Fire Alarm Detection in High-Ceiling Rooms

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Abstract

For life extension of nuclear power plants, new codes must often be applied. For fire alarm systems, these codes can result in the addition of fire detectors in locations where none had previously been required. In rooms with ceilings at typical heights, designing detection is generally not problematic. It can, however, be more challenging to design fire alarm detection in spaces with high ceilings. In these environments, fire alarm systems should be designed considering the effects that high ceilings can have on the dynamics of a fire. If not, they can be ineffective, and result in significant cost for the installation and maintenance of a system that does not meet its design objectives.

1. Introduction

Many areas in nuclear plants can have high ceilings; examples include warehouses, equipment areas, workshops, reactor buildings, and turbine halls and crane halls. Providing fire detection in these areas can be difficult for a number of reasons. The intent of this paper is to provide an understanding of the difficulties that can arise in providing detection in high spaces, and to describe a case study showing one method of analyzing whether detection will be effective in a given area.

2. Fire Dynamics in High Ceiling Spaces

Model codes and standards do not typically define what a "High Ceiling" is. Rather, increasing ceiling heights can affect detector design in a number of ways. For example, North American fire alarm installation standards ULC-S524 [1] and NFPA 72 [2] have prescriptive requirements for the spacing of spot heat detectors in spaces up to 9m high; above 9m, no prescriptive requirements are provided. For smoke detectors, however, these same standards provide prescriptive requirements for ceilings only up to 3.6m. To install detection above these heights, the installation standards require either specific manufacturers' installation requirements to be followed or an engineering evaluation of the detection in the room.

In some cases, detection of a fire happens remotely from the combustion gasses (i.e. radiant energy or video fire detectors); however, in most cases, detection requires the products of combustion (i.e. hot gasses and particles) to be transported to a detection device so that it can analyze the products to look for a specific fire signature (i.e. gas temperature, number of particles in the air, or light obscuration). An analysis of the transport of the products of combustion and a discussion of how high ceilings can affect fire signatures with respect to fire detection is the focus of this paper.

In some situations, high ceilings can result in a change to a product of combustion fire signature; in other situations, the products of combustion can be prevented from reaching the ceiling. To better understand the issues involved with designing detection systems in high ceiling spaces, a discussion of smoke plumes and ceiling jets follows.

2.1 Smoke Plumes and Ceiling Jets

The products resulting from the combustion process are a mixture of hot gasses and particles (i.e. smoke). As the smoke generated by a fire is hotter than the ambient air around it, it is buoyant, and will rise from the source in a plume. Turbulence at the plume/ambient air border will cause entrainment of some of the ambient air into the plume, increasing the volume of the smoke. This phenomena leads to the concept of the V-shaped smoke plume, as shown in Figure 1.

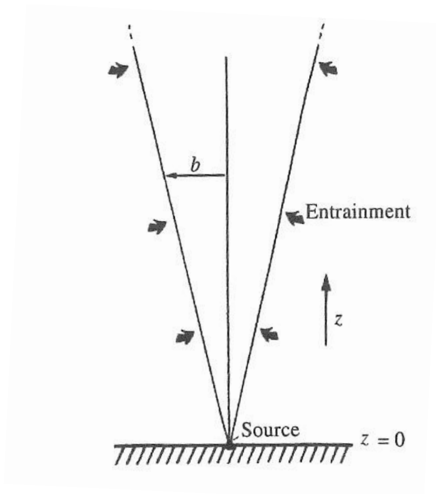

Figure 1 – A buoyant plume, rising from a point source fire. [3]

The entrained ambient air not only increases the volume of smoke; it also has the net effect of cooling the smoke as it rises. Expressions have been developed for steady-state fires for quantifying idealized smoke plume characteristics. One such equation was determined by Heskestad for the centerline temperature of the plume of an axisymmetric[1] fire, at a point above the mean height of the flames. This equation is shown as follows, where T_o (℃) is the plume centerline temperature, T_∞ (℃) is the ambient temperature, $\dot{Q}_{conv}$ (kW) is the convective heat release rate of the fire (generally taken as 70% of the total heat release rate of the fire), and z_m (m) is the height above the fire.

