> When faced with substantially higher smoke exhaust rates, designers may struggle more with replacement air than the exhaust itself.

essential reading, particularly with respect to the methodology of calculating required system volumetric exhaust rate.

Once the necessary smoke removal volumetric exhaust rate is determined, HVAC engineers set out to design a practical system for implementing smoke exhaust. UL-listed[7] smoke removal fans are commercially available from multiple manufacturers. Smoke removal often is achieved via one or more exhaust fans expelling air from a point near the top of the atrium, directly to the outdoors.

However, the literature tends to offer far fewer tips, practical guidance, or design suggestions for delivery of replacement air. When 6 air changes per hour was the norm for smoke exhaust design, replacement air often could be accommodated with relative simplicity, sometimes just by allowing for leakage from surrounding spaces and/or the outdoors. When faced with substantially higher smoke exhaust rates, designers may struggle more with replacement air than the exhaust itself.

Replacement Air Goals

Before discussing various methods of delivering replacement air to the atrium, a review of the goals is necessary. The replacement air system should be selected and designed according to the following:

1. Replacement air should be uncontaminated outdoor air, so intakes must be sufficiently remote from the smoke exhaust discharge point.
2. Replacement air should be supplied at low velocity—less than 200 fpm (1 m/s) when measured at the potential fire location,[8] and should be sufficiently diffused into the atrium.
3. Replacement air should be delivered into the atrium—not at the top—but at locations below the level at which smoke is expected to aggregate[9] (the "smoke layer interface" as it is called in the literature).
4. The replacement air system should be reliable and conducive to periodic testing.
5. The replacement air rate must be controlled to a volumetric rate less than the exhaust rate,[9] to maintain the atrium at a negative pressure relative to the ambient pressure of adjacent spaces.
6. In some cases, particularly when the atrium is part of a high-rise building, the local authority having jurisdiction may require the smoke management system to be controllable from the firefighter's command center via a firefighter's smoke control station. This allows the emergency response team to override operation of the smoke management system according to its own judgment at the scene.
7. The designer should be mindful of unintended consequences, being alert for secondary effects of the replacement air method.
8. The system should not be so complex as to cause operator confusion or misimplementation. If the only person who understands the replacement air system is the design engineer, this goal is not achieved.
9. Atria, where they exist, tend to be the showcase or focal point of the entire facility. Architects are keenly interested in the impact on aesthetics of any mechanical design decision regarding the atrium.
10. Finally, the design engineer should be sensitive to the system cost and client's budget.

With these parameters in mind, this article compares, contrasts, and offers pros and cons of three methods of replacement air delivery in support of atrium smoke exhaust. This article discusses the three methods independently, but hybrids of the three could be used, and other options may be available.

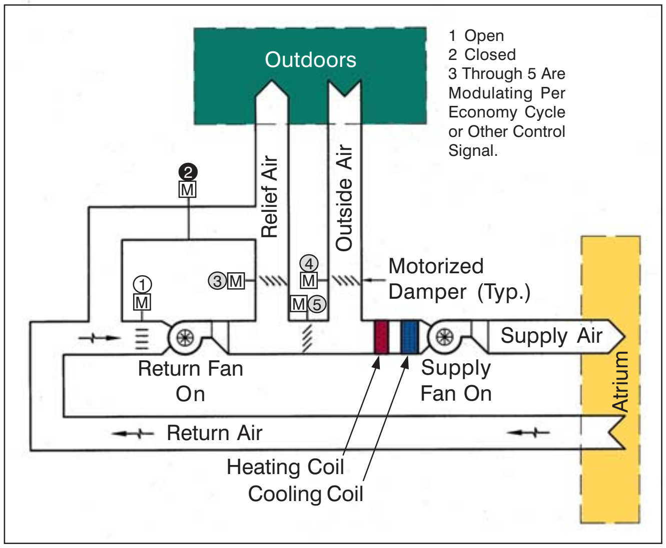
Method A: Nonmechanical Replacement Air System

Perhaps, the simplest method of delivering replacement air into the atrium is via direct outdoor openings. Examples include automatic doors or louvers, hinged panels incorporated into a curtain wall, or drop-away window panels. Many architects may be able to suggest commercially available components that can be incorporated into the exterior skin of the atrium. The HVAC engineer's role is to coordinate the controls and activation of these devices to operate automatically in a smoke emergency. No mechanical fans, ductwork, or other air movement components are involved.

