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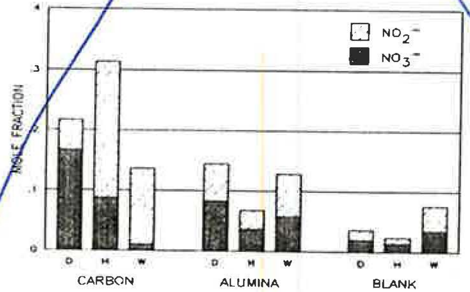

Figure 1. Concentrations of NO_2^- and NO_3^- removed from 20-mg particles exposed to 7 ppmv NO_2 in air for 10 min at a flow of 1 ℓ min^{-1}. Concentrations are expressed as mole fractions of the total NO_2 gas introduced into the reaction vessel. Abscissa code: D - dry; H - air stream at 50% relative humidity; W - wet slurry (10-mg particles in 10 ml H_2O, flow 0.16 ℓ min^{-1}).

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TWO-ZONE MODELLING FOR AIR EXCHANGE RATES AND NO_2 SOURCE AND DECAY RATES IN A SOUTHERN CALIFORNIA RESIDENTIAL INDOOR AIR QUALITY STUDY†

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Abstract

BNL/AIMS‡ and NO_2 measurements were applied to 640 homes in Southern California during Mar '84, Jul '84, and Jan '85. Whole house AERs had median values of 0.84/h, 1.5/h and 0.55/h respectively. NO_2 decay rates for 18 all-electric homes, and for the bedroom zone across all homes, had a median of about 0.6/h and did not vary noticeably among test periods. Median NO_2 source rates for the living zone (kitchen and living room) were 10.6 mg/h, 12.3 mg/h and 7.4 mg/h, while medians for the bedroom zone were all 0 mg/h. Outdoor sources made the largest contribution to NO_2 in the bedroom zone, while indoor sources were marginally more important than outdoor in the living zone (Southern California has high concentrations of outdoor NO_2).

Introduction

The work reported here was part of Phase 1 of Southern California Gas Company's **(SoCal Gas)** Residential Indoor Air Quality Characterization Study of Nitrogen Dioxide (The Characterization Study or simply **The Study**). The Study (1,5) was initiated in 1983 based on concerns raised by previous studies in other regions. These previous studies had found that energy conservation measures limiting air infiltration into homes, together with gas appliances, could lead to high indoor NO_2 concentrations. While such results were a concern to SoCal Gas, Southern California is different in many ways from the regions that had been previously studied. Differences include, for example, the mild climate, the number and type of gas appliances, and the fact that much of the area serviced by SoCal Gas experiences outdoor NO_2 concentrations that are above US federal air quality standards.

The Characterization Study is described in detail elsewhere (5), and related papers appear in this proceedings (1). 640 homes were randomly selected from within the SoCal Gas service area. Phase 1 of the Study surveyed these homes in March 1984, July 1984 and January 1985. The surveys included measurement of indoor and outdoor NO_2 concentrations, measurement of air infiltration rates using the BNL/AIMS, and collection of an array of information about the home, its appliances, and activity within the home through a questionnaire.

This paper specifically examines the results of the air infiltration measurements and their application together with an Indoor Air Quality **(IAQ)** model to determine NO_2 source rates and decay rates within the homes. The 2-zone, mass balance models for perfluorocarbon tracer **(PFT)**

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‡Brookhaven National Laboratory's Air Infiltration Measurement System **(BNL/AIMS)** consists of passive perfluorocarbon permeation sources and passive samplers and is used to measure multi-zone ambient air flows in buildings (3).

gas and NO_2, which are the basis of this study, are presented in detail elsewhere (4). While more complex models are possible, the cost of applying them (e.g. measurement of additional zones) to the number of homes represented in this study would be substantial. On the other hand, simpler models would fail to differentiate among sources within the home, and it is known from previous studies that the bedroom and living zones of most homes are quite different. The coupled BNL/AIMS -IAQ model represents a promising new approach; however, further testing needs to be done to determine its accuracy and reliability.

Application of the Two-Zone Model

The Indoor Air Quality mass balance model coupled with the PFT mass balance model allows the determination of NO_2 source and decay rates (decay represents removal processes in the building materials and fabrics of the home). Mathematically, there is no unique solution for the source and decay rates. However, logical restrictions allow the development of a reasonable algorithm for the determination of rates. If the decay rate, calculated by assuming that there is no source, is negative, then there is a source; if it is positive, then the source is probably small or absent. By looking at a large set of data including some all-electric homes, it was determined that a negative or small (<0.1/h) decay rate in the living zone could be replaced by the bedroom zone decay rate to calculate a source rate. If the bedroom zone decay rate is also too small, then 0.6/h is used for both zones.

The coupled BNL/AIMS - IAQ model can also be used to break down the indoor NO_2 concentration and attribute it to outdoor NO_2, indoor sources in the living zone, and indoor sources in the bedroom zone. Playing the model "backwards" in this fashion also allows questions such as, "what are the consequences of reducing the air exchange rates," to be answered.

