THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

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PAPER 3

A STANDARD FOR MINIMUM VENTILATION

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SYNOPSIS

The air infiltration associated with ventilation in buildings is recognized in ASHRAE Standard 62-1981, Ventilation for Acceptable Indoor Air Quality. Especially in the residential sector, and particularly in houses, infiltration is assumed to supply most of the required ventilation. In the light of recent trends toward increasingly tight housing, which limits air infiltration, dependence on this source of outside air is one point that must be carefully considered in the Revised Standard.

Giving credit to either air infiltration or ventilation air as the means to dilute sources of indoor pollution, and thereby maintain acceptable indoor air quality, depends upon the degree of mixing with the interior air. The mixing efficiency is an important question that must be properly evaluated in the Revised Standard. Recent studies have pointed out how widely this "ventilation efficiency" can vary from building to building.

Activities within the living space such as smoking have prompted the previous standard committee to carefully discriminate between smoking and nonsmoking areas. Ventilation rates for smoking areas were raised as much as a factor of five times that of nonsmoking areas. Are these ratios sufficient in the light of recent studies involving necessary dilution of particulates? Flows between smoking and nonsmoking zones also require further consideration in the Revised Standard.

As with any pollutant, maintaining suitable interior environments means understanding the significance of building operation, the systems that move the air (such as variable air volume systems) and the effects of both interior and exterior environments. Changes in humidity, air temperature and local heating may alter pollutant levels in buildings due to the building materials and must be considered in revising the Standard.

1. INTRODUCTION AND HISTORY

The need for ventilation of inhabited, enclosed spaces was undoubtedly recognized by early cave men when they brought their campfire into the cave. The first recorded effort to quantify ventilation needs appears to be the work of Tredgold in 1836.[1] He determined that four cubic feet per min (2 L/s) of outdoor air per person was needed to dilute the carbon dioxide exhaled by the occupants of a space. As stoves and controled heating systems displaced open fireplaces during the last century, and building technology improved, the recommended ventilating rates had increased to 30 cfm (15 L/s) per person by the beginning of the 20th century. These higher ventilating rates were found necessary to control body odors. Personal hygene began to improve about that time, and recommended ventilation dropped to 10 cfm (5 L/s) of outdoor air per person when Yaglou published his work in 1936.[2]

1.1 First U.S. Standard

The first ventilation standard was published by the American Standards Association in 1946.[3] It included recommendations for both lighting and ventilation. ASHRAE up-dated the ASA Standard when it published Standard 62-73 in 1973.[4] Both ASA A53.1 and ASHRAE 62-73 recommended basic rates of 10 cfm (5 L/s) of outdoor air per person based on Yaglou's work. The ASHRAE Standard specified an absolute minimum of 5 cfm (2 1/2 L/s) per person to control the carbon dioxide level. This was in agreement with Tredgold's original recommendation. At 5 cfm (2 1/2 L/s) per person sedentary occupants can raise the steady state CO2 level to about 2500 ppm (0.25%). This is considered to be an acceptable upper limit for normally healthy people. Nuclear-powered submarines, and spacecraft operate at CO2 levels as high as 1%, however, odors are sometimes noticable at those high CO2 levels.

1.2 Energy Considerations

The 1973 oil embargo suddenly created a strong emphasis on energy conservation in buildings. While Standard 62-73 presented both minimum and recommended outdoor air ventilating rates, the ASHRAE Energy Standard 90-75 first published in 1975, specified use of the minimum rates.[5] Thus, one objective of the review of Standard 62-73, begun in 1978, was to rectify differences between Standard 90 and Standard 62. The result was Standard 62-1981.[6]

1.3 Standard 62-1981

The 1981 Standard addressed air quality much more directly than earlier Standards. The basic outdoor air ventilating rate was reduced to 5 cfm (2 1/2 L/s). Only minimum rates were presented for various applications. Tobacco smoke was recognized as a special problem that could not be handled with an outdoor air flow rate of only 5 cfm (2 1/2 L/s) per person. Thus the "perscriptive part" of Standard 62-1981, the ventilation rate procedure, specifies substantially higher rates when smoking is permitted. The recommended rates, based on the dilution of particulates, assumes that one third of the population smokes at a rate of two cigarettes per hour. The recommended minimum outdoor air flow rate for this case is 20 cfm (10 L/s) per person, four times the non-smoking rate. (This rate is specified for all occupants, both smokers and non-smokers when the smokers are not segregated). The recommended rate is increased to 35 cfm (17 1/2 L/s) for applications such as bars where the incidence of smoking is generally higher. Standard 62-1981 also defined acceptable contaminant levels for the outdoor air used for ventilation.

