

Considerations in the Design of Smoke Management Systems for Atriums

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This Update discusses the use of an engineered approach to the design of smoke management systems for atrium buildings, based on the principles of smoke management in atriums outlined in Construction Technology Update No. 47.

Engineered smoke management systems often play a role in extending the use of an atrium space by demonstrating that the basic

requirements of the applicable building and fire codes can be met or in providing additional protection for occupants and property. Typically, this involves the use of mechanical exhaust systems to limit the accumulation of smoke in the atrium and its migration into evacuation routes and communicating spaces.²

Some model codes in the United States and other countries have introduced requirements for smoke management systems based on the design criteria found in engineering design guides such as NFPA 92B (published by the National Fire Protection Association), "Guide for Smoke Management Systems in Malls, Atria and Large Areas." These guides include atrium smoke management considerations and design criteria.[1,2,3]

Atrium smoke management design is based on the principles used in multi-zone fire models: The fire produces hot gases, which rise above the fire, forming a plume. As this plume rises, it entrains air, increasing its diameter and mass flow rate (rate of smoke build-up) with elevation — an expanding cone. At the ceiling, the hot gases form a layer of smoke (see Figure 1). As smoke accumulates, the layer thickens and descends, and can ultimately fill the atrium (resulting in reduced visibility and increased distribution of gases to other areas of the

