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Residential Air Pollution Levels: Observation and Data Interpretation

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ABSTRACT: A program to characterize the air quality in the residential environment has been undertaken. The generation of the data base, the interpretation of the data, and the formulation and application of an indoor-outdoor numerical model will be discussed.

Pollutant concentrations are sampled in three indoor locations and one outdoor location. "Instantaneous" readings are obtained for carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), ozone O_3, sulfur dioxide (SO_2), total hydrocarbons (THC), methane (CH_4), and carbon dioxide (CO_2); 24-h averages are monitored for total suspended particulate (TSP) and respirable suspended particulate (RSP) matter, sulfates, nitrates, lead and organics; aldehydes are sampled on a 4-h basis. In addition, the meteorological conditions both indoors and outdoors are measured, and the air exchange rate of each residence is experimentally determined. Elemental analysis is performed by proton-induced X-ray emission (PIXE). Finally, the kilowatt hours for heating, cooking and alternate current; the furnace efficiency; structural specifications; and other energy parameters are measured. The objective of this project is to develop causal relationships between the energy conservation measures-indoor (residential) air pollution concentrations and health effects.

Data analysis shows that the national ambient standards have been violated in the indoor residential environment for two pollutants, ozone and nonmethane hydrocarbons. Additionally, the American Society for Heating, Refrigerating, and Air-Conditioning Engineers' (ASHRAE) recommended indoor air pollution standards are violated by the following pollutants: carbon dioxide, total suspended particulate matter, and aldehydes.

A numerical model relating indoor and outdoor air pollution levels has been developed for the project. The model has been validated with the large data base sampled in the field studies. A series of numerical simulations indicate that under certain conditions energy conserving measures will increase the indoor air pollution levels.

KEY WORDS: residential air pollution, energy conservation, numerical simulations, air infiltration, measurements

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The objective of the GEOMET Indoor Air Pollution project is to characterize the air quality of the indoor residential environment. The motivation for the study is the realization that residential air quality may be as important a health factor as the outdoor air quality. The expected impact is the optimization of the relations involved in the dynamic system of air quality-energy conservation in the residential environment.

In order to meet these goals, we began with a literature search on indoor air pollution, continued with an 18-month field monitoring program, and will finish with a series of publications on the interpretation of the collected information.

The indoor air quality of five detached dwellings, two attached dwellings (townhouses), six apartment units, two mobile homes, one school, and one hospital was monitored during this program. These structures are located in five different metropolitan areas: Baltimore; Washington, D.C.; Chicago; Denver; and Pittsburgh. Each unit is monitored for a period of approximately 14 days. A mobile laboratory fully equipped with the necessary monitoring equipment is placed very near the structure to be monitored. Gas concentrations are measured at one location outdoors (adjacent to the building) and at three locations indoors (typically the kitchen, bedroom, and living room). Twenty-four hour averages of particulate pollutants are measured in the same four locations. Samples for gas pollutants are obtained by a continuous monitoring system that is used in conjunction with a programmable solenoid switching mechanism to collect 4-min samples, three times in each hour, at each of our locations. The state-of-the-art of commercially available instruments is used for this study, only the elemental analysis performed by the proton-induced X-ray emissions (PIXE) is not a commercially available technique.

The field observations and collected data have been classified in seven generic categories shown in Table 1.

Eight pollutants are monitored continuously by the previously mentioned system: carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), methane (CH_4), total hydrocarbons (THC),

TABLE 1—*Data classification.*

Continuous monitoring	CO, NO, NO_2, SO_2, O_3, CH_4, THC, CO_2
Intermittent monitoring	TSP, RSP, SO_x, NO_x, ALD, Pb and organic compounds
Physical data	outdoor—wind speed and direction, and indoor and outdoor—temperature and relative humidity.
Energy data	kilowatt hours for heating, cooking, air conditioning and other furnace efficiency, number of door openings and closings, structural specifications, house blueprints, and crack length investigation.
Tracer data	air exchange rate; indoor zone identification
Family daily logs	daily activity record of the occupants of the dwelling
Elemental analysis	proton-induced X-ray emission analysis (PIXE)

