Air Infiltration and Indoor Air Quality—A Critical Review

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ABSTRACT

In one- to six-unit residential dwellings, natural ventilation and uncontrolled air infiltration are expected to be the predominant mechanisms for comfort and indoor air quality control in the foreseeable future. Air infiltration is also expected to be responsible for a progressively larger share of the total heat losses in future new residential construction.

Simple design-day or time-averaged air infiltration knowledge is quite sufficient for energy conservation considerations and various tracer gas or passive techniques can be used to acquire it. On the contrary, such techniques can be cumbersome, time consuming and prohibitively expensive, when used alone to characterize the influence of air infiltration on comfort and, especially, on indoor air quality.

Various models have been developed to facilitate the estimation of detailed and internally consistent air infiltration data. These models have, generally, been based on first principles and on actual data developed under laboratory or field conditions. The actual data used for model development and verification have either been obtained by the fan-pressurization method or by tracer gas techniques. The predictive ability of the existing models has also been tested by third-party investigators in this country and abroad.

This presentation is intended to cover comprehensively the factors affecting air infiltration and indoor air quality, the utility of existing air infiltration models, and the ideal and practical requirements of a relevant indoor air quality model that could be used as a tool for management of atmosphere in tightly enclosed residential spaces.

INTRODUCTION

The single most effective way to conserve energy in residential buildings is to reduce heating and air conditioning demands. This is most easily accomplished by reducing air infiltration (natural ventilation) of buildings, especially during periods when heating or air conditioning equipment is being operated. A growing trend in new construction substantially reduces infiltration, with such reductions often made from typical levels of about 1.0 air change per hour (acph) to as little as 0.2 acph.

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Most recently, concern has been focused on the impact of "energy conservation-through-infiltration reduction" (in new building construction) on indoor air quality (IAQ), and particularly on the role of NO_x (NO and NO_2) and CO (from unvented fossil-fueled appliances), formaldehyde (from wall insulation), freons (from aerosol sprays), and radon (from concrete, stone, ground water). As a result, the attention of researchers and governmental bodies began to shift to aspects of indoor air quality, and its relationship to indoor air pollution epidemiology, to potential emission control strategies for indoor contaminants, and to the control of indoor humidity.

Most of these efforts have focused exclusively on simple air dilution for indoor contaminant and moisture control, in tight residential atmospheres, by employing forced ventilation (with heat recovery) schemes, and equipment usually known as Air-To-Air Heat Exchangers (ATAHE). Already, serious drawbacks (payback, ventilation efficiency, etc.) and other potential shortcomings (core freeze-up, heat exchanger surface fouling, etc.) have been identified, regarding presently available equipment.

In addition to "source" emission control of unvented appliances (low NO_x burners), "source" exclusion for formaldehyde and asbestos (surface masking or covering with sealants) and ATHAE equipment, there are at least two other strategies for reducing contaminant concentration levels within residences, which may be proven potentially most cost effective. These are combinations of "direct" exhaust spot ventilators with air cleaning (active agent) filters or cartridges, located near the source and activated by it, and "integrated" controls which can respond to the dwelling atmosphere needs, as opposed to a specific emission source or air contaminant.

Proper implimentation of the former, and particularly of the last two approaches, require comprehensive understanding of the factors affecting air infiltration and indoor air quality, of the utility of available means to characterize both, and of the practical requirements of an indoor air quality model, to be used as a tool for the management of atmosphere in tightly enclosed residential spaces.

This paper presents a summary critical review of the state-of-knowledge of air infiltration measurement and modeling for indoor environment control, with particular emphasis on emissions, contaminants, and sources related to fossil-fueled residential equipment.

DISCUSSION

My purpose of performing a summary Critical Review of the relationship between residential air infiltration and indoor air quality stems from the need, I perceive, for a consensus approach to be used in the assessment and control of the quality of the indoor environment. Very significant and extended efforts have been undertaken, during the last decade, in the understanding, measurement and modeling of air infiltration for energy conservation purposes. On the other hand, only recently has there been an interest in the comprehensive characterization of indoor air quality, and its ultimate control, under "real world" conditions. Earlier efforts have been limited to laboratory simulation studies, "controlled home" case studies of limited applicability, and field epidemiologic surveys in which indoor environment characterization was only crude, insufficient or irrelevant to the understanding of the factors affecting it.

One part of the problem arises from general lack of comprehensive understanding, in my view, of the role played by air infiltration; another part, from the attempt to gain such understanding, on a case-by-case basis, through limited (due to cost) air infiltration measurements. Even worse, such limited understanding is at the base of currently available IAQ control approaches and equipment of limited or questionable value to the consumer, and of air infiltration control techniques which, by aggravating the IAQ problem, tend to nesessitate remedial actions that can be conventiently provided by less than adequate equipment and methods.

