Extension of the Multiple Spaces Concept of ASHRAE Standard 62 to Include Infiltration, Exhaust/Exfiltration, Interzonal Transfer, and Additional Short-Circuit Paths

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ABSTRACT

ASHRAE Standard 62-1989 provides the multiple spaces method to accommodate the ventilation needs of buildings without excessive energy utilization. This is accomplished by utilizing unvitiated outdoor air in the return air from overventilated spaces. Some spaces are overventilated because the outdoor air fraction in the primary air, dictated by the critical space, is higher than that required for other noncritical spaces. In the derivation presented in the standard, the unvitiated outdoor air centrally mixes with the new outdoor air at the air-handling unit. Consequently, the derivations in the present standard will not accommodate fan-powered variable-air-volume systems where unvitiated plenum air is mixed locally at the terminal with the primary air. This restriction has been addressed in the literature. However, infiltration, exhaust, and interzonal transfer have been assumed not to exist in both the standard and all of the work presented in the literature to date. This deficiency is addressed in this paper. Unfortunately, a single equation could not be found to accommodate the added complexity introduced by the additional airflow paths and associated potential short-circuit paths. This paper demonstrates that the problem can be solved using spreadsheet templates. The spreadsheet reduces a complicated problem to one that is easily solved.

INTRODUCTION

Outdoor air (OA) deficiency, particularly in variable-air-volume (VAV) systems, during minimum air modes has been well documented in the literature for at least ten years (Mumma and Wong 1990; Gardner 1990; Kettler 1995). ASHRAE Standard 62 (ASHRAE 1989) addressed the OA deficiency problem without requiring excessive energy consumption by introducing the concept that overventilated spaces return unvitiated air that can be credited as OA in the return air. By taking advantage of this concept, the fraction of new outdoor air (OA drawn in directly from outside at the air-handling unit) to supply air required at the air-handling unit falls between the fraction required by the space with the smallest ratio of ventilation air (new and unvitiated OA) to supply air and the space with the largest ratio of ventilation air to supply air (Mumma and Bolin 1994; Mumma 1995, 1997; Ke and Mumma 1997). This relationship is expressed in Standard 62 as the multiple spaces equation, Equation 6-1. The derivation of the equation assumes the following: the air in the zone is well mixed (i.e., no short-circuit paths between supply and return), the terminal device is not capable of recirculating return air locally (i.e., shut off VAV boxes, not fan-powered boxes), and there is no local infiltration, no interzonal transfer, and no local exhaust or exfiltration.

Widespread application of fan-powered boxes (not addressed by Equation 6-1) required that the original multiple spaces equation be expanded. This work was undertaken independently by two parties unbeknown to one another. The first publication of the work was by Warden (1995), which expanded Equation 6-1 to include fan-powered boxes (FPB) and introduced mixing efficiencies in the primary air supply stream, in the space, and in the plenum. Ke and Mumma (1996) also expanded Equation 6-1 to include FPB. They did not include mixing efficiencies in their work but did develop it for multiple-plenum systems. Both of the derivations reduce to Equation 6-1 for shut-off VAV boxes and are identical when the mixing efficiencies are assumed to be unity. However, the Warden and Ke/Mumma equations do not appear to be identical because of the way Z is defined in the two papers. Warden defines Z as the ratio of required ventilation air to supply air (primary plus plenum air) for the critical zone, while Ke and Mumma defined Z as the ratio of required ventilation air to primary supply air for the critical zone. This subtle difference has caused considerable confusion in the minds of readers of the two works. Note that the denominators of the two definitions differ, with Warden using the sum of the

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primary air and the plenum air while Ke and Mumma use only the primary air. These derivations have filled a real need but still fail to accommodate local infiltration, zone transfer, and exhaust/exfiltration (three general air transfer paths).

The central thrust of this paper is to further extend Equation 6-1 to accommodate not only fan-powered VAV boxes as Warden and Ke/Mumma have done but also the three general air transfer paths. It is worth noting at this point that many new mixing efficiencies are introduced when these three new airflow paths are introduced. For example, a fraction of the infiltration air, which is considered 100% outdoor air, could proceed to either the return, the exhaust, and/or the transfer points directly without completely mixing (i.e., partial short-circuiting) with the zone air. This alone introduces six mixing efficiency possibilities, a topic that will be developed later in the paper.

SOLVING FOR THE REQUIRED VENTILATION AIR WHEN INFILTRATION, EXHAUST/EXFILTRATION, AND TRANSFER AIR IS CONSIDERED

A reasonable effort was undertaken to expand the generalized multiple spaces equation further to accommodate the three general transfer paths discussed above, as well as the additional mixing efficiencies. Unfortunately, that effort was not successful. This may be providential since the authors have observed that a portion of the design engineering community is not willing to use equations that become cumbersome and challenging. Therefore, the effort was redirected toward development of a spreadsheet template to solve for the required ventilation air for any given flow rates, transfer rates, and mixing efficiencies. Commercially available spreadsheet software is equipped with robust equation-solving capabilities, which make this approach very attractive. It is anticipated that such an approach may eventually become a part of Standard 62.