This method is more readily applied in atria with direct access to the outdoors via an exterior wall. For atria with no adjacency to the outdoors, an additional level of complexity exists since this method would result in replacement air being drawn through communicating spaces.

The nonmechanical approach meets several goals:

- The location of the outdoor air openings can be strategically placed to avoid intake of contaminated air.
- The openings can be sized for proper air velocity and located to allow introduction of air at appropriate points.
- This system is easily understood by both technical and non-technical persons.



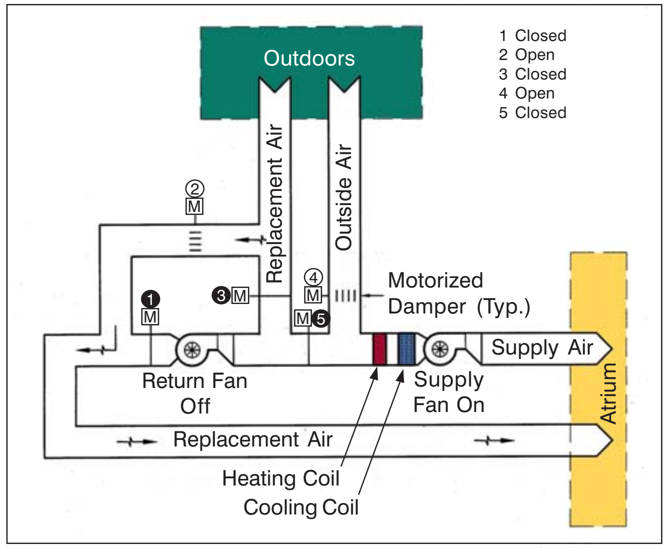


Figure 1 (left): Atrium HVAC system normal mode. Figure 2 (right): Atrium HVAC system emergency mode.

- The installed cost generally is low.

Drawbacks of this approach include:

- Once activated, many of the commercially available products remain open until manually reset. Some of these products cannot be overridden remotely.
- Passive ventilation is subject to wind effects, stack effect, and other external forces that may be difficult to take into account. Locating the inlets to ensure the design airflow may be difficult.
- Seldom does a practical way exist to heat or cool the replacement air under this method. This discourages periodic testing of the system in climates with long, cold winters or

hot, humid summers. Since smoke-management system volumes can be quite high, even a brief test on a cold day can have severe consequences in the building.

- Some architects veto hinged panels or drop-away window sections as detrimental to the aesthetics. Street-level exterior doors used for passive replacement air may present an intrusion concern during testing or nuisance alarm.

Statistic	Corporate Leadership Center I-P	Corporate Leadership Center SI	Medical School Classroom Building I-P	Medical School Classroom Building SI
Area of Atrium, ft² and m²	5,800	539	5,854	544
Height of Atrium, ft and m	44.0	13.4	73.7	22.5
Volume of Atrium, ft³ and m³	255,200	7226	431,245	12 211
Distance Floor to Smoke Layer, ft and m	35.0	10.7	57.75	17.6
Design Protection Time, seconds	1,200	1200	1,200	1200
Fire Heat Release Rate, BTU/s and kJ/s	2,000	2110	2,000	2110
Smoke Exhaust Rate, cfm and L/s*	78,438	37 000	174,584	82 400
Net Effective, ACH	18.4		24.3	
Replacement Air Method Selected	Method C		Method C	
Base Supply Air, Normal Operation, cfm and L/s	56,500	26 700	96,000	45 300
Balance of Replacement Air Induced Via RA Path	Yes		Yes	

* Calculated via Formula 922.2.1.2(a) of the 1999 BOCA Building Code.

Table 1: Atria statistics for the two case studies discussed here.