My attempt to provide the need for a dialog, among those active in a field which is at once very complex and challenging, has necessitated that I focus on "Critical" rather than on "Review". There is recent precedent for this approach, and I do not claim novelty, but I have also endeavored to provide sufficient reference material for the major subjects covered, for anyone to pursue a "review" option of these subjects on his/her own.

1. Residential Air Infiltration

Historical trends in new residential dwelling construction have resulted in gradual decreases in air leakage rates (or air infiltration) of the building envelop. For the forseable future, this trend is expected to continue so that air infiltration (natural ventilation) rather than forced ventilation will be the predominant mechanism for IAQ control due to the low turnover rate of the building stock.[1]

Enchanced public awareness of the need for energy conservation has also resulted in similar decreases in existing dwellings and this trend should continue in the future as a result of —

- Gradual replacement of chimney-vented appliances (e.g. gas furnaces) with through-the-wall-vented higher efficiency models.[2]
- Projected proliferation of unventd space heaters,[3] either as the only source or for supplemental space heating, due to the gradual reduction of the building's heat loss rate.

Relatively tight homes are not a novelty of the last decade but have been around through the 1950's and 60's. With the exclusion of inner-city dwellings and rowhouse structures, city perimeter and suburban single family dwellings in the East and West North Central states, that have been equipped with central forced air heating and air conditioning, are examples of such homes. In these homes, weatherstripping, caulking and year-round use of storm windows and doors have been standard practice, with the number of such homes increased as central air conditioning saturation increased in homes built after World War II.

Table 1 summarizes the characteristics of 23 test homes in the Chicago Metropolitan area, tested by IGT in 1976-77, varying in age from 2 to 130 years. Table 2 is a summary of weather and other data, and corresponding air infiltration data while the furnace is operating, for 12 of these test homes. Table 2 shows that the measured air infiltration rates varied between 0.16 and 0.67 air changes per hour (acph), inspite of the large variability in charcteristics and weather between homes.[4] These measurements were carried out using a tracer technique, with ethane (C_2H_6) gas used as the tracer.

Table 1

23 FIELD TEST HOMES —CHARACTERISTICS—

AGE:	2-130 yr
SIZE:	800-3850 ft^2
CONSTRUCTION:	BRICK, FRAME, COMBINATIONS
HOUSE HEIGHT:	1-, 2-STORY, SPLIT LEVEL
FURNACE INPUT:	80,000-160,000 Btu/h
CHIMNEY HEIGHT:	12-34 ft
VENT DIAMETER:	4-6 in.

Table 2.

AIR INFILTRATION DATA FROM CHICAGO FIELD HOMES

OCCUPANT NAME	FURNACE INPUT, CFM	INDOOR TEMP, °F	OUTDOOR TEMP, °F	WINDSPEED & DIRECTION, MPH	AIR INFILTRATION CHIMNEY CLOSED SCFM	AIR INFILTRATION BURNER ON SCFM	AIR INFILTRATION BURNER ON ACPH
INGEMANSON	93	69	60	S 14	98	111	0.36
SCHALK	126	69	61	S 18	143	145	0.67
VAVRIK	122	68	58	W 8	79	97	0.32
MURA	122	69	67	S 15	84	107	0.55
PATTERSON	110	72	59	SW 23	96	119	0.41
WHITE	117	74	50	S 10	170	211	0.46
WEBER	90	71	40	SW 21	59	51	0.16
SODERQUIST	128	76	67	S 14	95	179	0.60
SIMPSON	108	72	62	S 7	128	136	0.43
STAATS	115	72	61	S 16	187	199	0.50
MACRISS	72	65	35	SW 19	78	107	0.45
HIRSH	107	72	35	SW 16	53	81	0.38

In the ensuing years, air infiltration measurement techniques and instrumentation have improved substantially in the U.S. and abroad, and a recent publication[5] presents a comprehensive review of most alternative tracer gas techniques, pressurization methods, and other miscellaneous approaches, and of instrumentation. These improved methodologies and instrumentation, coupled with weather measuring equipment, have broadened the scope, detail and accuracy of air infiltration and air leakage measurements possible. On the other hand, use of these techniques for extensive and comprehensive measurements can be time consuming and, therefore, prohibitively expensive. In order to reduce cost or increase cost effectiveness, additonal passive techniques[6] have been recently proposed.

