

Kuffner completed a master's thesis on exploring different methods for accurately predicting smoke detector activation. [23] First, important parameters for smoke detection evaluation and tenability were discussed. Visibility was considered by the researcher to be the most important parameter to consider, along with smoke density, smoke generation, smoke transport and stratification height. The logic behind this testing is that since smoke detectors are typically evaluated based on their ability to detect smoke within a specified range of optical density, a minimum visibility value can be considered a reasonable metric for evaluation of the detectors.

Experimental Testing

The purpose of the tests performed was to predict the activation time of detectors at varying ceiling heights. The process of testing began with determining the smoke behavior regarding formation of a ceiling jet or stratification, determining the plume's maximum height, and determining the largest smoke concentration at the furthest distance fire location. Once these parameters were obtained, the predicted values were converted to maximum obscuration values. These maximum obscuration values were compared with specified obscuration levels. The time to activation of the smoke detector was then predicted. If all of the conditions indicated smoke detector activation within an acceptable time frame, then the smoke detector spacing could be recommended for use.

The three types of fire tests performed were using a paper fire, a flammable liquid fire, and a Douglas fir fire. Data regarding the impact elevation and radial distance from the fire source had on the obscuration levels is provided in Table 4.

Table 4: Obscuration Levels Association with Elevation and Radial Distance

Testing Material	Association with Elevation	Association with Radial Distance
Paper Fires	No association between obscuration levels and elevation	Obscuration levels decrease with increased radial distance
Liquid Fuel Fires	Up to 9 m (29.5 ft.) elevation: Reduced max obscuration levels Beyond 9 m (29.5 ft.): No association	Obscuration levels decrease with increased radial distance
Wood Crib Fires	Reduced max obscuration levels with increased height	Weak association with distance from source

Results of Testing

Overall, smoke detectors were proven to be effective during standard test fires up to 15 m (49.2 ft.) for newsprint fires, up to 12 m (39.4 ft.) for wood crib fires, and up to 15 m (49.2 ft.) for 20 ml liquid fuel fires. So long as devices are able to recognize lower than standard obscuration levels, they may be used at higher elevations than what is currently standardized, with reduced spacing accordingly. Detection time was not significantly impacted during testing for fires in ceiling elevations between 9 m (29.5 ft.) and 15 m (49.2 ft.).

The main conclusion is that smoke detectors are proven to be able to remain effective at spacing greater than current nominal 30 ft. spacing and higher than standard elevations. Additionally, the CFD models used by the researchers were not accurate enough at the time to recommend changes to the standard (were over-predicting obscuration level in comparison to experimental testing); This is also noted by other researchers (i.e. Floyd et al.) [24].

2.2.4 Review of Chagger Literature- Smoke Detection in High Ceiling Spaces

Table 3 compares smoke detector limitations in high ceiling spaces in codes from different countries. [6] This logic is used to show how in other countries, higher elevations for different types of detectors are already permitted by the code. Generally, in European codes the limits on height for smoke detection are similar, requiring additional levels/layers of detection at lower heights only if a ceiling exceeds ~ 7.5-20 m (25-65.6 ft.).

<u>CFD Modeling</u>

To test detector locations, Chagger utilized a 40 m high space and fires with different fuels as well as heat release rates. Overall conclusions were made based on test data and simulation data using FDS. It was found that temperature gradients cause the volume of smoke at the ceiling level to be reduced, but at lower levels to be increased. Cross-flows cause the volume of smoke to be reduced at the ceiling level and increased at lower levels. Without cross-flows or temperature gradients, small fires are detected at the ceiling level by aspirating smoke detectors and beam smoke detection. [6]

<u>Fire Testing</u>

During testing, seven optical beam detectors and three aspirating smoke detectors were used, all installed in a 43.5 m (142.7 ft.) high hangar. [25] In clear air the beams initially reported 100% transmission level, implying there was no obscuration, and with the addition of smoke this percentage decreased. The alarm threshold was set to activate an alarm when the beam senses an obscuration level of 35%, the minimum approved level.

<u>Characterization of Fire</u>

Both flaming and smoldering fires were used during testing which resulted in detectors being exposed to a wide range of smoke types and varying amounts of thermal energy. Response times of detectors at varying locations were measured and analyzed.

<u>Test Results</u>

The test results confirm that smoke from relatively small fires can extend 43.5 m (142.7 ft.) vertically into a high ceiling space. Both beam and aspirator systems are capable of detecting small amounts of smoke in high ceiling spaces, but it was emphasized what is more important, than the detector spacing at the ceiling, is the sensitivity settings of the detectors. The sensitivity settings used in testing were appropriate for small smoky fires; however, they could have been significantly more effective if they had been set at a 25% threshold instead of 35% (i.e. response when 25% of the beam is obscured).

2.3 Key Variables Affecting Detector Performance

2.3.1 Variables Affecting Smoke Detector Performance

Table 5 provides an overview of the variables, which were described in literature reviewed. While many of the environmental variables are similar, the key differences have to do with the fire and the detectors themselves. This is important as it is not possible to use the same correlations for heat detectors as for smoke detectors.

Table 5: Variables Affecting Smoke Detector Performance

Variable Category	Spot Type Smoke Detector Variables	Heat Detector Variables
Environmental Variables	Temperature, Air Velocity, Ceiling Height, Space shape, Smooth Ceiling vs Obstructed Ceiling.	Temperature, Air Velocity, Ceiling Height, Space Shape, Smooth Ceiling vs Obstructed Ceiling.
Fire Variables	Types of Combustible (Fuel), Smoldering or Flaming Fire, Fire Growth Rate, Smoke Characteristics	Fire Size, Fire Growth Rate
Detector Characteristics	Ionization Detector, Photo-Electric Detector, Characteristic Length	RTI, Device Location

3 Review of Test Data

The literature review reveals that there are numerous studies, which report on the performance of heat detectors and smoke detectors. Some of these reports are reviewed in detail in Section 2, and some are summarized. The purpose of including these studies is that they provide a significant amount of important data, especially if future phases of this research topic seek to perform either fire modeling or fire tests to support detector spacing in high ceiling spaces.

3.1 Fire Tests

The fire tests included in this study features some studies that are key to the development of smoke and heat detector response. The studies included in this list all have detailed descriptions of the fire tests setup, the fire-testing environment, and results in graphical or tabular form. Depending on the study there might also be an empirical correlation derived from the results of the test.

The inclusion of this list serves to guide future efforts to find related research studies. The data within the reports may be utilized to validate data that is produced by a modeling program or other fire tests.

