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# AN EVALUATION OF CRITICAL FACTORS ASSOCIATED WITH DESIGN, PROTOCOL, IMPLEMENTATION AND DATA MANAGEMENT OF LARGE-SCALE MULTIPOLLUTANT INDOOR AIR QUALITY FIELD STUDIES

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**ABSTRACT**

Large-scale multipollutant indoor air quality field studies must be designed and conducted to satisfy a broad array of scientific and programmatic interests of its sponsors. A comparative evaluation to identify critical factors associated with field study design, protocol, implementation, and data management problems and issues was done based on experiences of three multipollutant studies. These studies involved over 400 residences in the States of Tennessee, Alabama, Georgia, and Mississippi. Critical factors identified and discussed in this comparative evaluation are: factorial study design; participant selection and communications; interactive effects; regional and environmental variability; relational data base management; new protocol evaluations; and multiple sponsor coordination. Field study data and methodologies are used to support and illustrate the comparative assessment of objectives and practices.

Field studies which comprehensively examine indoor air quality in residential buildings are both technically complex and expensive. Therefore, most current large-scale indoor environmental research studies are cost-shared by different sponsors. Consequently, to satisfy the broad array of programmatic interests





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the cosponsors represent, careful attention must be given to the design, protocols, implementation, and data management for the investigation. Over the last three years, the Tennessee Valley Authority (TVA) and Oak Ridge National Laboratory (ORNL) have implemented three multiple-sponsored studies which are examining the interrelationships among indoor air pollutant levels, building air change rates, housing characteristics, and occupant activity and health. Over 400 residences have been involved in these field studies. The first study which was completed in 1984 was comprised of forty homes in the Oak Ridge/ Knoxville, Tennessee, area. The second study involved seventy homes in a four-State area of the Southeast (Alabama, Georgia, Mississippi, and Tennessee). The third study is an expansion of the Harvard University Six-Cities Air Pollution Study in 300 homes in the Kingston-Harriman, Tennessee, area. Since various sponsors funded each effort to meet a different set of program objectives, study designs and methods were developed to meet evolving data requirements and to ensure data quality and cost effectiveness. In the following sections each of these multipollutant field studies is described with special emphasis on their design, protocol, implementation, and data management objectives and practices. In conclusion, a comparative assessment of critical factors associated with large-scale multipollutant indoor air quality field studies is provided.

## FORTY-HOME EAST TENNESSEE FIELD STUDY

The first phase of this study was originally funded by the Consumer Product Safety Commission (CPSC) and the Department of Energy (DOE), and was conducted between April 1982 and February 1983 in the Oak Ridge/West Knoxville area of Tennessee [1]. A cross-sectional design representing a semi-urban population was utilized. A sample population of forty was selected as a compromise between the requirement for a large sample size and available resources. The pollutants monitored were: formaldehyde (HCHO), volatile organics (VOC), combustion gases ($CO_x$-$NO_x$), particulates, and radon. Other data were obtained from a house survey by the ORNL researchers, air exchange rate measurements, and meteorological measurements. Data were maintained in a large Statistical Analysis System (SAS) database.

Participants in the study were primarily solicited through local newspaper articles. Although more than 150 persons responded to the newspaper solicitations, special efforts were needed to enlist participation of homeowners in certain design categories (e.g., homes less than five years old and homes with urea-formaldehyde insulation). Homeowner briefings were held to inform participants of the study's activities and to answer any questions the homeowners had.

Conclusions from the first phase of this study which were important to subsequent monitoring and analysis were:

- diurnal and seasonal fluctuations of indoor formaldehyde levels;
- variation of the indoor formaldehyde levels between old and new housing;
- location-specific variability of indoor radon levels; and
- increased $CO_x$ and $NO_x$ levels indoors from unventilated combustion appliances.