Due to high measurement costs, the tendency has been to limit air infiltration characterization to the "whole house". As shown in Table 3, knowledge of whole house air infiltration is useful for energy consumption and conservation considerations.[7] On the other hand, comfort and indoor air quality are affected or controlled by local sources (window leakage of cold air-draft, emission source - kitchen range) and, therefore, whole house air infiltration is of little value in these cases.

Table 3.

HEATING SEASON AVERAGE INFILTRATION AND INDUCED HEATING LOAD

	WASHINGTON, D.C.			MADISON, WISCONSIN		
	HEATING SEASON AVG. INFIL'N RATE		AIR INFIL'N HEATING LOAD,	HEATING SEASON AVG. INFIL'N RATE		AIR INFIL'N HEATING LOAD,
HOUSE	cfm	ACPH	therms	cfm	ACPH	therms
IGT-CC	165	0.72	267	187	0.81	445
IGT-CW	124	0.56	201	140	0.63	334
OSU-KTSC	113	0.39	180	131	0.45	304
OSU-SRSG	134	0.34	212	151	0.38	351
TAMURA	39	0.21	62	44	0.23	102

Washington: Heating Season, 4774 h, 40.7 °F, 8.4 mph
Madison: Heating Season, 5487 h, 33.0 °F, 10.1 mph

Isolated measurements of air infiltration, or single number characterization of the air exchange rate of a single family dwelling, are of very limited value to energy conservation, comfort or indoor equality. Table 4 illustrates the effect of a chimney and furnace operation on the seasonal range, seasonal mean, minimum and maximum air infiltration rates, measured in the 23 IGT test homes mentioned earlier.[4] Table 5 summarizes monthly average and monthly and yearly maximum and minimum air infiltration rates, in another IGT test home.[7] Finally, Table 6 illustrates the effect of weather and of a solarium, in a passive solar home, on measured air infiltration rates.[7]

Table 4.

23 FIELD TEST HOMES
-AIR INFILTRATION RATES-

	ACPH
WITH FURNACE ON	
SEASONAL RANGE	0.30-1.7
SEASONAL MEAN	0.67
MINIMUM	0.25
MAXIMUM	2.65
WITH CHIMNEY CLOSED	
SEASONAL RANGE	0.25-1.25
SEASONAL MEAN	0.55
MINIMUM	0.12
MAXIMUM	2.41

Table 5.

MONTHLY AVERAGE, MAXIMUM AND MINIMUM, AIR INFILTRATION RATES IGT-CW HOME/MADISON

MONTH	HOURS	AVG. T, °F	AVG. WS, mph	AVG. ACPH	MAX. ACPH	MIN. ACPH
JANUARY	744	17.0	10.1	0.54	0.79	0.36
FEBRUARY	672	21.3	11.3	0.54	0.87	0.43
MARCH	744	28.7	12.4	0.52	0.86	0.31
APRIL	720	47.7	12.5	0.44	0.97	0.12
MAY	744	58.4	10.7	0.37	1.03	0.06
JUNE	720	67.4	10.8	0.32	0.79	0.06
JULY	744	71.9	8.7	0.25	0.66	0.03
AUGUST	744	68.1	7.0	0.24	0.71	0.01
SEPTEMBER	720	62.3	9.6	0.31	0.85	0.07
OCTOBER	744	51.0	8.5	0.35	0.68	0.09
NOVEMBER	720	36.3	10.7	0.47	0.86	0.27
DECEMBER	744	25.4	8.5	0.50	0.80	0.37
YEAR	8760	46.4	10.1	0.40	1.03	0.01

Table 6.

MEASURED AIR INFILTRATION RATES IN THE NORTHERN HOME

TEST NO.	WEATHER CONDITIONS DBT/WS/WD	INDOOR TEMP, °F	MEASURED INFILTRATION RATES	
			SCFM	ACPH
SOLARIUM CLOSED				
1-1	34/10/SW	74	204	0.44
1-6	40/15/SW	70	235	0.51
1-8	47/21/S	73	373	0.81
2-1	0/13/W	62	315	0.70
2-4	7/15/W	67	306	0.66
3-1	31/ 8/W	65	178	0.38
SOLARIUM OPEN				
1-7	44/13/S	72	426	0.81
2-3	6/15/W	65	382	0.73
3-2	38/ 9/NW	67	160	0.31

The previous discussion makes quite clear that understanding the impact of air infiltration on indoor air quality requires an enormous amount of air infiltration data from a home. Such extensive and comprehensive measurements of air infiltration rates can be so time consuming as to be prohibitively expensive. While the passive measurement approach may reduce such costs, the need for an alternative approach, i.e. a comprehensive and accurate but practical model, has been indicated as far back as 1957.[8]

It is necessary at this point, that a brief account of sources, emissions and indoor air contaminant concentrations be presented, before the potential utility of these models to the understanding and control of indoor air quality can be properly assessed.