carbon dioxide (CO_2). Meteorological conditions greatly affect the outdoor pollution levels and therefore are of importance in this study. Twenty-four hour averages are obtained for total suspended particulate (TSP) matter, and for respirable suspended particulate (RSP) matter. Indoor and outdoor levels for nitrates, sulfates, lead and aldehyde levels (ambient aldehyde levels) are obtained from 24-h samples. Ammonia concentrations are obtained from hourly samples. Ammonia is introduced into the environment by cleaning the kitchen floor with ammonia cleansers. The energy data collected is essential for the air quality inputs and for the optimization task; the tracer experiments determine the air exchange rate of each dwelling for different meteorological conditions. The family logs have been of particular help in identifying the mode of operation of certain indoor pollutant generating activities. A member of the family, usually the housewife, answers the 18 questions daily.

During each monitoring period every family followed its usual behavioral pattern. Since there were virtually no experiments staged, the air samples collected are representative of the everyday "real-life" residential air quality.

The bulk of the data base acquired combined with the time and space allocation for this presentation require that the conclusions be general and descriptive rather than quantitative and detailed.

Indoor air quality has been shown to be markedly different from outdoor air quality. The field observations of the indoor air quality study show that the concentrations of CO, NO, CO_2 hydrocarbons, and aldehydes in the residential environment are often higher than outdoors; indoor concentrations of NO_2, TSP matter, and RSP matter are 50:50, sometimes higher and sometimes lower than outdoors; finally indoor concentrations of SO_2, O_3, sulfates $SO_4^{=}$, nitrates NO_3^-, and lead are often and almost always lower than the corresponding outdoor pollutant concentrations.

One of the findings of this study is that there are no pollutant standards for the indoor residential environment; however, the field measurements show that for certain pollutants and under certain conditions the National Ambient Air Quality Standards and the residential standards recommended by American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE Standards 62-73 and 90-75) are exceeded indoors. These ASHRAE standards are currently under revision. Table 2 is a tabular summary of the observed data; it shows that concentrations of ozone, nonmethane hydrocarbons and TSP exceed the national ambient standards in the indoor environment; the 8-h ambient standard of carbon monoxide is not exceeded indoors but it is equaled in certain residences. The data base generated by this project reveals that for approximately 70 percent of the total monitored hours, indoor pollutant levels exceed corresponding ambient concentrations. In general, the air quality measured in either the outdoor or the indoor environment was relatively clean.

TABLE 2—*Tabular summary of observed data for indoor-outdoor air pollutant concentrations at 17 rrsidences.*

Pollutant	Indoor Levels Typical Range[a]	Maximum Indoor Concentrations[a]	Indoor Exceedances of Ambient Standards: Federal Ambient	Indoor Exceedances of Ambient Standards: ASHRAE Indoor[c]	Indoor-Outdoor Pollutant Relations[d]
		1-H AVERAGES			
CO	1.0 to 3.0 ppm	22 ppm	none	none	A
NO	60 to 200 ppb	470 ppb	N/A[b]	none	A
NO_2	20 to 62 ppb	180 ppb	N/A	none	B
CO_2	500 to 1300 ppm	2200 ppm	N/A	many	A
O_3	1 to 6 ppb	82 ppb	few	few	C
SO_2	2 to 8 ppb	29 ppb	none	none	C
NMHC	2 to 8 ppm	58 ppm	many	many	A
		24-H AVERAGES			
TSP	30 to 100 $\mu g/m^3$	500 $\mu g/m^3$	many	many	B
RSP	20 to 80 $\mu g/m^3$	268 $\mu g/m^3$	N/A	N/A	B
$SO_4^{=}$	2 to 18 $\mu g/m^3$	34 $\mu g/m^3$	N/A	N/A	C
NO_3^-	0.9 to 4.0 $\mu g/m^3$	6.3 $\mu g/m^3$	N/A	N/A	C
Pb	0.1 to 2.8 $\mu g/m^3$	12.5 $\mu g/m^3$	N/A	none	C
Aldehydes	100 to 300 $\mu g/m^3$	950 $\mu g/m^3$	N/A	many	A

[a]From Moschandreas, D. J. et al, 1978, *Indoor Air Pollution in the Residential Environment—Volume I: Data Collection, Analysis and Interpretation.* GEOMET, Inc., Gaithersburg, Md., EPA Publication No. EPA-600/7-78-229a.