1.4 Air Quality Procedure

A new feature of Standard 62-1981 was the inclusion of an alternate, "Air Quality Procedure." This procedure specifies recommended limits for the most common contaminants and allows the designer to use whatever amount of outdoor air he finds necessary to dilute the containants to the recommended level. Under this procedure it is possible to use a high efficiency filter to remove particulates from the recirculated air and thus reduce the outdoor air requirements to nearly equal the non-smoking rate even when smoking is permitted. The committee that wrote Standard 62-1981 felt it was desirable to include the air quality procedure so that innovative methods to achieve energy efficient ventilation could be permitted.

One pollutant level, the recommended limit of 0.1 ppm for formaldehyde (based on comfort criteria rather than health risk) created a problem with the manufactured housing industry. Although that industry can exercise controls over emissions from widely used urea-formaldehyde-bonded plywood and chipboard (through low emissions specifications or substitute materials), and from choices made with regard to urea-formaldehyde foam insulation, they have no control over carpeting, drapery, and furniture all of which also emit formaldehyde vapors. Thus the publication of a low recommended formaldehyde limit in the ventilation standard, even though it was part of an alternate procedure, was perceived as a threat to the industry. Since single-family residences do not usually have mechanical ventilation systems, which can be evaluated by building inspectors, it was feared that the air quality procedure would be adopted as the only choice in building codes. This situation has served to emphasize the residential problem: if there is no mechanical ventilation system, now can we deal with infiltration which approaches zero flow under mild weather conditions?

2. HOUSES AND MINIMUM VENTILATION

Past AIC conferences have revealed the variation in ventilation rates between the different rooms in European residences.[7] Such room-to-room variations, as large as 10 to 1, most certainly take place in US homes as well, but because of restricted constant-concentration tracer gas testing to document such variations, the data base has been very limited. Except for the mechanically ventilated, very tight home which is almost weather independent, the conventional US home experiences major variations in ventilation rate over the seasons and during any one season. This has been dramatically pointed out in recent testing in two side-by-side homes in Gaithersburg, Maryland.[8-10] The testing program has extended over the entire weather year which is a rarity in infiltration testing. Typical seasonal data are shown in Fig. 1 and illustrate that these two houses with noticeably different tightness, approximately 6 and 10 air changes per hour at 50 PA based on fan pressurization tests, exhibit a marked variation in infiltration rates over the year and differ by about 25%. Only in

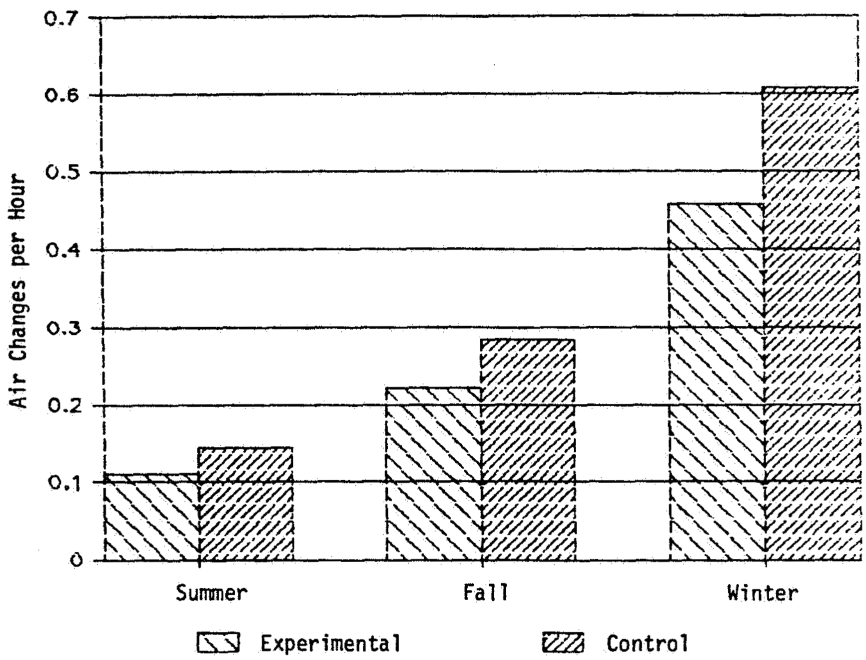

Fig. 1 Effect of Retrofit, by Season, on Infiltration Rates[10]

