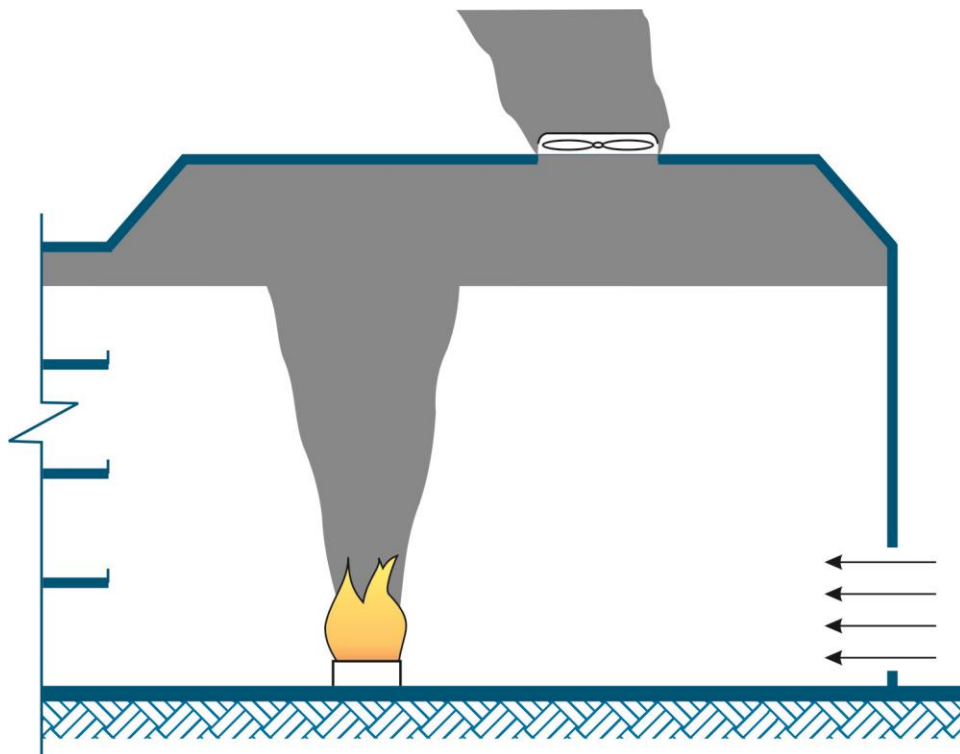# AtriumCalc
## Atrium Smoke Control Calculator
## Version 1.1

## Technical Information and User Guide

**Dr. John H. Klote, PE**

# AtriumCalc

## Atrium Smoke Control Calculator
### Version 1.1

## Technical Information
## and User Guide

**Dr. John H. Klote, PE**

**July 16, 2014**
**Updated February 3, 2015**

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# Contents

# Preface

A few years ago, an engineer told me that he had designed his first atrium smoke control system using the algebraic equation method, and he was pleased that the calculations only took him six hours. I responded that the calculations would take about six minutes with my proprietary Excel application. Further, I told him I was highly confident of its accuracy because I had carefully checked the results of his application. AtriumCalc is an improved version of this proprietary application.

I decided to make AtriumCalc available at no cost to engineers, code officials, and others as a way of paying back to a profession that has given me so much. Thanks are due to the ASHRAE Smoke Control Application Subcommittee for their generous support and constructive comments. The members of this subcommittee are William A. Webb (Chair), Jeffrey S. Tubbs, and Douglas Evans. Special thanks are due to Steve Comstock of ASHRAE who arranged for AtriumCalc to be made available from the ASHRAE website, www.ashrae.org. A beta version of AtriumCalc was circulated for one year, and a number of improvements were made in response to many reviewer comments.

An advantage of AtriumCalc is that engineers new to atrium smoke control can focus on learning the essentials of atrium smoke control systems and use AtriumCalc to do the calculations quickly. However, it must be stressed that design of atrium smoke control requires an understanding of the atrium smoke control systems operation and the capabilities and limitations of the equations involved. ASHRAE's *Handbook of Smoke Control Engineering* (Klote et al. 2012) is the most complete and up-to-date source of such information.

Questions and technical comments about AtriumCalc should be sent to me through my website, www.SmokeControlExpert.com.


John H. Klote
May 2014

# AtriumCalc: Atrium Smoke Control Calculator

## Technical Information and User Guide

Possibly the most common approach to design analysis of atrium smoke control systems is the algebraic method for a steady fire. AtriumCalc is a Microsoft® Excel® application consisting of a number of routines that use this algebraic equation method. This document describes AtriumCalc, including the algebraic equations, a discussion of each routine, and user information.

It is essential that users of AtriumCalc have a good understanding of atrium smoke control technology. While AtriumCalc and its documentation provide some information, they are not a complete treatment of the subject. For information about smoke control, see the *Handbook of Smoke Control Engineering* (Klote et al. 2012) and the *Standard for Smoke Control Systems – NFPA 92* (NFPA 2012)[1]. The handbook is referred to here as the Smoke Control Handbook. For summer design temperatures, winter design temperatures, design wind speed, and atmospheric pressure of many locations in the United States, Canada, and other countries, see Chapter 2 of this handbook. For information about design fires, see Chapter 5. Users of AtriumCalc should have some experience with Excel.

For AtriumCalc, the term *atrium* is used here in a generic sense to mean any large-volume space, such as sports arenas, multistory hotel lobbies, or airplane hangars.

Increasingly, computational fluid dynamics (CFD) is being used for analysis of atrium smoke control systems. CFD is capable of very realistic simulations, but CFD simulations are time consuming and require a high level of expertise. AtriumCalc can be used to quickly analyze an atrium smoke control system. Further, AtriumCalc can be used to obtain initial values for a CFD analysis.

## 1. AtriumCalc Concept

AtriumCalc consists of a number of routines that are commonly used for design of atrium smoke control systems. For example, one routine calculates the smoke exhaust needed to maintain a steady smoke layer height when there is a steady design fire in the atrium with an axisymmetric plume. Each routine can be printed on a page suitable to be inserted in an engineering report. The page consists of a relevant figure, the equations used for the calculation, input, and output. Other routines address balcony spill plumes, window plumes, preventing plugholing, and opposed airflow.

Most engineering software is programmed in a computer language using SI units for internal calculations and checking input for appropriate range. AtriumCalc is very different in that it is an Excel application that allows users to select either I-P or SI units for the calculations, input and output[2]. This allows users to have calculations performed with the user's customary units and equations. Because AtriumCalc has no check on the range of many input values, users are responsible for choosing realistic input values.

Because of software or hardware problems, occasionally computers produce incorrect results. For this reason, users of AtriumCalc should check their computer against the sample input and output of Appendix A.

## 2. Equations

The algebraic equations used in AtriumCalc are consistent with those in the Smoke Control Handbook and NFPA 92. The *International Building Code®* (ICC 2012) requires that atrium smoke control be in accordance

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[1] Unless noted otherwise, all references to NFPA 92 in this paper apply to the 2012 version of this standard.
[2] For information about I-P and SI units, see Chapter 1 of the Smoke Control Handbook.

with NFPA 92. As a convenience to those who want to verify that the equations are consistent with those of NFPA 92, the relevant NFPA 92 sections for the equations are indicated in the following text. Some equations needed for calculations are not in NFPA 92 but are based on fundamental principles of engineering, and these fundamental equations are identified as such in the following discussion.

Because of the desire to limit output of each routine to one page, each output page has one variable list, and sometimes equivalent equations are used. For this paper, consistent equations are ones that are the same or equivalent. Equivalent equations may not appear to be exactly the same, but calculations based on them produce the same results. For example, the equations $Q_c = \chi Q$ and $Q_c = \chi_c Q$ are equivalent because $\chi$ and $\chi_c$ mean the same thing.

Another more complicated example is

$$\rho = \frac{144 p_{atm}}{RT} \quad \text{where } T \text{ is in } °R, \text{ and } \rho = \frac{144 p_{atm}}{R(T+460)} \quad \text{where } T \text{ is in } °F.$$

The other variables are $\rho$, which is density in lb/ft$^3$; $p_{atm}$, which is atmospheric pressure in psi; and $R$, which is a gas constant of 53.34 ft·lb$_f$/lb$_m$·°R. Because the temperature in °R equals that in °F plus 460°, the two equations above give the same results, and they are equivalent.