All of the calculations in this report were accompanied by an error analysis based on a first-order Taylor-series expansion of the calculational formulae (2). The results were used in quality control and trouble shooting on the overall dataset.

The computation of the NO_2 source strength, or emission rate, for each zone is important for subsequent analyses for a number of reasons. In particular, many of the other variables that one might examine to develop a statistical model for predicting indoor air quality are confounded; that is, there are multiple factors and functional relationships affecting the dependent variable that make it difficult to separate the simple, direct relationships one would like to evaluate.

For example, indoor NO_2 concentration depends on outdoor NO_2 concentration. However, that dependence is affected by the air exchange rates and the NO_2 decay rates. Furthermore, it is partially hidden by the "noise" of indoor NO_2 sources which add on to the NO_2 which comes from the outdoors. Therefore, an effort to statistically model indoor NO_2 concentrations on other measured variables will meet with substantial difficulty and will not be easy to interpret.

In the approach of this report, physically based mathematical models (the combined BNL/AIMS - IAQ model) are used to calculate the NO_2 source strengths. This substantially reduces the statistical uncertainty, since the effects of outdoor NO_2 concentrations, air exchange rates and indoor sources are now accounted for by an appropriate model (which, by the way, is not of a form that could be discovered through stepwise regression with all the variables available). Subsequent work can concentrate on the relationship between indoor source strengths (not NO_2 concentrations) and the variables that affect them, with most of the confounding factors already removed.

Results

To maintain consistency and comparability among time periods and homes, a final dataset was selected so that all results presented represent the same set of homes analyzed in the same fashion. There are *181 homes* in this final set, and each of these homes was successfully modelled as 2-zone in all three test periods using both the PFT model and the IAQ model for NO_2. While a complete dataset is available containing all 640 homes, many homes are represented as missing, or could not be modelled as 2-zone, in one or more test periods. For this report, it was considered to be more productive to work with *a single dataset that was consistent and complete across all presented results.*

Because of the skewed nature of the distributions for most of the results, comparisons have not been made using standard errors to see if the confidence intervals overlap. Confidence intervals on the mean may not even include the median for the same distribution. However, since all the results presented are for the same set of homes, nonparametric paired comparisons are very easy. Therefore, *all statistical tests in this paper are based on the Wilcoxon signed-rank test.*

Whole House Air Exchange Rates

Whole house air exchange rates were clearly seasonal with median values of 0.76/h, 1.4/h and 0.56/h during March, July and January respectively. The quartile spreads (50% spread) during the 3 test periods were 0.56/h to 1.09/h, 0.74/h to 2.30/h, and 0.41/h to 0.81/h. The distributions are all significantly different at <0.01.

NO_2 Source and Decay Rates

The NO_2 decay rates, calculated assuming no source, do not differ significantly among test periods, but do differ very significantly between zones across all test periods (all <0.0001). For the living zone, the median decay rates were -0.37/h, -0.25/h and -0.11/h for the 3 test periods (March, July and January), with 130, 122 and 105 homes (out of 181) having negative decay rates. For the bedroom zone, the median decay rates were 0.68/h, 0.45/h and 0.66/h with 165, 153 and 169 homes having positive decay rates. These results show clearly that most homes have an NO_2 source in the living zone (implied by the negative decay rates obtained when one assumes no source) and few homes have any significant source in the bedroom zone. This lends support to the approach of using the bedroom zone decay rate, when it has a value above 0.1, to calculate the living zone source.

The calculated NO_2 source rates are in a sense a scale transformation from the decay rates (from units of 1/h to units of mg/h), although it is somewhat more complicated since the transformation depends on the volume, decay rate and NO_2 concentration for each home. Consequently, it is not surprising that the source rates, like the decay rates, show little difference among test periods and much difference between zones across all test periods. The median living zone NO_2 source rates were 12 mg/h, 13 mg/h and 12 mg/h with 138, 138 and 120 homes having positive (non-zero) sources. The median bedroom zone NO_2 source rate is zero for all three test periods with 157, 137 and 165 homes having no sources.

The living zone NO_2 source rates go as high as 200 mg/h for some homes in each of the three test periods, but 90% of the homes are below 55 mg/h, 56 mg/h and 47 mg/h respectively during the 3 test periods.

The bedroom zone NO_2 source rates go no higher than 44, 46 and 69 during the three test periods, while 90% of the homes are below 4, 9 and 0 mg/h.

Attributing Indoor NO_2 Concentration to its Sources

The degree to which NO_2 sources contribute to the concentrations of NO_2 in the home are determined by the air exchange and NO_2 decay rates. A low air exchange rate tends to keep indoor NO_2 in and outdoor NO_2 out. The removal of NO_2 by adsorption and reaction on and in building materials within the home makes it possible to "keep outdoor NO_2 out." If there were no decay, the base level concentration of NO_2 would be the outdoor concentration (the ultimate source of all air), and any indoor sources would simply add to the base level.