the most severe winter climate do the air infiltration rates measured by the tracer gas method approach the same ventilation differences between these houses as measured by the pressurization tests (i.e., 40%). Throughout the testing, the air infiltration fluctuates day-to-day, or even hour-to-hour due to weather variations and clearly causes significant variations in the ventilation rate as shown in Fig. 2.

One technique that has been employed in these two house tests is to generate a "synthetic' yearly ventilation rate profile.[10] It provides an improved approach to quantifying average ventilation rates but questions of meeting a "ventilation standard" during all periods of house operation remain. This yearly ventilation rate profile is shown in Fig. 3 and points out the average infiltration rate is only 0.25 ACH for the tighter, retrofitted house and 0.34 ACH for the control house (compared to 0.5 ACH which has often been viewed as a desirable lower ventilation limit).

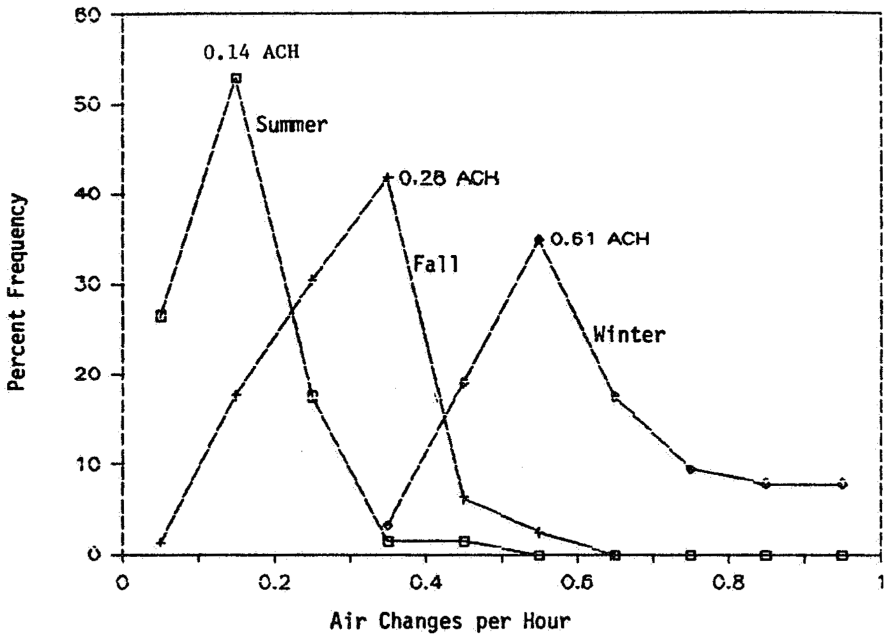

Fig. 2 Seasonal Frequency Distributions of Infiltration Rates[10]