FORMULATING THE GENERAL SPREADSHEET APPROACH

To develop the concept of employing a spreadsheet template to solve for the ventilation air required in a limited way, only four separate zones were considered.

Figure 1 is an illustration of an *n* zone system that possesses the basic zone and system elements envisioned for the template. The small system consists of one AHU, one return plenum, and four zones. Each zone may have infiltration, exhaust/exfiltration, four interzonal transfer points (where air may transfer into or out of the zone), and a fan-powered VAV box where primary air and plenum air mix to satisfy the zone's thermal loads. It should be noted that by setting the plenum airflow rate to zero, the FPB becomes a conventional shut-off VAV box. It is not expected that every zone would simultaneously experience flow at every one of the arrows depicted in Figure 1.

As discussed earlier, the three new general transfer paths introduce many new mixing efficiencies that do not appear in the literature. The three included in Warden's paper are depicted as dashed lines in Figure 1. First is the incomplete mixing at the AHU, thus delivering incompletely mixed primary air to the critical zone. Under this condition of imperfect mixing and with the critical zone satisfied (meaning the total flow of unvitiated air in the primary air is higher than would be necessary with perfect mixing of the primary air), the noncritical spaces would be overventilated more than for the situation with well-mixed primary air. In concept, the overventilated air could be treated as though it followed a short-circuit path from the primary air duct to the plenum along the dashed line path illustrated in Figure 1. Handling this mixing efficiency as a short-circuit path between the primary air supply duct and the plenum will, however, lead to calculation errors. Since incomplete mixing does not actually represent a short circuit directly to the plenum as illustrated, the partially mixed unvitiated air flows on to the other noncritical spaces. Consequently, more unvitiated outdoor air than computed will

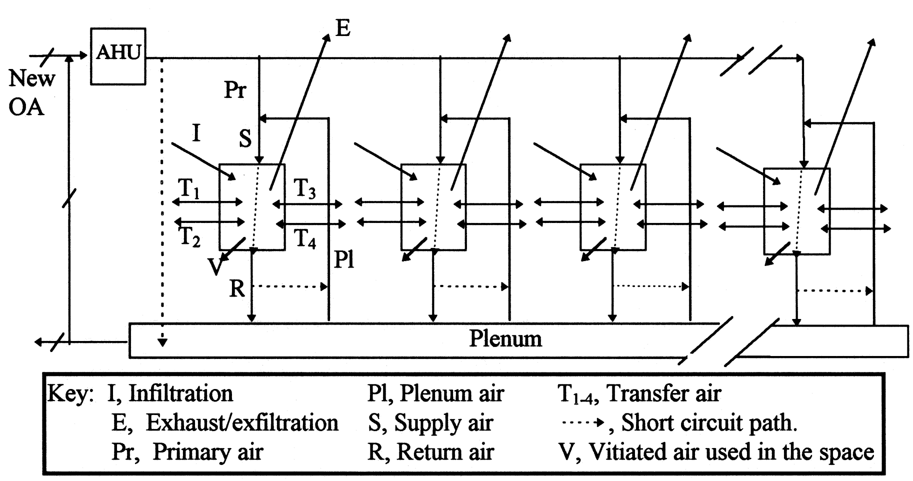

Figure 1 *Basic* n *zone system physical elements embedded in the spreadsheet template.*

leave the building at exhaust/exfiltration points, and in some situations more unvitiated OA than computed will transfer to the critical space from a noncritical space. For these reasons, every effort should be taken to ensure good mixing in the primary air duct.

The second mixing efficiency described by Warden is the incomplete mixing that may occur in the zone. Such a condition would occur if part of the supply air short-circuits directly to the return air path, also illustrated by the dashed line within the four zones. Finally, it can be considered that a portion of the return air does not mix perfectly in the plenum but, rather, is short-circuited to the fan-powered box as illustrated by the dashed line between the return and the plenum path to the VAV box. In addition to the three mixing efficiencies mentioned above by Warden, there are many other possible short-circuit paths. Specifically, every supply source could short-circuit to some extent to any outlet point.