## 2.1 Atrium Smoke Exhaust with Steady Fire

Figure 1 shows smoke exhaust with different kinds of smoke plumes. The equations for analyzing atrium smoke exhaust are based on the zone fire model concepts, which include the smoke layer interface that is a horizontal plane with smoke above and no smoke below. There is some diluted smoke below the smoke layer interface, but this cannot be evaluated by the algebraic equations.

### 2.1.1 Convective Heat Release Rate

The convective portion of the heat release rate (HRR) is

$$Q_c = \chi Q \tag{1}$$

where
$Q_c$ = convective heat release rate, Btu/s (kW),
$Q$ = heat release rate, Btu/s (kW),
$\chi$ = convective fraction, dimensionless.

The above equation is the same as the equation of NFPA 92 section 5.5.1.3. A convective fraction of 0.7 is commonly used for most design applications, but the value of $\chi$ is much different for some fuels.

### 2.1.2 Axisymmetric Plume

Design fires located in the large atrium space are usually analyzed as having an axisymmetric plume (Figure 1a). For $z$ greater than or equal to $z_l$ ($z \geq z_l$), the mass flow of this kind of plume is

$$m = 0.022 Q_c^{1/3} z^{5/3} + 0.0042 Q_c$$
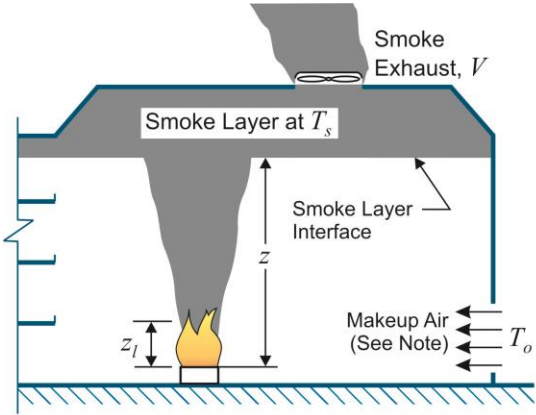$$m = 0.071 Q_c^{1/3} z^{5/3} + 0.0018 Q_c \text{ for SI} \tag{2}$$

For $z$ less than $z_l$ ($z < z_l$), the mass flow is

$$m = 0.0208 Q_c^{3/5} z$$
$$m = 0.032 Q_c^{3/5} z \quad \text{for SI} \tag{3}$$

where
$m$ = mass flow in the plume, lb/s (kg/s),
$Q_c$ = convective heat release rate, Btu/s (kW),

$z$ = distance above the base of the fire, ft (m),
$z_l$ = limiting elevation, ft (m).



Note: Makeup air is shown as being supplied by an opening or openings to the outside, but it can also be supplied by mechanical fans.

(a) Atrium Smoke Exhaust with an Axisymmetric Plume
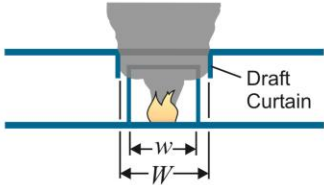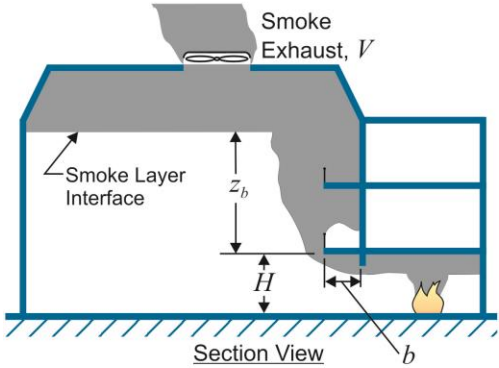
View of Door with Draft Curtains

Notes:
1. Makeup air is not shown.
2. In the absence of draft curtains, the effective value of $W$ needs to be calculated as $W = w + b$.

(b) Atrium Smoke Exhaust with a Balcony Spill Plume
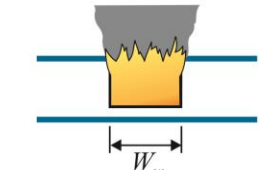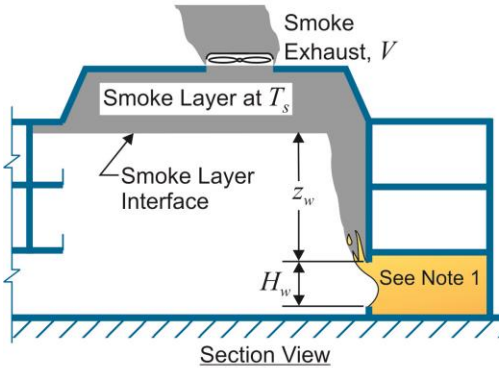
View of Opening to Fire Room

Notes:
1. Because this room is fully involved in fire, window plumes are not normally used for atrium smoke control in fully sprinklered buildings.
2. Makeup air is not shown.

(c) Steady Atrium Smoke Exhaust with a Window Plume

***Figure 1.*** *Atrium Smoke Exhaust and Different Smoke Plumes.*

3

The limiting elevation is

$$z_l = 0.533Q_c^{2/5}$$
$$z_l = 0.166Q_c^{2/5} \quad \text{for SI}$$

(4)

where

$z_l$      = limiting elevation, ft (m).
$Q_c$      = convective heat release rate, Btu/s (kW).

The limiting elevation is approximately the average flame height. Equations (2), (3) and (4) are the same as the axisymmetric plume equations in NFPA 92 section 5.5.1.1.

## 2.1.3 Balcony Spill Plume

Design fires in communicating spaces are often modeled as having a balcony spill plume. A communicating space is a space that has an open pathway to a large-volume atrium space. The equations in this section are applicable to balcony spill plumes in a room that opens onto a balcony as shown in Figure 1b.

There are balcony spill plume equations for the following regions:

      Region 1:    $z_b < 50$ ft ( $z_b < 15$ m),
      Region 2:    $z_b \geq 50$ ft and $W < 32.8$ ft ($z_b \geq 15$ m and $W < 10$ m),
      Region 3:    $z_b \geq 50$ ft and $32.8$ ft $\leq W \leq 45.9$ ft ($z_b \geq 15$ m and $10$ m $\leq W \leq 14$ m).

For region 1, the mass flow of the plume is

$$m = 0.12\left(QW^2\right)^{1/3}\left(z_b + 0.25H\right)$$
$$m = 0.36\left(QW^2\right)^{1/3}\left(z_b + 0.25H\right) \quad \text{for SI}$$

(5)

For region 2, the mass flow of the plume is

$$m = 0.32Q_c^{1/3}W^{1/5}\left(z_b + 0.098W^{7/15}H + 19.5W^{7/15} - 49.2\right)$$
$$m = 0.59Q_c^{1/3}W^{1/5}\left(z_b + 0.17W^{7/15}H + 10.35W^{7/15} - 15\right) \quad \text{for SI}$$

(6)

For region 3, the mass flow of the plume is

$$m = 0.062\left(Q_cW^2\right)^{1/3}\left(z_b + 0.51H + 52\right)$$
$$m = 0.2\left(Q_cW^2\right)^{1/3}\left(z_b + 0.51H + 15.75\right) \quad \text{for SI}$$

(7)

where

$m$      = mass flow rate in plume, lb/s (kg/s),
$Q$      = heat release rate, Btu/s (kW),
$Q_c$      = convective heat release rate, Btu/s (kW),
$W$      = width of the spill, ft (m),
$z_b$      = height of the plume above the balcony edge, ft (m),
$H$      = height of balcony above fuel, ft (m).

In the absence of draft curtains, the equivalent width of the spill is

$$W = w + b \tag{8}$$

where
$w$       = width of opening from area of origin, ft (m),
$b$       = distance from opening to balcony edge, ft (m).

The balcony spill equations above are consistent with those in NFPA 92 section 5.5.2[3].