A second phase of research in these homes was cosponsored by TVA and the Electric Power Research Institute (EPRI), whose interest was in more fully assessing the interactions among home weatherization, air exchange, energy use, and indoor pollutant levels [2]. The specific objectives for this phase were to:

- collect additional indoor radon data;
- repeat formaldehyde measurements in homes with high levels;
- ascertain interrelationships among indoor pollutant levels, home weatherization, air change rates, and energy use; and
- develop a relational indoor air quality database compatible for mainframe and microcomputer applications.

A new aspect in the field investigations of this phase of the study was the use of TVA residential energy auditors to characterize the degree of weatherization of the structure. Houses were classified on the basis of the auditors assessment of whether the windows and/or doors needed additional weatherization. This assessment included recommendations for weatherstripping, caulking, a storm door, a door threshold, or a storm window. The classification of the degree of weatherization of twenty-six homes audited is presented in Table 1.

An important observation is that of the original participants in the study only twenty-six agreed to an energy audit in the next phase. Also, during the first phase, additional homeowners were later included to replace those who dropped out of the study. These occurrences illustrate a critical subjective factor in the implementation of the indoor air quality field studies, namely, the need not to overly burden the participant in the study. In the two other field studies, actions were pursued to encourage a continuing and comprehensive involvement by the participants are discussed in their respective sections.

Table 1. Degree of Weatherization of Twenty-Six Houses

| *Number of Houses* | *All Doors Weatherized* | *All Windows Weatherized* |
|---|---|---|
| 7 | Yes | Yes |
| 4 | Yes | No |
| 5 | No | Yes |
| 10 | No | No |

Table 2. Averages and Standard Deviations of Air Exchange Rates ($h^{-1}$) for Groups of Houses in Different Seasons

| | | *Doors and Windows Weatherized* | | *Doors Weatherized but Windows Not Weatherized* | | *Doors Not Weatherized but Windows Weatherized* | | *Doors and Windows Not Weatherized* | |
|---|---|---|---|---|---|---|---|---|---|
| *Fan* | *Season* | *Mean* | *SD* | *Mean* | *SD* | *Mean* | *SD* | *Mean* | *SD* |
| Off | Spring | 0.22 | 0.03 | 0.23 | 0.08 | 0.47 | – | 0.38 | 0.18 |
| | Summer | 0.26 | 0.08 | 0.27 | – | 0.41 | 0.08 | 0.62 | – |
| | Fall | 0.55 | 0.34 | 0.73 | – | – | – | 0.51 | – |
| | Winter | 0.50 | – | – | – | 0.96 | 0.03 | 0.62 | 0.40 |
| On | Spring | 0.46 | 0.07 | 0.94 | 0.28 | 0.64 | 0.25 | 0.33 | 0.02 |
| | Summer | 0.67 | 0.03 | 0.58 | – | 0.80 | 0.09 | 0.92 | – |
| | Fall | 0.88 | 0.41 | 1.10 | – | – | – | 0.78 | – |
| | Winter | 0.96 | – | – | – | 1.01 | 0.15 | 0.79 | 0.26 |

This second phase resulted in a detailed assessment of spatial and temporal variations of indoor formaldehyde levels and indoor pollutant levels associated with the use of unventilated combustion appliances. From a field study viewpoint, the statistically significant interactions between the degree of weatherization of the structure and air change rates, indoor formaldehyde, and indoor radon were examined.

Table 2 presents air change rate data for the degree of weatherization versus operation of the HVAC fan and by season. An analysis of variance indicated that significance existed for operation of the HVAC fan and season of the year ($p < 0.01$). A statistically significant interaction was found between air change rate and weatherization only for the case where both the doors and windows were fully weatherized ($p < 0.01$). Although the importance of the state of weatherization on air change rates is recognized as a factor in residential field studies, the significance of season and, moreover, the operation of the HVAC fan in the development of the study design and during the field measurements may be less appreciated.