Table 6: Important Research Containing Fire Tests

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
1961	**BRE**	**Hird, Bigmore & Pickard** [26]	**Siting of Heat-Sensitive Fire Detectors in Buildings**	Applicable for flat or joisted ceilings, corridors, clerestory or north-light roofs.	Experimental measurements of hot-air streams from fires are examined and results are compared to general principles for siting detectors	Methylated fuel in tray Tests and variables: Corridor with one closed end: corridor width & tray diameter Building with clerestory roof: tray diameter, tray position& window open/closed Building with north-light roof: tray diameter & tray position Building with large flat ceiling: tray diameter & distance between fuel and ceiling Large building with joisted ceiling: fire size/type, estimated convective heat output & distance between fuel and ceiling	Results given for each test type on pgs. 5-6 It is possible to estimate the size of fire which would be detected under different detectors, by first calculating the temperature rise of the airstream to operate detectors. It is then possible to calculate the rates of heat output necessary to operate detectors at different ceiling heights and radial distance. Min. fire size detectable depends on height to the power 5/2. The maximum improvement which can be achieved by spacing is that a fire with half the rate of heat output can be detected compared with one detector in a building with a flat ceiling	Compare with similar experiments and findings

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
1975	NIST	Bukowski [27]	Large-Scale Laboratory Fire Tests of Smoke Detectors	Performance analysis of smoke detectors	Experiments to determine photoelectric-type detectors' response in comparison to other detector testing requirements	26 tests in accordance with UL Standard 167, in addition to a smoldering cotton fire, and several flaming polyurethane flexible foam fires 8 photoelectric smoke detectors Air velocity: 17ft/min- 168ft/min Ceiling height: 15.75ft, 12ft above fire surface Spacing: 30ft	Repeatability between tests was difficult Smoke entry characteristics measured in smoke test tunnels at low velocities predict well the detector response to small real fires TGS sensor detectors were not responsive to clean burning fires (w/out significant unburnt hydrocarbons & CO) Ionization smoke detectors performed better than photoelectric in flaming tests w/out visible smoke. In smoldering fire photoelectric out-performed ionization. In flaming fires w/significant visible smoke- performance was comparable	Recognize variations in testing results, and new test sensitivities

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
1997	NIST	Gott, Lowe, Notarianni, & Davis [28]	Analysis of High Bay Hangar Facilities for Fire Detector Sensitivity and Placement	Applicable for 49.2-72.2ft ceiling height	Hangar tests are performed to analyze behavior of heat and smoke in high bay areas, and response times of detection and sprinkler suppression systems. Draft curtains, ambient temperature, flat/curved ceilings, and open/closed doors are considered	33 full-scale tests in two Navy hangars Ceiling height: 49.2, & 72.2ft 100kW-33MW fires Fuel: JP-5 & JP-8 (higher flash points than previously used jet fuels)	Spot-type detector spacing could be increased to 40ft w/out significant variation in response time Rate-compensated detectors with a rating of 79C performed most effectively	Compare to other high ceiling results Conduct CFD modeling to extend the scope of the study

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
1998	**NIST**	**Davis & Notarianni** [29]	**Prediction Based Design of Fire Detection for Buildings with Ceiling Heights 9m - 18m**	Applicable for 30-60ft ceiling height	Experimental and theoretical approaches for ceiling mounted detection devices. Ceiling jet algorithms are improved. Testing is compared to a computer modeling approach.	Fixed temp (57.2C), line type heat detector (RTI=58), fusible elements (79C, 141C, and 182C, quick standard and slower response) Ceiling height: 15m & 22m	Draft curtains improved activation times of ceiling mounted sprinklers and heat detectors for 15m and 22m ceiling heights For 29.5ft ceiling height, in a draft curtained area, if detection is designed for threshold fires, detector spacing should be set at the expected plume width. For non-threshold fires, spacing may be increased to as much as 39ft at a ceiling height of 49ft without affecting activation time.	Compare to other high ceiling results

2003	**SP**	**Andersson & Blomqvist** [22]	**Smoke Detection in Buildings with High Ceilings**	Applicable for 23-39ft ceiling height	Full-scale experiments were conducted using smoke generators and measured fires. Heating Ventilation and Air-Conditioning (HVAC) systems were used. Parametric studies were conducted to study influence of temperature gradients and ventilation systems on smoke movement in large industrial buildings. Simulations of the full-scale testing was modeled and results were compared.	Experiments were conducted in two industrial buildings, while in operation Ventilation: displacement, & total mixing Ceiling height: 7.25m & 11.8m Detectors: optical point, ASD sampling system, CO optical detectors, beam detectors, & video	Local velocities were not taken into account by the CFD simulations Experimental tests varied significantly for trials of the same configuration- which models cannot capture	Compare to other high ceiling results

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2003	**NIST**	**Davis, Cleary, Donnelly, & Hellerman** [30]	**Predicting Smoke and Carbon Monoxide Detector Response in the Ceiling Jet in the Presence of a Smoke Layer.**	Applicable for turbulent plume represented by an axisymmetric point source. Flat ceiling	Algebraic correlation for smoke or carbon monoxide concentration in the ceiling jet in the presence of a smoke layer is developed	Room: 3.15m x 3.02m Ceiling height: 2,19, 1.5, & 0.77m Burner: round d=0.085m, square d=0.194m Flame heights scale as the 2/5 power of HRR Fuel: propane & propene	Discrepancy between TEOM and laser attenuation Ceiling jet algorithms are developed for predicting smoke and CO concentrations in the presence of a growing layer and have been incorporated in the zone model JET	Impact of temperature effecting laser measurements to be investigated Smoke, CO, and temperature as a function of depth should be investigated to compare to ceiling jet structure

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2003	UMD	Geiman [31]	Evaluation of Smoke Detector Response Estimation Methods	Estimation methods for detector response	Investigation of uncertainty in estimation methods for smoke detector response based on optical density, temp rise, and gas velocity thresholds	Experimental data is compared to recommended alarm thresholds to quantify error	Less than 50% of predicted alarm times occurred within 60 seconds of the experimental alarms Error 20-60% for smoldering fires using optical density threshold Error 100%-1000% over-prediction of experimental alarms	Recognize uncertainty inherent in these estimation methods for future code change recommendations

