A Ventilation Standard Debate:

Should Pollutant Source Strengths Be Added When Calculating Ventilation Rates?

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A discussion of whether the Additivity Principle should be substituted for the currently used Maximum Source Principle as the basis for future ventilation standards

Fundamental to the design of residential and commercial buildings is the calculation of appropriate levels of ventilation. Since 1989, ANSI/ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality*,[1] has provided guidelines for design engineers in specifying adequate ventilation. Standard 62-1989 and other international ventilation standards incorporate the Maximum Source Principle, which states that diluting the strongest pollution source in a room will naturally provide enough ventilation to dilute other pollution sources present as well. However, a recently proposed change[2] to Standard 62-1989 would forgo the Maximum Source Principle in favor of the Additivity Principle, which states that each pollution source in a room requires its own dilution ventilation, and thus the strengths of all pollution sources, no matter how different, should be added together and ventilation provided for this total source. (Due to changes in procedures in implementing multidisciplinary standards, ASHRAE has withdrawn the proposed changes and placed Standard 62-1989 on continuous maintenance.)

The use of the Additivity Principle, which we will show is unsupported, represents a radical departure from the established utility of the Maximum Source Principle, which we believe is supportable, as shown in the accompanying sidebar. This would result in standards that require dramatically increased amounts of ventilation relative to current standards. However, the Additivity Principle has been the subject of much debate within the engineering community. In the remainder of this article we examine the background of evidence for and problems with the use of the Additivity Principle in setting ventilation standards.

Olfs and decipols

In the late 1980s, the Danish researcher Ole Fanger observed that in some buildings that met existing ventilation rate standards, not all of the occupants were satisfied with indoor air quality. Since ventilation rates are based on standards that assume that building occupants and their activities are the primary source of indoor pollution, Fanger has reasoned that these buildings may therefore contain additional pollution sources in the form of building materials, carpets, office furniture, and so forth. If so, the provision of appropriate ventilation levels would require some account of these additional pollutant sources. Note that these considerations do not include toxic air pollutants representing immediate threats to human health, such as carbon monoxide (which is odorless) and ammonia (which has a strong odor).

In an attempt to address this challenge, Fanger struck upon the idea of quantifying the strength of pollutant sources on a common scale. Fanger chose human beings as the referent pollutant source and coined the term *olf* as the unit of pollutant source strength. One olf is defined as the emission rate of air pollutants (bioeffluents) from a standard person. Thus one person has a source strength of 1 olf, two persons have a source strength 2 olfs, and so on. The olf value of any other (non-human) pollution source is defined as the number of standard persons required to cause the same level of dissatisfaction as the original source.

Furthermore, Fanger postu-

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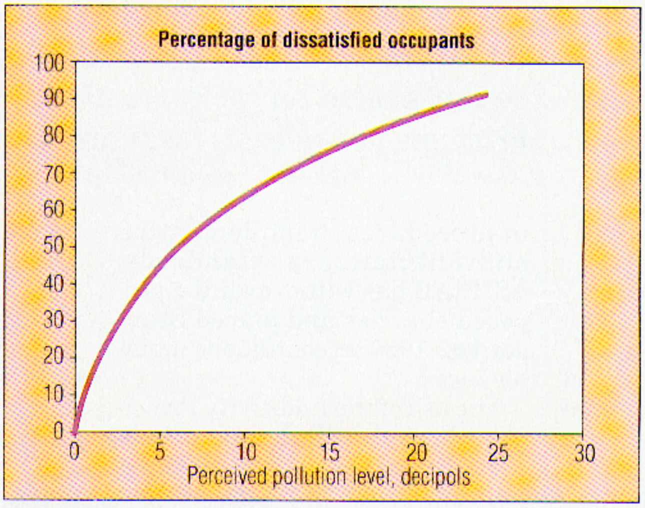
[1] *Superscript numerals indicate references listed at end of article.*

lated that if a room contained several pollutant sources, the olf values of the individual sources could be added to obtain an overall olf value or measure of the total pollution strength in the room. Ventilation rates for the room would then be based on this total pollutant source strength.

The application of the Additivity Principle to compute design ventilation rates would require an engineer to total up the olf values for all of the component pollutant sources and then multiply the ventilation rate required for one olf by the total number of olfs in the room.