For the purposes of this spreadsheet template, the authors have chosen to define the quantification of these short-circuit flows as a percent of the outlet flow rates. For any one zone in this four-zone arrangement, a total of 33 short-circuit paths can be defined. The paths are defined in words in Table 1 under input variables 14-46. Notice that the first six short-circuit paths (input variables 14-19) are defined as percentages

TABLE 1
Spreadsheet Input Variables

Input Variables Per Zone					
1	zone #	18	% return from transfer #3	35	% transfer #2 from transfer #4
2	primary air flow, scfm (g/s)	19	% return from transfer #4	36	% transfer #3 from supply
3	plenum air flow, scfm (g/s)	20	% exhaust from supply	37	% transfer #3 from infiltration
4	exhaust air flow, scfm (g/s)	21	% exhaust from infiltration	38	% transfer #3 from transfer #1
5	infiltration airflow, scfm (g/s)	22	% exhaust from transfer #1	39	% transfer #3 from transfer #2
6	transfer #1airflow into zone, scfm (g/s)	23	% exhaust from transfer #2	40	% transfer #3 from transfer #4
7	source zone of transfer #1 air	24	% exhaust from transfer #3	41	% transfer #4 from supply
8	transfer #2 airflow into zone, scfm (g/s)	25	% exhaust from transfer #4	42	% transfer #4 from infiltration
9	source zone of transfer #2 air	26	% transfer #1 from supply	43	% transfer #4 from transfer #1
10	transfer #3 airflow into zone, scfm (g/s)	27	% transfer #1 from infiltration	44	% transfer #4 from transfer #2
11	source zone of transfer #3 air	28	% transfer #1 from transfer #2	45	% transfer #4 from transfer #3
12	transfer #4 airflow into zone, scfm (g/s)	29	% transfer #1 from transfer #3	46	% plenum air from return
13	source zone of transfer #4 air	30	% transfer #1 from transfer #4	47	occupancy, people
14	% return from supply	31	% transfer #2 from supply	48	OA scfm (g/s)/person
15	% return from infiltration	32	% transfer #2 from infiltration	49	CO_2 (L/s)/ person
16	% return from transfer #1	33	% transfer #2 from transfer #1	50	zone floor area, ft^2
17	% return from transfer #2	34	% transfer #2 from transfer #3	51	OA scfm (g/s)/ft^2
Global Input:					
1) OA CO_2, ppm			2)% primary air directly to plenum		

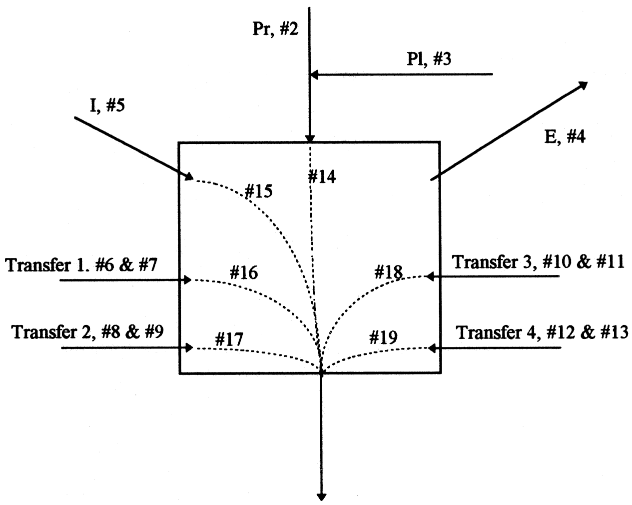

Figure 2 *Short circuit paths from the six sources to the return and spreadsheet input data numbers.*

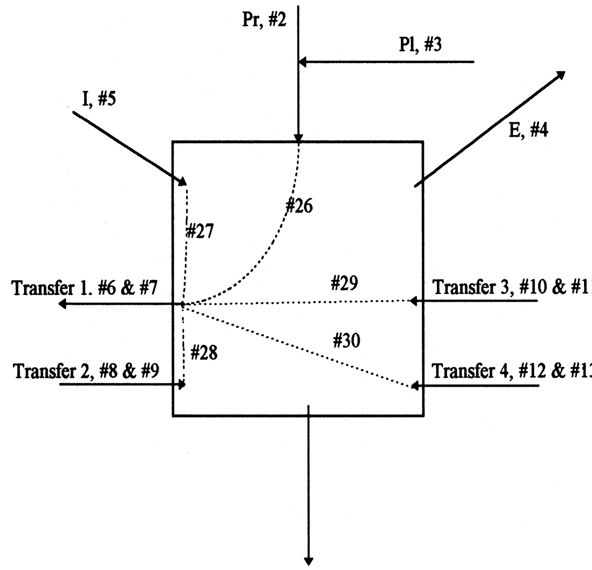

Figure 3 *Short circuit paths from the five sources to the interzonal transfer path 1 and spreadsheet input data numbers.*

of return originating from the various sources entering the zone, i.e., supply, infiltration, and interzonal transfer. These short-circuit paths are illustrated in Figure 2. The sum of the short-circuit flow rates (input variables 14-19), defined as a percent of the return airflow rate in this situation, cannot exceed 100% of the return air and will certainly be much lower than 100% since the bulk of the return air is expected to come from the well-mixed air in the zone. Similarly, input variables 20-25 define the short-circuit paths between all potential inlet paths and the exhaust/exfiltration. Variables 26-45 consider all of the short-circuit paths to the four interzonal transfer paths, first assuming that transfer path #1 leaves the zone and all other transfer paths lead to the zone (variables 26-30). The short-circuit paths leading to interzonal transfer path #1 are illustrated in Figure 3.