[b]N/A = not applicable.

[c]From ASHRAE Standard 62-73, 1973, "Standards for Natural and Mechanical Ventilation," The American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.

[d]Key: A = air pollutant concentrations indoors often higher than outdoors; B = air pollutant concentrations indoors sometimes higher, sometimes lower than outdoors; and C = air pollutant concentrations indoors often lower than outdoors.

In addition to the data collected on indoor pollutant levels, mathematical models have been developed for predicting indoor concentrations of the pollutants identified previously. The GEOMET indoor-outdoor air pollution model (GIOAP) is a first order differential equation which dynamically relates the exchange of the indoor pollutant concentrations to the rate of introducing a pollutant indoors, through ventilation, infiltration, and recirculation and indoor sources, minus the rate of eliminating the pollutant from the indoor environment via exfiltration, exhaust, indoor chemical sinks, and cleaning devices. The numerical details of this model are available in the literature[2]; they will not be repeated here.

However, two unique aspects of the model deserve mentioning:

1. The model and the data available to this project allow for a very refined time resolution; almost all of the simulations undertaken for this study have been on hourly basis, a unique aspect of the GIOAP model.

2. The GIOAP model includes a transient form. It can be shown that for relatively inert pollutants (such as CO, CO_2, NO) the impact of this term is substantial; however, for chemically reactive pollutants such as ozone and SO_2 the transient term is negligible and the GIOAP model results agree with the numerical simulations by Dr. Shair's linear dynamic model,[3] which assumes no transient terms.

The data base collected in the field was used to validate the GIOAP model. Table 3 illustrates the predictive power of the model against the observed

TABLE 3—*Assessment of the GEOMET indoor-outdoor air pollution model.*

Pollutants	Comments on the Model's Predictive Ability
CO, NO_2, NO, NMHC, CH_4 and CO_2	satisfactory—Model estimated values within 25 percent of observed values
O_3	questionable—Eighty-five percent of the observed indoor values are in the low range of 0 to 6 ppb. The model estimated values are mostly within 2 ppb (less than the instrument precision) of the observed values. The numerical output does not satisfy the predetermined model validation criteria, but it provides a realistic estimation of the indoor ozone concentrations.
SO_2	not validated—Due to low outdoor levels and a negative interference of CO_2 on the SO_2 monitor a large number of hourly sulfur dioxide concentrations are measured close to the threshold value of the monitor. In the indoor environment SO_2 and NO_2 decay similarly. It is thus judged that the GIOAP model would validate satisfactorily against higher SO_2 values.

[2] Moschandreas, D. J. and Stark, J. W. C., "The GEOMET Indoor-Outdoor Air Pollution Model: Scientific Report," GEOMET Report Number EF-628, prepared for the U.S. Environmental Protection Agency and the U.S. Department of Housing and Urban Development, 1978.

[3] Shair, F. H. and Heitner, K. L., *Environmental Science Technology*, Vol. 8, 1974, pp. 444–451.

values on an hourly basis. The pollutants in the first category are predicted often within 15 percent of the ideal condition. Ozone would be usually considered acceptable; however, the predetermined criteria were not satisfied owing to the particularly low indoor levels. The problem with SO_2 is unique to the high CO_2 residential atmospheres, and it was not noticed before.

The physical quantity that associates energy conservation measures and pollutant concentrations in the residential environment is the ventilation (air exchange rate) induced by the infiltration-exfiltration mechanism. Energy is conserved when the ventilation rate is decreased. Figure 1 illustrates that by decreasing the air exchange rate the indoor pollutant concentrations are increased. The outdoor fluctuation of CO, a separate pollutant, is a typical Los Angeles variation. The 1-h ambient standard is not violated throughout the day but the 8-h National Ambient Air Quality Standard is violated between the hours 0600 and 1400. The GIOAP model is used to simulate the same house but with three decreasing air exchange rates. The CO concentrations over the time period between 0600 and 1400 exceed the national ambient standard indoors. This is obviously caused by the high ambient levels due to automobile emissions indicating that tight houses do not shelter their inhabitants for all cases and all pollutants, even though the hourly peak is decreased. The 8-h period between 1500 and 2300 is of particular interest. Note the low outdoor levels; indoors the stove emits carbon monoxide for 2 h while one burner and the oven are used (this is not a typical household activity). All three simulated indoor environments exceed the 8-h National Ambient Air Quality Standard; only one, the energy-conserving house with an assumed air exchange rate of 0.2 air changes per hour, exceeds indoors the 1-h national ambient carbon monoxide standard.