Table 3 provides indoor formaldehyde data for the degree of weatherization versus month and the type of insulation. Analysis suggests that type of insulation, month, and window weatherization are significant ($p < 0.01$). Door weatherization was only found to be significant when jointly considered with wall insulation or with window weatherization. The importance of sources and temperature effects on indoor formaldehyde levels are usually recognized factors

Table 3. Monthly Averages and Standard Deviations of Formaldehyde Levels (ppb) for Groups of Houses

| | | *Doors and Windows Weatherized* | | *Doors Weatherized but Windows Not Weatherized* | | *Doors Not Weatherized but Windows Weatherized* | | *Doors and Windows Not Weatherized* | |
|---|---|---|---|---|---|---|---|---|---|
| *Insulation* | *Month* | *Mean* | *SD* | *Mean* | *SD* | *Mean* | *SD* | *Mean* | *SD* |
| UFFI | April | 94 | 44 | 102 | – | 107 | 36 | 25 | – |
| | May | 94 | 35 | 131 | – | 72 | 73 | 16 | – |
| | June | 77 | 67 | 89 | – | 62 | 71 | 12.5 | – |
| | July | 97 | 51 | 127 | – | 99 | 78 | 15 | – |
| | August | 122 | 76 | 184 | – | 127 | 62 | 12.5 | – |
| | September | 104 | 90 | 172 | – | 108 | 99 | 12.5 | – |
| | October | 33 | 13 | 23 | – | 23 | 16 | 23 | – |
| | November | 48 | 34 | 102 | – | 38 | 27 | 44 | – |
| | December | 31 | 7 | 46 | – | 38 | 30 | 41 | – |
| non-UFFI | April | 47 | 12 | 42 | 5 | – | – | 34 | 14 |
| | May | 33 | 25 | 30 | 30 | 12.5 | – | 24 | 11 |
| | June | 49 | 49 | 35 | 32 | – | – | 12.5 | 0 |
| | July | 27 | 20 | 29 | 0.3 | 43 | – | 43 | 46 |
| | August | 47 | 43 | 30 | 30 | 184 | – | 38 | 33 |
| | September | 45 | 28 | 49 | – | 30 | – | 26 | 14 |
| | October | 36 | 41 | 12.5 | 0 | – | – | 20 | 14 |
| | November | 21 | 14 | 12.5 | 0 | – | – | 20 | 14 |
| | December | 24 | 19 | 20 | 13 | 188 | – | 31 | 32 |

in many field study designs. However, the interaction of formaldehyde levels with partial weatherization of the structure's windows is not. This relationship could be a data artifact due to the small sample size or could be indicative of a structural characteristic which may affect indoor formaldehyde source/sink or indoor relative humidity relationships. The latter suggests that relatively minor structural factors may significantly affect indoor formaldehyde levels and may necessitate additional consideration of these factors in the study design and interpretation of data.

Table 4 depicts indoor radon data relating the degree of weatherization to site of the residence and location of the measurement within the residence. The results of analysis indicate significant interactions between indoor radon levels and the house site, measurement locations, and weatherized doors ($p < 0.01$). Weatherized windows were only significant in combination with doors or house site ($p < 0.01$). The identification of a partial weatherization effect (this time for doors) is interesting. Since an effect from partial weatherization is not observed for the air change rate data set, factors not related to fresh air infiltration may affect indoor pollutant levels. For radon this may be of special

Table 4. Averages and Standard Deviations of Upstairs or Downstairs Radon Levels (pCi/L) for Groups of Houses

| | | Doors and Windows Weatherized | | Doors Weatherized but Windows Not Weatherized | | Doors Not Weatherized but Windows Weatherized | | Doors and Windows Not Weatherized | |
|---|---|---|---|---|---|---|---|---|---|
| *Location* | *Area* | *Mean* | *SD* | *Mean* | *SD* | *Mean* | *SD* | *Mean* | *SD* |
| Valley | Downstairs | 1.13 | 0.30 | – | 2.26 | 1.90 | 0.80 | 6.04 | 2.17 |
| | Upstairs | 0.60 | 0.31 | 1.23 | 0.78 | 1.50 | 0.29 | 3.33 | 2.76 |
| Ridge | Downstairs | 9.99 | 5.57 | 7.02 | 1.57 | – | – | 2.12 | 0.50 |
| | Upstairs | 9.35 | 4.75 | 2.27 | 1.40 | 1.88 | 0.42 | 2.52 | 1.19 |

interest because subtle interrelationships may exist between the weatherization of the structure and building depressurization which drive radon entry. Such results could also be anomalous, and contradictory interpretations may be seen when different subsets of the data are examined.