## 2.1.4 Window Plume

Because a window plume comes from a room that is completely involved in fire, window plumes are not normally considered in fully sprinklered buildings, but it can be appropriate in unusual applications. The equations in this section are for a fire room with only one opening, which opens onto the large atrium space as shown in Figure 1c. The HRR of a fully developed fire in a room is

$$Q = 61.2 A_w H_w^{1/2}$$
$$Q = 1260 A_w H_w^{1/2} \quad \text{for SI} \tag{9}$$

where
$Q$       = heat release rate, Btu/s (kW),
$A_w$     = area of ventilation opening, ft$^2$ (m$^2$),
$H_w$     = height of ventilation opening, ft (m).

The mass entrainment for window plumes is given as

$$m = \left[ 0.077 (A_w H_w^{1/2})^{1/3} (z_w + a)^{5/3} \right] + 0.18 A_w H_w^{1/2}$$
$$m = \left[ 0.68 (A_w H_w^{1/2})^{1/3} (z_w + a)^{5/3} \right] + 1.59 A_w H_w^{1/2} \quad \text{for SI} \tag{10}$$

where
$m$       = mass flow rate in plume, lb/s (kg/s),
$A_w$     = area of ventilation opening, ft$^2$ (m$^2$),
$H_w$     = height of ventilation opening, ft (m),
$z_w$     = distance from the smoke layer interface to the top of the window, ft (m),
$a$       = $[2.40 A_w^{2/5} H_w^{1/5}] - 2.1 H_w$, ft (m).

The window plume equations above are the same as those of NFPA 92 section 5.5.3.

## 2.1.5 Smoke Temperature, Density and Exhaust

The smoke layer temperature is calculated from

$$T_s = T_o + \frac{K_s Q_c}{m C_p} \tag{11}$$

where
$T_s$      = smoke layer temperature, °F (°C),
$T_o$      = ambient temperature, °F (°C),
$K_s$      = fraction of convective HRR contained in smoke layer, dimensionless,
$Q_c$      = convective heat release rate, Btu/s (kW),
$C_p$      = specific heat of plume gases, 0.24 Btu/lb·°F (1.0 kJ/kg·°C),

---

[3] The regions and mass flow equations listed here have been corrected. In NFPA 92 (2012), there is an error in one of the bounds for region 2 and errors in the IP versions of equations (6) and (7). NFPA has issued an errata sheet correcting the equations. A correction of the bounds of region 2 is expected in a future edition of NFPA 92.

$m$ = mass flow rate of the plume where it enters the smoke layer, lb/s (kg/s).

For calculating the volumetric flow rate of smoke exhaust, a value of $K_s = 1.0$ needs to be used except when another value of $K_s$ is supported by test data or an engineering analysis. For plugholing calculations, a value of $K_s = 0.5$ needs to be used except when another value of $K_s$ is supported by test data or an engineering analysis. The temperature equation above is the same as that of NFPA 92 section 5.5.5.

The density of smoke can be calculated from

$$\rho = \frac{144\,p_{atm}}{RT_s}$$

$$\rho = \frac{p_{atm}}{RT_s} \quad \text{for SI}$$

(12)

where
$\rho$ = density of smoke, lb/ft$^3$ (kg/m$^3$),
$p_{atm}$ = atmospheric pressure, psi (Pa),
$R$ = gas constant, 53.34 ft·lb$_f$/lb$_m$·°R (287 J/kg·K),
$T_s$ = temperature of smoke, °R (K).

An alternate form of the above equation is

$$\rho = \frac{144\,p_{atm}}{R(T_s + 460)}$$

$$\rho = \frac{p_{atm}}{R(T_s + 273)} \quad \text{for SI}$$

(13)

where
$\rho$ = density of smoke, lb/ft$^3$ (kg/m$^3$),
$p_{atm}$ = atmospheric pressure, psi (Pa),
$R$ = gas constant, 53.34 ft· lb$_f$/lb$_m$·°R (287 J/kg·K),
$T_s$ = temperature of smoke, °F (°C).

The density equations above are consistent with those of NFPA 92 section 5.8. The volumetric rate of smoke exhaust is

$$V = 60\frac{m}{\rho}$$

$$V = \frac{m}{\rho} \quad \text{for SI}$$

(14)

where
$V$ = volumetric flow rate of smoke exhaust, cfm (m$^3$/s).
$m$ = mass flow rate of smoke exhaust, lb/s, (kg/s).
$\rho$ = density of smoke, lb/ft$^3$ (kg/m$^3$).

The volumetric flow rate is determined using the smoke density $\rho$ at the smoke layer temperature. The equation above is the same as that of NFPA 92 section 5.7.

## 2.2 Plugholing

Plugholing is the condition where air from below the smoke layer is pulled through the smoke layer due to a high exhaust rate (Figure 2). The number of exhaust inlets must be chosen so that the flow rate at the exhaust

inlets does not result in plugholing. The maximum volumetric flow rate that can be exhausted by a single exhaust inlet without plugholing is

$$V_{max} = 452\gamma d^{5/2}\left(\frac{T_s - T_o}{T_o}\right)^{1/2}$$

$$V_{max} = 4.16\gamma d^{5/2}\left(\frac{T_s - T_o}{T_o}\right)^{1/2} \quad \text{for SI}$$

(15)

where
$V_{max}$ = maximum volumetric flow rate without plugholing at $T_s$, cfm (m³/s).
$T_s$ = absolute temperature of the smoke layer, °R (K).
$T_o$ = absolute ambient temperature, °R (K).
$d$ = depth of smoke layer below the lowest point of the exhaust inlet, ft (m).
$\gamma$ = exhaust location factor, dimensionless.

The exhaust location factor depends on the location of the inlet, as explained in notes 1, 2, and 3 in Figure 2. The ratio $d/D_i$ must be greater than 2, where $D_i$ is the diameter of the inlet. The requirements for preventing plugholing are listed in notes 4, 5, and 6 in Figure 2. For rectangular exhaust inlets, the effective value of the inlet diameter should be used:

$$D_i = \frac{2ab}{a+b}$$

(16)

where
$D_i$ = effective diameter of the inlet, ft (m),
$a$ = length of the inlet, ft (m),
$b$ = width of the inlet. ft (m).
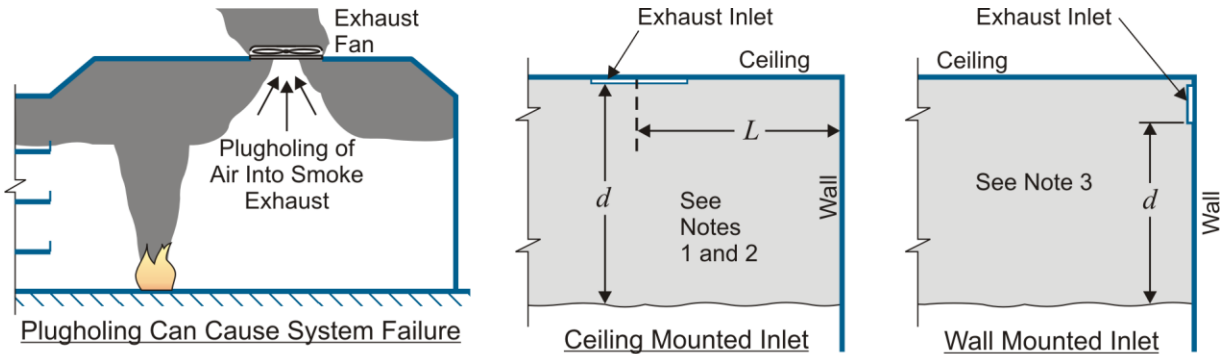


Notes:
1. For a ceiling mounted exhaust inlet with $L < 2 D_i$, $\gamma = 0.5$.
2. For a ceiling mounted exhaust inlet with $L \geq 2 D_i$, $\gamma = 1$.
3. For a wall mounted exhaust inlet, $\gamma = 0.5$.
4. $d/D_i$ must be greater than 2.
5. $V_e$ must be less than or equal to $V_{max}$.
6. The edge-to-edge distance between inlets must not be less than $S_{min}$.
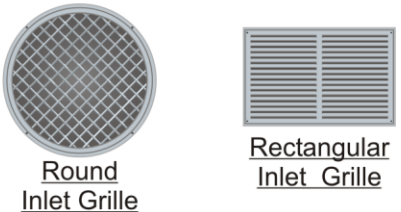
**Figure 2.** *Plugholing.*

If inlets are located too close together, they act as one inlet with respect to plugholing. In order to be considered separate inlets for plugholing purposes, the minimum separation between exhaust inlets is

$$S_{min} = 0.065V_e^{1/2}$$
$$S_{min} = 0.9V_e^{1/2} \quad \text{for SI}$$

(17)

where
$S_{min}$ = minimum edge-to-edge separation between inlets, ft (m),
$V_e$ = volumetric flow rate of one exhaust inlet, cfm (m³/s).