The evidence is rather strong that indoor sources generate high pollutant concentrations indoors and that reduction of the ventilation rate accentuates the adverse conditions. The point is that energy conservation measures are not the cause of the problem, rather it is indoor pollutant sources that generate potentially unhealthy residential environments. A recent study of 11 cities indicates that the average residential ventilation rate is about 0.7 air changes per hour. Figure 2 shows the impact that the normal operation of a stove has on the environment of a 200-m^3 dwelling with an 0.7 air exchange rate. The cumulative exposure to NO_2 levels of the inhabitants with indoor sources is about three times as much as the house without sources; the ambient exposure is in between. These simulations indicate that (1) the indoor environment is different from the outdoor and (2) the indoor environment can be classified in at least two categories: (*a*) residences with source gas appliances and (*b*) residences with electric appliances. The data base of our study suggests a further classification of each of the above categories in tight, typical, and permeable residences. The differences between gas tight and gas permeable are indeed substantial. Reduction of the residential ventilation rates leads to two conflicting ends; namely, it conserves energy and it in-

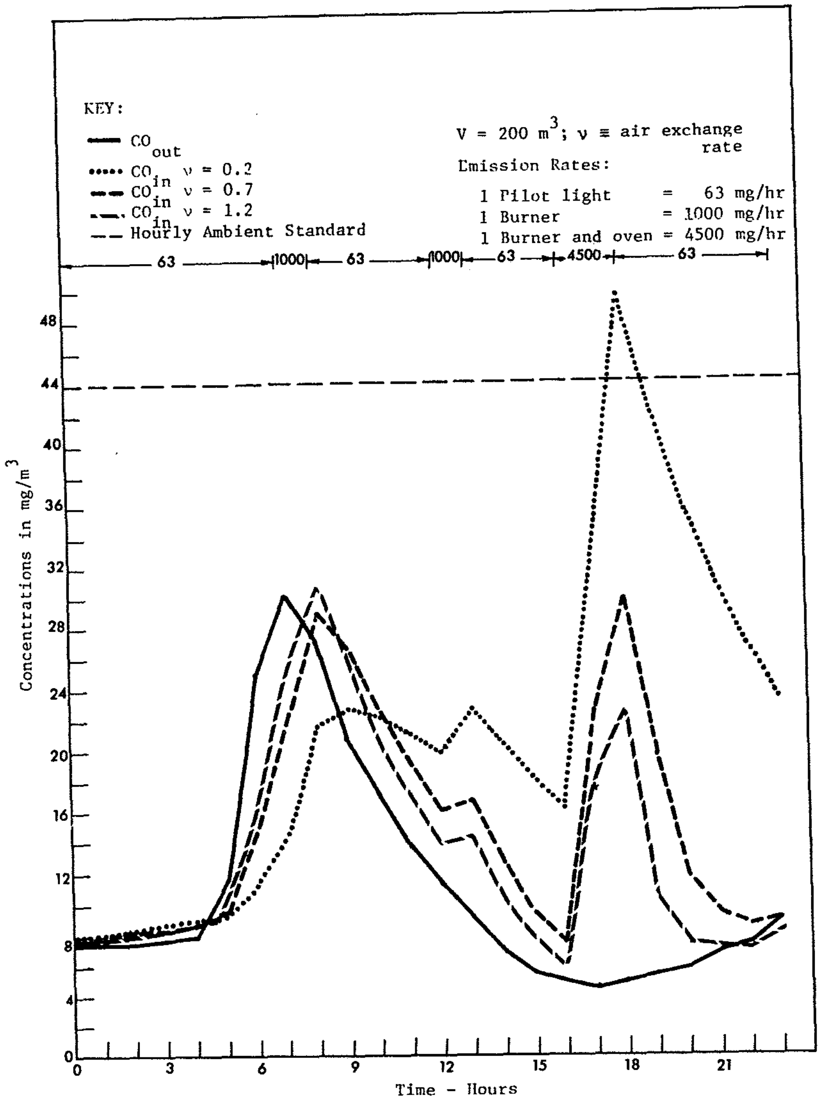

FIG. 1—*Numerical estimations of the indoor CO concentrations as a function of the illustrated outdoor variation, a typical pattern of CO emission rates from a gas appliance, and three air exchange rates.*