The other transfer paths are treated in the same fashion. It is very important to understand that it would be impossible to have all 33 short-circuit paths defined in any one zone simultaneously. This is true because the 33 short-circuit paths consider all possible combinations of interzonal transfer airflow direction. For any one calculation, a specific interzonal transfer airflow can be in one direction only. Finally, input variable 46 is used to define the short circuit between the return and plenum air to the VAV box.

The other variables that must be defined in the spreadsheet template are listed in Table 1. They include the zone number (input variable one), the airflow rates in scfm (g/s) (input variables 2-6, 8, 10, and 12), variables used to determine the required new OA and CO_2 concentrations (input variables 47-51), and the two global input variables. The fact that a single zone could require up to 51 inputs illustrates the potential bookkeeping complexity of the problem. Specification of realistic short-circuit path percentages is beyond the scope of this paper. However, Appendix G of ASHRAE Standard 62 1989R (ASHRAE 1996) offers some mixing efficiency parameter selection guidance.

Now that an overview of the nature of the problem and input variables used in the spreadsheet template has been developed, attention will be directed toward the spreadsheet calculations. The ventilation airflow rate in the primary air is calculated by establishing the complete set of continuity equations and solving for the minimum unvitiated air fraction (UVPA) needed in the primary air to satisfy the critical zone requirements. UVPA is a function of the critical zone ventilation air requirements, OA flow from infiltration into the critical zone, unvitiated air exhausted from the critical zone, unvitiated air transferred to or from the critical zone, and unvitiated air in the plenum air drawn into the fan-powered VAV box of the critical zone. The spreadsheet starts with a trial value of UVPA and iterates the value until there is no over-ventilation in the critical zone.

RELATIONSHIP BETWEEN MIXING EFFICIENCIES AND SHORT-CIRCUIT PERCENTAGES

A separate section is considered necessary in this paper to discuss the relationship between a mixing efficiency and the equivalent short-circuit percentage because specifying short-circuit percentages as developed in this paper is unique. Consider first the situation of a zone with a single inlet source (i.e., supply air) and a single outlet destination (i.e., a plenum). In this situation, a mixing efficiency of 100% would correspond to a short-circuit percentage of 0%. Likewise, the same zone with a mixing efficiency of 85% would have a short-circuit percentage of 15%. Under this condition of a single source and sink, there would be no advantage in switching from mixing efficiencies to short-circuit percentages. However, if another zone had one inlet source and three outlets consisting of exhaust, transfer, and return, then a mixing efficiency of 85% could not be used to accurately write the continuity equations without more information. The 85% mixing efficiency implies that 15% of the supply air escaped from the room before it could become mixed. The 85% mixing efficiency does not specify which of the one or more outlet destination paths were taken. Therefore, in order to write the continuity equations, it is imperative that the short-circuit path flow rate, origin, and destination be known. The authors suggest that defining the short-circuit path is a better way of accomplishing that objective than mixing efficiencies. The path alone, however, is not sufficient. The flow rate must also be specified. It could be specified as a percentage (or actual flow) of the source or the sink. The authors suggest it is easier to check that the continuity equations have not been violated (not a certainty, however) if the flow rate is defined as a percentage of the destination flow rate. It is this logic that caused the authors to select the variables to define short-circuit paths as presented above in Table 1.

FIVE EXAMPLE CASES

The five example cases will all involve four zones and will increase in complexity. Cases A, B, and C assume perfect mixing, i.e., no short circuiting. Cases D and E are identical to cases B and C, respectively, but with short circuiting added to the considerations. Figure 4 illustrates case A where zone one has infiltration and zones two through four each have exhaust. Figure 5 illustrates cases B and D. Case B is identical to case A with the exception that interzonal transfer from zone two to zone one is added. Case D is identical to case B with the exception that some short circuiting is added. Figure 6 illustrates cases C and E. Case C is similar to case A with the exception that zone four is served completely by transfer air from zone three, and the exhaust flow rate is 200 scfm (114 g/s) greater than that of case A. Case E is identical to case C with the exception that some short circuiting is added. The input variables required for these five cases are presented in Table 2. Input variables 14-16, 20, 22, 26, and 46 define the short-circuit percentages of the destination flow rates and sources for each of the five cases. For example, variable 14 in Table 2 specifies that 4%, 15%, 20%, and 0% of the return air for zones one through four, respectively, came directly from the supply air for case D.

A MATHEMATICAL FORMULATION OF CASE E AS A CHECK OF THE SPREADSHEET TEMPLATE

For the sake of clarity and simplicity in this paper, the mathematical formulation for only one case will be presented in detail. Case E was selected for the illustration.