The above equations for preventing plugholing are the same as those in NFPA 92 sections 5.6.3, 5.6.8, and 5.6.9. When each inlet has the same flow rate as the others, the volumetric flow rate of one exhaust inlet is

$$V_e = \frac{V}{N}$$

(18)

where $N$ is the number of inlets. The average velocity at an inlet has a major impact on noise at the inlet, and this velocity is

$$v_i = \frac{V_e}{A_f}$$

(19)

where
$v_i$ = average velocity at inlet, fpm (m/s),
$A_f$ = free area of inlet grille, ft² (m²).

For a rectangular inlet, the free area is

$$A_f = abA_r$$

(20)

where $A_r$ is the ratio of free area to total grille area. For a round inlet, the free area is

$$V_f = (\pi D_i^2 / 4)A_r$$

(21)

Equations (18) to (21) are based on fundamental principles of engineering.

## 2.3 Opposed Airflow

Smoke flow can be controlled by opposed airflow provided that the airflow velocity is at least a value that is called the *limiting average velocity*.

### 2.3.1 Airflow to or from a Communicating Space

For a fire in a communicating space below the smoke layer interface (Figure 3a) or a fire in a communicating space above the smoke layer interface (Figure 3b), the limiting velocity can be calculated from

$$v_e = 38\left( gH \frac{T_f - T_o}{T_f} \right)^{1/2}$$
$$v_e = 0.64\left( gH \frac{T_f - T_o}{T_f} \right)^{1/2} \quad \text{for SI}$$

(22)

where
$v_e$ = limiting average air velocity, fpm (m/s),

$g$ = acceleration of gravity, ft/s$^2$ (m/s$^2$),
$H$ = height of opening, ft (m),
$T_f$ = absolute temperature of smoke, °R (K),
$T_o$ = absolute temperature of ambient air, °R (K).

When the limiting average air velocity, $v_e$, calculated from equation (22) exceeds 200 fpm (1.02 m/s), the airflow method is not be used to control smoke flow.

### 2.3.2 Airflow to a Plume

To keep smoke from a plume from entering a communicating space as shown in Figure 3c, the limiting velocity can be calculated from

$$v_e = 17\left(\frac{Q}{z}\right)^{1/3}$$

$$v_e = 0.057\left(\frac{Q}{z}\right)^{1/3} \quad \text{for SI}$$

(23)

where
$v_e$ = limiting average air velocity, fpm (m/s),
$Q$ = heat release rate, Btu/s (kW),
$z$ = distance from the base of the fire to the bottom of the opening, ft (m).

Equation (23) is not applicable when $z$ is less than 10 ft (3 m). When the limiting average air velocity $v_e$ calculated from equation (23) exceeds 200 fpm (1.02 m/s), the airflow method is not be used to control smoke flow. The above equations for limiting velocity are the same as those of NFPA 92 section 5.10.

### 2.3.3 Volumetric Flow

The volumetric flow of opposed airflow is

$$V = \frac{v_e}{A}$$

(24)

where $A$ is the area of the opening in ft$^2$ (m$^2$). This equation is based on fundamental principles of engineering.

## 3. Routines

### 3.1 Smoke Exhaust with Steady Smoke Layer Height (Routines 1 to 3)

These routines calculate the smoke exhaust needed to maintain a steady smoke layer height when there is a steady design fire.

**Routine 1: Axisymmetric Plume.** This routine is for a design fire in the atrium that has an axisymmetric plume as shown in Figure 1a. The convective heat release rate is calculated with the equation of section 2.1.1, and this equation also is used for routines 2 and 3. The mass flow rate of smoke exhaust is calculated with the equations in section 2.1.2. Smoke temperature, smoke density, and smoke exhaust are calculated with the equations in section 2.1.5, and these equations also are used for routines 2 and 3.

**Routine 2: Balcony Spill Plume.** This routine calculates the smoke exhaust needed to maintain a steady smoke layer height when there is a steady design fire in a communicating space with a balcony spill plume as shown in Figure 1b. The mass flow rate of smoke exhaust is calculated with the equations in section 2.1.3.

**Routine 3: Window Plume.** This routine calculates the smoke exhaust needed to maintain a steady smoke layer height when there is a steady design fire in a communicating space with a window plume as shown in Figure 1c. The mass flow rate of smoke exhaust is calculated with the equations in section 2.1.4.

Atrium
(Large-Volume Space)

$H$
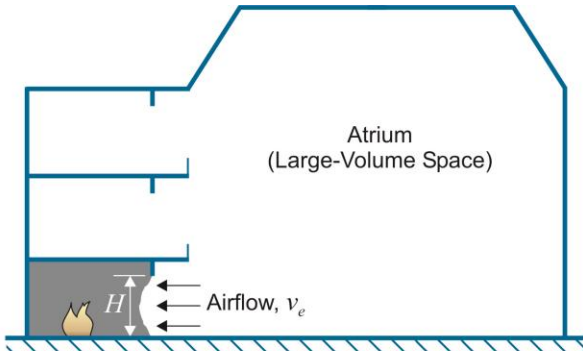
Airflow, $v_e$

Notes:
1. Smoke exhaust from the communicating space is not shown.
2. The smoke exhaust from the atrium and the makeup air to the atrium are not shown.

**CAUTION**

**Airflow Can Supply Oxygen to the Fire**: The airflow approach can supply oxygen to the fire with the potential of catastrophic failure. Even full sprinkler protection does not completely eliminate this potential. For any application that uses the airflow approach, this failure mode needs to be addressed in the design analysis.

(a) Airflow to Control Smoke Flow from a Communicating Space

Airflow
$v_e$

$H$

Notes:
1. Air supply to the communicating space is not shown.
2. The smoke exhaust from the atrium and the makeup air to the atrium are not shown.

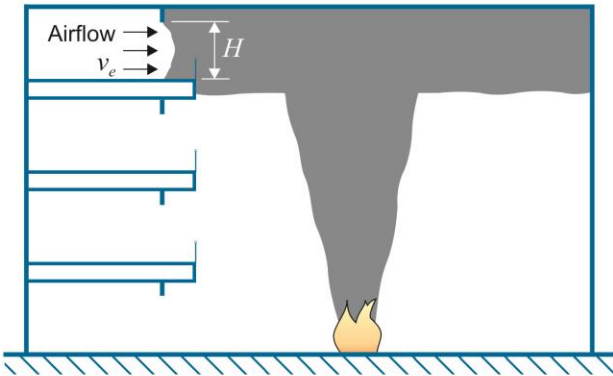(b) Airflow to Control Smoke Flow from the Smoke Layer

Airflow
$v_e$

$H$

$z$

Notes:
1. Air supply to the communicating space is not shown.
2. The smoke exhaust from the atrium and the makeup air to the atrium are not shown.

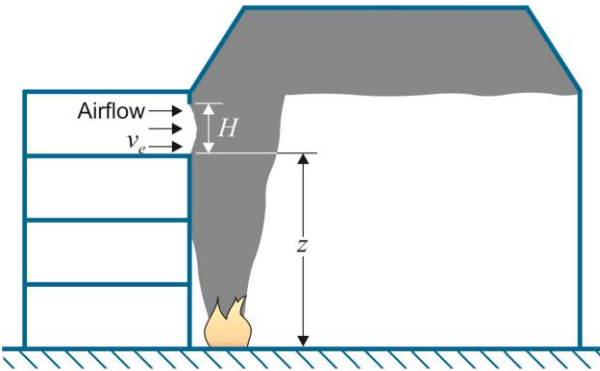(c) Airflow to Control Smoke Flow from the Plume

***Figure 3.*** *Applications of Airflow to Control Smoke Flow*

## 3.2 Preventing Plugholing (Routines 4A and 4B)

Routine 4A is for calculation of the number of rectangular exhaust inlets and the separation between them needed to prevent plugholing. This routine is based on the condition that all the inlets are similar. The equations for these routines are in section 2.2.