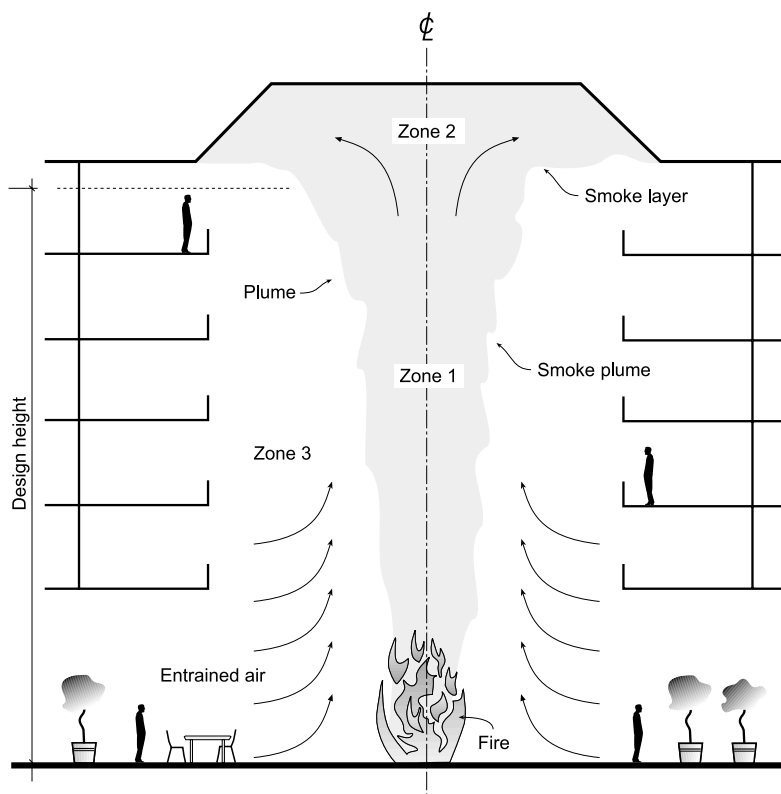


Figure 1. Smoke production in an atrium¹

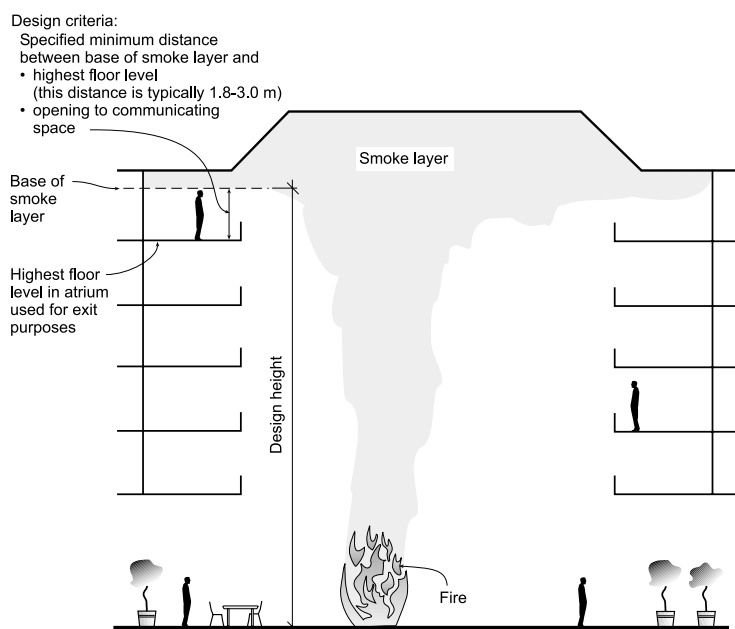


Figure 2. The smoke management system must maintain the base of the smoke layer above the design height.

building). The plume, the smoke layer, and the ambient or cold layer of air not entrained by the rising plume constitute three separate zones within the room (see Figure 1).

Equations based on experimental data have been developed for estimating the properties of the smoke plume, the thickness of the smoke layer and its average properties such as temperature, gas concentrations and smoke optical density. The balance of mass and energy among the three zones in the atrium is also reflected in the design equations. These empirical equations form the basis for smoke management system design using the engineering design guides.[1,2,3]

Design Process

The basic steps in designing an atrium smoke exhaust system are as follows:

1. **Design criteria.** Determine the specific design objectives that must be met by the smoke management system and develop suitable criteria.
2. **Design fire.** Determine the size and location of the fire(s) for use in the calculation of smoke production.
3. **Mechanical exhaust considerations.** Determine whether the design criteria can be met by allowing smoke to fill the atrium space without provision for smoke exhaust. If this is not the case, calculate the requirements of the mechanical exhaust system that can meet the design criteria.

The various approaches used in codes and engineering guides for each of these steps are summarized in the following sections.

Design Criteria

Engineered atrium smoke management systems are typically designed to meet one of the objectives of the NBC, which is to protect human life. For design purposes, the area of the building that must be kept smoke free is established, usually by assuming that the base of the smoke layer should remain above a pre-determined height (i.e., the design height, which is measured from the floor of the atrium) for a specified period of time. Two examples of design criteria for meeting this objective are as follows:

- The smoke management system must be able to maintain the base of the smoke layer above the highest unprotected opening to adjoining spaces, or
- The smoke management system must be able to maintain the base of the smoke layer at 1.8-3 m above the highest floor level in the atrium used for exit purposes for at least 20 minutes following ignition (Figure 2).

Another possible design approach is to ensure that building occupants are not subjected to untenable conditions. However, most engineers are reluctant to design systems that could expose occupants to any smoke at all, even if that exposure is not lethal. Engineering guides such as NFPA 92B include methods for calculating smoke parameters, which can be used in a hazard analysis for the design of a system based on tenability criteria.[1]

Design Fire (Size and Location)

The design fire selected for smoke management design calculations must be representative of the most realistic, or expected, fire that is likely to occur in the atrium based on the specific design of the building and its use, which together determine the materials used to construct the building and those contained in it. The degree of interconnection or openness between the atrium, or atriums, and the adjacent spaces is also a critical factor in the design of the system. An open or partially open atrium requires more complex fire protection than a closed atrium to limit smoke movement and protect evacuation routes — the greater the interconnectedness, the greater the possibility of smoke spread.

