Small Atria Smoke Control *

By Kurt Ruchala, P.E.

This article describes the design of a smoke control system for an existing three-story college dormitory that recently underwent renovation. The building included three distinct sections: a central, open, three-story exhibit hall and two connecting wings of dormitory rooms located on opposite sides. The renovation included filling in most of the exhibit hall space with new dorm rooms and bathrooms while retaining a three-story atrium in the center. Each floor provided approximately 12,000 ft^2 (1,100 m^2) of space. The incorporation of the atrium triggered the requirement by the local building code (based on the 1996 BOCA model code) for an atrium smoke-control system. Although it was a small atrium, the building code has a prescriptive requirement that any atrium over two stories in height requires a smoke-control system. Part of this project consisted of analyzing approaches to provide atrium smoke-control requirements for the renovated three-story college dormitory.

Under the current building regulatory environment in the United States, performance-based design, or engineered solutions to specific fire-protection challenges, is typically provided through the code equivalency process. Code equivalencies for alternative approaches are usually limited in scope and focus to a specific building subsystem. The goal of the code equivalency process is to show that a similar level of safety is provided by the alternative protection[1].

In this project, only a specific portion of the building's total fire protection system was analyzed with the objective to find an alternative approach to the provision of a mechanical smoke-removal system. The project illustrates the usefulness of engineering analysis even on small projects. Engineering criteria and a performance-based design thought process were used to design an adequate smoke-control system and demonstrate code equivalency. Due to time schedules, contracted scope of work and budgetary constraints, only a conceptual analysis was performed. The budgetary figures used were based on discussions with individuals who provide or contract for the services indicated. They were not developed specifically for this project. The figures are not exact but provide an order of magnitude estimate for demonstration purposes. Even though a good portion of the work was conceptual, it provided an appropriate level of analysis to demonstrate code equivalency to the Authority Having Jurisdiction (AHJ) and resulted in a cost benefit to the client.

CODE SOLUTION

The building code requirement for an atrium smoke-control system is prescriptive in nature. It states, in part, that if the building has an atrium of more than two stories, the atrium shall be provided with a smoke-control system. The code requirements for smoke-control systems are performance-based. The code allows several solutions for addressing the smoke-control issue, including both passive and active systems and engineered alternatives. The performance objective specifies that for 20 minutes, the smoke layer must be maintained at least six feet above the highest walkway open to the atrium. For this project, both passive and mechanical systems were reviewed.

A passive smoke-control system relies solely on the open space volume of the atrium, located above the highest walkway, to act as a holding space for the smoke during the specified 20 minutes. The configuration of the project was not conducive to the use of passive control. The atrium configuration provided only approximately 5,500 ft^3 (160m^3) of usable volume above the highest walkway. Based on the theoretical smoke produced from the code-specified steady-state design fire, the space was calculated to fill within 10 seconds.

The mechanical system requirements were calculated based on the calculation method outlined in the building code, resulting in the need for an exhaust fan with a minimum rating of 37,000 cfm (17 m^3/s). In addition to the exhaust fan, a ducted make-up air system was

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Design Fire

The building code defines the design fire as a steady-state heat-release rate fire and establishes release rates.

1. 4,400 BTU/Sec (4,642 kW) for mercantile, moderate-hazard storage and moderate-hazard, factory-type facilities.

2. 2,000 BTU/Sec (2,110 kW) for all other use group occupancies.

Building Code Specified method for calculating the Volumetric Smoke Production Rate

$$V = (17.6 Q_c^{1/3} \bullet Z^{5/3}) + 3.36 Q_c$$

Where:
V = Volumetric Smoke Production (cubic feet per minute)
Q_c = Convective Heat-Release Rate (BTU/Sec)
Z = Height from the floor to the smoke interface (feet)

required to provide the proper volume of make-up air. Also, standby power was required, which prompted the design of an emergency electric generator system and, due to space constraints, an outside building to house the generator.

The cost of the mechanical smoke control equipment, additional duct work and standby power was estimated by the project architect to be around $100,000. In addition to the upfront costs, the annual maintenance and testing costs of the smoke extraction and standby power systems, based on discussions with mechanical contractors and building managers, was estimated at approximately $2,000 for the fan and $1,000 for generator. Over a 20-year life expectancy, the maintenance and testing would cost an estimated $60,000, resulting in approximate total cost of $160,000 for the smoke-management system.