2. Sources, Emissions, and Indoor Air Quality

The effects of air pollution on human health and welfare have been a major national concern. The main emphasis to date has been directed to outdoor sources and outdoor contaminant concentrations. As a result, Source Emission Standards and National Ambient (Outdoor) Air Quality Standards have been in force since the early 1970's covering several air contaminants such as carbon monoxide (CO), nitrogen dioxide (NO_2), particulate, photochemical oxidants (such as ozone), and hydrocarbons.

As implementation of the above standards followed its natural course, attention shifted to the indoor environment. As early as 1972 and 1974, ASHRAE co-sponsored the first two conferences in the U.S. on Indoor Air Quality, organized and administered also by Engineering Foundation Conferences.[9,10] These have been followed, in most recent years, by other more comprehensive, national[11] and international[12] workshops, symposia and conferences, which signify enhanced current interest.

A recent summary assessment[3] of the factors affecting indoor concentrations of air contaminants from the operation of fossil-fueled appliances is shown in Figure 1. This figure illustrates the many and complex issues needing to be addressed towards the understanding and control of indoor air quality, under realistic conditions. One such example may be "sources", such as space heating appliances and equipment to be found in the home. These can be represented by:

- Various types of kerosene heaters.
- Various types of unvented gas space heaters.
- Wood burning equipment, such as open fireplaces and wood stoves.

FACTORS AFFECTING INDOOR CONCENTRATIONS FROM COMBUSTION APPLIANCES

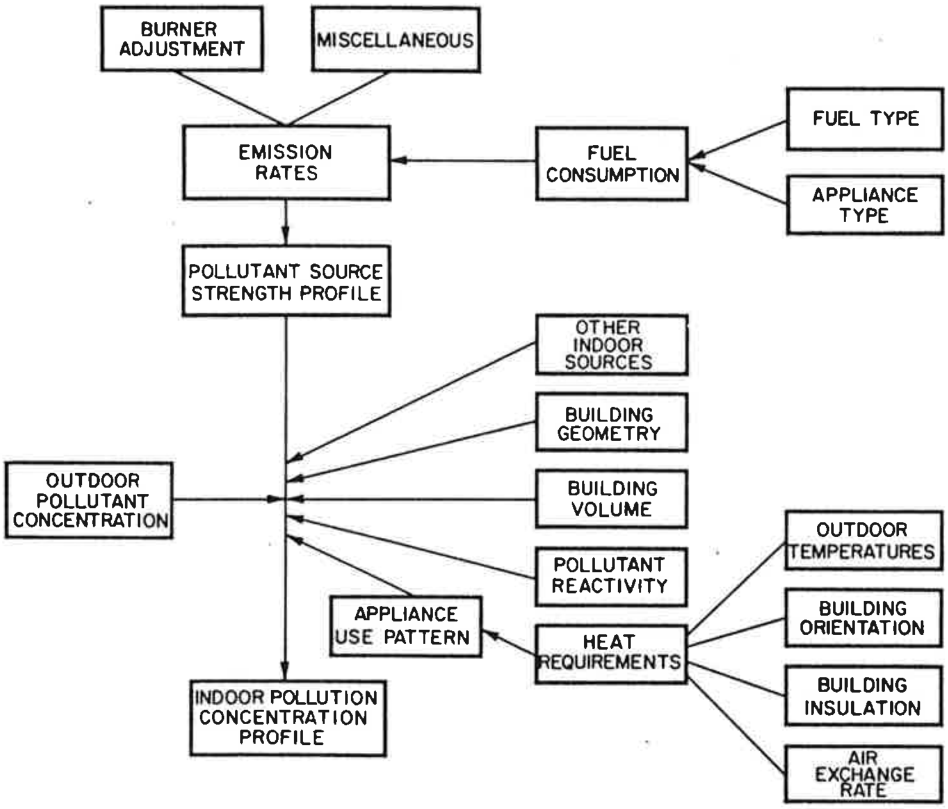

Figure 1.

Table 7 summarizes emission levels of contaminants produced in such equipment, per unit energy input, as a function of the type of fuel burned.[13] Table 7 illustrates how little leakage into the indoor environment (from otherwise vented fireplaces and stoves) might it take to swamp the effect of emissions from any other unvented appliance in the home.

Table 7.