Even for a modestly sized study, such as this, data management is of critical importance both during the conduct of the investigation and during the data analysis phase. The development of a relational database using D-base III software was undertaken and described in the project report [2]. This approach proved useful not only for data analysis but for exchange of primary study data with other researchers. A formatted floppy diskette is provided with the report rather than a supplemental volume containing the primary data.

## SEVENTY-HOME FOUR-STATE STUDY

The four-State study is an outgrowth of a TVA-sponsored investigation to examine background radon progeny levels in homes [3]. This study was restricted to homes with basements in order to maintain a reasonable sample size requirement and to look at those dwellings which tend to be most suspectible to radon entry. Seven cities in the four-State area were selected as sites for the field monitoring (Oak Ridge and Chattanooga, Tennessee; Rossville, Georgia; Birmingham, Florence, and Huntsville, Alabama; and Tupelo, Mississippi). Four quarters of monitoring began in the late summer of 1985.

Since the primary costs of indoor air quality field studies are in soliciting participants and site visits, additional measurements in the homes and the addition of more homes in a site area can be done very cost effectively. Consequently, other organizations expressed a willingness to fund new measurements. TVA's Office of Power and the Alabama Power Company supported activities to make multizonal air change (upstairs/downstairs) measurements, energy surveys, and housing characteristics assessments [4].

CPSC supported VOC monitoring. The U. S. Environmental Protection Agency (EPA) sponsored HCHO, $NO_2$, $H_2O$ (passive), and PNA measurements in each house and particulates in a subset of homes [5]. They also funded detailed active and passive measurements in six houses. The Alabama Power Company additionally sponsored the inclusion of ten energy-efficient houses in the Birmingham area.

Participants were first solicited by targeted mailings, but the response was poor. Next a combined appeal through television news conferences and newspaper press releases in each of the site cities obtained the desired participation. Selection was complicated by two factors:

1. homes with basements comprised a low percentage of houses in the study areas; and
2. the basement walls were screened to determine whether Florida phosphate slag was used in the block.

Houses were excluded if Florida phosphate slag was present so only natural radon phenomena could be examined. Since participation agreements for both the monitoring and the energy survey were presented and explained to the homeowners at the start of the survey, over 90 percent agreed to the energy survey. Also, to maintain the interest of the homeowners throughout the year-long study, a quarterly newsletter was prepared and mailed to each participant providing them with preliminary data results and the schedule of field visits and activities for the quarter.

An overview of measurements is as follows. Radon is the primary measurement objective and entails: quarterly and year-long alpha-track measurements downstairs and upstairs; quarterly radon progeny measurements with MODs; quarterly grab (Lucas cell type) radon measurements; and quarterly alpha spectrometry on ten-minute filter samples [3]. Air change rates using dual source perfluorocarbon tracers (PFTs) to assess upstairs/downstairs pollutant transport were done. $NO_2$, HCHO, $H_2O$, and PNA passive dosimeters were exposed for a one-week period each quarter. Particulate matter 2.5 (using slit impactors) and VOC (using triple-sorbent sample tubes) measurements were made in a subset of the houses [6].

Although the field study is still in progress, some preliminary data are available which illustrate phenomena important to large area field investigations. The radon and radon progeny data permit examination of equilibrium factors and regional distribution. Figure 1 shows the distributions of equilibrium ratios estimated from preliminary data from alpha spectroscopic measurements and from measurements using modified Lucas cells. Data are taken from cases when the level of radon was greater than 3 pCi/L and the level of progeny was greater than 0.015 WL. Ratios were calculated by multiplying the ratio of progeny, in WL, to radon, in pCi/L, by 100. Only data from cases when both progeny and radon were easily detected were used. The median ratio of the upstairs data was