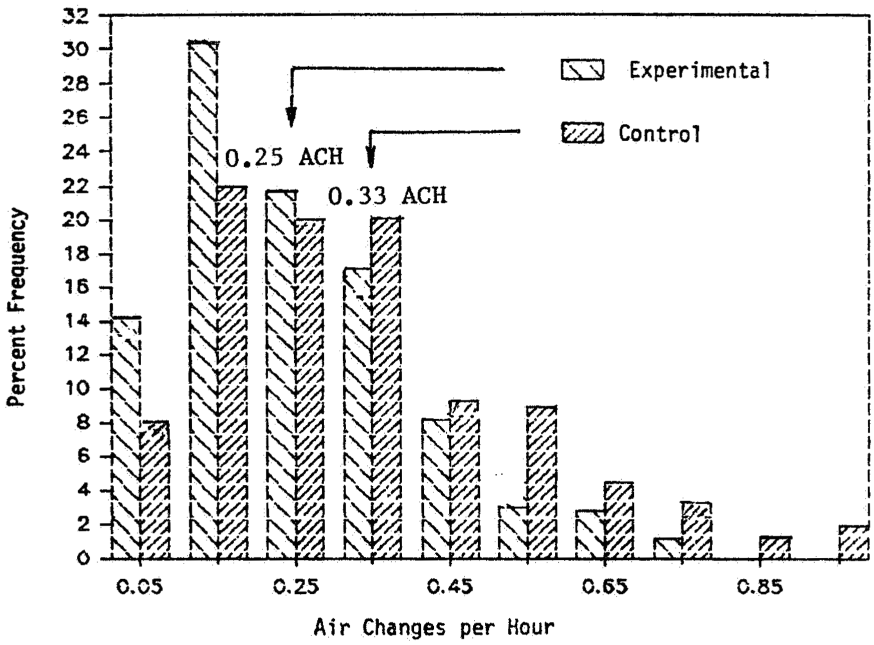

Fig. 3 Synthetic Annual Frequency Distribution of Infiltration Rates[10]

Standard 62-1981, as now constituted, states (in Section 5.1) that adequancy of ventilation via natural ventilation and air infiltration "shall be demonstrable". Have the detailed tests (just discussed) only proved what we have all suspected, namely as our housing becomes tighter there will be periods - sometimes extended periods - when air infiltration will be inadequate to supply the ventilation requirements of our homes? How adequate was the actual ventilation in the past? How can we treat this problem in the Revised Standard is a question that must be resolved within the committee. Should we move away from statements that "ventilation rate shall be demonstrated" to a statement that specifies an improved method of measurement? How cautiously should we proceed to improved tightness standards in our residential housing, such as in ASHRAE SPC-119,[13] in light of our present knowledge? These are just some of the questions that must be answered in the months ahead.

3. MEASUREMENT OF AIR EXCHANGE RATES

Since ASHRAE 62-1981 was written, marked improvements in our ability to measure air exchange rates have taken place and our knowledge of air exchange in buildings both large and small has been considerably advanced. In our larger buildings we are now able to document the amounts of outdoor air entering the buildings under various seasonal conditions. Differences between floors are also evident.[11,12] What is still missing is how the amount of outside air changes with the different settings of the ventilation systems, especially the variable air volume systems. Since VAV systems are today's standard method of providing ventilation air in our larger buildings, it is important that the Revised Standard address questions that deal with the VAV operations that affect ventilation. The fresh air or recirculated cleaned air requirements in the Standard are a function of the occupancy levels, and/or floor space. Thus, it is important that there be no reduction in these air flow levels when the total amount of air flow is reduced to a given zone based upon comfort considerations. Measurements of these air quantities are now being undertaken by such groups as the National Bureau of Standards and hopefully will impact the Standard as it is being revised.

4. POLLUTANT LEVELS AND LARGER BUILDINGS

Viewing the ventilation question from the standpoint that pollutants must not exceed a prescribed level, the Indoor Air Quality Procedure of ASHRAE Standard 62-1981, one would like to find a simple testing approach. Some have proposed CO2 and particulate levels as surrogate measures of this adequacy. CO2 levels have been the basis for determining ventilation rates incorporated in the ASHRAE 62 Standard over the years. Although maximum CO2 levels have been set at 2500 ppm (0.25%), recent data have indicated that level may be too high. Canadian studies point to 1,000 ppm as a level that eliminates occupant problems such as mild headaches. Japanese data would appear to confirm those values placing the desired maximum in a similar range. This adjustment in CO2 level would have a profound influence on Standard 62. To meet the Canadian and Japanese recommendations would mean that the minimum ventilation rate would be 12.5 cfm (6.3 L/s) not the 2.5L/s 5 cfm (2.5 L/s) as in Standard 62-1981. Before discussing this question of minimum ventilation rate further let us turn our attention to particulates.

4.1 Particulates

In the discussions that have taken place in Atlanta and Kansas City (sites of ASHRAE semiannual and annual meetings) the topic that has received the most attention in the 62-1981R Subcommittee on Building Performance has been particulates. Even before these deliberations, there has been a high degree of interest in particulates that are a result of smoking. Representatives in the tobacco industry question the concept of smoking versus non-smoking ventilation rates where the ventilation rates have often been specified to be five times that in the non-smoking zones, in Table 3 of the 62-1981 Standard. The discussions in the subcommittee covered more than the smoking issue and are looking at particulates in the 0.3-1, 1-3, and 3-5 micron sizes, covering a range that includes and exceeds those particles that could be attributed to smoking alone. One explanation was that the particles larger than 1 micron (i.e., larger than those associated with smoking), were often "people generated." By this we are speaking of skin shedding and other occupant related activities. New monitoring techniques have allowed these different sizes of particulates to be measured and the results interpreted in terms of ventilation efficiency. The early results are revealing that constant volume and variable air volume systems perform differently using these particulates as "tracers". Questions have been raised as to whether the "mixing efficiency" is the same over this range of particle sizes, i.e., that the possibility exists that some particles may concentrate in the occupied zones of a building.