COMPARISON OF EMISSIONS FROM SELECTED RESIDENTIAL SPACE HEATING SYSTEMS

SOURCE	EMISSIONS, $lb/10^6$ Btu: CO	NO_x AS NO_2	SO_x AS SO_2	TSP	$\mu G/10^6$ Btu B(a)P
GAS	0.02	0.08	0.0006	0.02	80
OIL	0.04	0.09	0.3-7	0.07	900
COAL	3.50	0.10	0.5-7	0.60	2,500,000
WOOD - F	3.00	0.25	--	1.30	45,000
WOOD - S	22.00	0.07	0.03	1.20	135,000

The local, time-averaged concentration of internally generated contaminants is not only a function of the source strength but of the source's schedule of operation and indoor-outdoor relationships. Table 8 compares ranges of steady-state (peak) contaminant concentrations and 1-hour average concentrations from actual homes using kerosene heaters. The peak levels were maintained over long periods (4-6 hours) in a study of 13 field homes,[14] while the 1-hour averages were obtained during the study of a "controlled" test home, using similar heaters.[3]

Table 8.

POLLUTANT CONCENTRATIONS FROM FIELD HOMES WITH KEROSENE HEATERS

	YALE 13 HOUSES (Peak Levels)	WESTON 1 HOUSE (Maximum one hour average)
BLUE FLAME HEATERS		
NO_2 PPM	0.07 - 0.15	0.08 - 0.14
CO PPM	3.0 - 19.0	9.4 - 25.3
SO_2 PPM	0.07 - 0.22	0.03 - 0.10
CO_2 %	0.21 - 0.37	0.39 - 0.75
WHITE FLAME HEATERS		
NO_2 PPM	0.08 - 0.31	0.21 - 0.38
CO PPM	0.0 - 3.4	2.6 - 6.2
SO_2 PPM	0.03 - 0.65	0.07 - 0.10
CO_2 %	0.33 - 0.54	0.82 - 1.09

The combined impact of changing ambient NO and NO_2 concentration, and of gas range operation, on indoor concentrations of NO and NO_2, in a California field home, is shown in Figures 2 and 3. The rapid increase of ambient NO concentration (Figure 2) starts at sunset, as the photochemical oxidation of ambient NO to NO_2 ceases in the absence of sunlight. Conversely (Figure 3) and simultaneously, the high concentration of ambient NO_2, during the daytime hours, rapidly decreases beginning with the time of sunset.[15] The relative influence of these changing concentrations on the respective peak-heights of NO and NO_2, produced by the normal operation of the gas range, is quite evident.

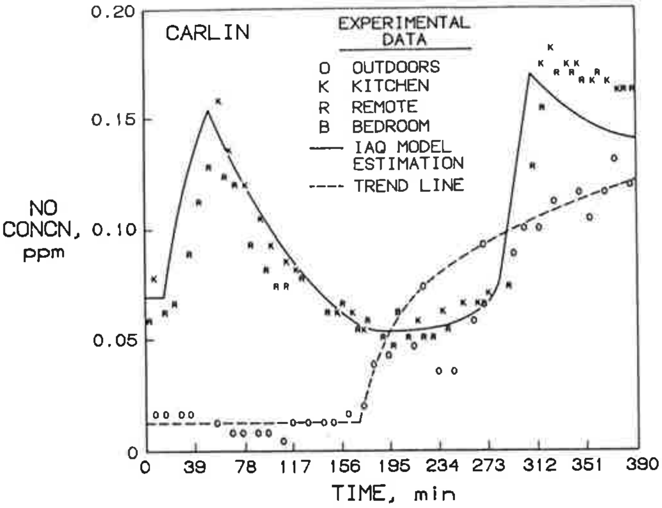

Figure 2. Outdoor effect on whole house no concentration

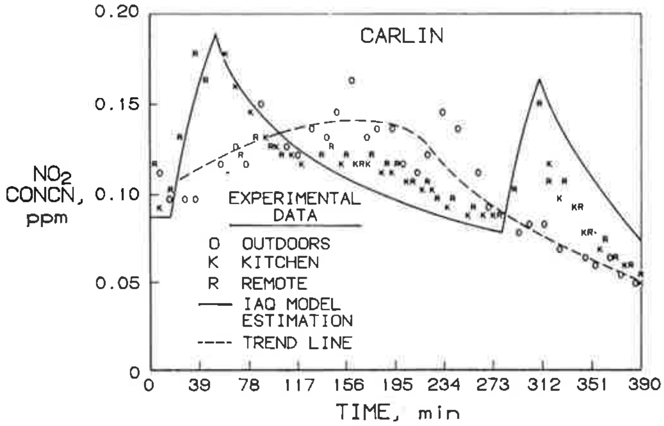

Figure 3. Outdoor effect on whole house no_2 concentration

The local concentrations of internally generated air contaminants is also much more strongly dependent on the level of communication between the various zones of the dwelling than on the whole house air infiltration rate. Table 9 illustrates 1-hour average and steady-state (peak) contaminant concentrations in a room heated by a kerosene space heater with the door open and communicating with the rest of the house, the door left ajar and closed.[3]

Table 9.