Method B: Dedicated Replacement Air System

A more rigorous and perhaps more complete method of delivering replacement air into the atrium is to provide an outdoor air-handling system dedicated solely to that purpose. One or more forced-air systems are designed to draw in outdoor air, filter and condition it according to local climate and conditions, and distribute it throughout the atrium via a network of ducts and diffusers. The system remains idle under normal circumstances, and is activated via automatic controls to operate in conjunction with the exhaust fans during a smoke emergency.

The dedicated replacement air approach delivers several benefits:

- Goals 1, 2 and 3 regarding placement and velocity are well within the control of the design engineer.
- Although perhaps somewhat more complicated than the non-mechanical approach, the dedicated replacement air system is commonly understood and simple to test, nonetheless.
- System override controls can be incorporated into a firefighter's smoke control station for override.
- The replacement air can be heated, cooled, filtered, or otherwise treated as the design engineer may deem prudent.
- The dedicated equipment and controls are less likely to be overridden or modified by building staff because they serve no additional purpose.

Some negative features of the dedicated system include:

- The installed cost is expected to be the highest of the three approaches presented here, since the owner is purchasing an entire air-handling system, which is not otherwise required. This factor may eliminate this option in many applications.
- Reliability is not necessarily ensured. The lack of day-to-day use of the dedicated system may hide equipment failures. Regular testing is absolutely essential if this approach is chosen.

Method C: Non-Dedicated Replacement Air System

The final method of delivering replacement air is to use the air-handling system that regularly serves the atrium. The base equipment shares both nonemergency and smoke emergency duties. One or more forced-air systems are designed to recirculate return air, mix in outdoor air (probably with an air-based economy cycle), filter and condition the air according to local climate and conditions, and distribute it throughout the atrium via a network of ducts and diffusers.

The system functions as the routine HVAC system for the atrium during normal circumstances, and transitions into emergency mode via automatic controls during a smoke condition. Mixing dampers must be driven to full outdoor air and no return air. If the supply air system includes VAV boxes, those VAV boxes must be driven to the fully open position in smoke emergency mode, regardless of thermostat instructions.

One should not overlook the return air path as a potential passageway for additional replacement air to the atrium. The volume of airflow in smoke emergency mode, when calculated according to the referenced literature, can exceed the entire supply air volume of the HVAC system intended for normal service. Hence, additional sources of replacement air must be considered.

Figure 1 illustrates a non-dedicated replacement air system operating in normal mode; and *Figure 2* illustrates the same system in smoke emergency mode. For a very modest additional cost of a few dampers and short length of ductwork, there exists a pathway via the return air system for induction of additional replacement air. This "backwards through the return air system" concept can contribute significantly to the availability of replacement air—provided, of course, the de-

Goal or Factor	Case Study: Corporate Leadership Center — Method A	Method B	Method C	Case Study: Medical School Classroom Building — Method A	Method B	Method C
1. Uncontaminated Intake Location	Achievable	Achievable	Achievable	Achievable	Achievable	Achievable
2. Air Velocity and Air Diffusion	Poor	Achievable	Achievable	Achievable	Achievable	Achievable
3. Replacement Air Supply Location	Poor	Achievable	Achievable With Care	Achievable	Achievable	Achievable With Care
4. Reliability and Ease of Testing	Moderate Reliability*	Moderate	Everyday Use	Moderate Reliability*	Moderate	Everyday Use
5. Proper Pressure Relationships	No Assurance	Achievable	Achievable	No Assurance	Achievable	Achievable
6. Firefighter Command Center Override	Not Required	Not Required	Not Required	Not Necessarily Achievable	Achievable	Achievable
7. Unintended Secondary Consequences	Detrimental Effects of Cold Weather Testing	Not Significant	Not Significant	Detrimental Effects of Cold Weather Testing	Not Significant	Upgrade Required for Seismic Bracing, Wiring
8. Simplicity of Approach	Simple	Moderate	Complex	Simple	Moderate	Complex
9. Architecture/ Aesthetics	Unacceptable, Per Architect	Acceptable	Acceptable	Unacceptable, Per Architect	Acceptable	Acceptable
10. Budget	Low Cost	High Cost	Low Cost	Low Cost	High Cost	Moderate Cost

* See Unintended Secondary Consequences.