4.2 Ventilation Efficiency

The whole question of ventilation efficiency is a key to the application of Standard 62. The pioneering works of Sandberg[14] and Skaret[15] point out the key elements of ventilation efficiency. If the ventilation air, whether it be outside air or cleaned and filtered recirculated air, is not reaching the occupants of the building because air mixing is inadequate in the rooms in which they are located, then the purpose of the Standard has been compromised. The achievement of suitable ventilation efficiencies must be a key element in satisfying the goals of the Revised Standard.

Dilution of contaminated indoor air with less contaminated outdoor air is the main method used for controlling indoor air contaminants. Commercial buildings use mechanical air handling systems to condition and distribute the ventilation air. The amount of outdoor air required is defined by building codes which usually depend on ASHRAE Standard 62. System designs are approved on the basis of the building plans and specifications. After the systems are installed they are balanced by measuring the volume of air discharged from each supply diffuser. This, however, does not assure a proper distribution of the outdoor air within the occupied space. Incomplete mixing of outdoor air with return air can result in a non-uniform distribution of the outdoor air. Further, the common practice of locating both the supply outlets and return inlets on or near the ceiling can permit short circuiting of some of the supply air directly to the returns without complete mixing at the occupied level in a room. When this happens effective dilution is compromised.

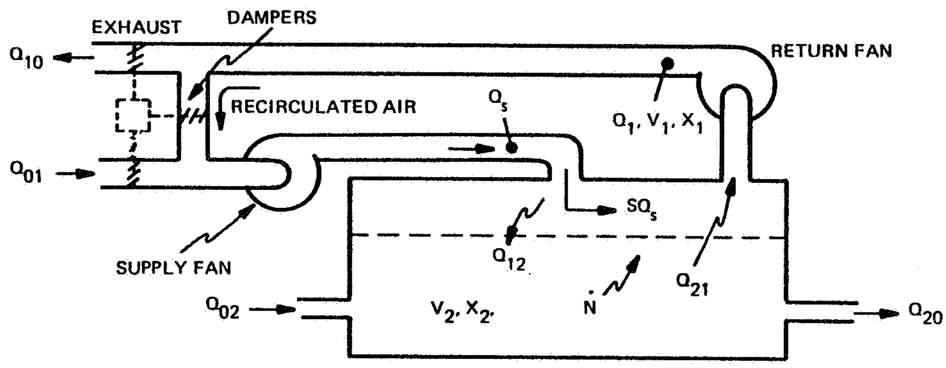

Fig. 4. Typical Air Distribution System.

Consider a typical distribution system as shown in Fig. 4.[16,17] Outdoor air, Q01 is mixed with recirculated air and supplied to the space. A fraction, s, of the supply air, SQs may flow along the ceiling to the return inlet or otherwise bypass the occupied part of the room. A fraction, r, of the return air may be recirculated to be mixed with the outdoor air. The remainder, 1-r, will be exhausted. The amount of this outdoor air that bypasses the occupied space and is exhausted is Q10-s and the relationship is:

$$Q_{10-s} = s(1-r)Q_{01}\ [1 + rs + (rs)^2 + \dots] \qquad (1)$$

$$\frac{Q_{10-s}}{Q_{01}} = \frac{s-sr}{1-sr}$$

The ventilation efficiency, η, can be defined as:

$$\eta = \frac{Q_{01} - Q_{10-s}}{Q_{01}} = \frac{1-s}{1-sr} \qquad (2)$$

Eqn. 3 defines the efficiency with which the outdoor air is circulated to the occupied space in terms of a stratification or mixing factor, s, and the recirculation factor, r. If there is no exhaust flow, r=1 and the efficiency is 100%. If there is no stratified or bypass flow, s=0, and the efficiency is also 100%. If, however, there is both stratified flow and recirculation, outdoor air can pass through the system without ever being used to dilute contaminants at the occupied level. This ventilation loss also represents an energy loss. Fig. 5 presents a set of curves describing Eqn. 3.