$$T_o - T_\infty = 25\dot{Q}_{conv}^{\frac{2}{3}} z_m^{-\frac{5}{3}} \qquad [4] \qquad (1)$$

As an example, consider a garbage bag fire. NUREG [4] has summarized tests from garbage bag fires that indicate total heat release rates in the range of 100 to 350 kW. Assuming an ambient temperature of 20℃ and a well-ventilated 350 kW fire in an open area, equation (1) indicates an expected

[1] An axisymmetric fire is one in which there is an axis of symmetry along the vertical centerline of the plume (i.e. a fire in the open). Expressions also exist for other fire plume formations (i.e. line fire, a fire against a wall or in a corner, a balcony spill plume, etc…).

centerline plume temperature at a point 5 m above the fire would be approximately 87℃, while at 10 m above would be 41℃, as shown in figure 2.

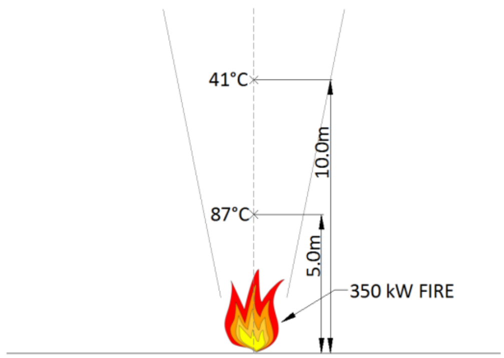

Figure 2 – Plume Temperatures

The buoyancy of the plume drives the smoke upwards. When it hits the ceiling, the plumes' momentum causes it to split, changing it into a radially outward-spreading "ceiling jet". As the jet spreads outward, energy losses continue to cause a cooling effect on the ceiling jet. Figure 3 shows a plume with a ceiling jet.

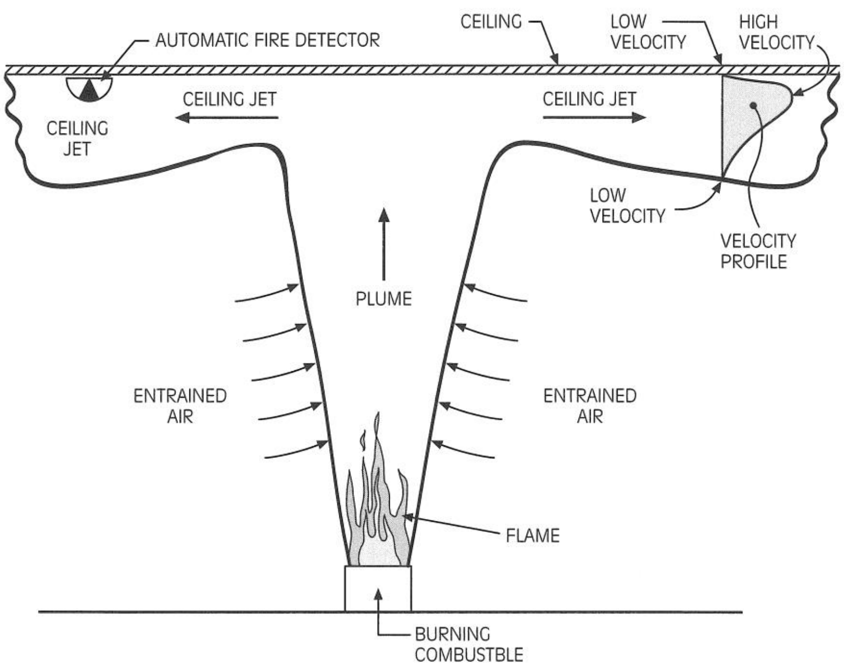

Figure 3 – Buoyant plume from a fire, after interaction with the ceiling [5]

Alpert developed relationships based on steady-state fires, with large, flat ceilings to estimate the temperature at a point in a ceiling jet. These equations are shown as follows, where H (m) is the ceiling height, $\dot{Q}_{Tot}$ (kW) is the total fire heat release rate, r (m) is the radial distance from the plume centerline, and T_{max} (℃) is the maximum jet temperature at the radial distance. The equations are given in two forms, one for the area outside of where the plume intersects the ceiling (i.e. $\frac{r}{H} > 0.18$), and one for inside of it ($\frac{r}{H} \leq 0.18$).