## 3.3 Airflow to Control Smoke Flow (Routine 5A to 5C)

Routines 5A, 5B, and 5C are for (1) airflow to control smoke flow from a communicating space, (2) airflow to control smoke flow from the smoke layer, and (3) airflow to control smoke flow from the plume (see Figure 3). The equations for these routines are in section 2.3.

# 4. Using AtriumCalc

Figure 4 shows the main page of AtriumCalc. There is a button that can be pressed to get more information about AtriumCalc and a button for frequently asked questions. There is a place for the user to enter the title of their project. There is a button for the general information. When the user clicks this button, Excel moves to a worksheet that has some general information about AtriumCalc and atrium smoke control design. There also are buttons for the routines in both I-P and SI units. When the user clicks on one of these buttons, Excel switches to the appropriate worksheet where the user enters data where indicated. Excel can be used to print a page of that worksheet for use in an atrium smoke control report.

AtriumCalc uses macros in the buttons that let the user navigate between the main page and the routines. When AtriumCalc is installed, these macros may be disabled, and they need to be enabled by clicking on the enable macro button as shown in Figure 5. The use of AtriumCalc is illustrated by an example below.

## 4.1 Example

Determine the smoke exhaust rate for an atrium with the following design parameters: 2000 Btu/s heat release rate, 35.5 ft distance from the base of the fire to the smoke interface, 92°F ambient temperature, and 14.7 psi atmospheric pressure. As is usual practice for smoke exhaust calculations, values of $K_s = 1$ and $\chi = 0.7$ are used. The ambient temperature was chosen as the summer outdoor design temperature, because the calculated smoke exhaust to deal with the design fire is largest with this summer temperature.

On the main page (Figure 4), the user enters the project name and clicks on the I-P button titled "1: Smoke Exhaust w/ Axisymmetric Plume". Excel switches to that worksheet, and automatically the name of the project is displayed near the top. There is a figure of an atrium exhaust system, relevant equations, boxes for data input, and output. The parameters are entered, and the worksheet looks like Figure 6 with all the calculations done. The user prints the worksheet (Figure 7). Figure 6 shows buttons to print the page and to return to the main page, and the other routines also have these buttons.

## 4.2 Plugholing

The routines for preventing plugholing are different in that the user will probably need to adjust some of the input values for $N$, $a$, $b$, or $D_i$ several times to satisfy the requirements needed to prevent plugholing (notes 4 and 5 in Figure 2). Because noise produced by airflow at the inlet grille may be an issue, the size of the inlet may also need to be adjusted so that this velocity is acceptable with respect to noise generation.

The plugholing routines consider that the conditions for all the inlets are the same. When inlets are different, the plugholing routine can be used for each group of similar inlets. For example, the total smoke exhaust is 120,000 cfm. It is desired to exhaust (1) 70,000 cfm from a number of inlets on the walls, and (2) 50,000 cfm from a number of inlets in the atrium ceiling far from the walls. All of the inlets in the walls are the same size and located the same distance above the bottom of the smoke layer, and all the inlets in the ceiling are the same size. In this example, the plugholing routine can be used twice: (1) for the 70,000 cfm of wall inlets, and (2) for the 50,000 cfm of ceiling inlets.
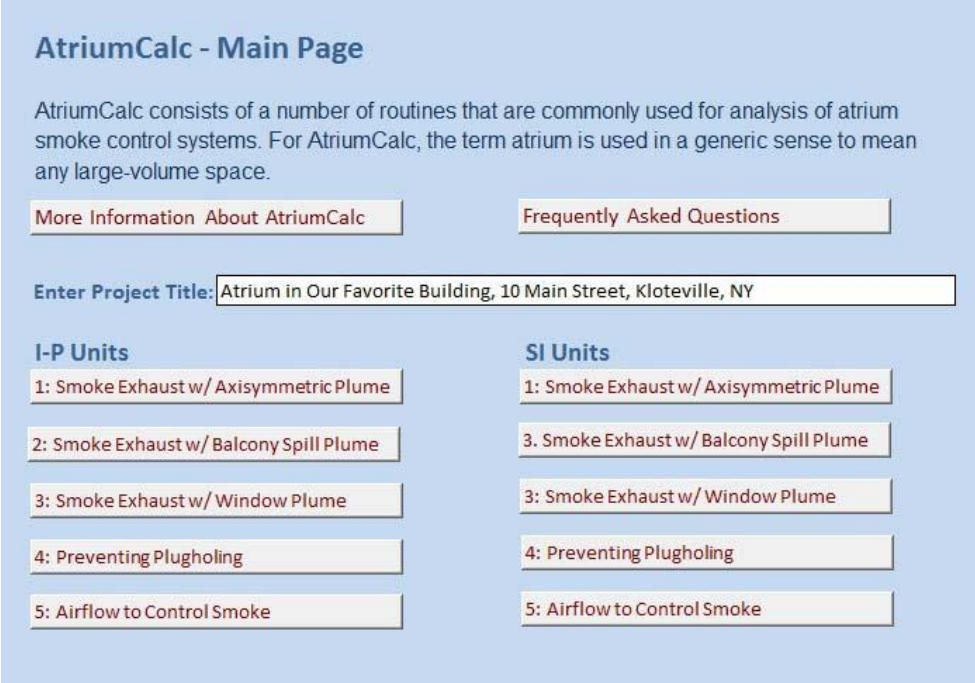
***Figure 4.*** *The main page of AtriumCalc.*
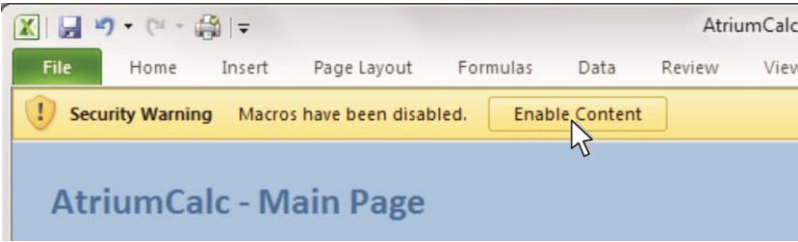


***Figure 5.*** *Enabling macros in AtriumCalc.*

**Project: Atrium in Our Favorite Building, 10 Main Street, Kloteville, NY**

**Routine 1: Atrium Smoke Exhaust with an Axisymmetric Plume**

Notes:
1. Makeup air is shown as being supplied by an opening or openings to the outside, but it can also be supplied by mechanical fans.
2. For calculating the volumetric flow rate of smoke exhaust, a value of $K_s = 1.0$ needs to be used except when another value of $K_s$ is supported by test data or an engineering analysis.
3. For smoke control design, a value of $\chi = 0.7$ is almost always used, and other values should be supported by engineering data.

$$Q_c = \chi\, Q$$

$$z_l = 0.533 Q_c^{2/5}$$

$$m = 0.022 Q_c^{1/3} z^{5/3} + 0.0042 Q_c \quad \text{for } z > z_l$$

$$m = 0.0208 Q_c^{3/5} z \quad \text{for } z \le z_l$$

$$T_s = T_o + \frac{K_s Q_c}{m C_p}$$

$$\rho_s = \frac{144 p_{atm}}{R(T_s + 460)}$$

$$V = 60 m / \rho_s$$

where

$C_p$ = specific heat (0.24 Btu/lb-°F).