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2005	WPI	**Ierardi** [32]	**Characterizing the Entry Resistance of Smoke Detectors**	Performance analysis/estimation method of smoke detector response	Entry resistance is tested by investigating the fluid mechanics and mass transport processes. Velocity in sensing chambers is measured and detectors are exposed to four aerosol sources. A mass transport model for smoke detector response is developed	Tests performed in NIST Fire Emulator/Detector Evaluator SS flow conditions 0.08-0.52m/s Photoelectric and ionization detectors Aerosol	The external velocity and detector geometry are related to the internal velocity by a resistance factor Resistance factor uncertainty 20-36% for external velocity 0.07-0.5m/s. For Interior velocity 20-48% The developed mass transport model predictions are within 5-20 seconds of experimental results (under prediction)	Further develop this mass transport and resistance factor model for predicting smoke detector response, incorporating characteristics of the smoke detector and external conditions Develop a general form of the resistance factor, based on detector geometry etc., so that it may be adapted to detectors without testing Recognize resistance at detectors, and include this consideration in future work

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2008	FPRF	Mealy, Floyd & Gottuk [33]	Spacing Requirements for Complex Beamed and Sloped Ceilings	Applicable for complex beamed and sloped ceilings	Volume 1: Experimental Validation Extension of the previous FPRF study to sloped ceilings and beams Validation of previous study	Corridor width: 5 & 12ft Ceiling type: smooth, 1ft beam bays, & 2ft deep beam bays Propylene fuel	Optical density previously established in modeling was not detectible in experimental analysis Deep beams do not negatively affect the expected performance of smoke detectors when the ceiling height is less than 24ft No significant difference in temperature rise or OD between detectors located on the bottom of beam or on ceiling in adjacent beam bay Conditions within a beam bay are approx. uniform and well-mixed throughout the volume of the beam bay. Requiring detectors to extend 12in below the ceiling in wall mounted configurations is not validated	Soot yield, fire size, and time difference limitations identified in this study should be taken into account for any code changes Compare to other beamed and sloped ceiling results

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2008	FPRF	Brookman [34]	Smoke Detection Performance Prediction Methodology	Performance analysis of smoke detectors in full scale tests and FDS, with ventilation conditions	Volume 2 Large-scale room fire tests Evaluating capabilities of FDS v.5.1.0 to predict smoke detector activation in response to low energy incipient fire sources	88 total tests Large scale texts of 8 incipient fire sources, 10ft ceiling height UL facility used for UL 217/268, 24 unventilated tests Alternate testing in representative mechanically ventilated commercial space, 64 ventilated tests FDS v5.1.0 32 scenarios	Uncertainty associated with FDS: The initial and boundary conditions specified (fire heat and smoke release rate histories, mechanical ventilation) The calculations performed by FDS to simulate heat and smoke transport Empirical models FDS uses to calculate smoke detector response and to predict smoke detector activation	Recognize uncertainties associated with FDS prediction of smoke detector activation Compare results to other detector activation performance, and results for ventilated rooms

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2009	**UoCarleton**	**Kuffner** [23]	**Method of Determining Smoke Detector Spacing in High Ceiling Applications**	Applicable for 9.8-37.4ft high ceilings	Commercial smoke detectors are tested in accordance with UL standard flaming acceptance test fires and non-standard test fires in large open spaces, and experimental results are compared to computer models are compared.	UL standard flaming acceptance test fires and non-standard test fires in large open spaces are performed and experimental results are compared to algebraic models, CFAST, & FDS. 72 burn tests are conducted 3 fuels, 7 fuel packages, 7 elevations	Detector outputs are limited to approx. 150% of their alarm value (approx. 10% obscuration/m) Models reviewed are not accurate enough to recommend using to adjust detector spacing at varying ceiling heights and detector spacing	Expand scope with additional ceiling heights Improvement in smoke flow predictions

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2012	**BRE**	**Chagger** [25]	**Smoke Detection in High Ceilings Spaces**	Applicable for 142.7ft high ceilings	Part 2: Fire tests Computer modeling & full-scale tests are conducted in a hangar	Ceiling height: 142.7ft Aspirating and optical beam smoke detectors Temp gradient: 0.18C/m-0.28C/m Test Fires: Wood crib, heptane, paper, potassium chlorate/lactose performance, & smoke pellet performance fires	Temperature gradients and cross-flows cause smoke concentration at ceiling to be reduced, but increased at lower levels- which supports using multiple detection types Detectors did not respond well to clean burn, or low thermal energy fire The sensitivity of the detector with high ceilings is critical The detector directly above the fire reached critical level prior to horizontal beam detectors	Compare to other high ceiling results, compare to other detector types Develop guidelines for appropriate sensitivity levels for beams and asp in high ceiling applications

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2016	**NIST**	Cleary [35]	**A Study on the Performance of Current Smoke Alarms to the New Fire and Nuisance Tests Prescribed in ANSI/UL 217-2015**	Performance analysis of smoke alarms	Full-scale ANSI/UL 217 experiments of currently available smoke alarms	ANSI/UL 217 test method New flaming and smoldering polyurethane foam fire tests 45 models tested	All but one model met the alarm response range in the smoke box	Recognize variations in testing results, and new test sensitivities

3.2 Fire Modeling

Fire modeling is used here to mean any calculation based exercise that can be used to predict smoke or heat detector activation. Earlier in the 2000s there was work done to develop empirical correlations between different aspects of the environment, the fire, and the detectors. A version of one of these methods is documented in NFPA 72 Appendix B to provide a performance based approach to detector spacing.

Table 7: Important Research Including Fire Modeling

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
1993	FPRF	Forney, Bukowski & Davis [36]	Field Modelling: Simulating the Effects of Flat Beamed Ceilings on Detector and Sprinkler Response	Applicable for smoke and heat detectors on flat beamed ceilings	Year 1 The goal of the work is to provide a basis for recommendations for modifications to NFPA 13 and NFPA 72. Field model verified against experimental results by Heskestad and Delichatsios. Parameter study conducted concerning the effects of sensor response under flat beamed ceilings of various geometries and growth rates.	Harwell-FLOW3D used for numerical simulations/ field model, and verified with 1/3 scale fire experiments 20 Modeled combinations of beam geometry and growth rates. Variables: • Growth rate: slow, medium, & fast • On center spacing: 4, 5, 6, 7, & 8ft • Beam depth: 0, 4, 8, 12, & 24in • Ceiling height: 11, 15, 19, 22, 25, & 28ft • Room area	Recommended Spacing Requirements for detectors are given for each of the following areas: • Smoke detectors and 100kW design fires • Smoke detectors and 1 MW design fires • Low thermal inertia devices (RTI≈50) and 1MW design fires • Medium thermal inertia devices (RTI≈100) and 1MW design fires • High thermal inertia devices (RTI≥300) and 1MW design fires	Compare recommended spacing requirements with other recommendations for flat beamed ceilings Convert into navigable guidelines Provide full-scale fire testing to support models Expand the modeling scope