An underlying assumption in the selection of a design fire, or fire scenario, is that it is sufficiently large, with little probability of a larger fire occurring, thus ensuring an acceptable level of safety as stipulated by the applicable building code or authority having jurisdiction.

Fire Size

The size of the design fire depends on the expected amount of combustible material (fuel loading) in the atrium, which in turn depends on the occupancy — a commercial occupancy, for example, is assumed to have a heavier fuel loading per unit floor area than an office building. (Some examples of design fires [4] are shown in Table 1, p. 4.) In general, the size and rate of growth of design fires are based on the analysis of fire statistics for a specific type of occupancy or from experiments on the combustible materials (fuels) typically found in the occupancy. The location of the fire in the atrium also has a significant impact on fire size and rate of growth (see “Fire Location” below).

Heat release rate is a measure of the size of the fire. The higher the heat release rate, the bigger the fire.

Smoke mass flow rate is the rate at which the volume/mass of the smoke increases in the smoke layer (the rate of smoke build-up).

The major fire parameters to be considered are the heat release rate and the resulting smoke mass flow rate. Over the years, various design fires representing different fire scenarios, with specified heat release rates, have been developed. Smoke mass flow rates are based on estimated heat release

rates for use in the design of a smoke exhaust system.[1,2,3] For complex atrium designs, numerical fire models may be required to assess the ability of the smoke management system to meet design objectives (see “Numerical Modelling for Smoke Management Design” below).[5]

Fire Location

There are two main locations for design fires:

- on the atrium floor
- in a communicating space.

Algebraic equations for estimating the smoke mass flow for each of these locations are provided in the design guides.[1,2,3]

When the fire is on the atrium floor, the plume of hot gases rises to the ceiling of the atrium, continually entraining air from the surroundings, thus increasing the volume of smoke. In high atriums, the amount of air entrained in the plume can be significant and can have a major impact on the requirements of the smoke venting system.

In principle, an atrium fire could be located anywhere on the floor — near a wall or in a corner. In both cases, the adjacent walls limit air entrainment into the plume. For most design applications, it is

generally assumed that the fire will be in the centre of the atrium where the smoke plume will be symmetrical about the central axis and will entrain air on all sides, producing the greatest volume of smoke — the worst-case scenario (see Figure 1).

Algebraic equations are also available for estimating the smoke mass flow rates for fires located in communicating spaces. This includes smoke flow through an opening, such as a window, located in the wall of an atrium. It also includes smoke flow from a connecting space that accumulates under a balcony before entering the atrium. The latter situation is known as a balcony spill plume, which can result in considerable air entrainment into the smoke flow, leading to high smoke production even for small fires.

Design Approaches Based on Fire Size and Growth

One of the most commonly used approaches to the design of atrium smoke management systems assumes a steady-state design fire (Table 1, p. 4) — i.e., the fire is always the same (largest predicted) size. A system designed to deal with this fire will also be able to handle the fire as it grows.[1,2,3] Steady-state design fires, with their simple algebraic equations, are relatively easy to use to estimate smoke parameters, including smoke mass flow rate based on the size of the fire (heat release rate). However, because this approach assumes the largest possible fire from the time of ignition, there is a large factor of safety resulting in a higher cost.

Maximum heat release rates for some products are given in NFPA 92B.[1] For example, the peak heat release rate from a plastic trash bag filled with paper is 120-350 kW and from a small (6.5-7.4 kg) dry Christmas tree it is 500-650 kW.

A second approach, which uses a fire that grows over time to model actual growth, can result in design criteria that are less onerous. Frequently, the fire growth is assumed to be proportional to time squared (t^2). There are four basic classifications for fire development, or growth rate: slow, medium, fast and ultra-fast. However, as in the case of fire size, fire development is dependent on a number of factors; thus, there is a range of possible fire growth rates. The designer selects the design fire growth rate that most closely represents what is likely to occur for the occupancy and expected fuel loads, and designs the system to provide adequate performance.