ALTERNATIVE APPROACH

The prime objective to the analysis was to determine if an equivalent approach to the provision of a mechanical smoke-control system could be developed. The tasks associated with this analysis were: (1) the performance of a code review to determine various levels of protection required by the code, and (2) to prepare and present alternatives to the design team. The key code issue was the number of floors opening into the atrium. Smoke control would not be required for a two-story atrium. The original design called for the third-floor opening to the atrium to be enclosed by nonfire-rated glass. Therefore, the most straightforward approach to alleviate the code-required smoke-management system was to make the three-story atrium into a two-story atrium. This was accomplished by a change in construction material. The recommendation was made to the architect that the ordinary glass be replaced with a fire-rated glass, which had undergone the ASTM E119 test[2]. Several manufacturers were able to provide glass with 60-minute and 90-minute ratings for relatively large wall sections. The cost to implement the rated glass wall system design approach was comparable to the cost of the smoke exhaust fan excluding the make-up air ductwork. This simple design alternative would have sufficed to meet the intent of the code; however, further analysis exposed an additional concern for egress.

Based on discussions with the design team, the local building department and the fire department, it was decided that, although the two-story atrium space did not require a smoke-control system, some form of a smoke-control system would improve the life safety of the building, as several dorm rooms on lower floors opened on to the atrium. Therefore, a passive smoke-venting system was proposed and approved. The smoke-venting system took advantage of relatively inexpensive passive vents and the capabilities of a new analog-addressable fire alarm system, which was already designed for the building.

VENT DESIGN

The original document referenced for the design of the smoke management system was NFPA 92B Guide for Smoke Management Systems in Malls, Atria, and Large Areas.[3] This guide was important in the development of the smoke-control strategy for the space and in providing the calculation methods for verifying the effects of smoke buoyancy on the passive system. However, a second guide was needed to size the passive venting system, NFPA 204M Guide for Smoke and Heat Venting.[4] Utilizing the equation for steady-state fires, the required vent area was determined to be 38 ft^2 (3.5 m^2). Applying a safety factor of approximately 2 resulted in a specified vent size of 75 ft^2 (7 m^2).

Because a single commercially available vent could not be found

Vent Sizing Calculation[4]

$$A_v = 0.073 Q^{1/3}\left[1 + 0.19 Q^{2/3}(H-d)^{-5/3}\right]\frac{(H-d)^{5/3}}{d}$$

Where:

A_v = Vent Area (square feet)
Q = Convective Heat Release Rate (BTU/Sec)
H = Ceiling Height (feet)
d = Curtain Depth (feet)

The curtain depth (d) for this case was defined as the height from the ceiling of the second level to the roof of the building. This was the holding area for the smoke and served a similar purpose as a curtain wall in a storage occupancy.

to provide the 75 ft^2 (7 m^2) specified, two vents were used. The list price of two typical vents is $1,500 each. The vents were connected to the atrium by a short, smokeproof, horizontal shaft. This enabled the vents to be hidden from view from the atrium.

A check to determine if the atrium would be affected by smoke stratification was conducted. Smoke stratification occurs when the smoke produced by the fire is not hot enough to reach the ceiling level. Smoke stratification can occur early in the fire when the heat released by the fire is: (1) low and is in a large space where the smoke cools as it travels toward the ceiling resulting in an equilibrium temperature; (2) located below a warmer air layer; or (3) in a space with high ventilation rates which mix the smoke with large amounts of cool air. The equation found in NFPA 92B was used to determine if stratification would be a concern. The convective portion of the code-specified design fire was used in this equation. A temperature difference of 275ºF (135ºC) was calculated. This indicates that, with the steady-state design fire burning on the atrium floor, the ambient temperature difference between the floor and the ceiling would have to be equal to or greater than 275ºF (135ºC) before smoke stratification would be expected. This indicates that if the ambient temperature is 70ºF (21ºC), the ceiling temperature would have to exceed 345ºF (173ºC) before smoke would stratify in the atrium. Therefore, smoke stratification is not expected in this scenario.

To avoid problems venting the smoke, a make-up air system was devised to open the two front doors upon selective detector activation. The make-up air entered the atrium through the

Smoke Stratification Calculation[3]

$$\Delta T_o = 1300 Q_c^{2/3} \bullet H^{-5/3}$$

Where:

ΔT_0 = Temperature Change from base of the atrium to the ceiling

Q_c = Convective Heat-Release Rate (BTU/Sec)

H = Ceiling Height (feet)

area created by the two door leaves, which open directly from the floor of the atrium to the exterior. The control system chosen to open the doors utilized a pneumatic system activated by a signal from the fire alarm system. The doors are operated by an air reserve contained within a pressurized tank. Upon fire alarm operation, a signal from the fire alarm system would activate the pneumatic system and air would be locked in the pipe, maintaining the doors in the open position. The pneumatic tubing for the system was specified to be metallic to minimize the potential of the fire burning through the tube and causing the system to fail. This subsystem would be constantly checked by its repeated use by mobility-impaired occupants opening the doors to enter and leave the building.