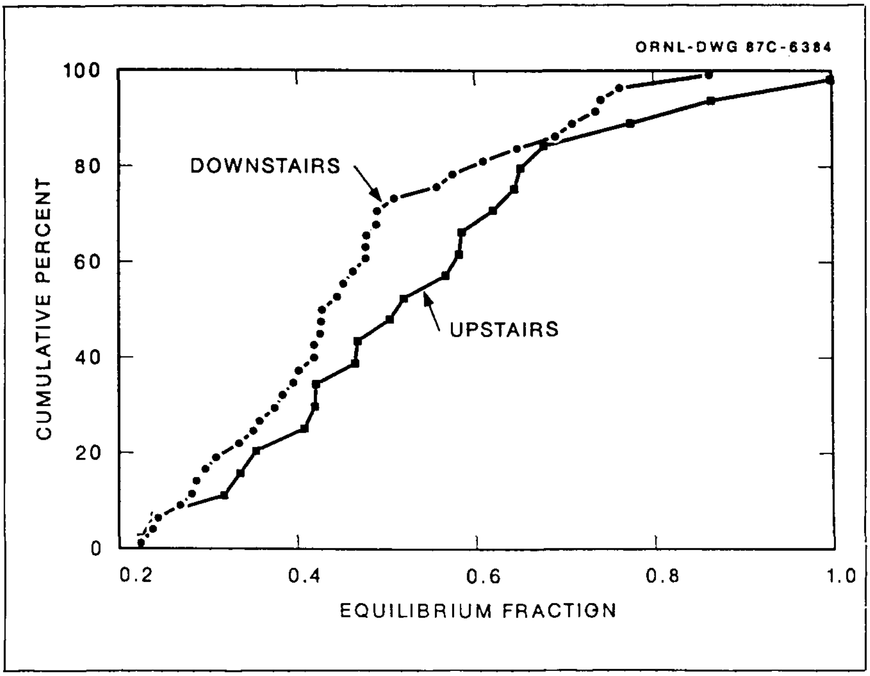


Figure 1. Downstairs and upstairs cumulative distributions of radon progeny/radon equilibrium factors for all site areas (summer 1985 data).

about 55 percent which is consistent with the standard assumption of 50 percent. The median of the downstairs data was less, about 40 percent. Both distributions are broad, ranging from below 30 percent to 60 percent. Assuming radon enters the basement essentially free of progeny, the equilibrium ratio might be expected to be less in the basement than in the upper levels of the house [7]. Figure 2 depicts the distributions of radon levels determined in homes in different site areas. Measurements were made at both upstairs and downstairs locations during the summer of 1985.

Figure 3 illustrates seasonal effects on formaldehyde levels measured downstairs in houses in Birmingham, Alabama. Measurements were made during the summer of 1985 and the winter of 1986. Summer levels were almost twice the winter levels. During the winter, temperature and humidity were much lower and emissions of formaldehyde from pressed wood products might be expected to be reduced under those conditions [8]. Indoor levels of nitrogen dioxide measured downstairs during the summer of 1985, vary between site areas, as seen in Figure 4. On average, indoor levels were 70 percent of corresponding outdoor levels of nitrogen dioxide in one city where multiple indoor and outdoor measurements were made. Further examination of the data is planned to explore the interactions of outdoor air