Table 1. Steady-state design fires for atriums.[4]

Fuel loading	Design fire (MW)
Low (minimum fire for fuel-restricted atrium)	2
Typical (minimum fire for atrium with combustibles)	5
High (large fires)	25

In this approach, the maximum fire size must be stated, the assumption being that the fire will only grow to a certain size because sprinklers are present to control the fire.

A third approach for determining the appropriate design fire uses information obtained from full-scale fire tests in which the fuel load corresponding to a specific occupancy has been recreated. These data can be used by designers to predict the consequences of the same fire (fuel load) in buildings of different geometries. This approach is useful when the anticipated fuel load is expected to be very similar to that used in the test arrangement.

At present, real fire test data are not readily available for use in the design of smoke management systems. Existing databases are quite limited, although there are some data in design guides such as NFPA 92B, which is probably the most widely used tool.[1] Results for both sprinklered and non-sprinklered fire scenarios can be found in the literature.

Determining the Need for Mechanical Exhaust

When the quantity and rate of smoke production have been determined using design equations as described above, a decision can be made about whether a mechanical exhaust system is required.

Smoke Management without Mechanical Exhaust

Engineering equations can be used to estimate the rate at which smoke will fill an atrium for a given design fire.[1] Some atriums have a large enough volume to allow smoke to accumulate above the design height for a specified period of time, permitting occupants to evacuate safely. If occupants can respond and evacuate before the atrium fills with smoke, further smoke management measures to limit smoke accumulation may not be required. An atrium that is only partially open to the adjoining building, for example, may not require a mechanical exhaust system because the smoke can be contained above the opening (see Figure 2).

Smoke Management with Mechanical Exhaust

When it is deemed that there is insufficient time for occupants to respond and evacuate before the smoke layer descends below the design height, a mechanical exhaust system can be used.

Typically, the mechanical exhaust system is designed to maintain the smoke above the design height for a specified design fire. By assuming a fire size and a height for the smoke layer, algebraic equations provided in the engineering design guides can be used to estimate the mass flow rate of smoke into the smoke layer above the design height.[1] In order to maintain the smoke layer at or above the design height, the fan for the smoke exhaust system must have the capacity to remove a sufficient quantity of smoke from the smoke layer (see Figure 3). This means that system designers must carefully consider phenomena that might compromise the effectiveness of the smoke exhaust system, such as plugholing and ceiling jets.

Plugholing. The possibility of fresh air from below the smoke layer being pulled into the exhaust inlets must be considered for designs in which the distance between the design height and the exhaust inlets is limited. This phenomenon in which the exhaust is made up not only of smoke but also of air from inside the atrium is known as plugholing. With plugholing, some of the capacity of the exhaust system is expended in removing air rather than smoke. This diminished efficiency of the system needs to be considered when determining the design height and the fan capacity (see Figure 4).

In a recently completed ASHRAE-sponsored research project, IRC fire researchers used full-scale physical model studies combined with numerical modelling to investigate this issue.[6,7,8] They found that a design approach similar to one used in the United Kingdom to prevent plugholing in gravity venting systems (open vents, no fans) could also be applied to an atrium mechanical smoke exhaust system. Design methods for addressing plugholing are provided in the 2000 edition of NFPA 92B.[1] The main approach used to minimize plugholing involves providing multiple inlets for the exhaust system in order to reduce the amount of exhaust that has to pass through a single inlet.