1 Percentage of occupants dissatisfied with air quality versus perceived pollution level.

Notice the snag in the description of the determination of *non-human* pollutant source strengths. A pollutant has an odor source strength of 5 olfs if it causes the same level of dissatisfaction as five persons, but what level of dissatisfaction is caused by five persons? To answer this question, Fanger introduced the concept of the decipol, defined as the perceived pollution caused by 1 olf, ventilated by 10 liters per second (l/s) of unpolluted air. In other words, perceived pollution is related to pollutant source strength and ventilation rates by the following equation:

$$D = S/V \qquad (1)$$

where

D = perceived pollution, decipols
S = pollutant source strength, olfs
V = ventilation rate, 10 l/s

Thus a perceived pollution level of 1 decipol may be achieved by 1 olf ventilated by 10 l/s, two olfs ventilated by 20 l/s, and so on.

The final key to Fanger's approach is the relationship between perceived pollution levels and the percentage of persons dissatisfied with the air quality. Based on a set of experiments in which persons were asked to rate air quality under various conditions of occupancy and ventilation in two auditoriums in Denmark, Fanger derived the empirical relationship shown in Fig. 1, which suggests that as perceived pollution levels increase, the percentage of persons who rate the air quality as unacceptable also rises in a nonlinear relationship.

Equation 1 and Fig. 1 are used together in two ways. First, to determine the olf value of a non-human pollution source, one might conduct an experiment in which persons were asked to rate air sampled from a room containing the pollutant source under a known ventilation rate. The percentage of persons who rate the air quality as unacceptable is translated into a decipol level using Fig. 1. This decipol level and the known ventilation rate are then used in Equation 1 to solve for the pollutant source strength. This gives a procedure for finding olf values for new pollutant sources.

Second, Equation 1 and Fig. 1 may be used to determine appropriate design ventilation rates. Suppose it is desired to achieve air quality that is unacceptable to no more than 20 percent of the building occupants. Using Fig. 1, one can determine that 20 percent of occupants will be dissatisfied at about 1.41 decipols of perceived pollution. Now the design engineer may add up the olf values of all the pollutant sources in the room and use this total olf value together with the decipol level of 1.41 to solve for the desired ventilation rate in Equation 1.

Under Fanger's hypothesis that pollutant source strengths may be added, it is an immediate consequence of Equation 1 that the ventilation rate required to dilute a mixture of pollutants is the sum of the ventilation rates required to dilute each individual pollutant in the mixture—*i.e.*, the Additivity Principle.

Source strength additivity

Despite its apparent simplicity, Fanger's hypotheses have remained the source of much controversy in the scientific literature.[3-6] In fact, in a recent European prestandard describing design criteria for the ventilation of buildings, the European Committee for Standardization (CEN) cautioned that "research involving a much wider range of pollution sources needs to be performed to check whether addition can generally be adopted."[7] In this section, we examine in more detail several problems with the olf/decipol concept in general and specifically with the hypothesis of source strength additivity.

At the foundation of the olf/decipol theory is the axiom that the polluting power of any Contaminant X may be expressed in terms of an equivalent number of "standard persons," or olfs. If it is determined through some means that Contaminant X is equivalent to, for example, 5 olfs, then in determining ventilation rates for a space that contains Contaminant X, one could instead assume that the space contains an additional five persons.

Surprisingly, the validity of the theory's fundamental axiom (that every contaminant is equivalent to bioeffluent pollution from some

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number of persons) has never been explicitly tested. Furthermore, a reanalysis of data published by Fanger himself suggests that the axiom is false. Knudsen, Clausen, and Fanger[8] published results of an experiment in which a trained panel of judges directly evaluated the decipol levels of air polluted by linoleum, carpet, or paint samples under various ventilation rates. Although the experimental ventilation rates were not explicitly presented in that paper, they may be recovered from the published data. This allows one to compute, using Equation 1, estimates of the source strength in olfs of each material (linoleum, carpet, or paint) at each of the different experimental ventilation rates. If each material is equivalent to some number of persons, these source strength estimates will be constant across all ventilation rates since, by definition, the olf value—a property of the polluting material—is independent of ventilation rate. Table 1 shows the results of these calculations.

It is obvious that estimated olf values for each material decrease with decreasing ventilation rates rather than remaining constant. For example, for carpet, the computed source strength varies from a high of 10.0 to a low of 3.2 olfs. If carpet truly had a constant source strength, by Equation 1, the decipol level should be inversely proportional to the ventilation rate (for example, the decipol level when the ventilation rate is, say, 3 l/s should be twice as high as the decipol level when the ventilation rate is 6 l/s). These results clearly demonstrate that none of the tested materials elicit the same response from the judging panel as would be predicted by the olf/decipol theory if a fixed number of persons had been the pollutant source. In other words, there are no olf equivalents for any of these common building materials.

Apart from the question of whether or not olf equivalents exist for all pollutants and how such olf values may be measured, there are several problems in assuming that olfs from different sources may simply be added. Five published studies[9-13] are generally cited as supporting Fanger's hypothesis of pollutant source strength additivity.