Table 2: Sample subjective evaluation of replacement air system methods.

signer permits no obstacles such as backdraft dampers.

Buildings in which Method C cannot be applied are those without a central air system. Buildings such as hotels or multifamily residences, for example, may be served entirely via water-source heat pumps, fan-coil units, or other hydronic-based systems. In those cases, Method C must yield to Methods A or B.

The non-dedicated replacement air approach of Method C generally offers these benefits:

- Goals 1, 2 and 3 are well within the control of the design engineer, but with several challenges because the designer must consider both regular and smoke emergency functions.
- Reliability is enhanced, as the failure of any component in the non-dedicated arrangement generally is discovered and repaired during the course of normal operation.
- System override controls can be incorporated into a firefighter's smoke control station for override.
- The replacement air can be at least partially heated, cooled, filtered, or otherwise treated.
- The architect designing the atrium may be satisfied since few, if any, additional grilles and diffusers are used beyond that required for the base HVAC system. The architect may also be grateful to avoid the nonmechanical methods described in Method A.
- The installed cost may not be appreciably more expensive than the system the owner is purchasing for regular use.

Among the drawbacks of the non-dedicated system are:

- This system certainly is the most complex of the three methods, and at risk of being misunderstood. The controls and sequences of operation must be clearly defined and clearly communicated to all involved parties. This method may be unsuitable where the operations staff has insufficient technical training or ability, or is known to implement their own "overrides" such as forcibly blocking closed certain dampers or disabling automatic controls.
- All of the normal system components, such as ductwork, dampers, controls, and VAV boxes, now have a life-safety role in addition to their normal service. In some jurisdictions, that fact may upgrade all of those normal system components to a more stringent code classification in terms of seismic bracing or life safety features (e.g., standby power).

Case Study: Corporate Leadership Center

To apply these goals of replacement air for atrium smoke exhaust, two case studies—one completed and one under construction—are presented.

The first is a three-story atrium, occupied on all levels, inside a major corporate leadership and training center in the Midwest. The atrium is located in the middle of the building,

Smoke Exhaust Rate Calculation

The primary purpose of this article is to address the replacement air component of atrium smoke exhaust—a topic the author has found to be somewhat scarce in the literature. Of course, the calculation of the smoke exhaust rate itself must precede an attempt to design for replacement air. The smoke exhaust rate is determined by considering a long series of factors which are not intended to be covered in this article, but which are thoroughly presented in the cited References.

Very briefly, the smoke exhaust rate for this article's case studies was determined as follows. A great deal of detail has been omitted for brevity, and the following should not be applied to other designs without a thorough understanding of the theory.

- Article 922.2 of the 1999 BOCA National Building Code was enforced.
- With respect to Paragraph 922.2.2.1, to maintain tenable conditions on the upper level of the atrium, the smoke exhaust rate was taken as equal to the calculated rate of smoke production. This is somewhat more conservative than calculating the rate associated with a 20-minute egress period.
- The rate of smoke production, and consequently the rate of smoke exhaust, was determined by the equations of 922.2.1.2.

$$V = 17.6 Q_c^{1/3} Z^{5/3} + 3.36 Q_c$$

where

V = volumetric rate of smoke production in cfm.

Q_c = 0.70 × Q

Q = 2,000 Btu/s as dictated by this code for this facility.

Z = The height in feet from atrium floor to a point 6 ft (1.8 m) above the highest occupied floor, i.e., the smoke layer interface.

- *Using the values listed in* Table 1 *for the corporate leadership center example:*

$$V = 17.6(0.7 \times 2{,}000)^{1/3}(35)^{5/3} + 3.36(0.7 \times 2{,}000)$$
$$= 78{,}438 \text{ cfm } (37\ 000 \text{ L/s})$$

- *Using the values listed in* Table 1 *for the medical school classroom building example:*

$$V = 17.6(0.7 \times 2{,}000)^{1/3}(57.75)^{5/3} + 3.36(0.7 \times 2{,}000)$$
$$= 174{,}584 \text{ cfm } (82\ 400 \text{ L/s})$$

interconnecting three levels of workshop, classroom, breakout, and lobby space via a grand staircase. This atrium is upscale, from the architectural design to the interior finishes to the selection of intrastructure systems. Important statistics of the atrium are found in *Table 1*.