$$Tmax - T\infty = 5.38 \frac{\left(\frac{\dot{Q}_{Tot}}{r}\right)^{\frac{2}{3}}}{H}, \text{ where } \frac{r}{H} > 0.18 \qquad [3] \qquad (2)$$

$$Tmax - T\infty = 16.9\, \dot{Q}_{Tot}^{\frac{2}{3}}\, H^{-5/3}, \text{ where } \frac{r}{H} \leq 0.18 \qquad [3] \qquad (3)$$

Using the same assumptions for the fire and ceiling, Alpert also developed equations that indicate the velocity of the ceiling jet at a given radial distance from the plume centerline. It is noted that at a given distance from the centerline, the ceiling jet velocity profile will not be constant, as shown in the velocity profile in Figure 2; in the following equations u_{max} (m/s) is the maximum gas velocity at a point in the ceiling jet.

$$u_{max} = 0.197 \frac{(\dot{Q}_{Tot}/H)^{1/3}}{(r/H)^{5/6}}, \text{ where } \frac{r}{H} > 0.15 \qquad [7] \qquad (4)$$

$$u_{max} = 0.947 \left(\frac{\dot{Q}_{Tot}}{H}\right)^{1/3}, \text{ where } \frac{r}{H} \leq 0.15 \qquad [7] \qquad (5)$$

If the 350 kW fire discussed above were to instead occur in a room with a 5m ceiling height, equations (2) and (3) indicate the maximum ceiling jet temperature at 1m from the plume centerline would be 73℃, while at 3m would be 46℃, as shown in Figure 4.

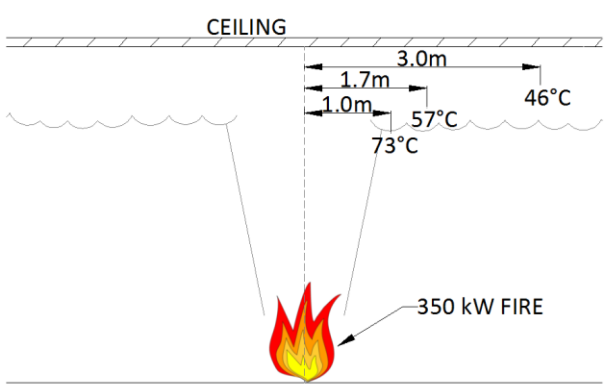

Figure 4 – Ceiling Jet Temperatures with a 5m Ceiling

This example readily demonstrates an issue with using heat detection in high areas. A standard alarm temperature for heat detectors is 57℃. Given this specific fire, a standard-temperature heat detector located on the 5 m high ceiling within a radial distance of 1m of the fire plume centerline would be expected to alarm; however, if the detector was 3m away, it would not. Rearranging equation (2) allows us to calculate the maximum radial distance at which the ceiling jet is at a given temperature; as Figure 3 indicates, for 57℃ this distance is 1.7 m.

2.2 Stratification

In rooms in general, the ambient temperature at the ceiling is typically higher than at the floor; this effect is more noticeable in rooms with high ceilings. This temperature difference effect is due to several factors, some of which include:

- Hot air tends to rise due to buoyancy
- Air conditioning systems are used to cool the air at the floor level of a room.
- The sun shining on a roof can heat it, causing a layer of hot air in the room at the ceiling level

Ceiling-mounted smoke detectors require that the smoke plume must reach the ceiling; however, if the smoke plume temperature drops to a point close to the ambient temperature, the smoke plume will cease rising, and stratify at that level. Current engineering guidelines suggest that a 2℃ temperature difference be used to consider a smoke plume buoyant enough to continue rising [6]. In high-ceiling rooms, the smoke plume temperature and room upper-level ambient temperatures must be considered.