It has been shown[17] also that tracer gas decay measurements can be used under the proper conditions to measure ventilation efficiency. A suitable tracer gas such as methane or sulfur hexafluoride can be

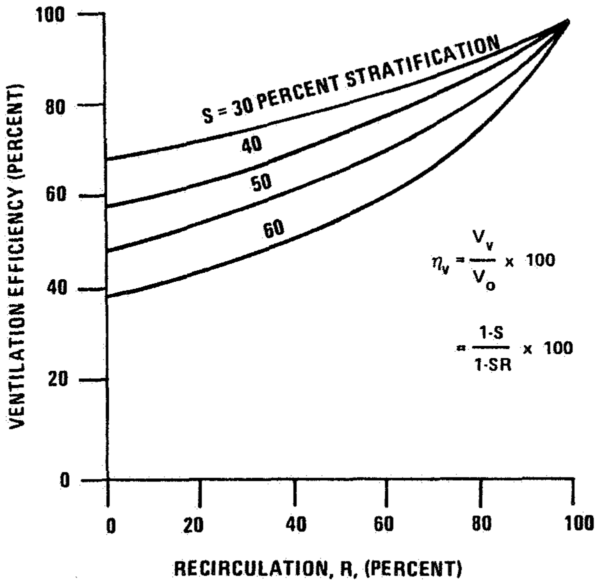

Fig. 5 Ventilation Efficiency

added to the supply air at a sufficiently rapid rate to build up a measureable concentration at the return inlet before there is a significant rise in concentration at the occupied level. The semi-log plot of the tracer gas concentration decay over time may reveal two curves similar to Fig. 6. The slopes of the lines are proportional to the outdoor air flow rate in volumetric air changes per unit time. In this case, Volume 1 refers to the supply and

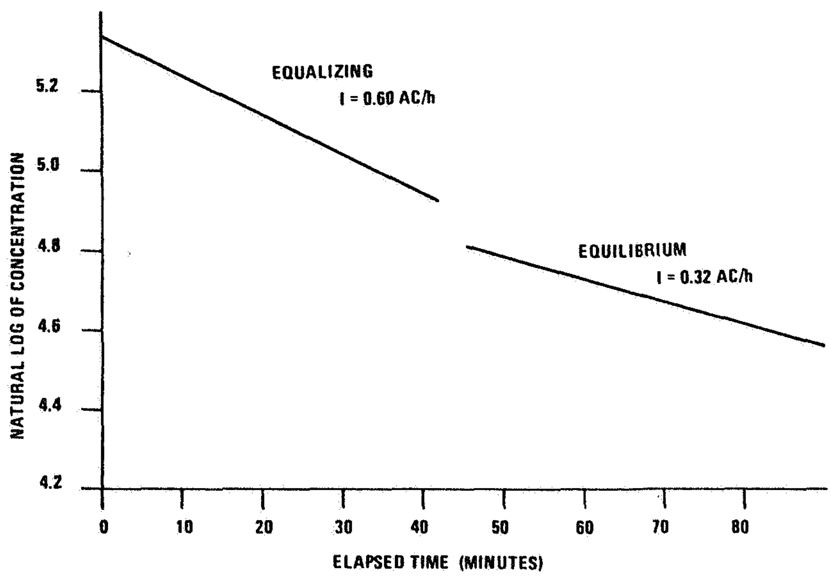

Fig. 6 Tracer Gas Decay in Volume 1 in a Two Chamber Study[16]

return duct volumes and the upper part of the room as shown in Fig. 4 Volume 2 is the lower or occupied part of the room.

The apparent change in infiltration or ventilation rate is caused by the initial loss of tracer gas both to Volume 2 and to the exhaust flow plus the infiltration loss. The final or equilibrium decay line is revealed when mixing between the two volumes is complete. This represents the actual outdoor air plus infiltration air flow rates. It can be shown [17] that the efficiency with which the outdoor air is used to dilute contaminants in Volume 2 (i.e., the occupied part of the room) is approximated by:

$$\eta = \frac{I_o - I_{oo}}{I_o} \qquad (4)$$

where I_o = initial apparent infiltration rate

I_{oo} = final infiltration rate.