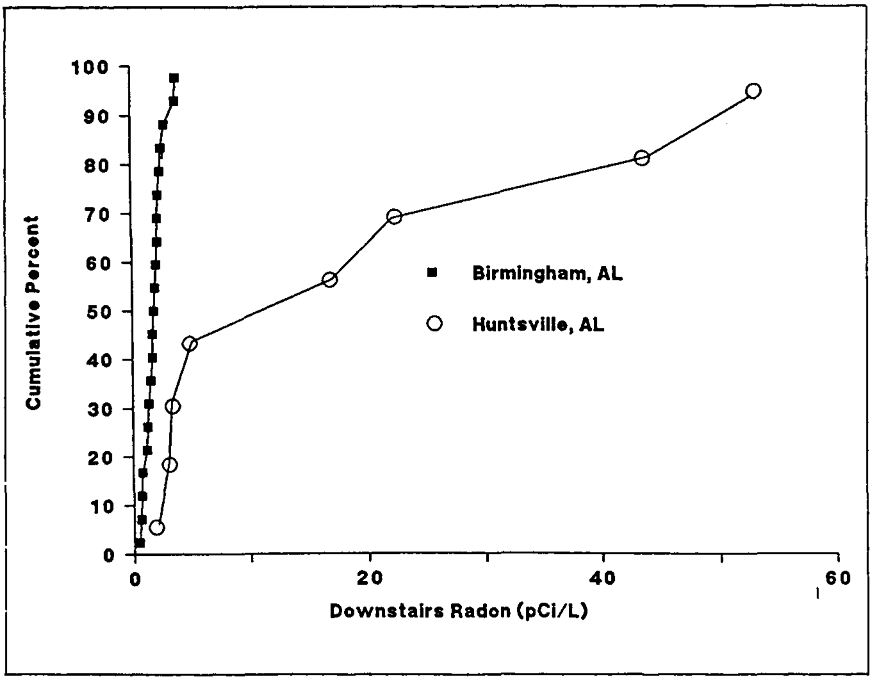


Figure 2. Cumulative distributions of three-month average indoor radon levels (pC/L) at Birmingham and Huntsville, Alabama (summer 1985 data).

pollutants and climate on indoor levels. However, it is clear even from these preliminary findings that an aggregated site or cluster approach to large area field studies must carefully evaluate the impact of regional variability when integrating, analyzing, and interpreting the field data.

## THREE-HUNDRED-HOME KINGSTON/HARRIMAN STUDY

The three-hundred-Home Kingston/Harriman Study is part of a decade-long study of air quality and respiratory health being conducted by the Harvard School of Public Health (HSPH) for the National Institute of Environmental Health Sciences, EPRI, and EPA [9, 10]. The houses in the study are the homes of elementary school children in the health study. Two weeks of back-to-back monitoring are conducted in the summer and the winter. Six cities around the Nation are included in the study representing different classifications of outdoor air quality. Core measurements consist of the following activities:

- child respiratory health log;
- occupant questionnaire;

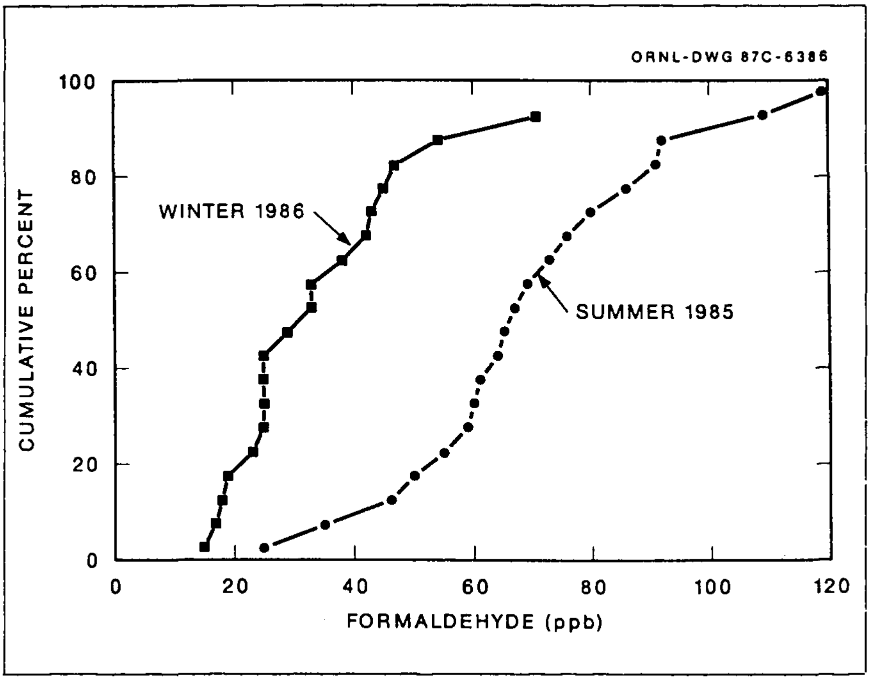


Figure 3. Winter and summer cumulative distributions of one-week average indoor formaldehyde levels (ppm) at Birmingham, Alabama (downstairs data).