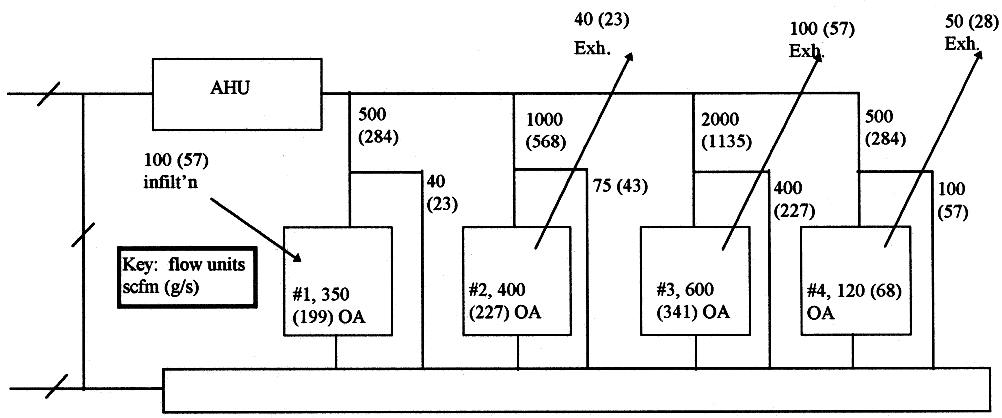

Figure 4 *Basic arrangement and flow rates for example case A to illustrate infiltration and exhaust.*

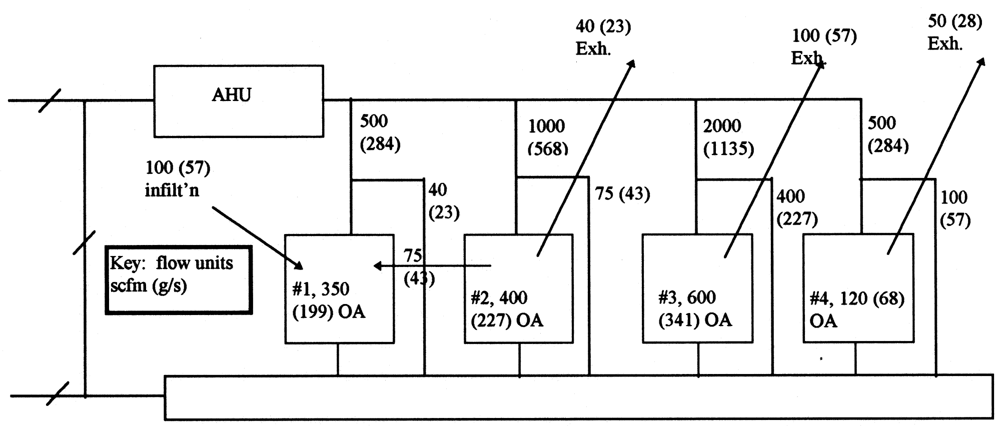

Figure 5 *Basic arrangement and flow rates for example cases B and D to illustrate infiltration, exhaust, and interzonal transfer.*

TABLE 2
Input Variables Used for the Five Example Cases

#	Input Variables	Cases: A/ B/ C/ D/ E			
1	**Zone #**	**1**	**2**	**3**	**4**
2	**primary airflow, scfm (g/s)**	500 (284)	1000 (568)	2000 (1135)	500/500/0/500/0 (284/284/0/284/0)
3	**plenum airflow, scfm (g/s)**	40 (23)	75 (43)	400 (227)	100/100/0/100/0 (57/57/0/57/0)
4	**exhaust airflow, scfm (g/s)**	0	40 (23)	100 (57)	50/50/250/50/250 (28/28/141/28/141)
5	**infiltration airflow, scfm (g/s)**	100 (57)	0	0	0
6	**transfer #1 airflow into zone, scfm (g/s)**	0/75/0/75/0 (0/43/0/43/0)	0	0	0/0/250/0/250 (0/0/141/0/141)
7	**source zone of transfer #1 air**	2	n/a	n/a	3
14	**% return from supply**	0/0/0/4/0	0/0/0/15/0	0/0/0/20/5	0
15	**% return from infiltration**	0/0/0/5/0	0	0	0
16	**% return from transfer #1**	0/0/0/1/0	0	0	0
20	**% exhaust from supply**	0	0/0/0/10/0	0/0/0/0/10	0
22	**% exhaust from transfer #1**	0	0	0	0/0/0/0/5
26	**% transfer #1 from supply**	0	0/0/0/20/0	0/0/0/0/20	0
46	**% plenum air from return**	0	0	0/0/0/25/10	0
47	**occupancy, people**	17.5	20	30	6
48	**OA scfm (g/s)/person**	20 (11)	20 (11)	20 (11)	20 (11)
49	**CO_2(L/min)/person**	0.3	0.3	0.3	0.3
50	**zone floor area, ft^2 (m^2)**	550 (57)	1100 (102)	2400 (223)	600 (56)
51	**OA scfm (g/s)/ft^2**	0	0	0	0
Global Input:					
1) OA CO_2, ppm, 300 ppm			2) % primary air directly to plenum, 0		