For the case represented in Fig. 6,

$$\eta = \frac{0.60 - 0.32}{0.60} = \frac{0.28}{0.60} = 0.47 \qquad (5)$$

This low ventilation efficiency was approximately confirmed by energy balance calculations.

The ventilation efficiency obtained with tracer gas tests and calculated from Eqn. 5 can be equated to Eqn. 3 to obtain the stratification factor, s :

$$s = \frac{1 - \eta}{1 - \eta r} \qquad (6)$$

The recirculation rate during the tracer decay measurements must be specified since this will influence the ventilation efficiency.

Duct systems similar to Fig. 4 can be expected to have a substantial reduction in ventilation efficiency as shown in Fig. 5. However, if the return inlet is located near the occupied level or if the exhaust is separated from the return system and is located in the occupied level, the ventilation efficiency can be high. ASHRAE Standard 62-1981 does not recognize this problem, but the revision to 62-1981 must address the issue.

Variable air volume systems tend to exacerbate this problem. Under heating conditions, the body heat-loss from a group of people in a room will offset some of the heat requirement for the room. This will reduce the air flow and ventilation air at the very time when it is most needed. The lower air velocities also reduce mixing efficiency. Such a system should be designed to increase the fraction of outdoor air in the supply air under these conditions. Use of a carbon dioxide sensor to measure the actual outdoor air requirement would be one way to correct this problem.

4.3 Smoking

Tobacco smoke presents the HVAC system designer and building operator with particular challenges. Approximately 30% of the US population smokes. The 70% non-smoking population has demanded special consideration in recent years. Standard 62-1973 recognized the requirements in a very superficial and indirect manner. The recommended outdoor air supply rates, for applications where the incidence of smoking could be expected to be high, was therefore increased to control the smoke and associated odors. In contrast, Standard 62-1981 addressed smoking directly. Outdoor air supply rates are specified for either smoking or non-smoking applications.

The average generation rate for total suspended particulates is 31.9 mg/cigarette[18]. The National Ambient Air Quality Standard specifies 0.260 mg/m^3 as the concentration limit for total suspended particulates for 24 hour exposure[6]. A mass balance for the particulates in indoor air is Eqn. E-1, Appendix E, Standard 62-1981:

$$\dot{V}_o \, (C_s - C_o) = \dot{N} \qquad (7)$$

where $\dot{V}_o$ = Flow rate of outdoor air

C_s = Particulate concentration in space

C_o = Particulate concentration outdoors

$\dot{N}$ = Particulate generation rate

The flow rate of outdoor air needed to achieve a given indoor particulate concentration is given by:

$$\dot{V}_o = \frac{\dot{N}}{(C_s - C_o)} \qquad (8)$$

If we assume the outdoor particulate concentration is zero, $C_o = 0$:

$$\dot{V} = \frac{31.9}{0.260} = 150 \text{ m}^3\text{/hr per cigarette} \qquad (9)$$

If we assume 25% of the occupants in a room smoke two cigarettes per hour, the outdoor air flow rate needed is:

$$\dot{V}_o = \frac{(0.25)\ (2)\ (150)}{60} = 1.25\ m^3/\text{min-person}$$

$$\dot{V}_o = (1.25)\ (16.67) = 20.8\ L/s \text{ or } 41.7\ cfm \qquad (10)$$

The flow rates recommended in Table 3 of Standard 62-1981 were adjusted up and down from this basic rate. Smoking in areas such as bars tends to be greater than the assumed rate, but the duration of exposure is substantially less than 24 hours. There are always some particulates in outdoor air which would increase the amount of outdoor air needed. The National Ambient Air Quality Standard specifies 0.075 mg/m^3 as the maximum particulate concentration for continuous (1 year) exposure.

Appendix E of Standard 62-1981 also shows how filters can greatly reduce the amount of outdoor air needed. The total circulation rate must be increased, however. This may present a problem in variable ventilation systems. Recent work by Repace[19] has confirmed the basic recommendation of 20 cfm (10 L/s) of outdoor air per person (in an office where smoking is permitted) as a practical ventilation level. Repace calculated the lifetime lung cancer risk as a function of the cigarette smoke concentration associated with various dilution rates. He found that at a minimum ventilation rate of 5 cfm (2 1/2 L/s) there would be ten extra cases of lung cancer per 1000 people over a lifetime. Increasing the outdoor air flow rate to 20 cfm (10 L/s) per occupant reduces the risk to about two extra lung cancer cases per 1000 people. Beyond this point the curve is quite flat; over 50 cfm (25 L/s) of outdoor air is needed to reduce the risk to one lung cancer case per 1000 people.