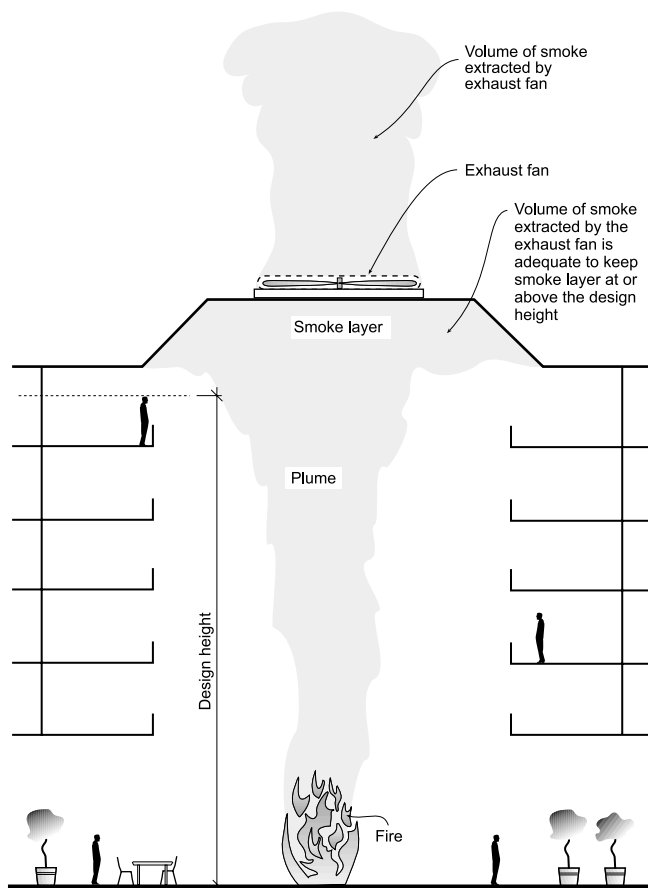


Figure 3. The smoke exhaust system must have adequate capacity to remove a sufficient quantity of smoke from the smoke layer.

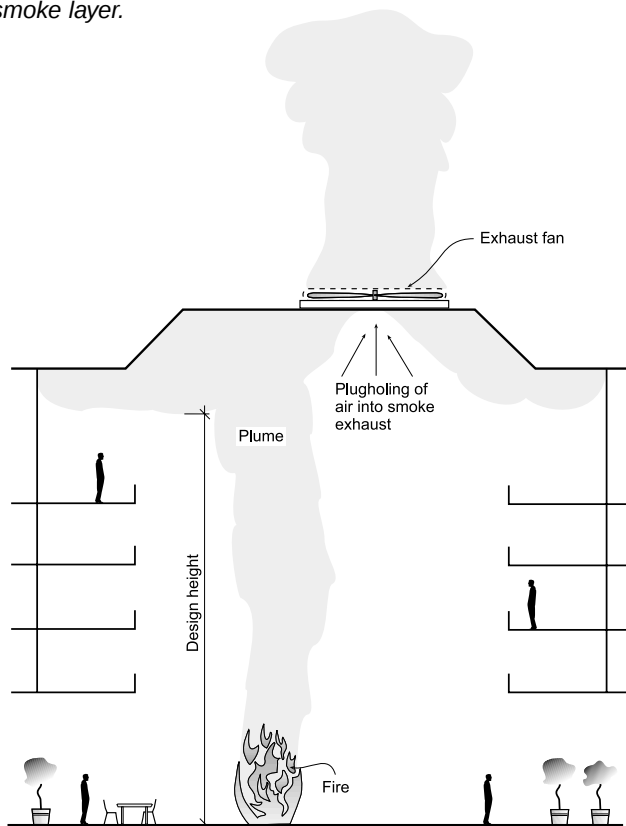


Figure 4. The plugholing phenomenon

Ceiling jet. In addition to addressing the plugholing phenomenon, NFPA 92B also recommends that the smoke layer depth below the exhaust inlets be sufficient to accommodate the smoke flow once the smoke reaches the atrium ceiling (see Figure 5, p. 6).[1] At this point, the smoke flows outwards to the walls. This flow is known as the ceiling jet. At the wall, the smoke flow will be redirected back into the atrium.