$Q$ = heat release rate of the fire (Btu/s).
$Q_c$ = convective portion of heat release rate of fire (Btu/s).
$z$ = distance from base of fire to smoke layer interface, (ft).
$z_l$ = limiting elevation (ft).
$m$ = exhaust mass flow (lb/s).
$R$ = gas constant (53.34 ft lbf/lbm/°R).
$T_s$ = smoke layer temperature (°F).
$T_o$ = ambient or outdoor temperature (°F).
$K_s$ = fraction of convective HRR in smoke layer.
$\rho_s$ = smoke density (kg/m³).
$p_{atm}$ = atmospheric pressure (psi).
$V$ = volumetric flow of smoke exhaust (cfm).
$\chi$ = convective fraction (dimensionless).

| Input: | | | | Output: | | |
|---|---|---|---|---|---|---|
| $Q =$ | 3,500 | Btu/s | | $Q_c =$ | 2,450 | Btu/s |
| $z =$ | 40.00 | ft | | $z_l =$ | 12.09 | ft |
| $T_o =$ | 92.0 | °F | | $m =$ | 149.0 | lb/s |
| $p_{atm} =$ | 14.70 | psi | | $T_s =$ | 160.5 | °F |
| $K_s =$ | 1.0 | (See note 2 above) | | $\rho_s =$ | 0.06396 | lb/ft³ |
| $\chi =$ | 0.70 | (Almost always 0.70) | | $V =$ | 139,822 | cfm |

***Figure 6.*** *Excel worksheet of AtriumCalc Routine 1.*

**Project:   Atrium in Our Favorite Building, 10 Main Street, Kloteville, NY**
**Routine 1: Atrium Smoke Exhaust with an Axisymmetric Plume**

Smoke
Exhaust, $V$

Smoke Layer at $T_s$

Smoke Layer
Interface

$z$

Makeup Air
(See Note)

$z_l$

$T_o$

Notes:
1. Makeup air is shown as being supplied by an opening or openings to the outside, but it can also be supplied by mechanical fans.
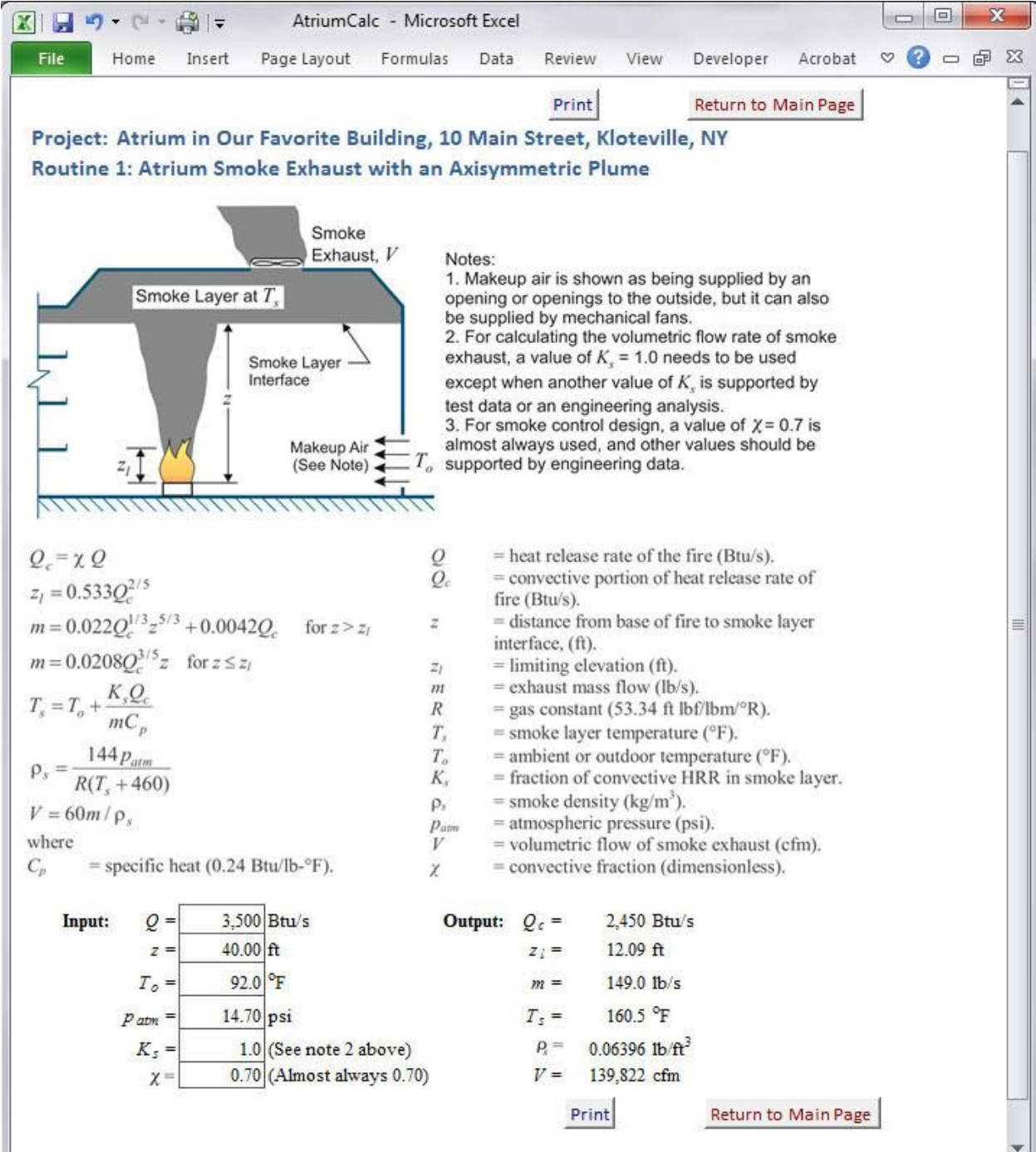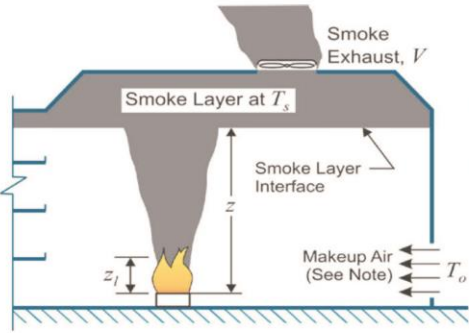2. For calculating the volumetric flow rate of smoke exhaust, a value of $K_s = 1.0$ needs to be used except when another value of $K_s$ is supported by test data or an engineering analysis.
3. For smoke control design, a value of $\chi = 0.7$ is almost always used, and other values should be supported by engineering data.

$Q_c = \chi Q$

$z_l = 0.533 Q_c^{2/5}$

$m = 0.022 Q_c^{1/3} z^{5/3} + 0.0042 Q_c$     for $z > z_l$

$m = 0.0208 Q_c^{3/5} z$    for $z \le z_l$

$T_s = T_o + \dfrac{K_s Q_c}{m C_p}$

$\rho_s = \dfrac{144 p_{atm}}{R(T_s + 460)}$

$V = 60 m / \rho_s$

where

$C_p$     = specific heat (0.24 Btu/lb-°F).

$Q$ = heat release rate of the fire (Btu/s).
$Q_c$ = convective portion of heat release rate of fire (Btu/s).
$z$ = distance from base of fire to smoke layer interface, (ft).
$z_l$ = limiting elevation (ft).
$m$ = exhaust mass flow (lb/s).
$R$ = gas constant (53.34 ft lbf/lbm/°R).
$T_s$ = smoke layer temperature (°F).
$T_o$ = ambient or outdoor temperature (°F).
$K_s$ = fraction of convective HRR in smoke layer.
$\rho_s$ = smoke density (kg/m³).
$p_{atm}$ = atmospheric pressure (psi).
$V$ = volumetric flow of smoke exhaust (cfm).
$\chi$ = convective fraction (dimensionless).

| Input: | | | Output: | | |
|---|---|---|---|---|---|
| $Q =$ | 3,500 | Btu/s | $Q_c =$ | 2,450 | Btu/s |
| $z =$ | 40.00 | ft | $z_l =$ | 12.09 | ft |
| $T_o =$ | 92.0 | °F | $m =$ | 149.0 | lb/s |
| $p_{atm} =$ | 14.70 | psi | $T_s =$ | 160.5 | °F |
| $K_s =$ | 1.0 | (See note 2 above) | $\rho_s =$ | 0.06396 | lb/ft³ |
| $\chi =$ | 0.70 | (Almost always 0.70) | $V =$ | 139,822 | cfm |