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
1994	**FPRF**	**Davis, Forney & Bukowski** [37]	**Field Modelling: Simulating the Effect of Sloped Beamed Ceilings on Detector and Sprinkler Response**	Applicable for smoke and heat detectors on sloped beamed ceilings	Year 2 Continuation of previous yr. study for flat beamed ceilings. Parameter study conducted concerning the effects of sensor response under sloped beamed ceilings of various beam and ceiling geometries.	CFDS-FLOW3D used for numerical simulations, with grid generator SOPHIA. 36 Modeled combinations of beam and ceiling geometry. Variables: Beam parallel to slope orientation • Slope: 10, 25, & 50^0 • Beam depth: 4, 8, 12, & 24in • Beam spacing: 4 & 8ft • Ceiling height: 11 & 15ft Beam perpendicular to slope orientation • Slope: 25^0 • Beam depth: 6, 12, & 18in Gaps between beam & ceiling • Slope: 25 & 50^0 • Beam spacing: 4ft & 8ft No beams • Slope: 10, 25, & 50^0 • Grid cells: 13,000 to 25,000 • Medium growth rate t^2 fire (stack of wood pallets) • Venting configuration	Smoke flow channeling more significant as ceiling slope increases, for parallel beams. Smoke collection at lower beams decreases as ceiling slope increases for perpendicular beams. Recommended Spacing Requirements for detectors are given for each of the following areas: • Smoke detectors and 100kW design fires • Smoke detectors and 1 MW design fires • Thermally activated devices and 1MW design fires	Compare recommended spacing requirements with other recommendations for sloped beamed ceilings Convert into navigable guidelines Provide full-scale fire testing to support models Expand the modeling scope

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
1994	**ASME**	**Forney, Bukowski & Davis** [36]	**Simulating the Effect of Flat Beamed Ceiling on Detector and Sprinkler Response**	Applicable for smoke and heat detectors on flat beamed ceilings	Directly references the work performed in 1993 FPRF Forney paper, see previously mentioned report.	-	-	-
1996	**NIST**	**Davis, Notarianni** [38]	**NASA Fire Detection Study**	Applicable for 60-120ft hangar	Modeling conducted to simulate the response of smoke, fusible link, heat, UV/IR, and obscuration devices to standard fire scenarios. Airflow is considered.	Harwell Flow3D, and radiation model Radtect are used to predict the performance of smoke, heat, and radiation detectors. Peak fire size: 50kW, 0.5, 1, 4, & 50 MW Reached in 100s, t^2 behavior Ceiling height: 60-120ft	Detector sensitivity is critical for small fires in high ceiling spaces	Validate model results with testing Compare to other high ceiling results

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
1996	**NIST**	**Davis, Notarianni, McGrattan** [39]	**Comparison of Fire Model Predictions with Experiments Conducted in a Hangar with a 15 Meter Ceiling**	Applicable for 49.2ft ceiling height	Model verifications above 10m ceiling height for full-scale testing in 15m high hangar. Temperature is compared as a function of the distance from the fire center and depth beneath ceiling, as is velocity to an extent.	Plume correlations, ceiling jet correlation, CFAST, FPEtool, LAVENT, CFX, and NIST-LES are used to model the trials Ceiling height: 14.9m Fire size: 500kW & 2.7MW	Plume centerline temperature within 20% for 4 out of 7 models. FPEtool off by 50% Detection prediction was poor via these models	Compare to updated versions of these modeling tools, identify improvements with respect to detection prediction

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
1996	**FPRF**	**Klote, Forney, Davis & Bukowski** [40]	**Field Modelling: Simulating the Effects of HVAC Induced Air Flow from Slot Diffusers on Detector Response**	Applicable for detectors where HVAC induced air flow from slot diffusers are present	Year 3 Continuation of previous FPRF studies Parameter study conducted concerning smoke movement in response to HVAC induced airflows from slot diffusers, slot returns, & rectangular returns.	Mass densities of smoke were calculated, and the computer model was modified to calculate activation times throughout the flow field. Activation mass densities were selected so that they would correspond to the activation temperature rise used in prior years for fires in open plan rooms with different ceiling heights. 31 Modeled combinations: • Variable air volume HVAC systems: slot diffusers, slot returns, & rectangular returns • Room size: 11.2x15.1, 15.1x17.4, & 34.4x59.6ft • Medium growth rate t^2 fire (stack of wood pallets) • Max diffuser supply flow: approx. 2.5cfm per ft2 of floor area (exterior zones of office buildings) • Fire proximity to diffusers/returns • Activation at 23F rise	Constrained to the scope of the diffusers and returns, therefore guidelines are provided in lieu of conclusive recommendations: Enclosed rooms • Detectors should be no closer than 3ft from a supply register, and the ends of slot diffusers Open plan rooms • 3ft zone should expand to area of non-activation which reached 11ft in front of diffuser Standard and low profile sensors (0.79 & 2in) provided similar activation performance Insufficient information to reach conclusions about detectors located near return air openings	Expand modeling scope: Simulate over a range of activation values Simulate over a range of air supply flow values (other than just 2.5cfm per ft2 of floor area) Simulate over a range of diffuser throw Simulate plan room with more detailed return model (done in following yr. study) Correlate flow velocity at a distance from a diffuser where a detector is located Simulate with different diffuser types (done in following yr. study) Provide full-scale fire testing to support model guidelines

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
1998	**FPRF**	**Klote, Davis, Forney & Bukowski** [41]	**Field Modelling; Simulating the Effects of HVAC Induced Air Flow from Various Diffusers and returns on Detector Response**	Applicable for detectors where HVAC induced air flow from diffusers and returns are present	Year 3 Continuation of previous years' study. Area of study expanded to addressing smoke flows induced by ceiling mounted slot diffusers, wall mounted slot diffusers, high sidewall diffusers, and ceiling diffusers from which airflow drops to the floor.	See previous yr. study CFX Flow Solver used for numerical simulations. More detailed simulation of flows in plenum space 28 Modeled combinations 5 enclosed rooms, and 2 open plan rooms Flow rates per diffusers on pg.6	Activation time of low profile detectors is the same or faster than for standard detectors Fire below return in enclosed room • Gases enter return, • decrease depth of activation in room, • increase non-activation distance in front of slot detector Non-activation area to side of diffuser in enclosed rooms Large areas of non-activation in open plan rooms; to the side of diffusers, adjacent to returns Non-activation distance in front of supply is dep. on discharge angle High sidewall diffusers resulted in the largest non-activation distances Computer room w/ downward air flow non-activation area extended 0.3ft to the sides of the grill, and below	Further study of high sidewall diffusers Review concept of locating detectors near return air opening as mentioned in code, not supported by these studies Provide full-scale fire testing to support model conclusions