Using the methodology required by the applicable building code,[1] the required atrium smoke exhaust is 78,500 cfm (37 000 L/s) (see sidebar). Note that if the system were sized using a blanket 6 air changes per hour, the smoke exhaust rate would have been far too low at 25,500 cfm (12 000 L/s). Two smoke exhaust fans of roughly 50% each are installed on the roof of the uppermost floor, and smoke exhaust intake is simply drawn directly from the top of the atrium.

Making provisions for replacement air was the more difficult task. Method A, the nonmechanical replacement air, was ruled out after careful consideration. The atrium is almost entirely surrounded by adjacent non-atrium occupied spaces, and there was a desire not to use communicating adjacent spaces as a conduit for replacement air. Only one small area of the atrium was adjacent to an outside wall at the far end of an oblong footprint. The architect expressed a desire to avoid hinged or fall-away panels in that location, as that portion of the curtainwall was the atrium's focal point—offering a magnificent view of bluffs and a river below. Method B, the dedicated replacement air system, could have been used but at significant added cost. Therefore, Method C, the non-dedicated replacement air system, was selected and used.

The main air-handling system serving the atrium and communicating spaces delivers 56,500 cfm (26 700 L/s) of supply air. While that was not enough to match the required exhaust, the return air system was used per *Figure 2* to create a path for the balance of the replacement air. In smoke emergency mode, the air-handling units are driven to 100% outdoor air, and all variable-volume terminal boxes are driven wide open, overriding temperature controls. Even during smoke emergency mode, the supply air (although not the portion induced through the return air path) continues to be air conditioned or heated.

The central system delivers air to both the atrium and surrounding spaces. In smoke emergency mode, that portion of the air delivered to surrounding spaces pressurizes those spaces with respect to the atrium. Transfer openings allow the replacement air to migrate from the surrounding spaces into the atrium to complete the replacement of air exhausted by the smoke removal fans. The system was tested in the presence of the local authority having jurisdiction, via theatrical smoke-generating machines. It performed as expected and was accepted.

Case Study: Medical School Classroom Building

The next case study is a four-story atrium, occupied on all four levels, inside a proposed new high-rise classroom and teaching laboratory building of a Midwestern university's medical school. As is often the case, the atrium is the architectural focal point of the facility. Important statistics of the atrium are found in *Table 1.*

Using the methodology required by the applicable building code,[1] the required atrium smoke exhaust is 175,000 cfm (82 600 L/s) (see sidebar). If the system were sized using a rate of 6 air changes per hour, the smoke exhaust rate would have been far too low at 36,300 cfm (17 100 L/s). Four smoke-exhaust fans of 43,800 cfm (20 700 L/s) each are installed on the roof of the uppermost floor, and smoke exhaust intake is drawn directly from the top of the atrium.

Replacement air via Method A was considered at length. The author did not protest Method A, although the owner, architect and code official all expressed concerns. The owner's budget quickly discouraged Method B. Therefore, Method C, the non-dedicated replacement air system, was ultimately selected and designed. Implementation is pending.

The main air-handling system serving the atrium and surrounding building delivers 96,000 cfm (45 300 L/s) of supply air. As was the case in the previous case study, the return air path is used per *Figure 2* to supplement the supply air. The details of the system function match that of the corporate leadership center case study.

One significant and unintended consequence of Method C developed in this application. In this particular geographic location and for this particular building occupancy classification, seismic bracing is required for life safety systems but not for routine systems. A city code amendment requires all wiring related to life safety to be installed in a raceway. By imparting a life-safety requirement on the otherwise-routine building air-handling systems, the entire system must be seismically braced, and all wiring (even 24 V control wiring) serving terminal boxes on the system must be routed in conduit. Even so, Method B appears to offer no advantage since it would require a large replacement air system, as large as the entire building's base system.

Summary

A summary of the goals of replacement air for atrium smoke exhaust, with the author's application of those goals to the two case studies, are presented in *Table 2*.

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