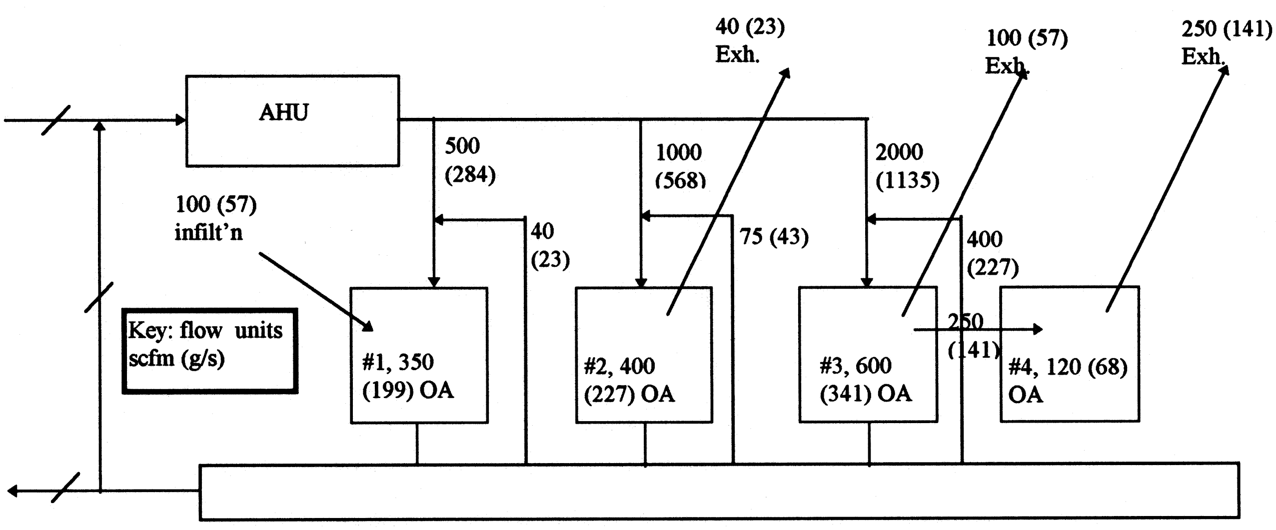

Figure 6 *Basic arrangement and flow rates for example cases C and E to illustrate infiltration, exhaust, and ventilation completely by interzonal transfer.*

The equations that follow are the result of applying ventilation air balances on each zone (refer to Figure 7 for a better understanding of zone three equations).

Zone 1: $500 \cdot P1 + 40 \cdot P2 + 100 - 350 - 640 \cdot PZ1 = 0;$

Zone 2: $1000 \cdot P1 + 75 \cdot P2 - 40 \cdot PZ2 - 400 - 1035 \cdot PZ2 = 0;$

Zone 3: $A = 2000 \cdot P1 + 360 \cdot P2 + 40 \cdot PR3;$

$PS3 = A / 2400;$

$A - 600 - PS3 \cdot (10 + 50 + 103) - 2238 \cdot PZ3 = 0;$

$PR3 = (PS3 \cdot 103 + 1948 \cdot PZ3) / 2050;$

Zone 4: $50 \cdot PS3 + 200 \cdot PZ3 - 120 - PS4 \cdot 13 - 238 \cdot PZ4 = 0;$

$PS4 = (50 \cdot PS3 + 200 \cdot PZ3) / 250.$

The equation resulting from the ventilation airflow rate balance on the plenum is

$$640 \cdot PZ1 + 1035 \cdot PZ2 + (2010 \cdot (1948 \cdot PZ3 + PS3 \cdot 103) / 2050) - P2 \cdot (40 + 75 + 360) - (3600 - 390) \cdot P2 = 0.$$

The equation resulting from the ventilation airflow rate balance at the AHU is

$$OA + (3500 - OA) \cdot P2 = (500 + 1000 + 2000) \cdot P1.$$

The variables used in the equations above are:

A, flow rate of unvitiated OA supplied to zone three;

OA, volumetric flow rate of new OA that must enter the system at the AHU;

P1, fraction of ventilation air in the primary air;

P2, fraction of ventilation air in the plenum air;

PR3, fraction of unvitiated OA in zone three's return air (note that because of the short circuit it is larger than Z3);

PS3, fraction of unvitiated OA in the total supply air to zone three;

PS4, fraction of unvitiated OA in the transfer airstream from zone three to four;

PZ1, fraction of unvitiated OA in zone one;

PZ2, fraction of unvitiated OA in zone two;

PZ3, fraction of unvitiated OA in zone three;

PZ4, fraction of unvitiated OA in zone four.

Numerical results are presented in Table 3.

The CO_2 calculation for each of these five cases is relatively simple. Since the activity level and ventilation requirements for each occupant are uniform throughout the four zones with a resulting saturation concentration of 825 ppm based upon an OA (as well as the unvitiated OA) concentration of 300 ppm, the zone concentrations can easily be computed. For example, in zone one, the CO_2 concentration is simply

$$PZ1 \cdot 300 + (1 - PZ1) \cdot 825 = 696 \text{ ppm}.$$

The spreadsheet template was set up to accommodate any prescribed activity level (CO_2 production rate/person), ventilation rate per person, and OA CO_2 concentration.