Two room ambient temperature profiles are commonly considered; one in which the room temperature is constant up to a point where it meets a hot air layer near the ceiling, and one where the room temperature increases linearly with height. An example of these profiles in an atrium are shown in Figure 5. The designer must evaluate the room characteristics to determine which profile is better-suited to a given situation.

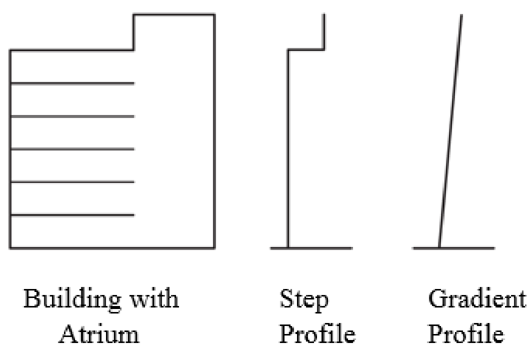

Figure 5 – Pre-fire atrium temperature profiles [2]

2.2.1 Step temperature profile

This profile can occur where the upper space of a room is unoccupied and unconditioned, such as a mall or atrium. If a step temperature profile is expected, the plume temperature will have to be greater than the upper hot air layer temperature; if it is not, stratification can be expected below the hot air layer. Equation (1) provided above for the centerline plume temperature can be used to determine the expected smoke plume temperature at the level of the hot air interface.

2.2.2 Gradient temperature profile

The temperature gradient profile is generally encountered in rooms such as unoccupied industrial spaces and storage rooms. For rooms with this profile, expressions have been developed to help determine when stratification will happen.

The following equation can be used to estimate the stratification height of a smoke plume. $\dot{Q}_{conv}$ (kW) is the convective heat release rate of the fire, $\triangle T_0/dZ$ (°C/m) is the room ambient temperature gradient, and Z_m (m) is the maximum height to which smoke will be expected to rise. It is noted that the convective heat release rate is generally assumed to be 70% of the total fire heat release rate.

$$Zm = 5.54\,\dot{Q}_{conv}^{1/4}\left(\frac{\nabla T_o}{dZ}\right)^{-3/8} \qquad [2] \qquad (6)$$

Alternatively, the minimum fire size required to drive a smoke plume to the ceiling can be calculated. The following equation can be used to determine the size of fire required.

$$\dot{Q}_{conv} = 0.0018H^{5/2}\Delta T_o^{\frac{3}{2}} \qquad [2] \qquad (7)$$

As an example, consider the trash bag fire used in earlier examples. Presuming the 350 kW fire was in a 20 m high room, with an expected gradient temperature profile and with a temperature difference from floor to ceiling of 10°C, the fire should be able to drive smoke to a ceiling height of 28 m. In this case, stratification would not be expected; a ceiling jet would be expected to reach ceiling-mounted detectors. If the fire was instead a small trash bag fire of 100kW, it could still be expected to drive smoke up to a level just over 20 m. If the 10 ℃ floor-to-ceiling temperature difference was not considered a conservative estimate, a designer who has a requirement to detect a 100 kW fire in the room would be advised to consider the possible effects of stratification.

2.3 Smoke transport time and detector spacing

The fire signature is transported to the detector by the smoke plume and ceiling jet. This transport takes time, which can be affected by a number of factors. Some of these factors include:

- Time for the smoke to rise and travel horizontally to the detector.

- Growth of the fire. A fire will typically start with a very small heat release rate, and grow as a function of time.

Fire detector listings define the maximum spacing between detectors, based on standard ceiling heights. It is noted that the detector spacing that is determined is not only based on whether the detector alarms, but also on how long it takes to alarm.

For flaming fires, mathematical models are available to estimate the time for transport of the fire signature to a detector, and also for the time detectors will take to respond to a fire signature. An analysis of smoke transport time and detector spacing is beyond the scope of this paper; refer to the referenced documents for further discussion on this topic.

2.4 Detector Activation

Once a fire signature reaches a detector, activation is neither instantaneous nor guaranteed. There are a number of factors that can affect the activation of detectors. Some of these factors include:

- Resistance to smoke entry. Typical spot smoke detectors require the smoke enter a detection chamber where it can be sensed. The design of the detector insect screen, the design of the smoke path in and out of the sensing chamber, and the design and location of the sensing chamber can affect detection.