PREDICTED EXPOSURE CONCENTRATIONS DURING HEATER USE

POLLUTANTS	DOOR OPEN		DOOR AJAR		DOOR CLOSED	
	DYNAMIC	SS	DYNAMIC	SS	DYNAMIC	SS
CO, PPM	4.18	4.66	9.02	9.18	19.54	19.70
NO_2, PPM	0.06	0.07	0.12	0.13	0.23	0.25
CO_2, %	0.13	0.15	0.31	0.30	0.63	0.65

The impact of zone communication is also amply illustrated in Figures 4 and 5 which show NO and NO_2 concentrations in the kitchen, bedroom and another remote from the kitchen location in a typical Chicago split-level home with basement.[16] Distinctly different levels of NO and NO_2, due to gas cooking, are shown between the kitchen and other locations. Conversely, similar data (Figure 6 and 7) from a typical California ranch home (with ample interior communication) show practically no difference in the concentration levels from room to room.[15]

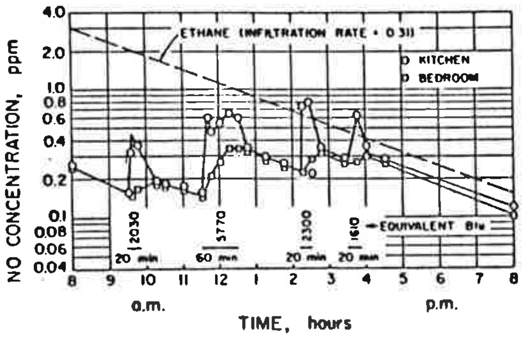

Figure 4. Continuous no monitoring in the glenwood home

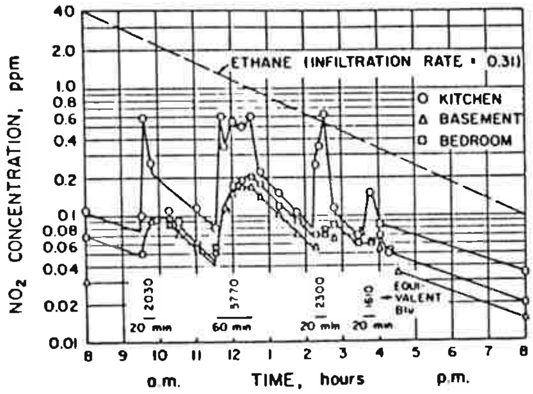

Figure 5. Continuous no_2 monitoring in the glenwood home

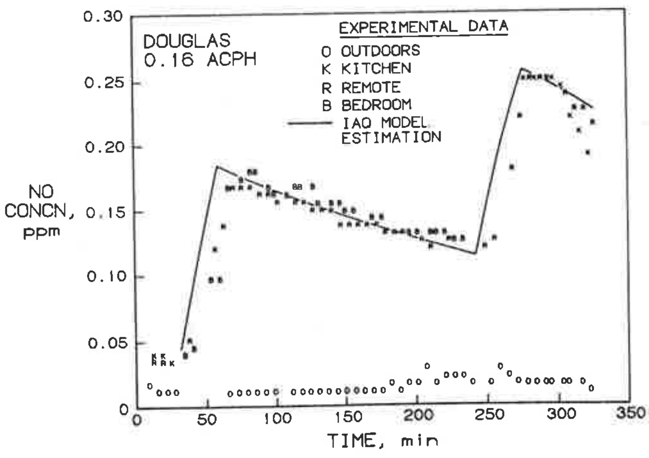

Figure 6. Gas cooking and whole house no concentration

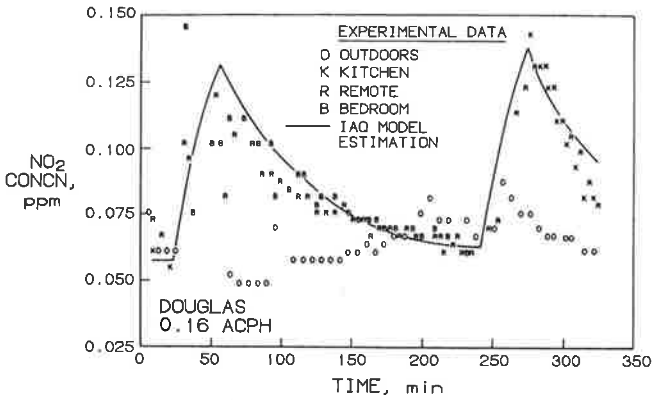

Figure 7. Gas cooking and whole-house no_2 concentration

Another significant factor in air contaminant distribution within the home is the existence, fan capacity and schedule of operation of the central air distribution system in the home. The quality of installation of the central air distribution system (level of leakage at duct joints, duct location, etc.) also can effect air contaminant levels and the whole house rate of air infiltration. Tables 10 and 11 illustrate quantitatively how communication between the furnace room and the rest of the house depends on the operation or setting of the air distribution system.[17]