- respirable particulate monitoring with HSPH impactor;
- $NO_2$ and water vapor monitoring with passive samples; and
- air change rate monitoring with PFTs.

ORNL was subcontracted by HSPH to manage field operations in the Kingston/Harriman area.

Several other research sponsors were interested in expanding the range of measurements in the study. The supplemental components and sponsors are:

- radon monitoring (EPRI and TVA);
- formaldehyde monitoring (EPRI and TVA);
- biogen (bacteria and fungi) monitoring (EPRI and TVA);
- PNA monitoring (CPSC and TVA); and
- energy survey and zonal mixing (TVA).

The immediate outcome of expanding the 300-home study was a redesign of the sample. The basic six-city design is a 2 x 2 block design of occupant smoking versus gas cooking [9]. Previous appliance surveys by TVA indicated little gas cooking was present in the area. However, wood heating and kerosene

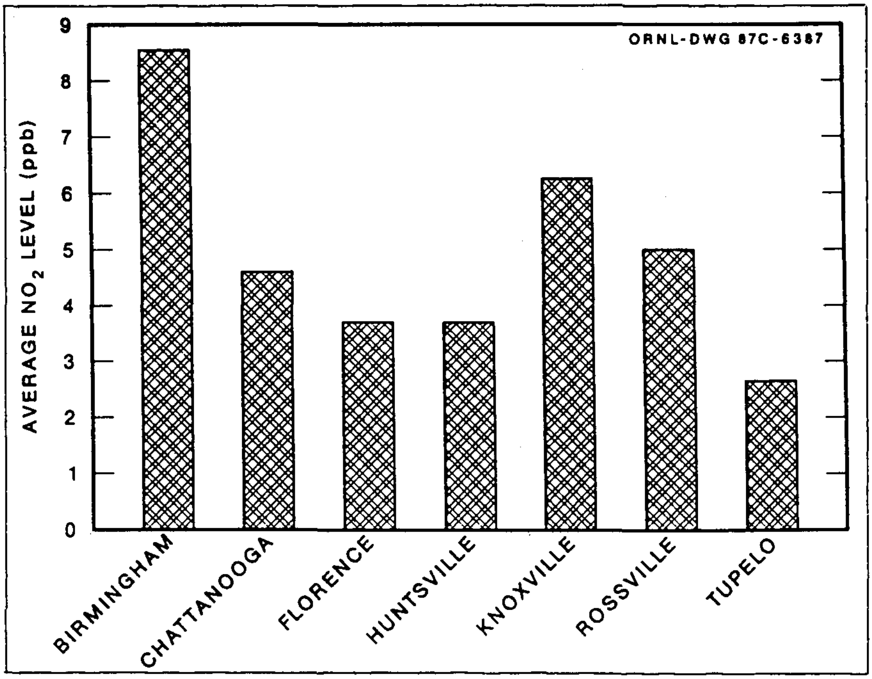


Figure 4. One-week average indoor nitrogen dioxide levels (ppb) by site area (downstairs, summer 1985 data).

space heating were used widely in the study site. Consequently a new 2 x 2 x 2 design stratifying on occupant smoking, wood heating, and kerosene heating was developed by various researchers involved in the study.

From a field study design perspective, this was a significant decision for several reasons. First, there was uncertainty as to how this design modification would affect the overall data analysis in the six-cities study. Second, there was a question of whether statistically relevant information could be obtained from the modified design to interpret respiratory health effects. Third, there was the uncertainty that sufficient numbers of participants could be found to fill the eight cells in the study. Table 5 presents the new stratified design, the target cell size, and recruitment as of January 13, 1986. Fortunately, suitable diversity existed in the sample population to adequately fill most cells. Also, this exercise indicates that in a large longitudinal cohort study it may prove desirable to selectively include a design alternative to obtain measurements on other indoor pollutant sources which may affect the final interpretation of the data. In this case alternative combustion space heating was assessed.