An additional factor that complements the vent design is the local fire department utilization of positive pressure ventilation. Their fire-fighting tactic places a large-capacity fan in an opening, typically a doorway, to pressurize the structure. When an opening opposite the fan is created, the flow through the structure carries the smoke out of the building. The building's vent design complements this strategy well, in that the two openings are already there, one at the fan location, the other in the roof, requiring the fire department only to position the fan in the doorway. These positive pressure ventilation fans typically provide large air flows well into the tens of thousands of cubic feet per minute.

FIRE ALARM AND VENT CONTROL

The fire alarm system specified for this building was an analog-addressable type. This type of system provides the flexibility to allow specific output functions, such as vent operation, based on the input received from specific detection devices. This system aided the vent control design in that specific smoke detectors and water flow switches could be selected to activate the vents. The selected detection devices were spot-type detectors located in the atrium, the atrium water flow switch (it was suggested to the architect that the atrium sprinklers be supplied by a dedicated main) and an atrium beam detector. This would provide reasonable assurance that automatic vent operation would only occur when the fire involved the atrium.

RELIABILITY ISSUES

One of the issues discussed during the preliminary stage of this project was the reliability of the smoke-control system options. A detailed statistical analysis was not undertaken for this project due to several issues including time, scope and budgetary constraints; lack of easily procured ventilation component reliability data; the relative simplicity of the mechanical ventilation option (a single ventilation fan); and the expected large impact of system life-cycle maintenance on overall reliability. Instead, reliability issues were discussed qualitatively, and a decision was made as to the overall perceived

benefit of each alternative. The following discussion provides a brief overview of the thought process used in the evaluation and outlines the basic relationships that govern the reliability of systems.

The overall reliability of the atrium fire-protection system includes the reliability of all its subsystems. These subsystems include the passive barriers, detection devices, fire alarm controls and smoke control devices. As the success of the entire system depends on the proper operation of all the sub-components, the system reliability can be expressed by the following relationship:

$$R_{system} = R_{detectors} \bullet R_{fire\ alarm\ controls} \bullet R_{mechanical\ extraction} \quad (1)$$

The reliability of the mechanical extraction smoke controls can be expressed by the following equation:

$$R_{mechanical\ extraction} = R_{smoke\ removal\ device} \bullet R_{standby\ power} \quad (2)$$

In the proposed alternative system, the mechanical extraction system was replaced by a combination of a passive barrier and a passive vent. This configuration results in a system reliability represented by equation (3).

$$R_{system} = R_{detectors} \bullet R_{fire\ alarm\ controls} \bullet R_{passive\ option} \quad (3)$$

Where:

$$R_{passive\ option} = R_{passive\ barrier} \bullet R_{passive\ vent}$$

The only differing variable between equations (1) and (3) is the third variable $R_{mechanical\ extraction}$ and $R_{passive\ option}$. Therefore, if $R_{passive\ option}$ is greater than $R_{mechanical\ extraction}$, the passive option would provide a more reliable alternative.

Based on a qualitative review of the potential failures, including the decreased reliability of mechanical systems if they are not properly tested and maintained, it was the opinion of the design team that the specified passive design option would provide a more robust system.

The issues that influenced this decision include the following:

1) Passive Glass Wall. Its highly visible location helps in its maintaining the level of protection it provides, as it will not be prone to penetrations, and any problems with its integrity (i.e., broken glass) should be apparent.

2) Make-Up Air. The make-up air system, the automatic opening exterior doors, will be used on a daily basis for access to the building. This will provide prompt detection of a problem and promote quick repair.

3) Vent Testing. Testing the vents will not require an additional contractor to measure their performance. The fire alarm testing contractor can test the vent simply by activating an atrium detector to determine if the vent will open or not.

4) Mutual Exclusivity. Two separate systems were implemented: a passive barrier and vents. These systems are mutually exclusive, in that the performance of one does not depend on the performance of the other.

5) Mechanical Systems. Mechanical systems require repetitive testing in order to verify that they will perform as designed. If these mechanical systems are not tested, their reliability could potentially decrease drastically. If the mechanical smoke control option was selected for this application, two mechanical systems, a fan and a generator set, would have been required. This creates a two-component system in which the components are not mutually exclusive, for if one component fails, the entire system fails.

The reasoning above is not intended to insinuate that mechanical smoke control is not a valuable design alternative. However, in this scenario, based on the size and configuration of the space, a more efficient option was available. The design is intended to be easy to maintain which will aid in ensuring its function and reliability.

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REFERENCES

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