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
1998	**NIST**	**Davis & Notarianni** [29]	**Prediction Based Design of Fire Detection for Buildings with Ceiling Heights between 9m and 18m**	Applicable for 30- 60ft ceiling height	Experimental and theoretical approaches for ceiling mounted detection devices. Ceiling jet algorithms are improved. Testing is compared to a computer modeling approach.	JET computer model used to compare experimental results with the predictive capacity of numerical simulations.	The algorithms used in JET to provide agreement with experimental results are being incorporated into CFAST. For 29.5ft ceiling height, in a draft curtained area, if detection is designed for threshold fires, detector spacing should be set at the expected plume width. For non-threshold fires, spacing may be increased to as much as 39ft at a ceiling height of 49ft without affecting activation time.	Research algorithms used Confirm algorithms have been included in current modeling software

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2002	**SP**	**Boras** [42]	**CFD Simulations of Smoke Detection in Rooms with High Ceilings**	Applicable for 13.1-32.8ft ceiling height	This report is included in a larger project, "Early detection in rooms with high ceilings". The effects of the existence of a temperature gradient on the smoke spread in a room, and the effects of a ventilation system on the smoke spread in large industrial buildings are evaluated.	Simulations performed with CFD software SOFIE. Choosing a smoke source model, simulating the temperature gradient and ventilation system, lab experiments, and a parametric study is performed to fit the experiments. Variables: Ceiling height: 13.1 & 32.8ft Temp. gradient: 0.5C/m and 1C/m	Smoke spread is affected by a temperature gradient in the room Temperature just under ceiling is greater than the smoke temperature, and the smoke would not reach ceiling. Smoke staying at certain height (4.75 m for a temperature gradient of 0.5C/m and 3.75 m for 1C/m). Smoke spread in a mushroom shape	Compare to other high ceiling recommendations

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2003	**SP**	**Andersson & Blomqvist** [22]	**Smoke Detection in Buildings with High Ceilings**	Applicable for 23-39ft ceiling height	Full-scale experiments were conducted using smoke generators and measured fires. HVAC systems were used. Parametric studies were conducted to study influence of temperature gradients and ventilation systems on smoke movement in large industrial buildings. Simulations of the full-scale testing was modeled and results were compared.	CFD parametric study with temperature gradient and ventilation system was run Full-scale simulation of Testing was run	Local velocities were not taken into account by the CFD simulations Experimental tests varied significantly for trials of the same configuration- which models cannot capture	Apply lessons learned to future analysis

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2006	**FPRF**	**O'Connor** [43]	**Smoke Detector Performance for Level Ceilings with Deep Beams and Deep Beam Pocket Configurations**	Applicable for flat beamed ceilings with deep beam pockets, corridors, and waffle ceilings	Expand NFPA 72 smoke detector scope beyond 12ft ceiling height, and 12in beam pockets Provides data for smoke flows and field conditions. Updated modeling from some configurations studied previously by FPRF 1993-1994 Hallways with deep perpendicular beams and rooms with deep beam pockets	Find full report for more detailed methods Variables: Beam depth: 12 &24in Beam spacing: 3ft Ceiling height: 12 & 18ft	Pan type ceilings w/beams or solid joists less than 24in deep, and beam spacing less than 12ft, linear configurations do not affect performance. Reservoir effect contributes to rise in OD. Ceiling height increases the fire size threshold needed for activation of the baseline detector Detectors in beam pockets/on beams is acceptable	Compare to other flat beamed ceiling recommendations Compile navigable guidelines Compare to experimental results

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2008	**FPRF**	**Brookman** [34]	**Smoke Detection Performance Prediction Methodology**	Performance analysis of smoke detectors and FDS, with ventilation conditions	Volume 4 evaluation of FDS smoke detection prediction methodology Evaluating capabilities of FDS v.5.1.0 to predict smoke detector activation in response to low energy incipient fire sources	88 total tests Large scale texts of 8 incipient fire sources, 10ft ceiling height UL facility used for UL 217/268, 24 unventilated tests Alternate testing in representative mechanically ventilated commercial space, 64 ventilated tests FDS v5.1.0 32 scenarios	Uncertainty associated with FDS: The initial and boundary conditions specified (fire heat and smoke release rate histories, mechanical ventilation) The calculations performed by FDS to simulate heat and smoke transport Empirical models FDS uses to calculate smoke detector response and to predict smoke detector activation	Recognize uncertainties associated with FDS prediction of smoke detector activation

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2008	**FPRF**	**Mealy** [33]	**Spacing Requirements for Complex Beamed and Sloped Ceilings**	Applicable for complex beamed and sloped ceilings	Volume 2: Modeling Extension of the previous FPRF study to sloped ceilings and beams Validation of this modeling, and previous study are found in Volume 1	74 flat ceiling scenarios, 117 sloped ceiling scenarios Ceiling type: smooth with long beam channels, & sloped ceilings with beams parallel to the slope, beams perpendicular to the slope, and waffle type 5 Ceiling heights Propylene fuel	Flat ceilings: Without the confinement of a side wall in the beam bay, with deep beams (> 10 % of the ceiling height) the smoke does not exit the beam channel Ceiling height ≤ 40 ft., beam depth ≤ 10 % of the ceiling height, detectors located on every other beam bottom with max spacing of: max irregular area spacing for smooth ceilings, only if spacing between alternate beam bottoms ≤ smooth ceiling required spacing Other flat ceilings: detector in every beam bay, with smooth ceiling irregular area spacing. Sloped ceilings: Parallel: detector in every bay, at smooth ceiling spacing Perpendicular: detector on every beam bottom, and spaced per smooth ceiling irregular area Waffle: detectors on beam bottom centered in bay and beam perpendicular to slope	Soot yield, fire size, and time difference limitations identified in this study should be taken into account for any code changes Compare to other beamed and sloped ceiling results