The Bluyssen and Fanger study[9] suggests that for an assortment of common office contaminants, measured source strength generally increases with source strength predicted by assuming additivity. However, in their published report, the sole support for additivity is a graph that plots measured source strength estimates against predicted source strength estimates. Unfortunately, the paper gives no measure of goodness of fit of the relationship and no indication of the level of statistical significance. It is impossible to tell just by looking at the published figure whether the data really do support the hypothesis of additivity and exclude other possible relationships.

Furthermore, the range of source strengths considered in the Bluyssen and Fanger study is quite small, from about 0.14 to 1.4 olfs. Fig. 1 is based on experimental situations in which the minimum source strength tested was 41 olfs. This necessitates a dramatic and unsupported extrapolation of Fanger's empirical decipol/percent dissatisfied relationship to data more than an order of magnitude below the empirical data on which it was based.

The evidence for source strength additivity is even weaker in the Lauridsen study.[10] This study, like Bluyssen and Fanger, graphically presents results of measured versus predicted source strengths, with no formal measure of goodness of fit or of statistical significance. The Lauridsen data appear just as consistent with many other hypotheses (including the hypothesis that measured air pollution is independent of predicted air pollution) as with the hypothesis of additivity.

The Cometto-Muniz and Cain (CMC) study[11] is cited as explicit evidence to support the claim that sensory contaminants can have an additive effect on irritation. However, the CMC study investigates the sensory detection threshold levels of various chemicals and mixtures—not the levels at which they cause discomfort or irritation. Claims that results of the CMC study support the hypothesis of source strength additivity are simply incorrect because the CMC study addresses an entirely different issue.

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TABLE 1—Perceived air quality and estimated pollutant source strength of materials at various ventilation rates. (Data published in Reference 8.)

Carpet			Paint			Linoleum		
Air , quality (D), decipols	Ventilation rate (V), 10 l/s	Source strength ($S = VD$), olfs	Air , quality (D), decipols	Ventilation rate (V), 10 l/s	Source strength ($S = VD$), olfs	Air , quality (D), decipols	Ventilation rate (V), 10 l/s	Source strength ($S = VD$), olfs
4	2.5	10.0	4	2.5	11.3	5	2.5	12.5
4	1.4	5.6	5	1.5	7.3	6	1.4	8.3
13	0.6	8.1	10	0.6	6.1	9	0.6	5.6
17	0.3	5.3	14	0.3	4.3	11	0.3	3.4
18	0.2	3.2	17	0.2	2.8	12	0.2	2.0

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Moreover, none of the studies attempts to account for the variability resulting from the fact that the unknown parameter *percent dissatisfied* is being estimated from a sample of observations. The available data are consistent with many other possible relationships apart from additivity.

A recently published paper presents results that explicitly do not support the concept of source strength additivity. Bluyssen and Cornelissen[14] describe an experiment in which panels of subjects were used to assess quality of air polluted by an assortment of office furnishings, both singly and in various combinations. The authors found that estimated olf values for combinations of materials were consistently lower than the sum of the olf values for each material in the combination. In fact, in this study, the olf values of a mixture of pollutants was predicted much better by the maximum olf value of any contaminant in the mixture than by their sum.

Direct use of the relationship between percentage of dissatisfied occupants and decipol level (Fig. 1) is made in three of the empirical studies[10,12,13] purporting to demonstrate evidence for source strength additivity. However, this relationship is the result of a regression line fitted to data from a single study.[15] Presenting only the fitted regression equation with no indication of the variability of the underlying data, of the goodness of fit of the regression line, or of the performance of alternative parametric models has been termed "misleading" by the Building Research Establishment[3] and severely limits the usefulness of the equation since it is impossible to judge, formally or informally, how well the data are represented by the summary line.

It is important to note that Fig. 1 is applicable only to (unadapted) Danish judges rating air polluted by Danish people and cannot be assumed to apply to other cultures as well. For example, Yugoslavian judges rating air polluted by Yugoslavian people showed a markedly different response.[16] The extent to which Fig. 1 simply reflects cultural biases is not known. Furthermore, the experimental subjects used in the evidence for source strength additivity are not representative of all building occupants but form a very narrow and biased selection of subjects.

All of the experimental studies use air quality ratings made by subjects who were not adapted for odor. There is simply no data regarding the hypothesis of source strength additivity among adapted building occupants. Furthermore, since there is no correlation between perceptions of air quality measured by unadapted persons and perceptions of the same air measured by adapted persons,[17] there is no reason to suspect that even if additivity holds for unadapted persons that it would hold for adapted persons as well.