- Sensing methodology. Different sensing methodologies (i.e. photoelectric detection, ionization detection, etc…) can have different reactions to the same fire signature.

- Smoke colour. Some types of smoke detectors react differently to smoke of different colours. It is noted that the current North American test regimes that are used when listing smoke detectors do not evaluate the smoke colour.

- Smoke aging. Aging of smoke can affect it in several ways. The temperature profile can be affected, the particle size can be affected (through deposition or agglomeration), the smoke density can be affected, etc…

- Settling of the ceiling jet. Settling of smoke within the ceiling jet can occur as the ceiling jet cools, and loses its buoyancy.

Each of these factors can affect detection in different ways. With some of these factors, it is recommended that designers consider the physical properties that could affect detection (i.e. is the expected colour of smoke of concern?) For other factors, mathematical models have been developed that can help evaluate whether detector activation will occur. These models typically differ between smoke and heat detectors as they react differently to fire signatures, and different methodologies have been used to evaluate them.

2.4.1 Heat detectors

Smoke colour and density has minimal impact on heat detectors. Rather, the temperature of the air surrounding the sensor is of prime importance. The detectors sensing element will have a thermal inertia that must be overcome, which causes a delay in activation. This delay has been characterized with a defined parameter, the "Response Time Index" (RTI). This delay time has been analyzed, and equations exist help analyze the effects of it. These time-based effects are beyond the scope of this paper; however, equations (1), (2) and (3) above can be used to provide a first-order indication as to whether the detectors can be expected to activate.

2.4.2 Smoke detectors

As different factors have unique and individual effects on smoke detectors, their individual effects on detector activation are difficult to quantify. Instead, methods have been developed to help estimate their overall effects on whether detectors will activate or not. Some of these methods are as follows.

- Critical velocity method. This method assumes that there is a "Critical Velocity" the ceiling jet must have that will result in a flow through the detector that will allow it to generate an alarm. Experimentation has determined that this velocity is in the range of 0.15m/s for both ionization and photoelectric detectors [2]. Equations (4) and (5) above can be used to estimate the ceiling jet velocities at detector locations.

- Temperature rise method. Research has shown that there is an approximately linear relationship between the optical density of smoke and the ceiling jet temperature. [2]. This method assumes the detector will alarm so long as the ceiling jets' temperature is a minimum amount above the ambient temperature. A temperature rise of 13℃ to indicate a detector alarm condition has been used in a number of fire modeling programs, although some studies suggest that ionization detectors have alarmed at lower temperature rises [2]. Equations (2) and (3) above can be used to estimate the ceiling jet temperatures at detector locations.

- Mass optical density method. This method assumes that a detector will alarm when the smoke optical density reaches a specific value. The method requires further information regarding the expected mass density of the smoke that is produced from the fire, which involves a further analysis of the combustible materials in the fire. The mass optical density method is not further discussed in this paper; refer to the referenced documents for additional information on this topic.

3. Case Study

A case study wherein this method was used to evaluate whether detection is beneficial in several high ceiling areas is provided.

A plant was considering the addition of detection in several high-ceiling rooms. A survey of the rooms was conducted, in which it was determined that the ceilings were flat, and that a linear gradient profile with a floor-to-ceiling temperature differential of 10°C was expected. The room characteristics were identified, and a fire hazard analysis was conducted, in which the combustible materials in the room were identified and the potential resulting fires evaluated. As well, a calculation was performed, where equation (7) above was used to evaluate the minimum size of fire required to drive a smoke plume to the ceiling. The room and fire characteristics are shown in Table 1.

Room Number	Width (m)	Depth (m)	Height (m)	Maximum Fire Heat Release Rate Expected in Room (kW)	Minimum Fire Size to Drive a Smoke Plume to the Ceiling* (kW)
1	9.2	63.0	6.2	250	7.8
2	11.1	18.0	7.3	350	11.7
3	6.1	63	8.9	450	19.2
4	6.1	13.3	23.4	369	215

* A 10°C temperature difference between the floor and ceiling was presumed.