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2008	Sup-Det	O'Connor, Cui, Sun [44]	A Further Review of Smoke Flows and Smoke Detector Response for Beam Pockets and Waffle Ceilings	Applicable for beamed and waffle ceilings	References 2006 O'Connor report. Expanded the previous computational domain to reflect conditions of a larger space, and multiple smoke detector locations	Variables: Waffle-type, and ceiling with beam bays 12x12ft	-	-

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
After 2008	**FPRF**	**Floyd** [45]	**Evaluating Smoke Detector Spacing Requirements for Parallel Beamed Hallways and Sloped Ceilings**	Applicable for parallel beamed hallways and sloped ceilings	Updated modeling on the FPRF previous studies in 1993 and 1994. Model validation from 2006 NIST studies, and expansion of modeling to evaluate flat beamed ceilings with long beam pockets, and sloped ceilings with beams parallel to the slope, perpendicular to the slope and beam pockets	FDS with multi-block feature used for simulations Activation: 0.14OD/m (upper bound of the 80% percentile activation threshold for flaming fires) Detection within 1min of the smooth ceiling detection time for the respective ceiling height is used as the equivalent performance	Recommendations for detector spacing for: • Flat Ceiling, parallel beams • Sloped ceiling, parallel beams • Sloped ceiling, perpendicular beams • Beam pockets	Compare to other results for beamed hallways and sloped ceilings

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2009	**UoCarleton**	**Kuffner** [23]	**Method of Determining Smoke Detector Spacing in High Ceiling Applications**	Applicable for 6.6-68.9ft ceiling height	The ability to predict obscuration levels and detection times is evaluated.	CFAST and FDS are compared against each other and experimental results Variables: Ceiling height: 6.6-68.9ft Radial distance from fire: 37.4ft	Smoke detectors are recommended for use in ceiling heights up to 19.7ft with spacing reduction of r/H≤0.2 Models reviewed are not accurate enough to recommend using to adjust spacing at varying ceiling height Variations between experimental results for the same test	Acceptance testing criteria for smoke detectors should be reviewed with results of these experiments, with ceiling heights as low as 9.8ft Expand scope with additional ceiling heights Improvement in smoke flow predictions

Date	Org.	Auth.	Title	Conditions	Outline	Methods	Conclusions	Further Development
2012	BRE	Chagger [6]	Smoke Detection in High Ceilings Spaces	Applicable for 131ft high ceilings, and temperature gradients	Part 1: Modeling Computer modeling & full-scale tests are conducted in a hangar, with aspirating and beam detectors. CFD was used to explore the effects of temperature gradients, and air velocity.	FDS v5 (LES) and JASMINE (RANS) were used for computer simulations Ceiling height: 131ft 1 Aspirating and 3 optical beam smoke detectors Peak fire size: 30, 50, 66, 100, & 200kW Fuel: kerosene, heptane, & timber Soot yield: 0.01, 0.015, 0.04, & 0.05 Temp gradient: 0, 0.15, & 0.3C/m Cross-flow: 0, 0.05, & 0.3m/s	Smoke from relatively small fires can be detected at high ceilings, without cross-flows Temperature gradients and cross-flows cause smoke concentration at ceiling to be reduced, but increased at lower levels- which supports using multiple detection types (horizontal beam) FDS and JASMINE predicted small fires differently, large fires were within 5% of each other 20s post-ignition The sensitivity of the detector with high ceilings is critical	Compare to other high ceiling results, compare to other detector types Develop guidelines for appropriate sensitivity levels for beams and asp in high ceiling applications

4 Gaps

The global literature review indicates that there are several paths forward for determining the spacing of smoke detectors in high ceiling locations; however, there are several existing gaps that require additional research before a determination of what the appropriate spacing requirements should be in terms of ceiling height.

Table 8 summarizes the gaps identified over the course of this research. There is a general lack of testing that has been conducted, which can be used to define the spacing for smoke detectors at different heights. The gaps identified are considered to be those items that were found to be important in the consideration of smoke detectors in high spaces.

Table 8: Summary of Gaps from Global Literature Review

Gap	Issue Level	Problem	Variables	End Goal
1. Available Data	Low	Lack of comprehensive collection of disparate data	Ability to classify data	Build database of comparable data from past research
2. Smoke Detector Sensitivity	High	Lack of basis for 30-foot spacing	Time to Detection Spacing	Codify life safety goals for smoke detectors, through spacing
3. Ionization & photoelectric detector characteristics	Moderate	Mechanism for smoke entry into the detector has not be characterized	Characteristic length Detection type	Characterize smoke entry into detectors.
4. Temperature Gradient	Moderate	Temperature non-uniformity in large spaces, causes reduction in plume buoyancy.	Temperature gradient over height HVAC strategy	Define a height limitation of 'high' ceiling spaces that apply in the prescriptive code
5. Ceiling Surface	Moderate	Beams, sloped ceilings, pockets,	Size of obstructions	Develop understanding of effect of

Gap	Issue Level	Problem	Variables	End Goal
		etc. block smoke travel to detector	Flow around obstructions	obstructions in high ceiling spaces
6. Airflows	Moderate	Mechanical air flows disrupt smoke plume	Air changes per hour Maximum air velocity	Develop understanding of the effects of increased airflow on smoke detector performance
7. Performance Metric	Essential	Unclear what the performance metric and technical basis for the current prescriptive requirements	Fire {size, growth rate, fuel, soot yield, combustibles} Smoke Detector Spacing Performance metric {obscuration %, time, smoke volume, other} Time to detection	Define hazard by which smoke detector performance is characterized, by means of a quantifiable metric.

4.1 Available Data

The literature review revealed many different published papers and reports including modeling exercises, fire testing, and performance based designs. This literature represents a collection of data developed by the fire community on this topic. Out of the many sources, there was no source that conducted the challenging exercise of organizing the disparate data sets into a comprehensive database. This literature review sought to identify and review datasets related to smoke detectors in high spaces, however no attempt was made to create a taxonomy for the existing data or provide analytical treatments.

4.2 Smoke Detector Sensitivity

Smoke detector sensitivity relates to the exact response of a smoke detector to detect a fire. This is typically related to the geometry of the smoke detector and the smoke sensor and measured in %/meter [%/foot obscuration]. Manufacturers test for sensitivity using a smoke test chamber device; however, this information was not found for any detector as a part of this study.

The current code presents 30 feet (9.1m) spacing as the maximum spacing limit, however there is little technical basis for this requirement except for the size of the test room. Research studies that considered the detector radius from the fire are surprisingly rare, with the primary example being from Kuffner [23].