Similarly, subjects in all of the experimental studies were drawn from a very select (and biased) group of building occupants—those aged about 18 to 30. Persons in this age group would be younger than a large proportion of occupants of many buildings. If odor perception or sensitivity to irritants changes with age, data from the younger age persons may not be representative of the perceptions of all occupants. There is simply no data regarding the hypothesis of source strength additivity among persons older (or younger) than 18 to 30.

Conclusions

The hypothesis of additivity of contaminant source strengths is clearly an over-

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Mathematical Support for the Maximum Source Principle

Assume a single compartment model that contains 6000 distinct pollution sources, with the strength of the i-th pollutant source being denoted by P_i (mg of pollutant per sec). If the ventilation rate in the compartment is R cu m per sec of clean air, the i-th pollutant source will achieve an equilibrium concentration of:

$$C_i^{EQ} = \frac{P_i}{R}$$

Suppose C_i^{TH} denotes an acceptable threshold concentration for pollutant i. Let

$$R_i = \frac{P_i}{C_i^{TH}}$$

R_i (in cu m per sec) denotes the ventilation rate required to dilute the i-th pollutant to an equilibrium concentration of C_i^{TH}; or in other words, if the ventilation rate in the compartment is R_i, then $C_i^{EQ} = C_i^{TH}$. Now let R be the maximum value of the 6000 individual R_is. Then under R cu m per sec of ventilation, for the j-th pollutant,

$$C_j^{EQ} = \frac{P_j}{R} \le \frac{P_j}{R_j} = \frac{P_j}{P_j / C_j^{TH}} = C_j^{TH}$$

In other words, if the ventilation rate in the compartment is the maximum of the ventilation rates required to dilute each of the 6000 individual pollutant sources, then *all* of the pollutant sources will be diluted to an acceptable (subthreshold) equilibrium concentration. This is precisely the prediction of the Maximum Source Principle. It is interesting to note that if the individual pollutant ventilation rates (R_is) are approximately constant, the Additivity Principle, in recommending an overall ventilation rate of

$$\sum_{i=1}^{6000} R_i$$

would prescribe about 6000 times the ventilation required to ensure that each pollutant is diluted to below its threshold concentration!

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simplification of the true state of nature and one whose status must be classified as speculative at best. As such, the Additivity Principle ought not to be entrenched as the basis for policy in a major international ventilation standard. Such was also the opinion of engineering governing bodies responsible for the CEN Ventilation Pre-Standard[7] and proposed changes to the ASHRAE Ventilation Standard 62-1989,[2] both of which are based on additivity. In October 1997, the CEN Pre-Standard was rejected; in June 1997, the proposed revisions to ASHRAE Standard 62-1989 were withdrawn, and the existing Standard 62-1989 put under continuous maintenance.

A review of recent research has shown that ventilation rates required by ASHRAE Standard 62-1989, based on the Maximum Source Principle, appear to provide acceptable indoor air quality for commercial and residential buildings.[18] Conversely, the Additivity Principle represents an unproven radical departure from the Maximum Source Principle and would result in unnecessary dramatic increases in required ventilation rates. We believe further revisions to the ASHRAE ventilation standard ought to be consistent with the current principle of providing ventilation sufficient to dilute the strongest pollutant source. **HPAC**

Acknowledgement

The authors wish to thank two anonymous reviewers, whose comments improved the quality of this article.

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tem architecture and interoperability by utilizing Echelon Corp.'s local operating network and Neuron® chip technology.

The building, with its distinctive pyramidal roof, is one of the great towers that define the lower Manhattan skyline. Located in the heart of the financial district, the building was completed in 1912 for Bankers Trust Co. Symbolizing the importance of the company, the 37-story, 539 ft high building was the tallest bank building in the world when it was completed.

A five-year restoration and modernization program, which began in 1992, was completed in 1996. It was undertaken to provide tenants with state-of-the-art building systems and facilities while accurately restoring every detail of this skyline landmark.

The restoration and modernization program began with the installation of the following components: the direct digital control system, an integration platform, a new supplemental chilled water plant, complete renovation of the elevator cabs, upgrade and modernization of all multi-tenant corridors and bathrooms, replacement of the building's 1800 windows with new operable windows, and a new lobby and main entrance, which also brought the building into compliance with ADA provisions.

The building's management staff chose flexible system controllers to control 22 primary air handlers that had been operated with pneumatic local loop controls and the start/stop function on the existing system. This retrofit eliminated the pneumatic controls and provided integration with the remaining points, CSI controllers, and the new DDC system to control the building's primary air handlers.

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