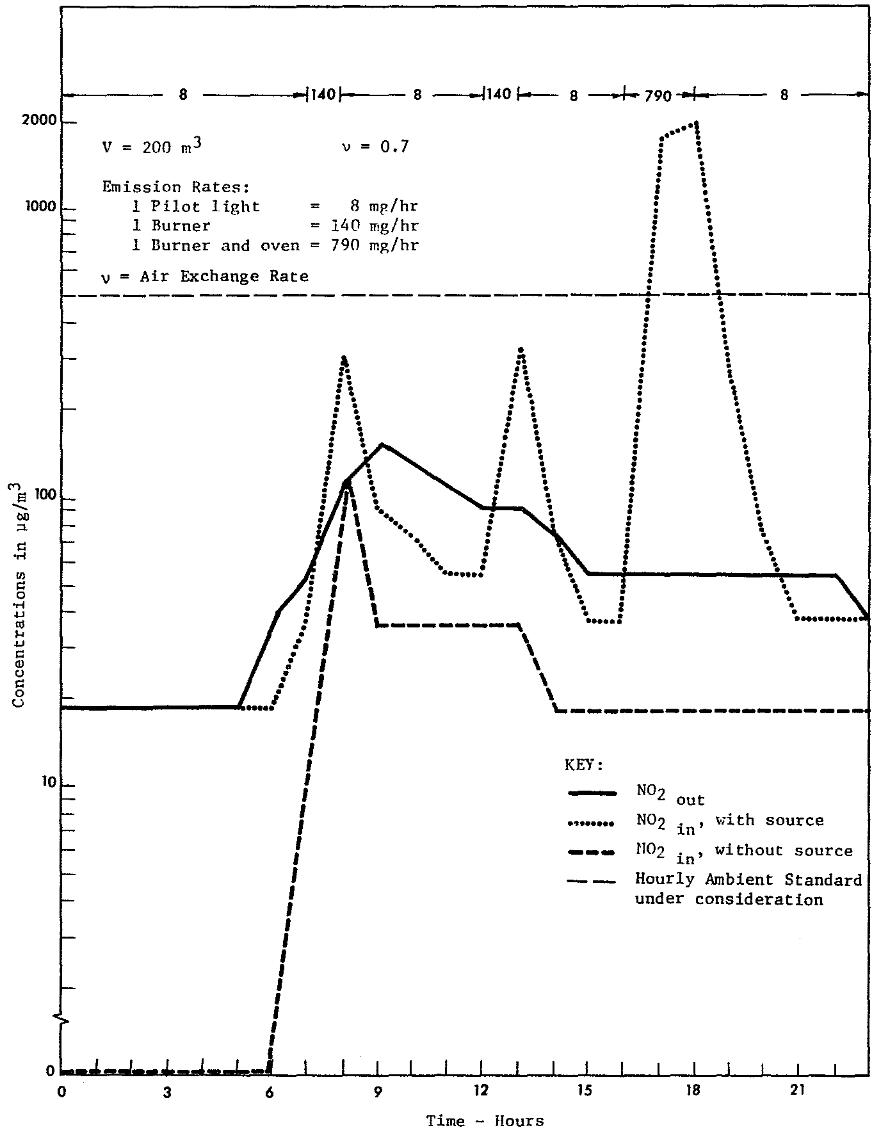

FIG. 2—*Indoor variation of NO_2 levels simulated as a function of the illustrated outdoor variation and a typical pattern of NO_2 emission rates from a gas appliance is compared to indoor NO_2 levels simulated as a function of the same outdoor variations without indoor pollutant sources.*

creases indoor pollutant concentrations. Large decreases in the emission rates from gas stoves and furnaces is an avenue that must be pursued more actively. The GEOMET study suggests that a reduction of residential air exchange rates from the present typical levels, 0.6 to 0.9 air exchanges per hour down to the range of 0.4 or 0.5 air changes per hour, optimize energy and environmental concern.