While performance based approaches to smoke detector spacing are available it would provide beneficial knowledge to the industry to gain further insight into the smoke detector performance. Measuring the smoke detector performance could allow the performance to be indexed against the smoke detector sensitivity.

4.3 Ionization & Photoelectric Detector Smoke Entry Characteristics

While this report did not go into depth on smoke entry into photoelectric and ionization type spot detectors, it is an important topic. An understanding of the fluid mechanics and mass transport of smoke as it travels to the detector element is not yet characterized. This is why most smoke detector models use an approximation such as gas-temperature rise. The ability to directly calculate the detection time for spot type detectors would greatly improve the fire community's ability to characterize detection time. While some work has been done in this area [32], more research is needed.

4.4 Temperature Gradient

The effects of the temperature gradient in high spaces can vary widely from the location of the fire to the ceiling level. The temperature gradient in a space can contribute greatly to stratification of fire plume. While this phenomenon is usually considered in the course of a performance-based design, it is generally found to be unique to different spaces and can change with the weather or internal heating and cooling.

It is difficult to characterize how this could be further studied, but it would be helpful to collect information on existing buildings to develop a representative range of temperature gradients for different height spaces. Additionally, modelling exercises could be conducted employing different temperature gradients to determine what model variables are important for understanding temperature gradients.

It is likely that temperature gradients, in the context of looking at specific buildings, would require an involved engineering analysis. This would involve understanding the building temperatures at the extremes, the specific fire safety objectives, and other building systems.

4.5 Ceiling Surface

In high ceilings that contain beam construction, girders, solid joist construction, or other obstructed ceiling types, the smoke detector performance has not been widely studied. NFPA 72 contains spacing guidance for spot-type detectors in non-smooth ceilings. The fire protection research foundation has invested into research to understand the mechanisms for the effects of ceilings with deep beams and pocket configurations (i.e. Schirmer & Hughes). [43] [24] This research was not reviewed in depth for this literature review, but the studies were limited to ceiling heights of 12 feet or less. It is anticipated that the basis for these spacing multipliers could be applied to higher ceiling heights, however further review is needed.

4.6 Airflows

The effects of airflows, especially those created by mechanical supply fans, have been demonstrated experimentally to cause plume disruption, resulting in longer detection times. High spaces may include an HVAC system for comfort control during normal building operations that could disrupt the plume and the performance of a detector.

The absence of conclusive studies on the effects of airflows, on smoke detector performance, in high ceiling spaces reveals that there is limited knowledge on this topic in reference to the effect on detector performance.

4.7 Performance Metric

An important gap not quantified in the code is the particular performance metric that a smoke detector must meet to achieve the code-required level of safety. This includes the absence of a definition of what is considered a 'severe fire' as well as what is the expectation of detector performance.

Smoke detector performance is affected by the fire. There are many variables that define a fire including fire size, growth rate, fuel, type of fuel, characteristics of the smoke, whether the fire is flaming or smoldering, among other fire characteristics. A few studies considered different types of fires using different fuels [23] [32] [3]; however, there is yet to be a definitive correlation between fire fuel and detector performance.

An important criteria for defining smoke detector performance acceptability is determining exactly when a smoke detector should go off. Smoke detectors are expected to provide occupants of a building with an early warning, however there is not a clear definition of whether that is a discrete time (i.e. 60 sec) or whether it is related to the occupant egress time (i.e. ASET vs RSET) or other performance goal (i.e. property protection, etc.).

5 Research Plan & Next Steps

The literature review and assessment of the knowledge gaps presents several avenues for new research and discussions amongst stakeholders. In particular, it is clear that there needs be future research to further analyze the data already available and to create additional data sets.

The proposed research plan consists of three major task and two minor tasks. The three major tasks feed into each other and cannot be conducted simultaneously. These tasks first characterize the available data, then use that data and future research to develop the performance metric, finally determining the technical basis for the high ceiling spacing.

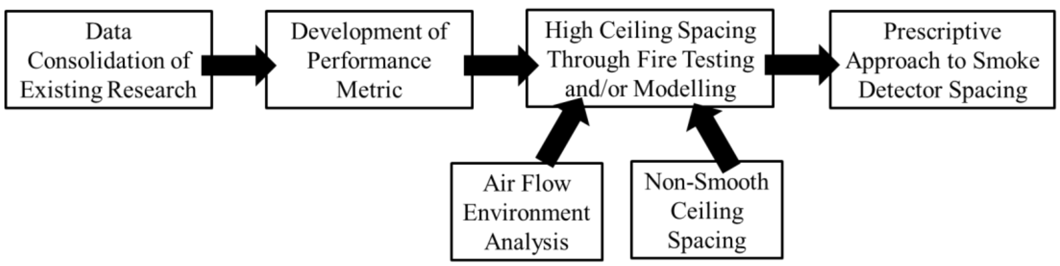

Figure 5: Flow of Research Tasks to Achieve Prescriptive End Goal

Table 9: Overview of research topics, associated tasks, and resolution

Research Topic	**Tasks**	**Resolution**
Data consolidation	1. Review the compendium of sources and especially the sources identified in Chapter 3 of this report. 2. Review reports for data from graphs, tables, text, etc. 3. Determine a taxonomy for that data in terms of important characteristics and parameters and its usefulness 4. Identify what data is needed.	Generate important characteristics and parameters important to smoke detector spacing in high ceiling locations and provide a database of: • Data which exists and is usable • Data which exists and requires analytical treatments • Data which is needed

Research Topic	**Tasks**	**Resolution**
Performance Metric	1. Define a representative fire, or set of fires. 2. Review models for suitability to purpose (i.e. 2d vs 3d, fire specific vs general fluids model, validation data sets, etc.) 3a. Apply fire(s) to code allowed smoke detector spacing using fire models or 3b. Perform full scale fire tests to gather data 4. Select performance metric which meets life safety objective as agreed by stake holders	Define a performance metric for smoke detector spacing in terms of a life safety objective (i.e. time to detection, smoke volume flow at a distance from the fire, percent obscuration).
Smoke Detector Spacing	1. Review models for suitability to purpose (i.e. 2d vs 3d, fire specific vs general fluids model, validation data sets, etc.) 2. Apply fire(s) from performance metric study to various ceiling heights for various smoke detector spacing using modelling tools or full scale fire testing 3. Analyze data to develop correlations between ceiling height and smoke detector spacing	Development of a tabular prescriptive table for smoke detector spacing corresponding to ceiling height
Air Flows	1. Construct a survey of airflow design metrics in high ceiling spaces. 2. Develop a range of typical airflows in high ceiling spaces. 3. Review models for suitability to purpose (i.e. 2d vs 3d, fire specific vs general fluids model, validation data sets, etc.) 4. Apply the general air flows per hour	Correlate the airflows in a space to a design metric (i.e. max velocity of mechanical flow, number of air changes per hour, etc.)
Non-smooth ceilings	1. Review basis and data sets for location and spacing in NFPA 72 and other relevant sources. 2. Provide justification on whether location and spacing for non-smooth ceilings in normal ceiling height locations can be applied in high ceiling height locations	Development of technical basis for prescriptive language of location and spacing of smoke detectors in non-smooth ceiling locations.