The coupled BNL/AIMS - IAQ model allows the concentration of NO_2 in the home to be separated into the parts attributable to each of the sources. Thus, it is possible to calculate, for each zone of a home, the concentration that is due to the outdoor NO_2, the concentration that is due to sources in the living zone, and the concentration that is due to sources in the bedroom zone. The sum of these is the observed concentration of NO_2 in the zone.

Two of the important factors determining indoor NO_2 concentrations show very significant differences among test periods. These are the AER and the outdoor NO_2 concentrations. The distributions of AER were reported above. The outdoor NO_2 concentration had median values of 51 $\mu g/m^3$, 71 $\mu g/m^3$ and 114 $\mu g/m^3$ for the 3 test periods. The differences are highly significant (<0.0001), and in January 108 of the homes experienced outdoor concentrations above 100 $\mu g/m^3$.

The median contributions of outdoor NO_2 to the living zone concentrations were 28 $\mu g/m^3$, 45 $\mu g/m^3$ and 53 $\mu g/m^3$ during the 3 test periods. The median contributions to the bedroom zone were 26 $\mu g/m^3$, 43 $\mu g/m^3$ and 48 $\mu g/m^3$. These contributions vary strongly among seasons as would be expected from the variation in AER and outdoor NO_2 concentration. The variation between zones within seasons is small, but indicates a slight difference due to bedrooms being somewhat more closed off.

The median contributions of NO_2 sources in the living zone to the concentrations of NO_2 in the living zone were 40 $\mu g/m^3$, 34 $\mu g/m^3$ and 47 $\mu g/m^3$. The significance levels for differences among test periods vary from 0.003 to <0.0001. This shows the strong influence of air exchange rates, since the indoor sources did not vary substantially among seasons.

The median contributions of NO_2 sources in the living zone to the concentrations of NO_2 in the bedroom zone were 12 $\mu g/m^3$, 8 $\mu g/m^3$ and 14 $\mu g/m^3$. Again, these are in keeping with the seasonal variation in AER and the separation of the bedroom zone from the living zone. The levels are 3 to 4 times lower than the contributions to the living zone, leading to an overall lower concentration of NO_2 in the bedroom zones.

Finally, in keeping with the fact that few homes had sources in the bedroom zone, the median contributions of NO_2 sources in the bedroom zone to the concentrations of NO_2 in the living zone and the bedroom zone were 0 for all test periods.

The additive effect of indoor and outdoor sources leads to median NO_2 concentrations in the living zone of 73 $\mu g/m^3$, 84 $\mu g/m^3$ and 102 $\mu g/m^3$ for the three test periods, and median concentrations in the bedroom zone of 46 $\mu g/m^3$, 62 $\mu g/m^3$ and 70 $\mu g/m^3$.

Simulated Effects of Changing Ventilation Rates

While some insight can be gained by comparing the results from the three test periods, there were many variables that changed between test periods, including AER, outdoor NO_2 concentration, indoor sources, and humidity. Thus, while such comparisons are useful, they are not entirely unambiguous.

Using the 2-zone NO_2 model, it is possible to enter values for the NO_2 source strengths, the NO_2 decay rates, and the air flow rates, and calculate the consequent concentrations of NO_2 in the living zone and in the bedroom zone. Using previously calculated values for these variables yields the actual measured NO_2 concentrations. The variables can also be changed, and the effect on the concentrations calculated. It is fairly obvious that source reductions of NO_2 (either indoor or outdoor) will reduce the indoor concentration of NO_2. The results in the previous section indicate how much can be gained by such mitigative actions. The effects of changes in the air exchange rates are more difficult to predict and are the subject of this section.

For this simulation, all air flow rates were reduced by 20% and then increased by 20% using the data for each of the 181 homes in each test period. When the air flow rates were changed by -20%, the contributions of the outdoor NO_2 to the living zone NO_2 concentration showed median changes of -10%, -8% and -11% for the 3 test periods. These decreases were offset by the contributions of sources within the living zone which exhibited median changes of 14%, 16% and 12%, giving net median changes in the living zone NO_2 concentrations of 4%, 2% and 0%. The contributions of outdoor NO_2 to the bedroom zone NO_2 concentration showed median changes of -10%, -7% and -12%, which were very close to the changes for the living zone. The contributions of sources from the living zone to the NO_2 concentrations in the bedroom zone changed by 6%, 10% and 3%, giving net median changes in the bedroom zone of -4%, -3% and -8%.

The consequences of changing the air flow rates by +20% were largely, though not precisely, mirror images of the results just reported for changes of -20%. It should be noted in addition that changes in concentrations are not expected to be linear with relation to changes in the air flow rates. Thus, while this brief study gives insight into the interactions among the different sources and air exchange rates, a precise answer for any given situation is best provided by applying the model.

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