Table 1 Room Characteristics

The expected fire sizes in each room would clearly be expected to drive the smoke plume to the ceiling and create a ceiling jet; further evaluation of the detection methods was indicated. Using the room height and maximum expected fire size for each room (from Table 1), the maximum expected ceiling jet temperature was estimated for two different points in the jet. The highest ceiling jet temperatures will be expected in the area immediately above the fire, where the plume intersects the ceiling. Equation (3) was used to determine these temperatures. As well, the ceiling jet temperatures were estimated at a point 2 m away from the centerline of the fire; equation (2) was used to determine these values. The results of these evaluations are summarized in Table 2.

Room Number	Expected Maximum Ceiling Jet Temperature, Directly Above the Fire (˚C)	Expected Maximum Ceiling Jet Temperature, 2m From the Center of the Fire (˚C)	Expected Maximum Ceiling Ambient Temperature (˚C)	Heat Detector Alarm Response Point (˚C)
1	52	42	35	57
2	51	43	35	57
3	46	42	35	57
4	25	25	35	57

Table 2 Heat Detector Analysis

To minimize spurious alarms, heat detectors should be a minimum of 14˚C above the expected ambient temperature [2]. As such, standard-temperature heat detectors, which alarm at 57˚C, would be recommended. The temperatures directly above the expected fires would not be expected to be high enough to activate a standard-temperature heat detector, although rooms 1 and 2 come within a few degrees. Further analysis shows that at a distance of 2 m away, the ceiling jet temperatures would be 15˚C or more than below the level required for an alarm. It is clear that if heat detectors were to be used, they would have to be spaced quite closely together; even with close spacing, it is not assured that the detectors would alarm.

An analysis was conducted to evaluate whether smoke detectors would be expected to alarm. Standard smoke detector spacing required by codes is for detectors to be located no farther than a radial distance of 6.4 m (21’) from a point where a fire could occur [1] [2]. Using this spacing, the temperatures and velocities of the ceiling jets were calculated using equations (2) and (4), assuming the maximum-sized fire heat release expected in the room (from Table 1). The results are summarized in Table 3.

Room Number	Temperature Rise Method			Critical Velocity Method		
	Ceiling Jet Temperature Rise above Ambient at 6.4m from Detector (°C)	Detector Alarm Threshold (°C)	Detector Alarm?	Maximum Ceiling Jet Velocity 6.4m from Detector (m/s)	Detector Alarm Threshold (m/s)	Detector Alarm?
1	10.0	10.0	Yes	0.66	0.15	Yes
2	10.6	10.0	Yes	0.80	0.15	Yes
3	10.3	10.0	Yes	0.96	0.15	Yes
4	3.4	10.0	No	1.46	0.15	Yes

Table 3 Smoke Detector Analysis

The results indicate that using the temperature rise method, and assuming a ceiling jet temperature 10°C above ambient is required for the detector to alarm, a smoke detector would be expected to alarm in rooms 1, 2 and 3, but not in room 4.

Alternatively, using the ceiling jet velocity method and assuming a 0.15 m/s ceiling jet velocity to indicate a detector alarm, a smoke detector would be expected to alarm in all four of the rooms.

The conclusion drawn was that based on the expected maximum fire size in each room, ceiling-mounted heat detections would not be a reliable means of detection in any of the rooms. For rooms 1, 2 and 3, however, ceiling-mounted smoke detectors would be expected to activate. Although smoke would be expected to reach the ceiling in room 4, smoke detection would not be considered a reliable means of detection.

4. Conclusion

The fundamental dynamics of smoke plumes were reviewed, and equations for estimating the temperature of smoke plumes, as well as the temperature and velocity of ceiling jets that develop from steady-state fires were discussed. The issue of stratification was also discussed, and two equations were identified that can help estimate whether stratification will occur. A case study in which a methodology involving several of the equations was presented; the study reviewed the likelihood of fire detectors located in high rooms activating. The study indicated several cases where smoke detectors would be expected to activate, and highlighted one case where smoke detectors would not be considered a reliable means of detection.

5. References

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