Table 10, for example, illustrates that under certain circumstances (furnace registers taped, fan operating), flow of air counter to buoyancy (from house to basement, where furnace is located) can take place. Table 11 (which relates to performance of a test home under constant house air infiltration rate) shows that under certain conditions (fan operating with furnace registers open), the rate of air circulation within the home can be 2 to 3 times larger than the rate of air infiltration into the home from outdoors.

Table 10.

MEASURED COMMUNICATION BETWEEN FURNACE ROOM AND HOUSE (GKC Final Report)

HOUSE ID	AIR FLOWS, SCFM — FAN-OFF FURNACE ROOM REGISTERS TAPED			FAN-ON FURNACE ROOM REGISTERS TAPED		
	F_{12}	F_{21}	F	F_{12}	F_{21}	F
N	0	103	253	128	206	256
O	14	58	137	116	207	166
A	11	44	106	136	153	122
B	14	75	132	286	460	218
MI	20	36	157	113	125	176
MA	21	32	153	191	234	134

F_{12} – Flow of air from house to furnace room.

F_{21} – Flow of air from furnace room to house.

F – Total house exfiltration.

Table 11.

MEASURED COMMUNICATION BETWEEN
FURNACE ROOM AND HOUSE
(GKC Final Report)
HOUSE N

	AIR FLOWS, SCFM		
	F_{12}	F_{21}	F
FOF/RT	0	103	253
FON/RT	128	206	256
FOF/RO	15	111	241
FON/RO	623	687	241

F_{12} - Flow of air from house to furnace room.
F_{21} - Flow of air from furnace room to house.
F - Total house exfiltration.

3. Modeling of Air Infiltration

In contrast to the dynamic models available for heat transfer by radiation, conduction and convection through the building envelop, early models of air infiltration have been either primitive, extremely limited and not comprehensive. A review of available models in the U.S. and Canada, before 1979, has been published[18] and, therefore, would not be addressed here. Since that time, however, significant efforts have been undertaken, in the U.S. and abroad, toward the development of relevant and comprehensive mathematical models and, at least, 14 such models have been reviewed in a 1982 publication.[19]

The details of IGT's air infiltration model have been published[18] earlier, as has its application to the simulation of air infiltration in existing homes.[20] Partial verification of this model by Persily and Linteris[21] has been published in the ASHRAE Transactions. Most recently, a validation and comparison of 12 different air infiltration models, with actual data from 3 test homes (Canadian, Swiss and British), was published.[22]

The results of this comparative evaluation are summarized in Table 12. Of the 12 models, 7 use complex multicell (M) mathematical formulations while the other 5 use a single cell(s) basic approach. The numbers under the heading "DATA SETS" indicate the percent of time that each model was able to simulate the actual air infiltration measurements available from each of the 3 test homes, within 25 percent of the measured value.

Table 12.

AIR INFILTRATION MODEL COMPARISONS
BY AIR INFILTRATION CENTER

		DATA SETS		
MODEL	CELL TYPE	SWISS	CANADIAN	BRITISH
1. BSRIA	M	100	49	--
			63	80
2. NRC	M	100	49	--
NRC	M	56	86	87
3. IMG-TNO	M	83	--	--
4. OSCAR FABER	M	--	--	--
5. BRITISH GAS	M	--	78	67
BRITISH GAS	M	--	76	80
6. NBRI	S	83	78	--
7. IGT	S	100	76	67
8. LBL	S	100	81	80
9. BRE	S	89	73	87
10. REEVES ET AL.	S	100	57	33

The most significant conclusion, drawn from this comparative evaluation of models, is that single cell models were more successful in simulating the actual data, with the LBL[23] and IGT[18,20] models being the most successful. It should be noted that for its operation, the LBL model requires actual pressurization data (available from the 3 test homes). The IGT model, on the other hand, requires no experimentation at the site, relying totally on standard ASHRAE crack length data, structure orientation and shielding by adjacent building or foliage, and weather data. Most of the required data can be obtained from house blue-prints, local weather station, etc.