*Figure 7.* *Page printed from AtriumCalc for Routine 1.*

## 5. Nomenclature

$a$ = length of the inlet, ft (m); or $[2.40A_w^{2/5} H_w^{1/5}] - 2.1H_w$, ft (m).
$A_f$ = free area of inlet grille, ft$^2$ (m$^2$).
$A_r$ = ratio of free area to total grille area, dimensionless.
$A_w$ = area of ventilation opening, ft$^2$ (m$^2$).
$b$ = width of the inlet, ft (m); or distance from opening to balcony edge, ft (m).
$C_p$ = specific heat of plume gases, 0.24 Btu/lb·°F (1.0 kJ/kg·°C).
$d$ = depth of smoke layer below the lowest point of the exhaust inlet, ft (m).
$D_i$ = effective diameter of the inlet, ft (m).
$H$ = height of balcony above fuel, ft (m).
$H_w$ = height of ventilation opening, ft (m).
$K_s$ = fraction of convective HRR contained in smoke layer, dimensionless.
$m$ = mass flow rate in plume or of smoke exhaust, lb/s (kg/s).
$N$ = number of inlets, dimensionless.
$p_{atm}$ = atmospheric pressure, psi (Pa).
$Q$ = heat release rate, Btu/s (kW).
$Q_c$ = convective heat release rate, Btu/s (kW).
$R$ = gas constant, 53.34 ft·lb$_f$/lb$_m$·°R (287 J/kg·K).
$S_{min}$ = minimum edge-to-edge separation between inlets, ft (m).
$T_o$ = ambient temperature, °F or °R (°C or K).
$T_s$ = temperature of smoke, °F or °R (°C or K).
$V$ = volumetric flow rate of smoke exhaust, cfm (m$^3$/s).
$V_e$ = volumetric flow rate of one exhaust inlet, cfm (m$^3$/s).
$v_i$ = average velocity at inlet, fpm (m/s).
$V_{max}$ = maximum volumetric flow rate without plugholing at $T_s$, cfm (m$^3$/s).
$W$ = width of the spill, ft (m).
$w$ = width of opening from area of origin, ft (m).
$z$ = distance above the base of the fire, ft (m).
$z_b$ = height of the plume above the balcony edge, ft (m).
$z_l$ = limiting elevation, ft (m).
$z_w$ = distance from the smoke layer interface to the top of the window, ft (m).
$\gamma$ = exhaust location factor, dimensionless.
$\rho$ = density of smoke, lb/ft$^3$ (kg/m$^3$).
$\chi$ = convective fraction, dimensionless.

## 6. References

Klote, J. H., Milke, J. A., Turnbull, P. G., Kashef, A., Ferreira, M. J. 2012. *Handbook of Smoke Control Engineering*. Atlanta: ASHRAE.

NFPA. 2012. *Standard for Smoke Control Systems – NFPA 92*. Quincy, MA: National Fire Protection Association.

ICC. 2012. *International Building Code*®. Washington, D.C.: International Code Council.

# Appendix A – Sample Input and Output

Because of software or hardware problems, occasionally computers produce incorrect results. For this reason, users of AtriumCalc need to check their computer against the sample input and output of this appendix.

**Routine 1: Atrium Smoke Exhaust with an Axisymmetric Plume – I-P Units**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $Q =$ | 3,500 | Btu/s | | $Q_c =$ | 2,450 | Btu/s |
| $z =$ | 40.00 | ft | | $z_l =$ | 12.09 | ft |
| $T_o =$ | 92.0 | °F | | $m =$ | 149.0 | lb/s |
| $p_{atm} =$ | 14.70 | psi | | $T_s =$ | 160.5 | °F |
| $K_s =$ | 1.0 | | | $\rho =$ | 0.06396 | lb/ft$^3$ |
| $\chi =$ | 0.70 | | | $V =$ | 139,822 | cfm |

**Routine 1: Atrium Smoke Exhaust with an Axisymmetric Plume – SI Units**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $Q =$ | 4,000 | kW | | $Q_c =$ | 2,800 | kW |
| $z =$ | 12.00 | m | | $z_l =$ | 3.97 | m |
| $T_o =$ | 30.0 | °C | | $m =$ | 67.98 | kg/s |
| $p_{atm} =$ | 101,300 | Pa | | $T_s =$ | 71.2 | °C |
| $K_s =$ | 1.0 | | | $\rho =$ | 1.025 | kg/m$^3$ |
| $\chi =$ | 0.70 | | | $V =$ | 66.3 | m$^3$/s |

**Routine 2: Atrium Smoke Exhaust with a Balcony Spill Plume – I-P Units**
**For Flow Region 1**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $Q =$ | 1,000 | Btu/s | | $Q_c =$ | 700 | Btu/s |
| $H =$ | 10.00 | ft | | $m =$ | 269.1 | lb/s |
| $W =$ | 19.00 | ft | | $T_s =$ | 93.8 | °F |
| $z_b =$ | 29.00 | ft | | $\rho =$ | 0.07165 | lb/ft$^3$ |
| $T_o =$ | 83.0 | °F | | $V =$ | 225,372 | cfm |
| $p_{atm} =$ | 14.70 | psi | | | | |
| $K_s =$ | 1.0 | | | | | |
| $\chi =$ | 0.70 | | | | | |

**Routine 2: Atrium Smoke Exhaust with a Balcony Spill Plume – SI Units**
**For Flow Region 1**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $Q =$ | 1,000 | kW | | | $Q_c =$ | 700 | kW |
| $H =$ | 3.10 | m | | | $m =$ | 116.2 | kg/s |
| $W =$ | 6.00 | m | | | $T_s =$ | 34.0 | °C |
| $z_b =$ | 9.00 | m | | | $\rho =$ | 1.150 | kg/m$^3$ |
| $T_o =$ | 28.0 | °C | | | $V =$ | 101.1 | m$^3$/s |
| $p_{atm} =$ | 101,300 | Pa | | | | | |
| $K_s =$ | 1.0 | | | | | | |
| $\chi =$ | 0.70 | | | | | | |


**Routine 2: Atrium Smoke Exhaust with a Balcony Spill Plume – I-P Units**
**For Flow Region 2**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $Q =$ | 1,000 | Btu/s | | | $Q_c =$ | 700 | Btu/s |
| $H =$ | 12.00 | ft | | | $m =$ | 262.1 | lb/s |
| $W =$ | 9.00 | ft | | | $T_s =$ | 94.1 | °F |
| $z_b =$ | 51.00 | ft | | | $\rho =$ | 0.07162 | lb/ft$^3$ |
| $T_o =$ | 83.0 | °F | | | $V =$ | 219,599 | cfm |
| $p_{atm} =$ | 14.70 | psi | | | | | |
| $K_s =$ | 1.0 | | | | | | |
| $\chi =$ | 0.70 | | | | | | |


**Routine 2: Atrium Smoke Exhaust with a Balcony Spill Plume – SI Units**
**For Flow Region 2**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $Q =$ | 1,000 | kW | | | $Q_c =$ | 700 | kW |
| $H =$ | 3.70 | m | | | $m =$ | 139.3 | kg/s |
| $W =$ | 3.50 | m | | | $T_s =$ | 33.0 | °C |
| $z_b =$ | 16.00 | m | | | $\rho =$ | 1.153 | kg/m$^3$ |
| $T_o =$ | 28.0 | °C | | | $V =$ | 120.8 | m$^3$/s |
| $p_{atm} =$ | 101,300 | Pa | | | | | |
| $K_s =$ | 1.0 | | | | | | |
| $\chi =$ | 0.70 | | | | | | |

**Routine 2: Atrium Smoke Exhaust with a Balcony Spill Plume – I-P Units**
**For Flow Region 3**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $Q =$ | 1,000 | Btu/s | | | $Q_c =$ | 700 | Btu/s |
| $H =$ | 12.00 | ft | | | $m =$ | 630.4 | lb/s |
| $W =$ | 34.00 | ft | | | $T_s =$ | 87.6 | °F |
| $z_b =$ | 51.00 | ft | | | $\rho =$ | 0.07247 | lb/ft$^3$ |
| $T_o =$ | 83.0 | °F | | | $V =$ | 521,984 | cfm |
| $p_{atm} =$ | 14.70 | psi | | | | | |
| $K_s =$ | 1.0 | | | | | | |
| $\chi =$ | 0.70 | | | | | | |

**Routine 2: Atrium Smoke Exhaust with a Balcony Spill Plume – SI Units**
**For Flow Region 3**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $Q =$ | 1,000 | kW | | | $Q_c =$ | 700 | kW |
| $H =$ | 3.70 | m | | | $m =$ | 295.4 | kg/s |
| $W =$ | 11.00 | m | | | $T_s =$ | 30.4 | °C |
| $z_b =$ | 16.00 | m | | | $\rho =$ | 1.163 | kg/m$^3$ |
| $T_o =$ | 28.0 | °C | | | $V =$ | 253.9 | m$^3$/s |
| $p_{atm} =$ | 101,300 | Pa | | | | | |
| $K_s =$ | 1.0 | | | | | | |
| $\chi =$ | 0.70 | | | | | | |