5.1 Research

A. Data Consolidation: There is already information and studies, which exist that can provide useful data to help guide future research in this process. The data consolidation exercise will begin by identifying the important characteristics and parameters (see Table 5) and collecting data by whether it is directly applicable, whether it needs analytical treatments, and what data does not exist. This initial bench exercise could decrease the fire testing and/or modeling recommended in the subsequent steps.

B. Performance Metric: The next step is to develop a performance metric that smoke detectors currently meet. This will focus on the current prescriptive requirements to determine what performance metric would be agreed to by the project technical panel, the NFPA 72 Technical Committee, and the fire community at large.

The two possibilities for the developing the performance metric will be based either (a.) on a standardized fire or set of fires, or (b.) on the time to detection. For the former a fire or set of fires of different growth rates, different fire fuels will be developed to for a representative range of fire scenarios. The fire(s) will then be considered against the range of detectors (i.e. spot type, beams, etc.) through fire modelling or fire testing. For the latter a timeline for detector response would be developed to determine when response would need to occur to provide a tenable environment.

Through this process a resulting data set will be developed including the obscuration level at the detector, the volume of smoke away from the fire, and the time of detection. This quantified result can be used to identify what metric best represents the life safety goal of the code, whether it be obscuration, volume of smoke across a certain area, or other metric defined in future work.

C. Technical Basis for Spacing of Smoke Detectors in High Ceiling Locations: The development of the technical basis for smoke detectors at different heights a testing regimen should include multiple different heights and multiple different smoke detector spacing. It is expected that this step should include some full scale testing and some modelling. Full scale testing should be considered to create a validation set for use in models considered applicable for the process. At least three ceiling heights from 10 feet up to 40 feet should be considered to capture the range of ceiling height from ‘normal’ to ‘high’ ceilings. Analysis of the data from testing is then used to develop a correlation for the spacing of smoke detectors at different ceiling heights consummate with the life safety goals of NFPA 72.

D. **Air Flow Analysis:** The effect of airflows and temperature gradients on smoke detector performance in high spaces was studied in a limited fashion, with no conclusive results. This is generally a fire dynamics or fire plume question problem. To shed light on this issue, a review of the applicable research identified in the related sources section as well as an analysis of improved methodologies for studying the issue to increase the potential for conclusive results.

E. **Non-Smooth Ceilings Review:** The effect of the non-smooth ceilings including beams, girders, pockets, and others obstructed high ceilings should be reviewed. An initial review of the applicable literature should be developed and especially developing the basis for the spacing and location guidance in NFPA 72. It is expected that this be done subsequently to any analysis around smooth ceilings, so that the data relating ceiling height, spacing, and activation time is available.

Stakeholders

There are also several items mentioned, which will require stakeholders' consideration and guidance on forming a definition of smoke detector performance. These include two major topics:

1. What is a severe fire, or set of fires, against which smoke detector performance can be tested?
2. What is an appropriate metric for smoke detector activation (i.e. time, obscuration, smoke volume, etc.)?

The identification of the smoke detector performance needs to be agreed upon by industry stakeholders. This is an important discussion as it will feed into and influence any research to be conducted on the topic. These include: fire size, or range of fire sizes expected in an occupancy; and the type of fuel, or range of fuels, that is most representative of a severe fire.

The time when a smoke detector activates is also an important item to discuss as it is not clear what the performance is intended to be. Additionally, the question of whether smoke detectors located in high ceiling occupancies are intended to be spaced so that the time to activation is the same as smoke detectors in typical ceiling heights needs to be answered.

6 Discussion & Conclusion

Smoke detector performance in high ceiling spaces or spaces with ceiling heights greater than 10 feet, is not currently defined by NFPA 72. The 30-foot (9.1 meter) nominal spacing currently used for smoke detector spacing presents a challenge in that a performance metric/criteria is not defined. Multiple variables as summarized in Section 2.3 affect the performance of detectors.

Various international codes and standards provide requirements for ceiling height limitations based on detector types, however it is evident that no specific spacing reduction requirements exist in a similar manner to the heat detection spacing reduction discussed in section 1.1. Several fire alarm manufacturers were contacted; however, no pertinent validated prescriptive information aside from the requirements of NFPA 72 were available for spacing requirements in high ceiling applications.

Literature reviewed in Table 6 and Table 7, as well as the previous sections, identifies a significant amount of research to validate modeling techniques, to develop an estimation method for detector response and to investigate the performance of smoke detectors. The major areas of investigation with respect to detector performance are based on the effects of ceiling type (e.g. smooth, waffled, flat, sloped, beamed, beam orientation, narrow corridor), ventilation conditions (e.g. mechanical ventilation, orientation, flow rate), and ceiling height (e.g. high ceilings, temperature gradient) and combinations thereof. Cross-flows, temperature gradients and detector sensitivity have proven a challenge for detectors on high ceilings under select conditions. Despite extensive research regarding smoke detector performance, there is limited information on conclusive studies that accurately describe the smoke detector spacing relative to ceiling height.

The lack of a basis in the literature for developing smoke detector spacing relative to ceiling height has led to the development of a description of the gaps and a subsequent research plan to fill those gaps. The research discussed in Chapter 3 of this report contains valuable data that can be used to provide guidance and should be consolidated into a database. The development of a performance metric, based on the current prescriptive requirements, is necessary to quantify the life safety goal of NFPA 72 in terms of smoke detectors. Finally, fire modeling, fire testing, or a combination thereof should be conducted with smoke detectors on ceilings of various heights using multiple spacing options. This research could be used to find a correlation for the smoke detector spacing relative to ceiling height and define a performance approach for engineering analysis of detector spacing.

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Appendix A

Compendium of Related Sources

Compendium of Related Sources

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