The biogen monitoring requires further comment because this is a relatively novel component of residential indoor air quality field studies and represents one of the first attempts to characterize noncomplaint homes. The major

Table 5. Stratification of Houses and Recruitment Level

| | *Combustion Source Stratification* | | | *Recruitment Level* | |
|---|---|---|---|---|---|
| *Code* | *Smoking* | *Kerosene* | *Wood/Coal* | *Target* | *As Of 1/31/86* |
| 1 | No | No | No | 45 | 43 |
| 2 | No | No | Yes | 45 | 68 |
| 3 | No | Yes | No | 45 | 5 |
| 4 | No | Yes | Yes | 45 | 8 |
| 5 | Yes | No | No | 45 | 35 |
| 6 | Yes | No | Yes | 45 | 49 |
| 7 | Yes | Yes | No | 45 | 37 |
| 8 | Yes | Yes | Yes | 45 | 27 |

objectives are to quantitate airborne microbial population and to determine the major bacterial and fungal genera. Also shower heads, heat pump and air-conditioner coils, humidifiers, and regrigerator/freezer drip pans were sampled. Since the biogen monitoring was largely an unknown factor, a two-stage approach was employed. The winter phase of the study was to evaluate and/or develop appropriate biogen monitoring protocol in a subset of the houses. A full complement of biogen data collection was undertaken during the summer phase. Flexibility in the development and implementation of protocols for new indoor substances may prove necessary to conduct a large multipollutant investigation.

## ASSESSMENT OF CRITICAL FACTORS

Critical factors associated with the conduct of multipollutant field studies can be categorized into the following areas:

- factorial study design;
- participant selection and communications;
- interactive effects;
- regional and environmental variability;
- relational database management;
- new protocol evaluations; and
- multiple sponsor coordination.

The importance of factorial design approaches may be seen in the seventy-home and the three-hundred-home studies where appropriate stratification was used to focus both studies on specific research priorities. However, extrapolation from such studies to the general population must be carefully undertaken. For example, extrapolation of radon data from the seventy-home four-State study to the region as a whole must be carefully done, if at all, because the measurements are only made in homes with basements which may comprise 25 percent or less of the housing stock.

Residential field studies will only succeed if homeowners are cooperative. Thus, keeping them informed is important to ensure their continued participation. Researchers also have an obligation to inform participants of adverse conditions which have been determined to exist in their homes, even if it compromises the outcome of the study.

Interactive effects among pollutant levels, housing parameters, and occupant activities are extremely important considerations in the design, protocols, and data analysis. These interactions may be subtle. For example, are housing parameters related to air infiltration or to home depressurization more important determinants of indoor radon?

Regional and environmental variability considerations are typically important factors regarding design and analysis. Consideration of this variability should be made when aggregating data from large area field studies and when isolating outdoor influences from indoor ones.

The use of a relational database management approach on personal computers in multipollutant studies serves several purposes. Detection and removal of data entry errors is enhanced. Tracking of laboratory analytical results and matching with records of field exposure conditions are facilitated. The use of standard data definitions and microcomputer data formats could greatly facilitate exchange of information among researchers.

Careful attention must be given to the development of new protocols to ensure the quality and comparability of research results. When possible such protocol development should occur as an integral part of the field study so it is evaluated over a broad range of conditions.

Since many indoor quality field studies are designed to serve many objectives and frequently have multiple sponsors, it is more important to develop a productive, sensitive, working relationship between the involved researchers. The payoff for such cooperation is reduced total cost and enhanced information for all parties involved.

The aforementioned factors not only illustrate the complexity of multipollutant indoor air quality field studies but suggest the importance of building an interdisciplinary team to undertake the investigation. Indoor air quality is not just an air resources problem for air quality researchers. Rather it can be better defined as an indoor environment evaluation requiring a multidisciplinary approach.

## ACKNOWLEDGMENTS

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