**Routine 3: Steady Atrium Smoke Exhaust with a Window Plume – I-P Units**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $H_w =$ | 9.00 | ft | | | $Q =$ | 11,567 | Btu/s |
| $W_w =$ | 7.00 | ft | | | $Q_c =$ | 8,097 | Btu/s |
| $z_w =$ | 40.00 | ft | | | $m =$ | 246.2 | lb/s |
| $T_o =$ | 80.0 | °F | | | $T_s =$ | 217.0 | °F |
| $p_{atm} =$ | 14.70 | psi | | | $\rho_s =$ | 0.05862 | lb/ft$^3$ |
| $K_s =$ | 1.0 | | | | $V =$ | 252,048 | cfm |
| $\chi =$ | 0.70 | | | | | | |

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**Routine 3: Steady Atrium Smoke Exhaust with a Window Plume – SI Units**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $H_w =$ | 2.80 | m | | $Q =$ | 12,988 | kW |
| $W_w =$ | 2.20 | m | | $Q_c =$ | 9,091 | kW |
| $z_w =$ | 12.00 | m | | $m =$ | 112.36 | kg/s |
| $T_o =$ | 26.7 | °C | | $T_s =$ | 107.6 | °C |
| $p_{atm} =$ | 101,300 | Pa | | $\rho_s =$ | 0.9274 | kg/m$^3$ |
| $K_s =$ | 1.0 | | | $V =$ | 121.15 | m$^3$/s |
| $\chi =$ | 0.70 | | | | | |

**Routine 4A: Preventing Plugholing with Rectangular Inlets – I-P Units**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $Q_c =$ | 1400 | Btu/s | | $T_s =$ | 99.1 | °F |
| $T_o =$ | 70.0 | °F | | $V_{max} =$ | 29,840 | cfm |
| $m =$ | 100.30 | lb/s | | $V_e =$ | 23,150 | cfm |
| $V =$ | 92,600 | cfm | | $S_{min} =$ | 9.89 | ft |
| $d =$ | 9.55 | ft | | $D_i =$ | 4.44 | ft |
| $\gamma =$ | 1 | | | $d/D_i =$ | 2.15 | |
| $K_s =$ | 0.5 | | | $v_i =$ | 2315 | fpm |
| $a =$ | 4.00 | ft | | | | |
| $b =$ | 5.00 | ft | | | | |
| $N =$ | 4 | | | | | |
| $A_r =$ | 0.50 | | | | | |

**Routine 4A: Preventing Plugholing with Rectangular Inlets – SI Units**

| **Input:** | | | | **Output:** | | | |
|---|---|---|---|---|---|---|---|
| $Q_c =$ | 1500 | kW | | $T_s =$ | 37.5 | °C |
| $T_o =$ | 21.0 | °C | | $V_{max} =$ | 15.35 | m$^3$/s |
| $m =$ | 45.50 | kg/s | | $V_e =$ | 10.93 | m3/s |
| $V =$ | 43.70 | m$^3$/s | | $S_{min} =$ | 2.98 | m |
| $d =$ | 3.00 | m | | $D_i =$ | 1.35 | m |
| $\gamma =$ | 1 | | | $d/D_i =$ | 2.21 | |
| $K_s =$ | 0.5 | | | $v_i =$ | 11.76 | m/s |
| $a =$ | 1.22 | m | | | | |
| $b =$ | 1.52 | m | | | | |
| $N =$ | 4 | | | | | |
| $A_r =$ | 0.50 | | | | | |

**Routine 4B: Preventing Plugholing with Round Inlets – I-P Units**

| Input: | | | | Output: | | | |
|---|---|---|---|---|---|---|---|
| $Q_c =$ | 1400 | Btu/s | | $T_s =$ | 99.1 | °F | |
| $T_o =$ | 70.0 | °F | | $V_{max} =$ | 29,840 | cfm | |
| $m =$ | 100.3 | lb/s | | $V_e =$ | 18,520 | cfm | |
| $V =$ | 92,600 | cfm | | $S_{min} =$ | 8.85 | ft | |
| $d =$ | 9.55 | ft | | $d/D_i =$ | 2.01 | | |
| $\gamma =$ | 1 | | | $v_i =$ | 2,090 | fpm | |
| $K_s =$ | 0.5 | | | | | | |
| $D_i =$ | 4.75 | ft | | | | | |
| $N =$ | 5 | | | | | | |
| $A_r =$ | 0.50 | | | | | | |

**Routine 4B: Preventing Plugholing with Round Inlets – SI Units**

| Input: | | | | Output: | | | |
|---|---|---|---|---|---|---|---|
| $Q_c =$ | 1500 | kW | | $T_s =$ | 36.5 | °C | |
| $T_o =$ | 20.0 | °C | | $V_{max} =$ | 15.38 | m³/s | |
| $m =$ | 45.50 | kg/s | | $V_e =$ | 8.74 | m³/s | |
| $V =$ | 43.70 | m³/s | | $S_{min} =$ | 2.66 | m | |
| $d =$ | 3.00 | m | | $d/D_i =$ | 2.07 | | |
| $\gamma =$ | 1 | | | $v_i =$ | 10.62 | m/s | |
| $K_s =$ | 0.5 | | | | | | |
| $D_i =$ | 1.45 | m | | | | | |
| $N =$ | 5 | | | | | | |
| $A_r =$ | 0.50 | | | | | | |

**Routine 5A: Airflow to Control Smoke Flow from a Communicating Space – I-P Units**

| Input: | | | | Output: | | | |
|---|---|---|---|---|---|---|---|
| $H =$ | 8.00 | ft | | $v_e =$ | 175.5 | fpm | |
| $T_o =$ | 72.0 | °F | | $V =$ | 5,265 | cfm | |
| $T_f =$ | 120.0 | °F | | | | | |
| $A =$ | 30.0 | ft² | | | | | |

**Routine 5A: Airflow to Control Smoke Flow from a Communicating Space – SI Units**

| **Input:** | $H =$ | 2.50 | m | **Output:** | $v_e =$ | 0.96 | m/s |
|---|---|---|---|---|---|---|---|
| | $T_o =$ | 22.0 | °C | | $V =$ | 2.89 | m³/s |
| | $T_f =$ | 52.0 | °C | | | | |
| | $A =$ | 3.00 | m² | | | | |

**Routine 5B: Airflow to Control Smoke Flow from the Smoke Layer – I-P Units**

| **Input:** | $H =$ | 8.00 | ft | **Output:** | $v_e =$ | 157.5 | fpm |
|---|---|---|---|---|---|---|---|
| | $T_o =$ | 72.0 | °F | | $V =$ | 7,875 | cfm |
| | $T_f =$ | 110.0 | °F | | | | |
| | $A =$ | 50.0 | ft² | | | | |

**Routine 5B: Airflow to Control Smoke Flow from the Smoke Layer – SI Units**

| **Input:** | $H =$ | 2.50 | m | **Output:** | $v_e =$ | 0.82 | m/s |
|---|---|---|---|---|---|---|---|
| | $T_o =$ | 22.0 | °C | | $V =$ | 4.09 | m³/s |
| | $T_f =$ | 43.0 | °C | | | | |
| | $A =$ | 5.00 | m² | | | | |

**Routine 5C: Airflow to Control Smoke Flow from the Plume – I-P Units**

| **Input:** | $Q =$ | 5000 | Btu/s | **Output:** | $v_e =$ | 93.6 | fpm |
|---|---|---|---|---|---|---|---|
| | $A =$ | 200.0 | ft² | | $V =$ | 18,720 | cfm |
| | $z =$ | 30.00 | ft | | | | |

**Routine 5C: Airflow to Control Smoke Flow from the Plume – SI Units**

| **Input:** | $Q =$ | 5000 | kW | **Output:** | $v_e =$ | 0.469 | m/s |
|---|---|---|---|---|---|---|---|
| | $A =$ | 60.0 | m² | | $V =$ | 28.140 | m³/s |
| | $z =$ | 9.00 | m | | | | |