4. Modeling of Indoor Air Quality

A basic model for describing the dynamics of air quality variations in enclosed spaces has been around for a long time in one form or another. For example, a derivation of the general equations involved was reported by Turk[24] in conjunction with the use of an odor test chamber in evaluating odor reducing devices or producing odor free environments, for test purposes. Sutton et al.[25] presented a theoretical analysis of an air cleaning system, in an enclosed space, for the purpose of determining air filter efficiencies. Since the Clean Air Act of 1970, similar derivations have been made for indoor air quality models, for NO_x by IGT[16] and for particulate and gaseous pollutant by NBS[26] and by Geomet[27].

Currently, while the equations involved in these modeling activities are rigorous, the models tend to be imprecise or of limited applicability, unless suitable sub-models are provided for the following:

- Internal generation rates for the contaminants of interest
- Air infiltration dynamics of the structure
- Decay or disappearance rates of the contaminants of interest
- Degree of mixing within the various sections of the house.

For such a model, therefore, to reflect the performance of real homes, additional information is required (part of it derived by measurements at the site) to be integrated with the fundamental equations.

A. Internal Generation and Decay Rates

Nitrogen oxides (NO_x) and carbon monoxide (CO) are generated indoors primarily in direct proportion to the amount of unvented combustion (for example, gas cooking) taking place. A generation model, in this case, consists of a gas cooking schedule which can be measured, or conforms to average cooking schedules, as previously used at IGT.[16] From past and recent studies, average NO_x and CO emission factors for gas cooking appliances are well known.[28,29]

Nitric oxide (NO) is quite stable and its disappearance internally is almost wholly due to dilution by infiltration and exhaust. Nitrogen dioxide, on the other hand, decays significantly faster than the infiltration rate due to absorption and reaction with various media in the house. IGT[16] as well as Geomet[27] data indicate that the internal decay rate for NO_2 is probably exponential (1st order) in nature.

B. Effect of Mixing Factor

The mixing factor in an indoor air quality model is an important but poorly understood quantity. It is usually defined as the ratio of the actual to theoretical air change rates and can vary between 0.1 and 1.0, but is normally considered[30] to vary between 0.1 - 0.33. It is important not only because of its effect on indoor air quality, in a ventilated space, but also because it affects the measurement of air infiltration.

The concept of the mixing factor has recently been redefined by Esman[31] strictly in terms of a mass balance equation, and a vast improvement in data fitting ability was demonstrated by comparison to real data by Ishizu.[32] The latter paper has shown that, if the mass balance equation is properly integrated, the model does in fact fit real time data much better than with the old definition of mixing factors mentioned above. As the mixing factors can be very small fractions, their effect on indoor air quality must be taken into account.

C. Integrated Air Quality/Infiltration Model

The only attempt to date at developing an integrated air quality/air infiltration model has been made by Geomet[27]. This model has been only partially successful, primarily due to lack of a good infiltration submodel. The Geomet model utilizes a literature infiltration model modified to account for differences in the tightness of the homes. The Geomet model is an empirical one based on a modification of the Achenbach-Coblentz[33] regression analysis of infiltration data obtained in 10 electrically heated homes in the Midwest.

The Geomet model also neglects the effect of wind speed on air infiltration which affects, almost solely, infiltration in mild climates, where the indoor-outdoor temperature difference is rather small. In addition, this model does not include a mass balance around the house; this is very important for an air quality model because of the existence of common contaminants (NO_x, CO, radon) in both the indoor and outdoor air.

CONCLUSIONS

The following significant conclusions can be drawn from the previous discussion —

- The generation, dispersion and fate of potentially harmful contaminants in the indoor air are complex relationships requiring a large amount of data and information to understand them or to control the quality of indoor air.
- To gain an understanding of the role natural infiltration plays in these relationships through air infiltration measurements can require an enormous quantity of detailed and comprehensive data as to be non cost-effective.
- Since natural infiltration is going to be a prime mechanism for indoor air quality control, in the residential structures of the next generation, comprehensive but practical and cost effective air infiltration models are more suitable alternatives.
- The need for interactive, multi-cell approaches to modeling indoor air exchange is imperative. Such approaches can be couple with existing single cell air infiltration models to develop more comprehensive indoor air quality models.
- Point source venting of undesireable contaminants can be more efficient, energy conservative and cost effective than other approaches, such as whole-house air-to-air heat exchangers, that operate with highly diluted products.
- Use of an air-to-air heat exchanger can be justified only on a retrofit basis, for safety reasons, as for example in a tight dwelling with a proportionally large open fireplace and associated chimney, that can counter proper venting of fossil-fueled equipment.
- Finally, proper selection of indoor air quality control mechanisms and equipment cannot be made in the absence of comprehensive indoor air quality models which have been verified under "real world" conditions.

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