TABLE 3
Numerical Results for Example Case E

A	1728, scfm (981 g/s)
new OA	2218, scfm (1259 g/s)
P1	0.782
P2	0.404
PR3	0.465
PS3	0.720
PS4	0.505
PZ1	0.245
PZ2	0.383
PZ3	0.452
PZ4	0.000

RESULTS AND DISCUSSION

The spreadsheet results are presented in Table 4. Details of zone three, example case E, are presented in Figure 7 for illustration. The results for each case were independently checked by solving the continuity equations simultaneously with another commercially available nonlinear modeling and optimization software code as discussed in the previous section.

The five example cases are theoretical. Therefore, the discussion of results must be weighed in that light. Further, it is obvious that these five cases do not cover all of the possibilities that exist at any moment in occupied buildings. The primary point to be made is that in each case the required new OA was successfully computed by the solution of the continuity equations, something that could not be accomplished with Standard 62's Equation 6-1, Warden's equations, or the Ke/Mumma work.

The discussion that follows will reference Table 4a for global information and Table 4b for zone level details. A comparison of cases A and B reveals that the addition of interzonal transfer of air from the overventilated zone two to the critical zone one caused the new OA required at the AHU to be reduced from 1619 scfm to 1597 scfm (919 g/s to 906 g/s). Since a smaller fraction of ventilation air was required in the primary air for case B, the overventilation of zones two, three, and four was less than for the base case A.

For case C, where the ventilation requirements for zone four had to be met entirely by transfer air from zone three (see Figure 6), zone three had to be highly overventilated (by 1152 scfm [654 g/s]). As a result, zone one was no longer critical as in case A; rather, zone four became the critical zone. Finally, the new OA required at the AHU increased from 1619 scfm (919 g/s) in case A to 2253 scfm (1279 g/s) in case C, creating a potential energy penalty in most geographic climates.

Cases D and E are identical to cases B and C with the exception that short-circuit paths were introduced. Because of