Fire-protection engineers have generally assumed that the smoke flow at the ceiling occupies between 10 and 20% of the height of the atrium, which was recently confirmed by IRC experimental work.[9] This type of smoke flow limits the depth of the smoke layer that can be accommodated using a mechanical exhaust system and therefore needs to be considered when determining the design height.[1]

Numerical Modelling for Smoke Management Design

While empirical equations are sufficient for design purposes in many applications, numerical fire models are required for more complex problems. Many zone fire models (numerical models based on the different zones in an atrium, as shown in Figure 1) can take into account exhaust from the smoke layer, and can therefore be used to simulate atrium smoke management systems. However, before using such a model, the designer should determine whether it has been verified for the heights typical of those found in the atrium under consideration.

Some modern buildings with multiple atriums and interconnected communicating spaces, or with very large open spaces, are too complex to be adequately represented by the available empirical equations and/or zone models. For these buildings, more extensive numerical modelling is warranted. Designers of smoke management systems often use Computational Fluid Dynamic (CFD) models for this task because they allow for a detailed examination of smoke flow in a building.

Summary

The design of a smoke management system for an atrium building depends on the use and the design of the building, both of which affect the size of the fire and its rate of growth, and hence the ability of occupants to evacuate. Various approaches or tools are available for the design of these

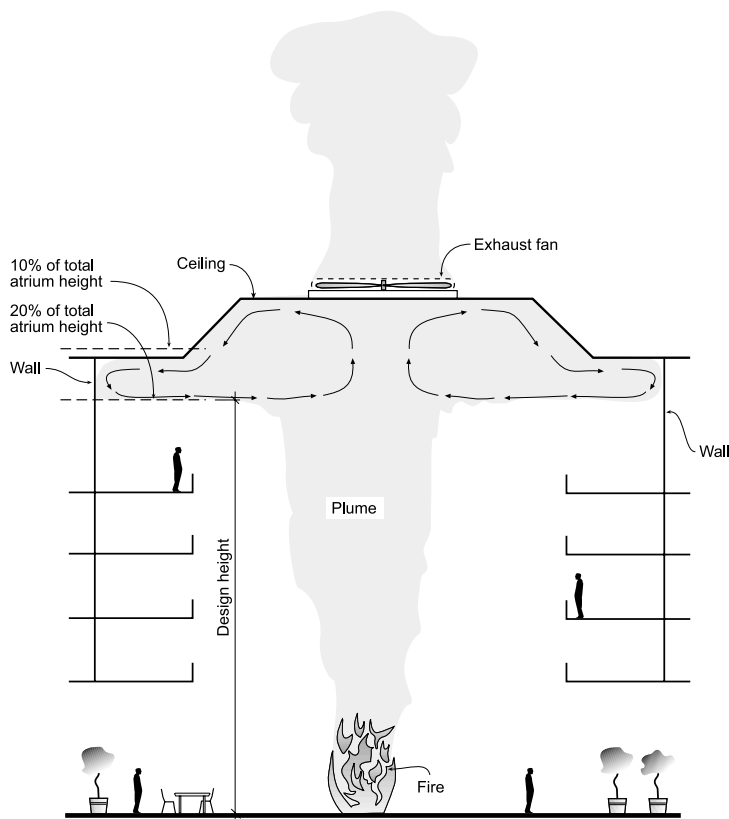


Figure 5. Ceiling jet smoke flow pattern

systems, from empirical equations for simpler buildings to numerical modelling for more complex ones.[1,2,3] The use of smoke management systems provides options for extending the use of the atrium while maintaining safe egress routes. However, in applying these systems, the designer must take into consideration factors that limit system effectiveness, such as plugholing and ceiling jets.

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Footnotes

1. Although the figures show a raised roof system, this is not a requirement of the National Building Code of Canada 1995.
2. "Communicating spaces" refers to those spaces in a building with an open pathway to the atrium such that smoke movement between the spaces and the atrium is unimpeded. This includes spaces that open directly into the atrium as well as those that connect through passageways.

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