Odor research of Leaderer, Cain[20] and Fanger, Berg-Munch[21] has shown that an outdoor air supply rate of 20 cfm (10 L/s) per person to a space where smoking is permitted will satisfy only about 50% of the visitors to the space. Acceptance increases after a minute or two due to saturation of the olfactory senses. Outdoor air flow rates of about 40 cfm (20 L/s) are needed to satisfy 80% of the visitors.

Although more than 2000 different species have been identified in tobacco smoke, particulates are the dominant contaminant. These can be effectively removed with electrostatic filters or high quality media filters. It can be shown (see Ref. 6, Appendix E) that the outdoor air flow rate can be reduced from 35 cfm (17 1/2 L/s) per person to 7 cfm (3 1/2 L/s) in a bar if a 90% efficient filter is used and a circulation rate of 31 cfm (16.5 L/s) per person is achieved. Thus efficient filters can greatly reduce the amount of outdoor air required.

A second method for reducing the amount of outdoor air needed to dilute tobacco smoke is to segregate smokers from non-smokers. ASHRAE Standard 62-1981 permits the outdoor air flow rate to be calculated separately for each group when they are segregated, and air from the smoking section does not flow into the non-smoking section. Location of smokers close to the exhaust inlet permits the supply air to sweep the smoke into the exhaust, then limitations imposed by diffusion and mixing no longer apply.

Based upon the latest findings on particulate levels in representative building, and measurements of ventilation adequancy, the 62-1981R Subcommittee on Building Performance will pursue these points and make certain that the most relevant performance criteria are emphasized in the Revised Standard. At present the subcommittee is rewriting the material in Appendix E - Rationale for Use of Cleaned, Recirculated Air. This Appendix deals with the problem of removing particulate matter, and depending upon the removal efficiency, states how much the flow of outside air can be reduced. Total suspended particulate concentrations of the outside air are part of the ventilation rate determination. The question of ventilation efficiency describing how effectively the ventilation air is reaching the occupants must be either incorporated into the calculation procedure at this point or a separate appendix must be addressed to the influence of ventilation efficiency. In the subcommittee discussions, suitable minimum ventilation rates were suggested as 20 cfm (10 L/s) based upon the mixing efficiency information resulting from particulate measurements. This matter is of highest priority in setting the Revised Standard.

5. BUILDING ENVIRONMENT AND EMISSIONS

How the building maintains temperature, relative humidity and air flow can directly influence the building indoor air quality. One example is formaldehyde outgassing, which is affected by both temperature and humidity. Formaldehyde compounds are very common in buildings and thus from a building performance standpoint the way in which we maintain the interior building environment can directly influence source strengths and thus dictate the required ventilation. This example only points out that we must be concerned with building materials and their associated ventilation requirements as well as the needs of the occupants.

In Standard 62-1981, under the heading of Variable Occupancy (Section 6.1.5 and associated Fig. 2), the Standard deals with transient or variable occupancy and allows the building operator to adjust dampers or even turn off the ventilation system during specified periods. These system adjustments may lag or lead occupancy depending upon whether occupant ventilation needs or pollutants associated with building materials are the principal concern. The 62-1981R Subcommittee on Building Performance is looking more deeply into these matters to determine in the light of more recent information whether or not this portion of the Standard should be altered.

6. SUMMARY

The discussions in this paper have traced the history of ASHRAE Standard 62, and point out the important current questions that are being addressed during the present revision. Building performance aspects of the standard have been emphasized in this paper with principal concerns for ventilation efficiency, handling special problems such as particulates especially those associated with smoking, and the variability of residential ventilation which has been highlighted by modern instrumentation.

This is a consensus standard and the various subcommittees and the committee as a whole will be seeking to provide the most realistic and up-to-date ventilation standard when the revision process is completed. What should be clear from this paper is that the standard revision is an ungoing process in the light of new information such as that supplied in abundance from the Air Infiltration Centre's prime function of promoting information exchange.

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