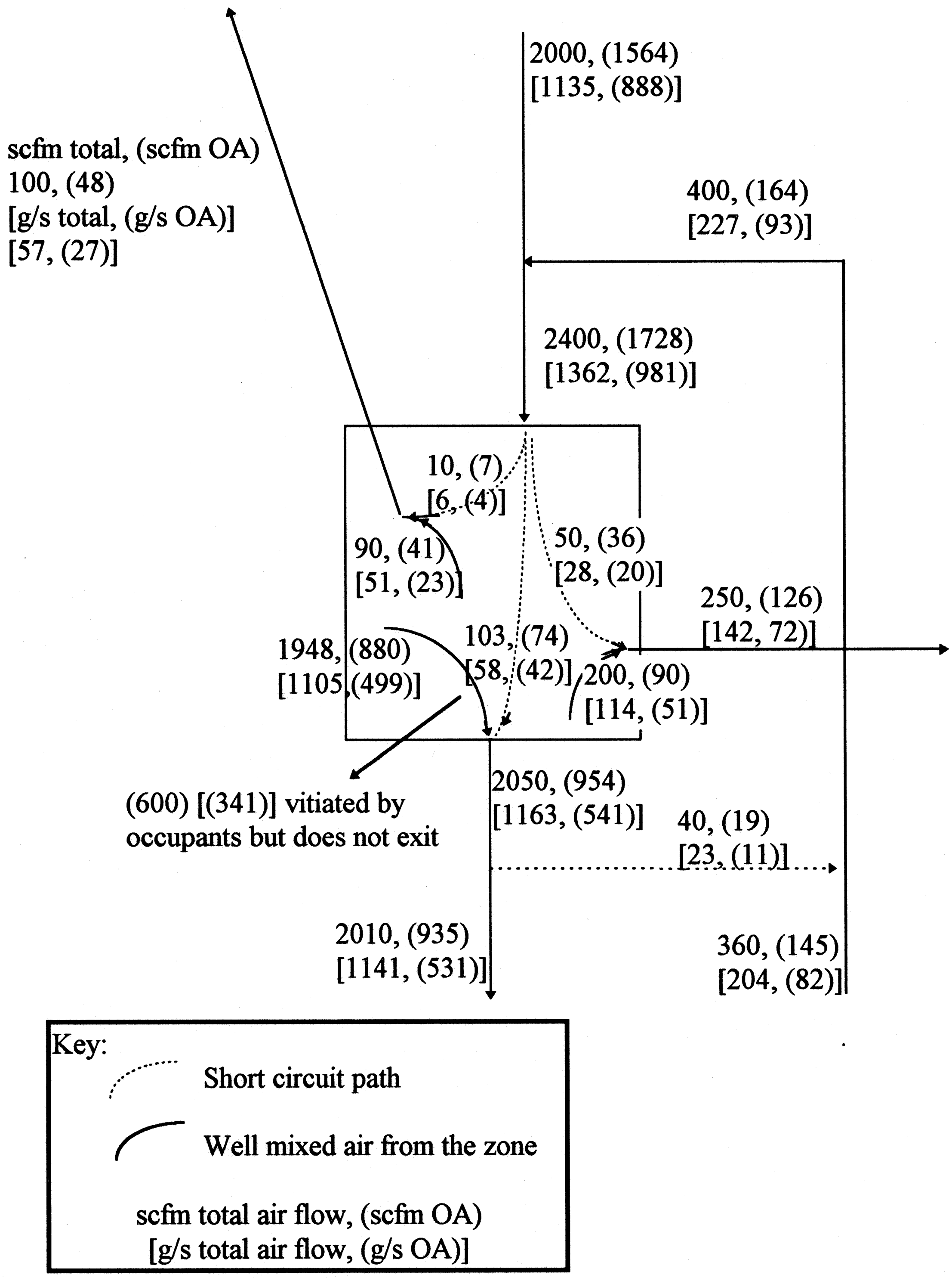

Figure 7 *Details of zone three, case E.*

TABLE 4a
Global Output for the Five Example Cases

Global Output					
Case	**A**	**B**	**C**	**D**	**E**
Required new OA, scfm (g/s)	1619 (919)	1597 (906)	2253 (1279)	1766 (1002)	2218 (1259)
Primary air CO_2, ppm	568	574	409	531	415
Plenum air CO_2, ppm	751	757	606	714	613

TABLE 4b
Zone Output for the Five Example Cases

Zone Output: For Cases A/ B/ C/ D/ E										
	Zone overventilation, scfm (g/s): if C, zone is critical					Zone CO_2 concentration, ppm				
Zone #	**Case A**	**Case B**	**Case C**	**Case D**	**Case E**	**Case A**	**Case B**	**Case C**	**Case D**	**Case E**
1	C,0 (0)	C,0 (0)	163 (93)	C,52 (30)	157 (89)	C,825	C,825	691	C,825	696
2	99 (56)	87 (49)	423 (240)	176 (100)	412 (234)	777	782	618	774	624
3	434 (246)	407 (231)	1152 (654)	609 (346)	1128 (640)	730	736	573	723	588
4	138 (78)	132 (75)	C,0 (0)	181 (103)	C,6.3 (3.6)	704	710	C,825	666	C,825

Note: Overventilation is the sum of ventilation air entering the zone from any source minus the required ventilation air for the zone. The overventilation air may leave the space at any of the exit points after mixing with the zone air or via the short-circuit paths defined.

the short-circuit paths in case D, critical zone four had 52 scfm (30 g/s) of unvitiated air that did not mix with the zone air, thus increasing the new OA required at the AHU from 1597 scfm to 1766 scfm (906 g/s - 1002 g/s) when compared to case B. The noncritical zones two to four are, consequently, substantially more overventilated in case D with short circuiting than in case B without any short circuiting. In case E, with short circuiting of 50 scfm (28 g/s) of supply air (36 scfm [20 g/s] of which is unvitiated air) to the interzonal transfer between zone three and zone four (see Figure 7), zone three does not require quite as much overventilation as was required in case C to meet the ventilation requirements of zone four. Consequently, the new OA required at the AHU is reduced from 2253 scfm (1279 g/s) for case C to 2218 scfm (1259 g/s) for case E. Overventilation of the noncritical zones one to three for case E was also slightly less than for case C. However, because of the short-circuit path between the transfer entry into zone four and the exhaust, 6 scfm (3 g/s) of unvitiated air left zone four without mixing with the zone. The two short-circuit paths, supply to transfer zone three and from transfer to exhaust in zone four, almost canceled each other out. It is worth noting that when short circuits exist between the supply and exit points, critical zones have unvitiated OA leaving just like the noncritical zones.

The zonal CO_2 concentrations directly reflect, as expected, the extent of the overventilation a space receives. For the cases presented in this paper, the saturation concentration is 825 ppm. Notice that the critical zones, listed in Table 4b, are at saturation even though for cases D and E there is overventilation. This is because the overventilation came as a result of short circuiting and, hence, the overventilation air was not really available to dilute the CO_2 produced.

CONCLUSIONS AND RECOMMENDATIONS

The objective of the work presented in this paper was to demonstrate that determination of the required ventilation air may be quickly and easily computed even when infiltration, exhaust/exfiltration, and transfer airflow exist. A single equation to accommodate the additional airflow paths was not obtained, but a spreadsheet template method was developed for use with commercially available software to go well beyond the current limit of Equation 6-1 of Standard 62-1989 and its extensions published in the ASHRAE literature. It is the author's recommendation that ASHRAE undertake the development of a more comprehensive spreadsheet template to accompany a future promulgation or supplement to ASHRAE Standard 62 so infiltration, exhaust, and interzonal transfer may be readily accommodated.

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